SOLVING COMPLEX OCEAN CHALLENGES THROUGH INTERDISCIPLINARY RESEARCH: ADVANCES FROM EARLY CAREER MARINE SCIENTISTS

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Table of Contents

frontiers | Frontiers in Marine Science

EDITORIAL
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Editorial: Solving Complex Ocean Challenges Through Interdisciplinary Research: Advances from Early Career Marine Scientists

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Editorial on the Research Topic

Solving Complex Ocean Challenges Through Interdisciplinary Research: Advances from Early Career Marine Scientists

Anthropogenic impacts on the world's coasts and oceans are accelerating at an unprecedented rate, threatening marine biodiversity and ecosystem functioning, and with it the sustainability of the goods and services marine systems provide, with downstream impacts on societal well-being and livelihoods. Embedded within complex social-ecological systems, coasts and oceans are subject to uncertain, unpredictable, and interconnected challenges, to which solutions cannot be developed through single disciplinary approaches. To this end, there has been growing recognition of the need for interdisciplinary and transdisciplinary marine science to push towards sustainable, productive, and healthy coasts and oceans at a time of significant global change (Kelly et al., 2019).

Early Career Researchers (ECRs) are at the forefront of this new research agenda, and this Research Topic showcases the diversity of research undertaken by the next generation of marine

scientists. We received 41 contributions which included first authors from 18 different countries. Themes of contributed papers include: (1) understanding and quantifying the state and variability of marine ecosystems; (2) improving scenarios, predictions, and projections of ocean-human systems at multiple scales; (3) improving and achieving sustainable marine governance; and (4) perspectives on ECRs' role in solving grand ocean challenges (**Figure 1**). The papers in this special issue highlight the wide-reaching and interdisciplinary nature of ECRs in identifying and developing innovative solutions to challenges associated with rapid changes in the world's coastal zones and oceans. We conclude that maximising the contributions of ECRs to interdisciplinary marine research requires the development of impact-based performance metrics (i.e. those that go beyond traditional publication-based metrics), building effective interdisciplinary institutional capacity, promoting diversity, equity, and inclusion, and integrating ECRs into global research efforts. This will help to unlock the full potential of ECRs to aid efforts to safeguard the future of marine environments for all of society and ensure a broader and more inclusive perspective. This is particularly pertinent as we enter the United Nations Decade of Ocean Science for Sustainable Development (2021-2030).

THEME 1: UNDERSTANDING AND QUANTIFYING THE STATE AND VARIABILITY OF MARINE ECOSYSTEMS

Climate change continues to disrupt ecosystem function and human communities globally, threatening biodiversity as well as food supply and economic security (IPCC, 2021). There is a clear need to quantify the current state of marine ecosystems, so as to define a present-day baseline and improve understanding of how ecosystems are responding to climate variability and climate change. This includes considering new forms of knowledge production and accounting for epistemologies when

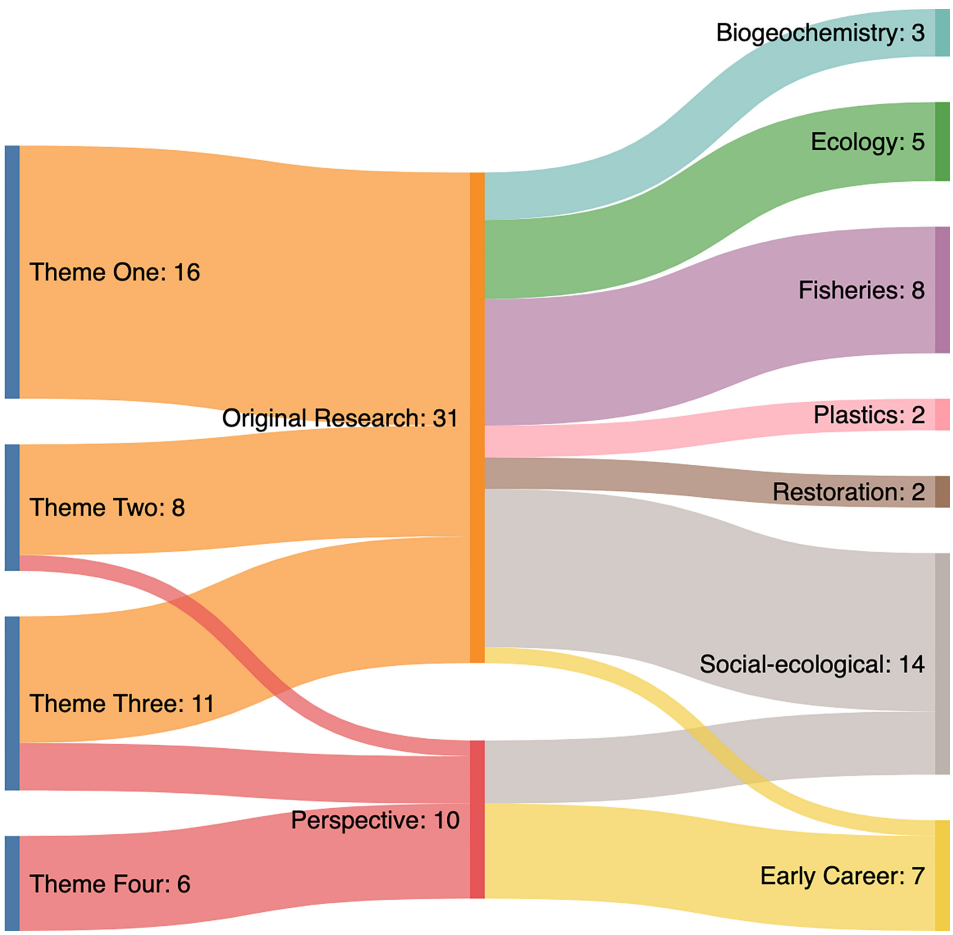

FIGURE 1 | Sankey diagram summarising the 41 articles contributed to this Research Topic (source: http://sankeymatic.com/build/). Diagram shows the distribution of articles across identified themes (left), whether they were an original research article or perspective piece (middle), and the general discipline or topic of the article (right). Numbers represent the number of papers in each category.

conducting integrative marine research (Moon et al.). The first theme to emerge from this Research Topic focused on understanding and quantifying the state and variability of marine ecosystems. Topics ranged across disciplines, from the need for improved marine biosphere observations, over the role of ecosystem services, to the vulnerability of ecosystems to climate extremes and variability.

In situ Observations of Marine Biosphere

In situ observations are necessary to assess changes in ecosystems, and contributions highlighted advances in marine biosphere observation systems. Aniceto et al. demonstrated that ocean gliders can provide effective observing platforms for collecting data on physical and biogeochemical environmental features in conjunction with information on cetacean presence using a coupled hydrophone. Relatedly, bioacoustic surveys are commonly used to estimate and monitor population size of key fish stocks. Wassermann and Johnson highlighted that incorporating individual fish behaviour into acoustic sampling would reduce uncertainty of bioacoustic surveys, and ultimately improve biomass estimates for economically important fisheries. Strategies used to sustainably manage fisheries harvests require information across all life-stages, not just information on population size. Izquierdo et al. used scientific trawl surveys to identify persistent hake nurseries using environmental and spatio-temporal variables and thus produced improved indices to calibrate length-based stock assessment models. Ocean and ecosystem observations are needed across all levels of biological organisation, including at the individual level. Assessing an individual organism's health can be an informative measure to evaluate impacts to specific populations, particularly for threatened species such as cetaceans. Derous et al. synthesised recent developments in cetacean blubber biology to support development of new cetacean health markers that can be used to observe the health of threatened cetacean populations.

Ecosystem Services

As climate change disrupts ecosystem function, the provision of ecosystem services and the well-being of human communities that depend on those services are at risk. Improved efforts to understand and quantify the role of ecosystem services are thus critically needed. For example, Benavides and Robidart highlighted the need to leverage high resolution measurements of dynamic seawater structures to better estimate the contribution of marine microbes (diazotrophs) to N_2 fixation and global nitrogen estimation. Likewise, Jiang et al. examined atmospheric nitrogen variability and its role in driving primary producer growth and subsequent feedback from climate events and coastal human activities. In another example, supporting ecosystem services such as carbon sequestration and carbon storage are vital to climate change mitigation programs, but high spatiotemporal variability in an example seagrass bed cautions against estimations of site-specific carbon stocks using generalised global values (Juma et al.). Changes to ecosystem function and services may require ecological restoration efforts as well, but caution is needed so as to better understand the cultural importance of ecosystem services and to use appropriate indicators that reflect ecosystem value and function more inclusively (Cadier et al.). Pouso et al. proposed an interdisciplinary approach to evaluate changes in cultural ecosystem services in restored systems. Likewise, Prinz et al. conducted stakeholder interviews to assess perceptions around an ecotourism activity that impacts local ecosystem function. While climate change is the major threat facing ecosystems globally, marine plastic pollution has also emerged as an international environmental issue of increasing public concern that threatens provisioning and cultural ecosystem services (Beaumont et al., 2019). Empirical studies that describe microplastic contamination (Barrett et al.) and toxicity (Sarker et al) for marine ecosystems will help to form a baseline for the continued impacts of plastic on coast and ocean health.

Climate Variability and Change

Extreme climate events, such as marine heatwaves, are interacting with longer-term climate change and leading to unprecedented environmental conditions globally (Gruber et al., 2021; IPCC, 2021; Oliver et al., 2021). Fogarty et al. explored how Australian state fisheries agencies are incorporating climate variability and climate change into their management plans, and how funded research is accounting for climate change locally. They conclude that there is a need for increasing climate research in Australia to assure the preparedness of fisheries management in the changing world. Building on this call for increasing climate research in fisheries, Champion et al. assessed variation in predicted rates of climate-driven redistributions among four recreationally important coastal-pelagic fishes from an ocean warming hotspot. They demonstrate variation in the sensitivity of multiple coastal-pelagic fishes to climate change and highlight changing fishing opportunities off eastern Australia. There are increasing calls to better consider the role and impact of climate variability and extreme climate events on ecosystem function and human communities. Blaisdell et al. addressed this need by using a so-called "stress-scape" framework to compare environmental conditions during marine heatwaves and the impacts on Pacific cod. The framework applies the fundamentals of dynamic seascape classification, where they discovered stress-scapes were able to capture unique marine heatwave and non-heatwave classes, and effectively resolved five dynamic stress-scapes in the coastal Gulf of Alaska ecosystem.

THEME 2: IMPROVING SCENARIOS, PREDICTIONS AND PROJECTIONS OF FUTURE OCEAN-HUMAN SYSTEMS AT MULTIPLE SCALES

The importance of improving modelling scenarios, predictions and projections at multiple scales was one of the themes that emerged from the articles in this Research Topic, and highlighted that the accuracy of these approaches is key to preparing and adapting to change. For instance, Franco et al. showed how deep warming hotspots of the southwest South Atlantic Ocean extend

in the water column, particularly in the mid-water and bottom layers, where species of different ecological and economic importance inhabit. Their findings aimed to draw the attention of stakeholders and decision-makers to develop better management approaches for marine biota in the context of climate change. Tonelli et al. used a suite of Earth System Model projections to indicate a loss of bacterial and archaeal diversity in surface waters of the Southern Ocean, with potentially large negative implications for key biogeochemical processes, such as carbon, nitrogen, and sulphur cycling. Levine et al. studied the water-column response to major storms using a simplified data mining technique and concluded that establishing a community of practice for early career scientists in oceanography can enhance their skills, promote collaborations and potentially create meaningful scientific innovations.

Saldívar-Lucio et al. discussed the importance of identifying climate risks and responses at the local level and how psycho-social factors and local attributes might operate and enhance climate resilience. The importance of spatial scales was highlighted by Magel et al., who assessed risk as a combination of exposure, where Dungeness crab reliance and social vulnerability indices demonstrated that communities along the US west coast showed different degrees of susceptibility to a decline in catch. In a similar focus on spatiotemporal resolution, Lawson et al. demonstrated the sensitivity of bioenergetic models to spatial, temporal, and ontogenetic variability in predator diets. Other studies identified how interdisciplinary approaches can help improve adaptive capacity and strengthen management. For instance, Gammage and Jarre describe how using scenario-based approaches (i.e structured decision-making tools) in a research process with marginalised stakeholders can enhance adaptive capacity at the local level. Quintana et al. examined how a short-term, inclusive and adaptive area-based conservation model can help achieve both social and ecological objectives given that area design is ecologically sound and supported by integrated social-ecological theory.

THEME 3: IMPROVING AND ACHIEVING SUSTAINABLE MARINE GOVERNANCE

Marine governance is critical to ensuring biodiversity conservation and the sustainable use of coastal and marine resources. In the context of fisheries, Mackay et al. examined evidence for the possible connection between illegal, unreported, and unregulated (IUU) fishing and organised crime, and the links among illegal fishing and other crimes with the aim to protect those working in the marine fisheries industry and to support the sustainability of global fisheries. Relatedly, Mackay et al. explored what psycho-social characteristics of individuals were associated with the responses to management incentives in recreational fisheries, and identified that ecological values and personality types were important factors for certain compliance groups. Understanding the behavioural characteristics of fisheries compliance will help to progress innovative fisheries management.

Ortega-Cisneros et al. urged the inclusion of climate change and adaptation approaches into relevant fisheries management documents in South Africa, since the inclusion of both approaches is limited for the marine aquaculture and fisheries sector. In the aquaculture sector, Selim at al. examined ways to ensure equitable development, so that the most marginalised coastal communities impacted by increasing salinity are able to benefit from new livelihoods that are adapted to climate change.

This topic also highlights the relevance of introducing significant changes in management tools to those which facilitate participatory modes of governance, which can also serve genuine knowledge co-production (Breckwoldt et al.), avoid exclusionary processes in underrepresented groups, and recognise the access, rights, and cultural values of marine social-ecological communities, with the aim to promote social equity and ecological conservation (Muhl et al.; Okafor-Yarwood et al.; Pennino et al.). Uffman-Kirsch et al. further argues that public participation in marine-based decision-making can offer legitimacy to governance decisions, whilst also bolstering marine actors to use and sustain their social licence. This is further evidenced by Cvitanovic et al. who found visitors to a marine World Heritage Area had a limited understanding of the rules and regulations in place to support its management. They highlight future considerations for managers when developing visitor-focused communication and engagement strategies.

THEME 4: PERSPECTIVES ON THE ROLE OF EARLY CAREER RESEARCHERS IN SOLVING OCEAN CHALLENGES

The fourth theme to emerge from this special issue highlights perspectives on the role of ECRs in solving contemporary coastal and ocean challenges. Contributed papers highlight the unique challenges faced by marine ECRs, many of which have been exacerbated by the COVID-19 pandemic (Pardo et al.). These include the availability of paid work within the marine biology and conservation market (Osiecka et al.), and the need for ECRs to understand and employ interdisciplinary research approaches and develop a broader set of skills beyond those traditionally taught as part of ECR training. Cosentino and Souviron-Priego discuss the expectations placed on ECRs to have a wide range of skills beyond their focal research discipline, particularly in relation to communication and collaboration across disciplines. In addition to scientific endeavours, papers within this Research Topic highlight that ECRs are increasingly working to navigate the science-policy interface to ensure that the outcomes of their research have real world tangible impacts. For example, Ferrer et al. describe their view of participating in the UN climate negotiations as ECRs, summarising the key themes of the negotiations and encouraging other young scientists to familiarise themselves with the negotiation processes to facilitate ECR representation.

In highlighting the challenges faced by ECRs, contributed papers also identify opportunities, actions and solutions to overcome these barriers. Wilson et al. reflect on the

experiences of graduate students who successfully completed the NSF-funded Research Traineeship Program in the USA and discuss the importance of developing relationships to overcome disciplinary differences. Building on this, Deininger et al. suggest that senior researchers are key enablers for the success of ECRs. For example, senior researchers can include ECRs in their long-term funding and project planning, expose them to their research networks, and implement steps to share experimental knowledge both within and amongst institutions.

CONCLUSION

The papers in this Research Topic highlight the wide-reaching and interdisciplinary nature of ECRs in identifying and developing innovative solutions to successfully navigate marine sustainability challenges. Supporting ECRs to undertake successful interdisciplinary research necessitates institutional reform and support (Kelly et al., 2019). Measures to achieve these goals include the development of impact-based performance metrics (i.e. those that go beyond traditional measures of academic performance to acknowledge the broader set of activities that comprise interdisciplinary research practice), building effective interdisciplinary institutional capacity including the support of female leadership (as identified and outlined in Blythe and Cvitanovic), and promoting inclusive metrics of success to dismantle a discriminatory reward system in science and improve diversity, equity and inclusion across all scientific spaces (Brodie et al., 2021; Davies et al., 2021). Similarly, global research networks such as the Integrated Marine Biosphere Research Project (IMBeR), and in particular its ECR network the Interdisciplinary Marine Early Career Network (IMECaN), of which all the authors are members of, can help to strengthen global research networks and provide important pathways to help ECRs to undertake collaborative interdisciplinary research (Hobday et al., 2020; van Putten et al., 2021) Through these, and other steps, we can unlock the full potential of ECRs to become the future ocean leaders that are needed both now as we enter the UN Ocean Decade, and into the future, to safeguard the future of global marine environments for all of society and nature.

AUTHOR CONTRIBUTIONS

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ORIGINAL RESEARCH
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To Feed or Not to Feed? Coral Reef Fish Responses to Artificial Feeding and Stakeholder Perceptions in the Aitutaki Lagoon, Cook Islands

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Feeding wild animals is a regular habit in ecotourism worldwide with poorly known consequences for ecosystem functioning. This study investigates how effective bread feeding is at attracting coral reef fish in the South Pacific, which feeding groups of fish are most attracted, and how natural foraging rates of an omnivorous and a grazing-detritivorous fish are affected. Data were collected at sites where fish are regularly fed bread by snorkellers and at comparison sites where bread was only provided for this study, within the Aitutaki lagoon (Cook Islands). The fish community was censused and foraging rates of two model species (*Chaetodon auriga, Ctenochaetus striatus*) were quantified one hour before, during, and an hour after feeding events. Twenty-five percent of the species present at all sites (piscivores-invertivores) were effectively attracted to bread. Overall, mean fish density was higher at tourism feeding sites than at the comparison sites. During bread feeding events, taxonomic richness decreased, compared to the hours prior and after feeding across all sites. As piscivore-invertivores were consistently attracted to bread, localized shifts in their dominance over other trophic groups may be expected if bread feeding persists, likely carrying consequences for ecosystem functioning. The effect of bread feeding events on natural foraging rates differed between the model species. *C. auriga* ceased foraging on natural foods to feed on bread. Although *C. striatus* never fed on bread, its foraging rate on epilithic algal matrices decreased during bread feeding events. This indirect non-lethal ecological consequence of bread feeding contributes a previously unanticipated example relevant to the "ecology of fear" in marine fish. Stakeholder interviews revealed that locals favor feeding to sustain tourist satisfaction, whereas tourists appreciate snorkeling regardless of feeding. This indicates an opportunity for restrictions on fish feeding with minimal drawbacks for tourism. Future research on fish metabolism and cascading effects on the reef benthos may reveal further impacts of feeding on coral reef communities.

Keywords: coral reef, tourism, ecosystem function, foraging rates, provisioning, supplementary feeding, recreation, conservation evaluation

INTRODUCTION

Wild animals have always fascinated humans. Procuring encounters with non-captive wildlife is therefore a core motivation for wildlife- and eco-tourism, two booming sectors in the tourism industry (Newsome et al., 2005; Burgin and Hardiman, 2015). Tourists' demand for prolonged encounters with elusive animals encourages tour operators globally to attract these artificially through food (Newsome et al., 2004; Milazzo et al., 2006; Trave et al., 2017). Feeding marine fauna whilst snorkeling and diving is therefore a common, yet poorly regulated practice in marine tourism (Green and Higginbottom, 2000; Moscardo and Saltzer, 2004; Corcoran et al., 2013), with potentially grave implications for the conservation of affected marine ecosystems.

Artificial feeding of marine megafauna by tourists has reportedly led to changes in population size, migration, reproduction, and behavioral patterns, as well as being detrimental to an organism's health (Reynolds and Braithwaite, 2001; Orams, 2002; Hammerschlag et al., 2012). Less well-understood are the consequences of feeding coral reef fish, which are most commonly encountered by tourists visiting tropical oceans (Sweatman, 1996; Bessa et al., 2017a; Mattos and Yeemin, 2018). Resource management agencies in different parts of the world enforce bans on feeding of large mammals but ignore the customary feeding of small species like birds and fish at the same locations (Orams, 2002).

Although concerns have been raised over artificial foods potentially interfering with critical ecosystem functions underpinned by coral reef fish (Cole, 1994; Milazzo et al., 2005; Medeiros et al., 2007; Bessa et al., 2017b), behavioral responses of the latter to artificial feeding events remain understudied. This is of importance, as behavior of reef fish is considered a major determinant of an organism's functional role (Bellwood et al., 2019). Not only may artificial foods prevent fish from interacting naturally with their environment, but food provisioning by tourists may also result in behavioral habituation (Harriott, 2002; Orams, 2002; Newsome and Rodger, 2008; Semeniuk et al., 2009; Brookhouse et al., 2013; Bessa et al., 2017b). Artificial feeding events aggregate predatory fish and exacerbate predatory behaviors, thus resulting in interference competition and elevated predation risk for certain species (Newsome et al., 2004; Milazzo et al., 2006; Semeniuk and Rothley, 2008). Importantly, when large species are attracted and excited through artificial foods, human safety can be compromised (Perrine, 1989; Moribe, 2000; Brookhouse et al., 2013; Trave et al., 2017).

Spatio-temporal alterations in the relative abundance of fish species and structure of the fish community, as well as in habitat use and movement patterns (e.g., diel inversion of activity), are likely to affect the structure of entire populations and communities (Milazzo et al., 2005; Corcoran et al., 2013; Bessa et al., 2017a; Geffroy et al., 2018). Despite evidence from the Mediterranean, Atlantic, and Indian Ocean (Hémery and McClanahan, 2005; Milazzo et al., 2006; Feitosa et al., 2012) indicating that fish feeding can alter the community structure of fish assemblages, only few studies have focused on community-scale effects of artificial feeding with bread (Hémery and McClanahan, 2005; Ilarri et al., 2008; Sanguansil et al., 2017). It follows that experimental approaches documenting the effect on the habitual foraging rates of species are scarce (e.g., Wen et al., 2018). These knowledge gaps complicate the quantification of the impacts of artificial feeding at the ecosystem level and the sustainability of this practice within the ecotourism industry (reviewed by Newsome et al., 2012; Trave et al., 2017).

In remote island countries surrounded by extensive coral reefs, tourism is an important source of income largely supported by activities on reefs (Mellor, 2003; Spalding et al., 2017). Reduced reef health may change the abundance of reef fish, decreasing the value of the experience for tourists (Jones et al., 2004; Bruno and Selig, 2007) and potentially reducing their interest in the area. This may, in turn, prompt snorkeling and dive operators to attempt maintaining the aesthetic value of the reef environment and customer satisfaction by feeding fish artificially. Customer expectations and satisfaction are fundamental driving forces of the profitability of tourism (Semeniuk et al., 2009). Further, maintaining profitability will guide the attitudes and behaviors of local tour operators (Vaske and Manfredo, 2012). Whether the perceptions of tour operators regarding the added value of artificial fish feeding match the actual levels of satisfaction tourists obtain from such activity, however, remains uncertain (Patroni et al., 2018). As drivers and consequences of food provisioning for wildlife touch the realms of social as well as ecological sciences (Newsome, 2017), approaches that consider both ecological implications of artificial fish feeding and stakeholder perceptions are crucial to guide conservation and management actions (Ziegler et al., 2015; Patroni et al., 2018).

This study investigated for the first time both, temporary changes in fish species composition and disruptions in species foraging rates in response to artificial bread feeding while considering the stakeholder perceptions regarding this practice. Focusing on Aitutaki Lagoon (Cook Islands), where fish are fed bread daily during snorkeling tours, it was hypothesized that: (1) reefs where bread feeding by groups of tourist is a well-established practice will have higher fish density and species richness compared to sites where bread was provisioned experimentally by one researcher, (2) omnivorous fish will be most attracted to bread whereas more specialized feeding functional groups will avoid it, (3) fish species that feed on bread will cease foraging on natural substrata during bread feeding events and display lower-than-usual foraging rates afterward likely due to satiation, and (4) bread feeding is considered essential for tourists' satisfaction during lagoon snorkeling tours by both tourists and local tour operators.

MATERIALS AND METHODS

Study Area

This study was conducted from 6th December 2016 to 9th March 2017 in the near-atoll Aitutaki, located in the South Pacific Ocean, 18°51′28″ S, 159°47′7″ W. With an area of 18.1 km^2 and ∼2000 inhabitants, Aitutaki is surrounded by a triangular carbonate forereef that encloses an approximately 50-km^2 shallow, sandy

lagoon, spiked with coral pinnacles (Loubersac et al., 1991; Berno, 1999; Hoffmann, 2002; Rankey and Reeder, 2009, **Figure 1**). An estimated 29,261 tourists visited Aitutaki in 2015, thus showing a tourists-to-residents ratio of nearly 15:1 (Cook Islands Tourism, 2019). Fish feeding has been practised regularly for more than 15 years, as a part of lagoon tours to areas where wildlife is naturally abundant and diverse. Two-hour snorkeling tours are offered daily by 10 different operators mostly within the marine protected area around One Foot Island (1–5 tours d^{-1}) and at Maina (1–3 tours d^{-1}).

This study was conducted in accordance with the research permit issued by the Foundation of National Research and Office of the Prime Minister (reference number: 24- 16), Ministry of Marine Resources and the Aitutaki Island Council, which covered all underwater surveys and stakeholder interviews. It was carried out in accordance with the regulations of Guideline 2010/63 of the European Commission, and was approved by the local authorities (Secretary, Ministry of Marine Resources, Cook Islands, December 2016).

Field Experiment

Effects of Bread Feeding Events on Fish

The field experiment spanned four sites located on lagoonal pinnacles. Two of these sites had been established as bread feeding locations by tourism operators and regularly visited by groups of snorkellers for 15 years and throughout this study. These represented the characteristics of fish communities habituated to a well-established food provisioning practice (i.e., hereafter referred to as tourism feeding sites). Two comparative adjacent sites that had never been used for food provisioning were also studied. At these sites, experimental bread feeding was conducted by one of the authors (NP) for the duration of the experiment (i.e., experimental feeding sites). Experimental feeding sites would therefore resemble the situation that would emerge immediately following the initiation of an incipient food provision practice. Experimental feeding sites were located between 600 and 850 m apart from the corresponding tourism feeding sites (**Figure 1**). This separation ensured no exchange of individual fish between tourism and experimental feeding sites at least for small species, including the focal species which commonly move over distances < 20 m (Krone et al., 2008; Matis, 2018). Although published home range sizes of large-bodied fish may exceed the separation between sites, in practice, these tend to be constrained by the extensive flat sandy areas separating pinnacles and reef patches in lagoonal habitats (Jordan et al., 2005). It is therefore unlikely that confounding effects would have emerged due to the exchange of fish between tourism and experimental feeding sites. The spacing between sites also avoided competitive foraging halos of snappers (Strelcheck et al., 2007). All sites were similar to each other in substratum composition, mean depth and topographic complexity (Wilson et al., 2007, **Supplementary Material S1**). One loaf of bread (approximately 500 g) was used per feeding treatment across all sites.

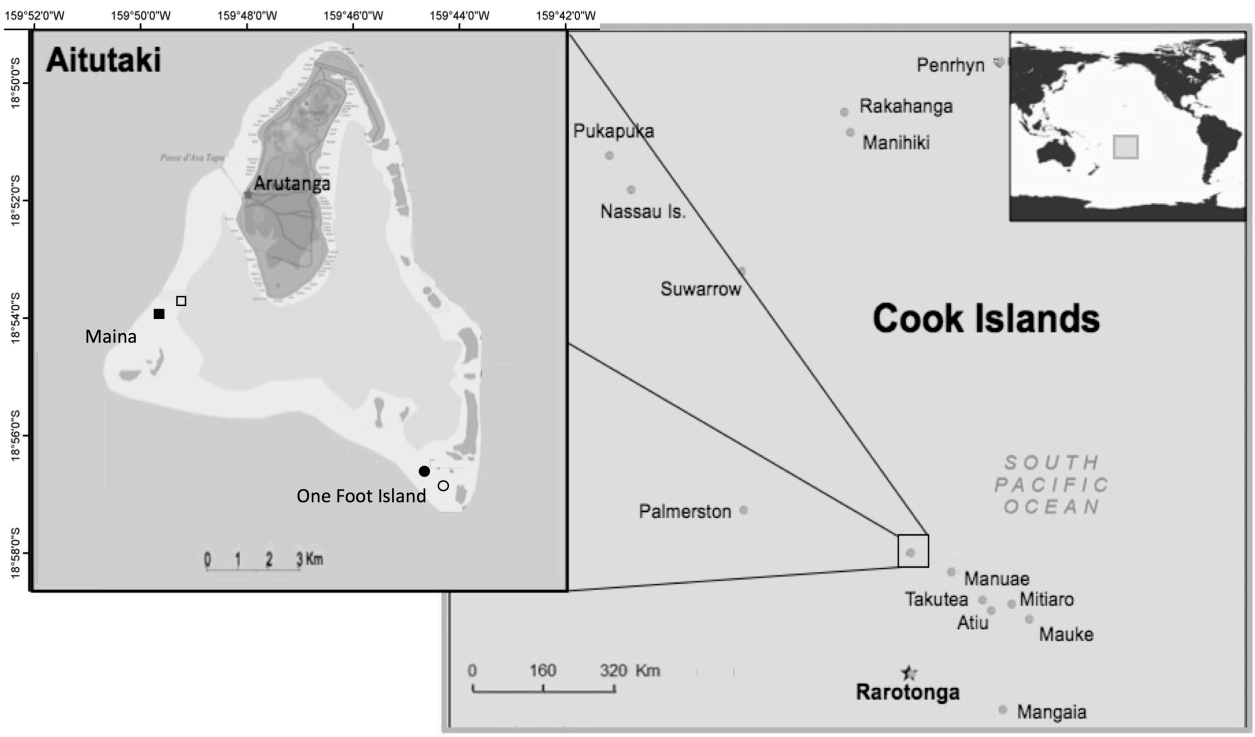

FIGURE 1 | Location of Aitutaki in the southern group of the Cook Islands **(right)** in the South Pacific Ocean. Map of Aitutaki near-atoll with its shallow lagoon **(left)**. Tourism feeding sites (filled symbols) and experimental feeding sites (open symbols) are indicated in One Foot (southeast) and Maina (southwest). Images adapted from Nevers (2008), creative commons.

To compare the effects of bread feeding events between tourism-established and experimentally-established artificial feeding practices, the 15-min surveys were conducted in tourism and experimental feeding sites at three time points, namely 1 h before, during, and 1 h after bread feeding episodes (Feitosa et al., 2012). Surveys focused on: (a) quantifying changes in fish density, fish community composition (by feeding group), and taxonomic richness in response to bread feeding events, (b) identifying fish species with high and low affinity for bread, and (c) detecting changes in natural foraging rates of two model species attributable to bread feeding. All surveys were conducted ± 2 h from high tide between 11:00 and 15:00 to capture diurnally active fish (English et al., 1997). No tourists were present at any time when surveys were conducted.

Quantifying the fish density, fish species composition (by feeding groups), and taxonomic richness is important because of the ecological relevance of these metrics, but also because they are important contributors to the aesthetic value of snorkeling tours for tourists. Fish density and taxonomic richness were quantified using stationary underwater visual censuses (Bohnsack and Bannerot, 1986), consistently conducted by the same observer (NP) to avoid inter-observer bias (Albuquerque et al., 2015). A 3 m radius (area of 28.27 m^2) was observed from a fixed position on the sea surface for 15 min while counting all active, non-cryptic fish. The maximum number of fish per species was recorded. At all sites, five censuses per site per feeding episode (before, during, after) were completed over 5 days. Species were assigned to feeding groups following Green and Bellwood (2009) and Pratchett et al. (2011) (**Table 1**). Mobile pelagic fish species, cryptic species and large wrasses were excluded from further analysis due to the bias that either their high variability and little attachment to single reef patches.

Species that fed on or avoided bread were identified through direct behavioral observations during the five bread feeding events initiated at both tourism and experimental feeding sites. Species were considered to display a high affinity for bread when more than 10 individuals fed on bread. Species were noted as having low affinity for bread when individuals were indifferent to or tried and rejected it.

Effects of Bread Feeding on Fish Foraging Rates

Two model species were selected for foraging rates observations given their ubiquity and important ecosystem function. Here, the species' function is defined as the species' role in the movement or storage of energy or material (Bellwood et al., 2019). Functionally, the omnivorous butterflyfish, *Chaetodon auriga* (facultative corallivore), consumes from very little to high amounts of live coral (Harmelin-Vivien, 1989; Pratchett, 2005; Cole et al., 2008), but also feeds on a variety of small invertebrates and algae (Myers, 1991). The detritivorous surgeonfish, *Ctenochaetus striatus,* targets the detritus entrapped within epilithic algal matrices, incidentally ingesting algal turfs and sediments (Crossman et al., 2001; Marshell and Mumby, 2012; Tebbett et al., 2017a). *C. striatus* plays a major role in benthic community composition structure dynamics and is one of the most important detritivorous fish species on Indo-Pacific coral reefs (Tebbett et al., 2017a). Species foraging rates (bites $minute^{-1}$) were considered a valid proxy for ingestion (Choat and Clements, 1993; Bellwood, 1995; Streit et al., 2015; Tebbett et al., 2017b). Gut content analyses were avoided as the study was designed to be minimally intrusive and target species were not found in fish markets. Foraging rates were further considered representative of the animal's ecological trophic function (Bellwood et al., 2006a; Fox and Bellwood, 2007, 2008). The extent to which fish trophic functions were affected by bread feeding was evaluated by quantifying foraging rates via 5-min focal follows of individuals of comparable size (i.e., ∼15 cm TL) conducted by a snorkeller from a conservative distance of ∼3 m (Lehner, 1996). The observers ensured the selected fish displayed no signs of disturbance, wariness, flight or hiding and continued behaving normally (Bellwood, 1995). As video recordings provide more accurate bite counts than those recorded visually by Scuba divers (Goatley and Bellwood, 2010), visual bite counts were supplemented here by recordings of the 5-min focal follow made with a GoPro video camera. Bouts of rapid consecutive bites that could not be discerned as individual bites were classed as single bites (Bellwood and Choat, 1990). Bites were not counted if dislodged material was ejected (Mantyka and Bellwood, 2007). Fifteen focal follows per species, site, and bread feeding event were completed over 5 days.

Stakeholder Perceptions

Perceptions regarding bread feeding of fish were investigated through a total of 104 questionnaires distributed among Cook Island nationals (50%, n = 52) and overseas-born stakeholders (50%, n = 52), including Aitutakian lagoon tour operators (n = 4), students (n = 28), employees of other sectors (n = 20), as well as foreign residents (n = 13) and tourists (n = 39) after obtaining prior informed consent (Questionnaire layout in **Supplementary Material S2**). The survey was conducted over a period of 2 weeks in March 2017 and respondents were selected

TABLE 1 | Feeding groups assigned to trophic level and as generalist or specialist feeder.

	Carnivores	Omnivores	Corallivores	Herbivores
Generalist feeding groups	Piscivore-Invertivore Invertivore	Omnivorous Planktivore Omnivore	Facultative Corallivore	
Specialist feeding groups	Ectoparasite feeder		Obligate Corallivore	Grazer-detritivore Scraper-small excavator Macroalgal browser

by opportunity sampling. Questions assessed whether the person agreed or not with feeding bread to fish and why. Tourists were asked to respond whether their level of satisfaction would decrease or remain unchanged if bread was not provided during snorkeling tours.

Data Processing and Statistical Analysis

To investigate responses in fish density, species composition by feeding group, and taxonomic richness to bread feeding and to determine whether the magnitude of these responses differed between places where the food provisioning is well-established or experimentally initiated, linear mixed-effects models (LMEs) were fitted (Pinheiro et al., 2015). Initial models included treatment (tourism or experimental feeding site) and timing relative to the bread feeding event (before, during, after) as fixed effects, and site as a random effect to account for the repeated observations. Model residuals were plotted against the fitted values to check for homogeneity of variance, and against each explanatory variable to check for violations of independence (Zuur et al., 2007). Stepwise model selection and AIC further identified the best-fit models. Models were followed by Tukey's *post hoc* tests to test for pair-wise differences whenever significant effects of multilevel factors were detected (Day and Quinn, 1989). Fish density was modeled using an LME, a fixed variance structure, and maximum likelihood estimates to account for heteroscedasticity (Zuur et al., 2009). Taxonomic richness was modeled using a generalized linear mixed-effects model (GLMM) with Poisson distribution verifying that the scale parameter φ was not significantly different from that assumed in a Poisson distribution (i.e., 1) (Crawley, 2007). To test the differences in fish species composition by feeding group, the densities were also compared between treatment (tourism or experimental feeding site) and timing relative to the bread feeding events (before, during, after) as fixed effects, and site as a random effect. To assess the degree of a species' affinity toward, or avoidance of bread, the absolute difference between its density during and before, during and after, and before and after bread feeding events were computed in both tourism and experimental feeding sites. This analysis focused on nine species commonly observed throughout all sites, including four carnivorous fish and five herbivorous fish that are considered to fulfill important functional roles in the reef.

To determine whether bread feeding disrupts fish trophic functions, we tested whether foraging rates of the model species changed before, during, and after bread feeding events, and whether such changes occurred both at sites where bread feeding is well-established or experimentally initiated. As foraging rates did not differ between the location Maina and One Foot, these were pooled together such that 10 feeding observations were available for *C. striatus* and nine for *C. auriga*. LMEs were fitted with treatment (tourism or experimental feeding site) and timing relative to the bread feeding event (before, during, after) as fixed effects, and site as a random effect. After model residual against fitted values were tested for homogeneity of variance, stepwise model selection and AIC further identified the best-fit models (Zuur et al., 2009). To test *a posteriori* pairwise differences, the Tukey's *post hoc* test was performed (Day and Quinn, 1989).

To obtain differences in (Yes/No) answers of stakeholders, questionnaire data were visualized in R-Studio and statistical analysis of frequency of particular responses among stakeholders was performed, using a Chi-square test (expected and observed values in **Supplementary Material S4**, and **Supplementary Table S3**). All statistical tests were performed using R-Studio (R Core Team, 2015).

RESULTS

A total of 5128 individuals of 71 species, belonging to 14 families, were recorded throughout the study (**Supplementary Material S3**). Overall, carnivores and herbivores were the dominant feeding groups, whereas corallivores were least represented across sites.

Effects of Bread Feeding on Fish Species Composition

Bread feeding events had significant short-term effects on fish assemblages. Mean fish density was significantly higher at

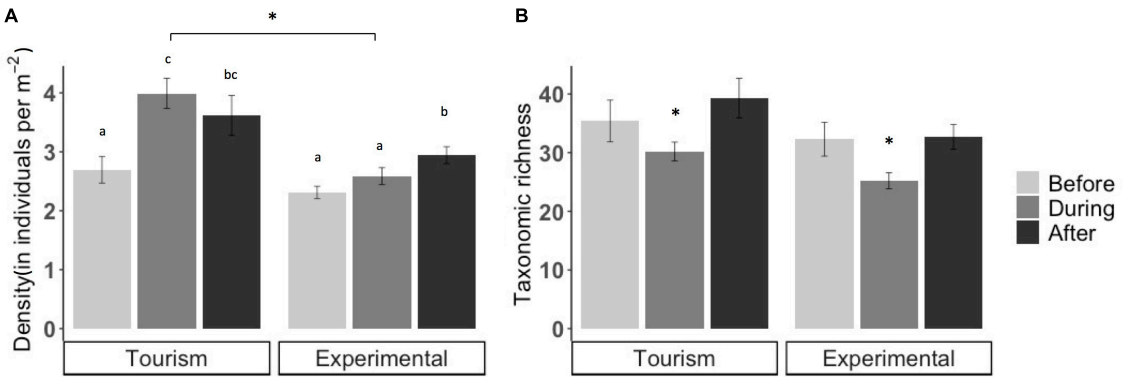

FIGURE 2 | Mean **(A)** fish density (± SE) **(B)** and taxonomic richness (± SE) before, during, and after artificial feeding events at tourism and experimental feeding sites. Note that the scale of y axes differs and significant differences are indicated by asterisks and letters.

tourism feeding sites compared to experimental feeding sites (density: $p = 0.046$; **Figure 2**). At tourism feeding sites, fish density increased by 29% during bread feeding events compared to 1 h prior to feeding ($p = 0.01074$). One hour after feeding events, the visible fish density remained high across sites (**Figure 2A**). At experimental feeding sites fish density increased after feeding compared to before ($p = 0.0136$). Taxonomic richness decreased during feeding events by an average of ∼20% compared to 1 h before feeding ($p = 0.001$, **Figure 2B**), but recovered 1 h after ($p < 0.00188$). This pattern was consistent through sites and treatments.

Piscivores-invertivores were consistently and strongly attracted to bread during feeding events at tourism feeding sites, but not at experimental feeding sites [$p < 0.001$, Tukey *Post hoc* (during $_{\text{Tourism}}$ – during $_{\text{Experimental}}$: $p = 0.00205$, **Table 2**)]. With the exception of large groups of planktivores (*Abudefduf sexfasciatus, A. vaigiensis*), which were consistently attracted to bread during feeding events and remained an hour after in only one of the tourism feeding sites (**Figure 3**), the density of all other groups remained unchanged by bread feeding events.

Affinity of Fish Species for Bread

During bread feeding events 25% of species fed on bread across sites, whereas 70% of species were indifferent to bread feeding episodes, and 5% tested but subsequently rejected or avoided the bread (**Table 3**). The majority of species that fed on bread were piscivore-invertivores (44%) and omnivores (28%). The relatively more specialized feeding groups, obligate corallivores, scrapers, macroalgal browsers, and grazer-detritivores did not feed on bread. About 40% of all species that fed on bread were non-scarine labrids (wrasses). Labrids ($p = 0.0486$) and lutjanids ($p < 0.0001$) congregated significantly when bread was supplied at tourism but not at experimental feeding sites (**Figure 4** and **Table 2**). For both non-bread-feeding families Acanthuridae and Scaridae the magnitude of the difference in density between before and during bread feeding events was not significantly different between tourism and experimental feeding sites.

Effects of Bread Feeding on Fish Foraging Rates

Across sites, foraging rates of *C. striatus* on the benthos significantly decreased by 22% during bread feeding events compared to an hour before ($p = 0.038$, **Figure 5A**). One hour after bread feeding events *C. striatus* resumed foraging rates similar to those observed prior to bread feeding (**Figure 5A**). *C. striatus* only tested the bread with consistently low rates across sites (**Figure 6**).

Foraging rates of *C. auriga* on natural substrata were significantly different between tourism and experimental feeding sites. The magnitude of the effect of bread feeding events differed between tourism feeding sites and experimental feeding sites ($p = 0.001$). At tourism feeding sites, foraging rates of *C. auriga* were eight times lower during bread feeding events (0.46 ± 0.34 bites min^{-1}) compared to the hour before (4.09 ± 1.8 bites min^{-1}, **Figure 5B**). This effect remained 1 h after the feeding episode (1.57 ± 0.5 bites min^{-1}). At sites where bread feeding was experimentally initiated, the foraging rates of *C. auriga* remained stable before (5.72 ± 1.5 bites min^{-1}), during (4.41 ± 1.1 bites min^{-1}), and after (4.29 ± 0.9 bites min^{-1}) bread feeding events. *C. auriga* fed on bread at very high rates (12.46 ± 1.8 bites min^{-1}) at tourism feeding sites, whereas it did not feed on bread at experimental feeding sites ($p < 0.001$, **Figure 6**).

Stakeholder Perceptions

Of all respondents ($n = 104$), 54% agreed that feeding may have a negative impact on the marine environment and modify natural fish feeding behaviors. All interviewed tourists that participated in a lagoon cruise declared they would appreciate these tours without bread feeding events, whereas only 54% of local stakeholders conceded that bread feeding was likely non-essential for the satisfaction of their guests ($p = 0.0003$, **Table 2**, Chi-squared expected and observed values in **Supplementary Material S4**, and **Supplementary Table S3**). Correspondingly, 75% of all local stakeholders (including tour operators) argued that bread feeding should continue, while 21% of all local stakeholders were in favor of stopping feeding fish artificially ($p < 0.0001$).

DISCUSSION

This study investigated for the first time both the ecological consequences of artificial feeding for coral reef fish in a Pacific Ocean lagoon, and whether this practice is considered necessary by local and foreign stakeholders. Although feeding fish artificially during recreational activities is commonly regarded as a possible cause for changes in fish behavior this had not yet been tested. Using a controlled field experiment this study demonstrates that bread feeding of coral reef fish influences short-term density and taxonomic richness at sites where bread feeding is a well-established practice, compared to sites where feeding is experimentally initiated. Species with relatively more generalist diets were consistently attracted to bread and drove the observed changes in fish species composition. Species-specific foraging rates were significantly altered by bread feeding events, and the magnitude of these alterations differed between tourism feeding and experimental feeding sites. As a result, the functional role of key species may be incompletely fulfilled in areas where fish are artificially fed. Whether these effects are strong enough to cause long term changes in ecosystem function remains to be tested. Perceptions of local tour operators regarding bread feeding being necessary to enhance tourists' satisfaction were not shared by tourists themselves. This indicates a potential opportunity to implement restrictions on bread feeding practices causing minimal drawbacks for local tourism.

Fish Density and Richness Are Modified at Well-Established Artificial Feeding Sites

The higher fish density observed at sites where artificial feeding practices are well-established compared to sites where the

TABLE 2 | Statistical outputs of mixed-effects models accounting for the temporal correlation among site observations and Tukey's *post hoc* test results for each research question and according models.

Research question 1: changes in density and taxonomic richness and fish species composition Linear mixed effects model [main factor = Timing (before, during, after), Treatment (tourism, experimental feeding sites) random factor = Site (Maina, One Foot)]

	Model	***df***	**AIC**	***L-Ratio***	***p*-value**
Density	Timing + Treatment	1	121.6709		
	Interaction	2	119.5135	6.157432	0.046*
	Post hoc	**Estimate**	***SE***	***z*-value**	**Pr(> |z|)**
	Before tourism – during tourism	−1.2947	0.3921	−3.301	0.01079*
	Before tourism – after tourism	−0.6332	0.1675	−3.780	0.00188*
	During tourism – during experimental	−1.4043	0.3691	−3.805	0.00172*
	During tourism – before experimental	−1.6802	0.3691	−4.553	<0.001*
	During tourism – after experimental	−1.0470	0.3691	−2.837	0.04545*
	After tourism – before experimental	−1.3053	0.3691	−3.537	0.00472*
	Before experimental – after experimental	−0.6332	0.1675	−3.780	0.00185*

Generalized linear mixed effects model [main factor = Timing (before, during after), Treatment (tourism, experimental feeding site) random factor = Site (Maina, One Foot), family = poisson]

	Model	***df***	**AIC**	***LRT***	***Pr(Chi)***
Richness (S)	Timing	2	429.68	23.32	<0.001*
	Post hoc	**Estimate**	***SE***	***z*-Value**	**Pr(> |z|)**
	Before – during	−0.20050	0.05727	−3.501	0.00136*
	During – after	−0.26209	0.05649	−4.639	0.00188*

Linear mixed effects model [main factor = Timing (before, during, after), Treatment (tourism, experimental feeding sites) random factor = Site (Maina, One Foot)]

Feeding group	**Model**	***df***	**AIC**	***L-Ratio***	***p*-value**
Piscivore-invertivore	Timing + Treatment	1, 11	403.2769		
	Interaction	2,13	392.0574	15.21955	< 0.001*
	Post hoc	**Estimate**	***SE***	***z*-value**	**Pr(> |z|)**
	During tourism – before tourism	24.500	4.380	5.593	<0.001*
	During tourism – after tourism	22.300	4.173	5.344	<0.001*
	During tourism – before experimental	27.700	7.106	3.898	<0.001*
	During tourism – during experimental	26.100	7.088	3.682	0.00205*
	During tourism – after experimental	23.900	7.140	3.347	0.00708*

Research question 2: species affinity to bread feeding Linear mixed effects model [main factor = Timing (before, during, after), Treatment (tourism, experimental feeding sites) random factor = Site (Maina, One Foot)]

Family	**Model**	***numDF***	**denDF**	***F-value***	***p*-value**
Labridae	Interaction	2	173	3.077278	0.0486*
	Post hoc	**Estimate**	***SE***	***z*-value**	**Pr(> |z|)**
	During tourism – before tourism	3.50000	1.07675	3.251	0.01452*
	During tourism – before experimental	4.23333	1.07675	3.932	0.00118*
	During tourism – during experimental	4.20000	1.07675	3.901	0.00134*
	During tourism – after experimental	3.43333	1.07675	3.189	0.01791*
Lutjanidae	Interaction	2	53	15.64637	<0.001*
	Post hoc	**Estimate**	***SE***	***z*-value**	**Pr(> |z|)**
	During tourism – before tourism	14.200	1.847	7.686	<0.001*
	During tourism – after tourism	14.700	1.847	7.957	<0.001*
	During tourism – before experimental	13.000	1.847	7.037	<0.001*

(Continued)

TABLE 2 | Continued

	During tourism – during experimental	10.400	1.847	5.629	<0.001*
	During tourism – after experimental	11.600	1.847	6.279	<0.001*

Research question 3(1): species-specific feeding rates, feeding on natural substrate Linear mixed effects model [main factor = Timing (before, during, after), Treatment (tourism, experimental feeding sites) random factor = Site (Maina, One Foot)]

Species	**Model**	***df***	**AIC**	***L-Ratio***	***p*-value**
Chaetodon auriga	Timing + Treatment	1,8	358.0112		
	Interaction	2,10	346.3495	15.66168	<0.001

Linear model [main factor = Timing (before, during, after), Treatment (tourism, experimental feeding sites)]

Species	**Model**	***numDF***	**denDF**	***F-value***	***p*-value**
Ctenochaetus striatus	Timing	6,2	7.00		0.0302
	Post hoc	**Estimate**	***SE***	***z*-value**	**Pr(> |z|)**
	Before – during	−6.71	2.74	−2.45	0.038*

Research question 3(2): species-specific feeding rates, feeding on bread Linear mixed effects model [main factor = Treatment (tourism, experimental feeding sites)]

Species	**Model**	***df***	**Chi-sq.**	***p*-value**
Chaetodon auriga	Tourism – experimental	1	14.197	<0.001

Research question 4: people's perception about fish feeding Chi-squared test (Cook Island locals, overseas-born)

Question	**Chi^2 value**	***df***	***p*-value**
Feeding changes marine environment?	1.479	2	0.48
Like the cruise even without feeding?	16.425	2	0.0003*
Should continue or stop?	30.004	2	<0.0001*

Significant terms and pairwise differences are highlighted with asterisks.

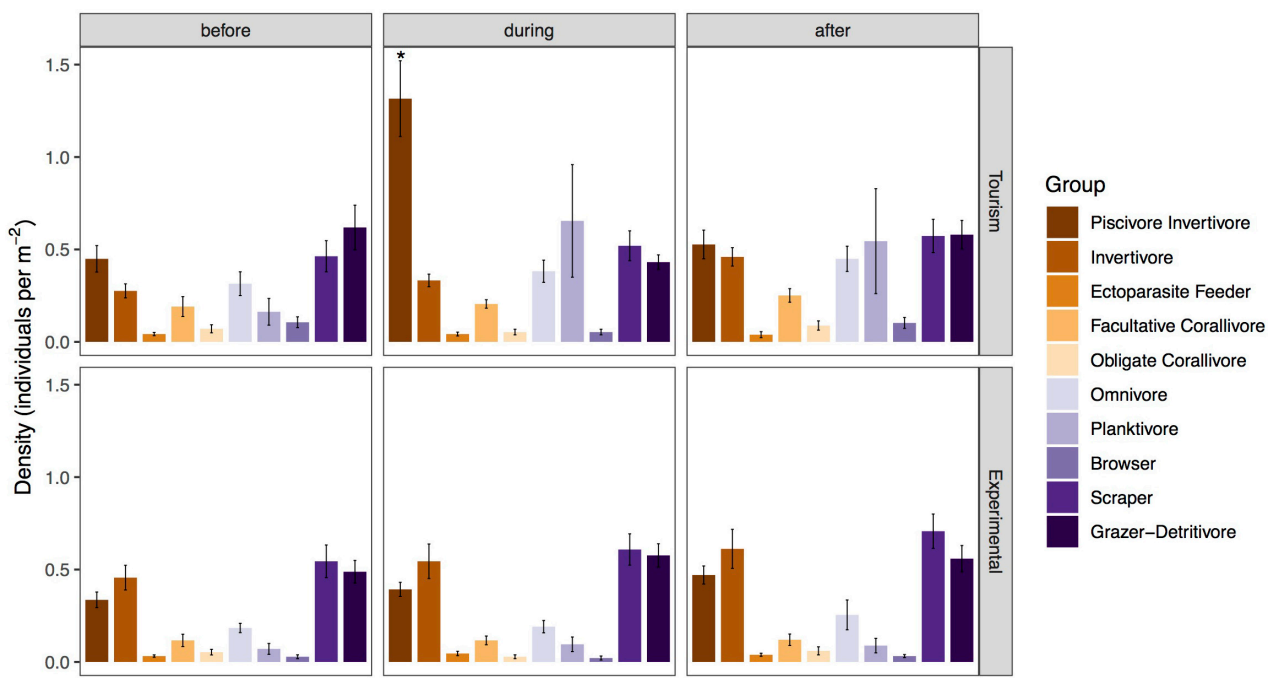

FIGURE 3 | Mean density (± SE) of fish classified in feeding groups before, during, and after bread feeding events at tourism and experimental feeding sites. Significant differences are indicated by asterisks.

TABLE 3 | Fish species feeding on or testing bread when it was provided during artificial feeding event.

Species	Family	Feeding group	Attraction during bread feeding
Rhinecanthus aculeatus	Balistidae	Omnivore	Feeding
Chaetodon auriga	Chaetodontidae	Facultative Corallivore	Feeding
Chaetodon ulietensis		Omnivore	Feeding
Cheilinus chlorourus	Labridae	Invertivore	Feeding
Gomphosus varius		Piscivore-invertivore	Feeding
Halichoeres trimaculatus		Piscivore-invertivore	Feeding
Labroides dimidiatus		Ectoparasite feeder	Feeding
Thalassoma hardwicke		Piscivore-invertivore	Feeding
Thalassoma lutescens		Invertivore	Feeding
Thalassoma quinquevittatum		Piscivore-invertivore	Feeding
Gnathodentex aureolineatus	Lethrinidae	Piscivore-invertivore	Feeding
Lutjanus fulvus	Lutjanidae	Piscivore-invertivore	Feeding
Abudefduf lorenzi	Pomacentridae	Omnivore	Feeding
Abudefduf sexfasciatus		Planktivore	Feeding
Abudefduf vaigiensis		Omnivore	Feeding
Pomacentrus brachialis		Omnivore	Feeding
Cephalopholis argus	Serranidae	Piscivore-invertivore	Feeding
Epinephelus merra		Piscivore-invertivore	Feeding
Acanthurus nigrofuscus	Acanthuridae	Grazer-detritivore	Testing
Ctenochaetus striatus		Grazer-detritivore	Testing
Chaetodon trifascialis	Chaetodontidae	Obligate corallivore	Testing
Chlorurus sordidus	Scaridae	Scraper	Testing

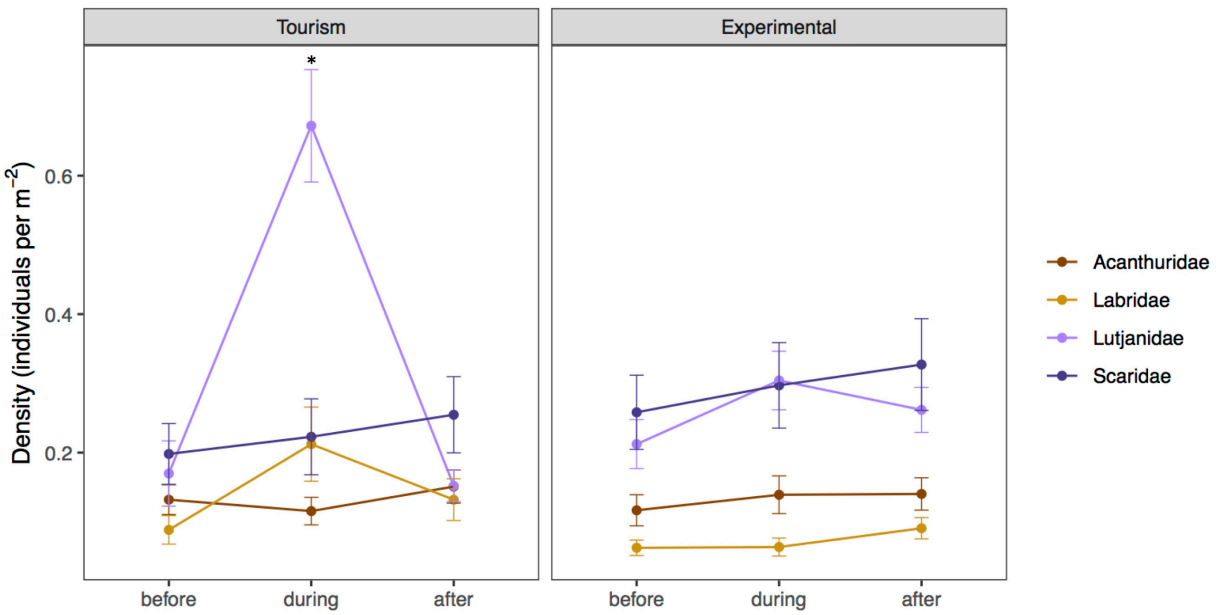

FIGURE 4 | Mean density (± SE) of the most ubiquitous species (grouped by family for graphical succinctness) before, during, and after bread feeding events at tourism and experimental feeding sites. Acanthuridae includes *Ctenochaetus striatus*, *Acanthurus nigrofuscus*, *Naso lituratus*, Labridae includes *Thalassoma hardwicke, Thalassoma lutescens,* and *Thalassoma quinquevittatum*, Lutjanidae corresponds to *Lutjanus fulvus*, and Scaridae includes *Chlorurus sordidus* and *Scarus frenatus*. Significant differences are indicated by asterisks.

practice was experimentally initiated, confirms an influence of bread feeding on the fish community structure, in accordance with previous studies (Hémery and McClanahan, 2005; Milazzo et al., 2006; Medeiros et al., 2007). At tourism feeding sites fish density peaked during bread feeding events, whereas at experimental feeding sites density was highest on the hour after. This suggests that well-established artificial feeding practices may alter diel cycles of fish abundance that are otherwise driven by

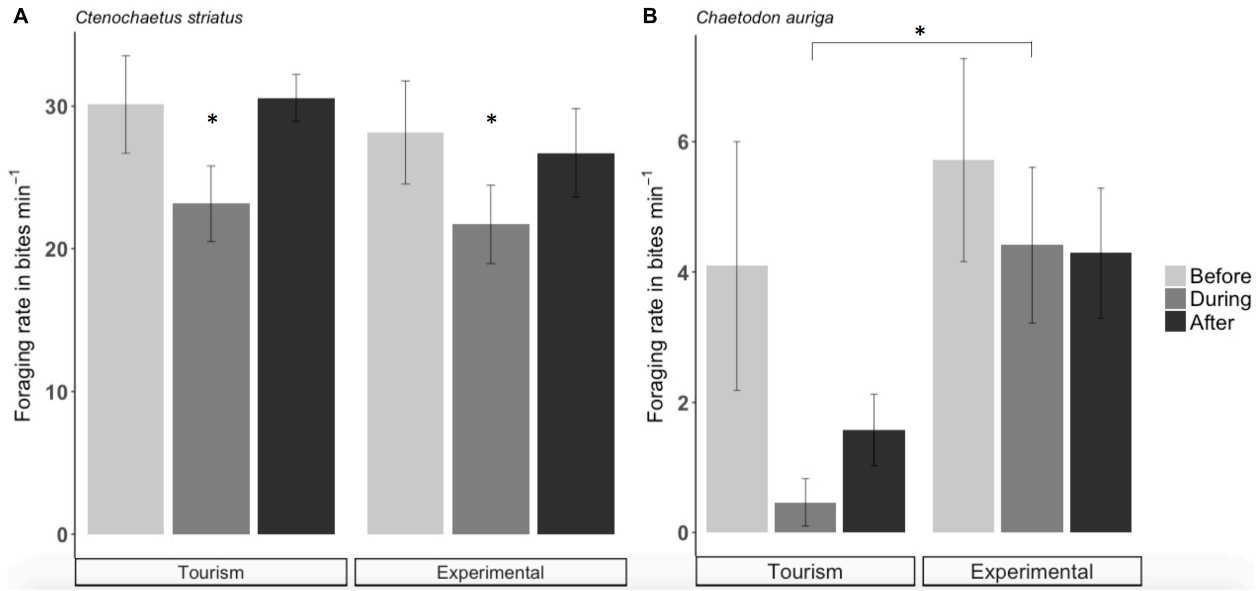

FIGURE 5 | Foraging rate (± SE) of *Ctenochaetus striatus* **(A)** and *Chaetodon auriga* **(B)** on natural food at tourism and experimental bread feeding sites before, during and after bread feeding events. Note that the scale of y axes differs and significant differences are indicated by asterisks.

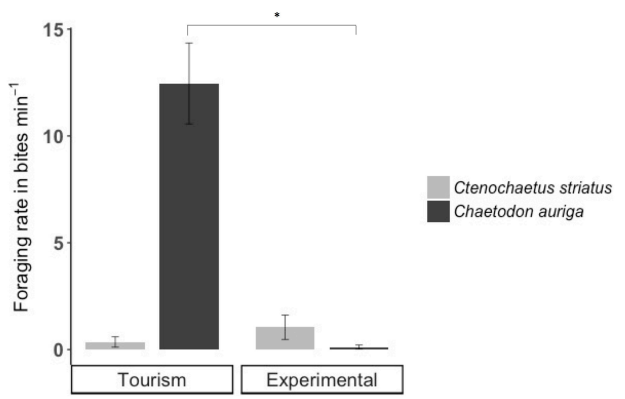

FIGURE 6 | Foraging rates (± SE) of *Ctenochaetus striatus* (light gray) and *Chaetodon auriga* (dark gray) on bread during bread feeding events. Significant differences are indicated by asterisks.

tidal changes or time of day (Corcoran et al., 2013). On Brazilian reefs where fishes are regularly fed with bread and crackers by divers, fish abundance and taxonomic richness remained higher than usual 1 h after feeding, indicating that the effect of artificial feeding can last several hours or days (Milazzo et al., 2006; Feitosa et al., 2012). Habituation of fish to artificial feeding can lead to the dominance of a few species and a long-term reduction of taxonomic richness (Medeiros et al., 2007). At several tourism feeding sites, fish also anticipate feeding events and congregate in response to the noise of boat engines (Newsome et al., 2004, reviewed by Whitfield and Becker, 2014). Although arguably possible, it is unlikely that the differences observed here between tourism and experimental feeding sites are confounded by fish moving across sites. Small-bodied reef fish tend to move over very small home ranges (i.e., <3 m for *C. auriga* and *Abudefduf sexfasciatus*, and <16.4 m *C. striatus*, Krone et al., 2008; Matis, 2018), and wide-ranging lethrinids and lutjanids were repeatedly observed at the same sites (NP, personal observation).

Taxonomic richness of fish assemblages decreased significantly during bread feeding events compared to an hour prior and an hour after at both tourism and experimental feeding sites, consistently with previous studies (Ilarri et al., 2008; Albuquerque et al., 2015). It is therefore argued here, that regular artificial feeding may account at least partially for an overall decrease in species richness at tourism feeding sites here and elsewhere. Although not necessarily permanent, this phenomenon is likely not in the interest of operators or tourists, as speciose fish assemblages are generally preferred over those dominated by a few species (Salim et al., 2015; Tribot et al., 2018). This decrease is also undesired from an ecosystems' perspective, given that decreases in taxonomic richness are usually accompanied by reductions in functional richness thus posing risks to reef health and ecosystem services other than those associated to tourism (Worm et al., 2006; Burkepile and Hay, 2008).

Carnivorous and Omnivorous Fish Were Consistently Attracted to Bread

Results from this study support the notion that trophic generalists are most attracted to bread compared to relatively more specialist feeding groups (e.g., macroalgal browsers, grazer-detritivores). Bread feeding events favored generalist trophic groups such as carnivores and omnivores, as observed elsewhere (Albuquerque et al., 2015; Bessa et al., 2017b; Mattos and Yeemin, 2018). Fish species composition by trophic groups in Brazil, for instance, was also significantly altered during artificial feeding events

compared to before and after (Feitosa et al., 2012). In the present study, piscivore-invertivores showed the steepest change in response to bread feeding events and fed profusely on bread. This was mainly driven by the immediate congregation of *Lutjanus fulvus, Thalassoma hardwicke,* and *Cephalopholis argus*, which dissipated when bread feeding ceased. Almost 40% of all species that fed on bread were non-scarine labrids (wrasses). These, together with Pomacentrids, were also the most representative family of bread feeding fish on reefs in Kenya and Taiwan (Hémery and McClanahan, 2005; Wen et al., 2018). *Labridae* are one of the most speciose, ecologically, and functionally diverse group of fish inhabiting the world's coral reefs feeding opportunistically as generalist predators (Thresher, 1979; Wainwright, 1991; Bellwood et al., 2006b).

Short-term variability in fish community composition is natural (McClanahan et al., 2007). Yet, the prevalence of omnivores (e.g., labrids) above the reef, which peaked during bread feeding events and persisted after feeding ceased, may have long-term consequences on the reef fish community. If repeated bread feeding events lead to a persistent dominance of predatory fish on certain reefs, important changes in the trophic structure of fish assemblages may be expected (Beukers-Stewart and Jones, 2004). The consistent prevalence of high-trophic-level fish at bread-feeding sites may equate to high predation risk for small-bodied fish, but may also lead to higher fish excretion rates, which might cascade into changes in algal productivity and benthic dynamics (Allgeier et al., 2017; Wen et al., 2018).

Artificial feeding events may influence key biological interactions, such as aggressive exclusion, predation pressure, competition for local resources, and grazing (Coker et al., 2009; Brookhouse et al., 2013). Importantly, this is one of the few studies detecting non-lethal ecological consequences of artificial marine fish feeding linked to pulse increases in predator abundance (see also Milazzo et al., 2006). In this present case, snorkelers cause a sudden increase in (artificial) food that congregates predatory fish in a feeding frenzy around the bread. This likely generates a momentary "landscape of fear" where both predation risk and competition levels increase for smaller fish. Although fish may not necessarily feed on bread, their behavior may be indirectly affected by the bread feeding event (Brookhouse et al., 2013; Paula et al., 2018). Wary species that are regularly spear-fished may react solely to the presence of snorkelers. Macroalgal browsers (*Naso lituratus* and *N. unicornis)*, for instance, tended to flee during bread feeding events, yet returned to their home reef an hour after. Changes observed in community composition during feeding events can therefore be attributed to both the congregation of opportunistic species habituated to feed on bread, and the departure of specialists that show alarm responses (Geffroy et al., 2017).

Bread Feeding Events Disrupted Natural Fish Foraging Rates

Foraging rates of both model species changed in response to bread feeding events across sites, yet the nature of these changes differed between species. At tourism feeding sites, the facultative corallivore *C. auriga* fed on bread whilst substantially decreasing foraging rates on natural prey. An hour after the tourism bread-feeding events, foraging rates of *C. auriga* remained lower than usual, suggesting possible satiation. During the hour prior to bread feeding events at experimental feeding sites, natural foraging rates of *C. auriga* on the benthos resembled those recorded in the Great Barrier Reef (Gregson et al., 2008). At experimental feeding sites, *C. auriga* disregarded bread and foraged on the benthos consistently throughout bread feeding events. This indicates that habituation of *C. auriga* to bread likely occurs beyond the time frame covered by this study (i.e., 12 weeks). This also corroborates previous findings, where none of the fish identified as bread consumers at tourism feeding sites in Thailand fed on bread when supplied by researchers at experimental feeding sites (Sa-nguansil et al., 2017). The ecological implications of the responses of *C. auriga* to bread feeding may not be immediately obvious, given the broad range of food items it consumes. The consumption of bread by *C. auriga* likely reflects its opportunistic feeding behavior and may not strongly affect predator-prey interactions (Pratchett, 2005; Cole et al., 2008). Yet, the high carbohydrate content of bread provokes unhealthy high glucose levels in the blood of carnivorous fish (Moon, 2001). Consequences of artificial feeding on growth, survival or reproductive success of animals feeding on unnatural diets such as bread are still to be evaluated (Rodgers, 2017). Further physiological effects of bread feeding on *C. auriga,* as well as changes in its natural diel foraging rates should be investigated. As a consequence of bread feeding, foraging ranges may be spatially restricted as fish concentrate within a few meters from the usual bread provisioning places. This could lead to artificially-enhanced levels of competition and feeding pressure on prey and other density-dependent processes, such as disease and parasite transmission (Vignon et al., 2010; Brookhouse et al., 2013). It is suggested here that these impacts may however be limited to generalist butterflyfishes, given that several obligate corallivore species observed during this study (e.g., *Chaetodon bennetti, Chaetodon lunulatus, Chaetodon reticulatus*) were not attracted to bread at all.

Natural foraging rates of the detritivore *C. striatus* were similar to rates recorded previously elsewhere (Bellwood and Choat, 1990). Likely reasons for the indifference of *C. striatus* toward bread may be the specialization of *C. striatus* to feed on benthic detritus of high nutritional value (Crossman et al., 2001). Interestingly, reduced foraging rates of *C. striatus* on the benthos during bread feeding compared to before and after, indicate a form of indirect disruption of its feeding activity. It is suggested here, that the feeding activity of *C. striatus* decreases during the bread feeding frenzy due to an increase in perceived predation risk. This alludes to the concept behind the "ecology of fear" which refers to the family of studies considering the ecosystemic consequences of prey fear responses (Brown, 2019). Previous research indicated that predation risk perceived by coral reef herbivorous fishes increased with distance from refuge habitat and affected herbivory rates (Gil et al., 2017). More generally, a number of studies on escape behavior yielded important implications for the reef fishes' ecology of fear (e.g., the influence of fishing, marine protected areas,

surveyors, prey body size, proximity of refugia, mutualism between preys, and group size) (Madin et al., 2011; Januchowski-Hartley et al., 2012; Lyons, 2013; Nunes et al., 2018). This study therefore contributes the first example linking a coral reef tourism-driven increase in perceived predation risk with potential ecosystemic consequences relevant for the reef fishes' ecology of fear. A similar finding for freshwater fish, which reduced foraging rates in response to tourism visitation and increased them again at the end of the day, was interpreted as a rebound effect of compensatory feeding following disturbance (Wu et al., 2002; Rubio et al., 2010; Bessa et al., 2017a). The bread feeding effect observed here in *C. striatus* may indirectly alter the way it fulfils its ecosystem function as an important detritivore, eroder, and transporter of sediments (Schuhmacher et al., 2008). Short-term alterations of foraging intensity may not drastically influence the functionality of the reef ecosystem, yet long-term effects may include *C. striatus* moving their feeding grounds or even abandoning the site entirely. This effect on the presence of *C. striatus* and its functional role may result in a more profound alteration of reef health through locally-reduced detritivory. Further research into the response of specific feeding groups to bread is required to substantiate that assumption, as a study from Taiwan found no effect on the bite rates of herbivorous fishes (*Acanthurus nigrofuscus* and *Scarus schlegeli*) between provisioned and non-provisioned sites (Wen et al., 2018). Bread feeding of fish may be a short-term intrusion, but where repeated consistently it may have significant implications for the ecosystem function of different feeding groups (Albuquerque et al., 2015). In light of increasing tourist numbers, artificial feeding practices may pose a long-term threat to the lagoon environment through lasting physiological and behavioral changes in fish (Geffroy et al., 2018). Fish may potentially "learn" to feed on bread and this habit may cause chronic satiation, have physiological consequences, and affect their metabolic pathways. This laid beyond the scope of this study and should be further investigated. Arguably, this study would have benefited from comparisons of tourism and experimental feeding sites with sites where no bread feeding was provided. Such comparisons would have disentangled more clearly the effect of well-established artificial feeding practices from those introduced by diurnal variability in fish biodiversity and feeding behavior. However, in this case, preliminary observations (NP) and the knowledge of local tour operators indicated that diurnal variability in fish community structure was low in all sites selected for experimental bread feeding exercises. In the face of logistical limitations preventing from adding more survey sites, preference was given to the establishment of experimental bread feeding sites. This allowed for the fully factorial comparison among before, during, and after artificial feeding episodes, and revealed important information on the process of fish habituation at the onset of artificial feeding practices. Ecological effects of bread feeding practices are likely shaped by multiple mechanisms including changes in fish behavior and community structure, but may also be mediated by the distribution of food, duration of bread artificial feeding events, number of tourists, and their behavior (Feitosa et al., 2012).

Tourists Did Not Consider Bread Feeding Essential

In order to regulate the frequency and intensity of fish feeding in coral reef systems, understanding the perceptions of stakeholders is essential (Newsome, 2017; Breckwoldt et al., 2018). A stakeholder's perception is largely dependent on their socio-demographic background, cultural context, knowledge, attitudes, norms, and personality (Beyerl et al., 2016). The respondents' perception that "bread feeding can impact fish feeding behavior and the marine environment" shows a relatively high level of awareness of the ecological consequences of this practice. A primary human motivation in the context of ecotourism is to observe nature in as natural a state as possible (Orams, 2002). The question remains whether tourists want to see wild animals completely uninfluenced by humans or "domesticated" by continued feeding over years (Orams, 2002). Orams (1999) cautioned that "fish feeding turns the sub-aquatic world into an aquarium without walls, a zoo without bars." Studies on the perception of whale-shark feeding tourism showed tourists supported the practice despite many being aware of the ethical complications of animal feeding for tourism purposes (Ziegler et al., 2018). In the present study, the question whether to feed or not to feed resulted in significantly different opinions between stakeholder groups. All overseas participants of snorkeling cruises declared that they would have enjoyed the activity with or without bread feeding, whereas local stakeholders highlighted the need for continued bread feeding practices in order to guarantee tourists' satisfaction during snorkeling cruises. This suggests that implementing restrictions on bread feeding practices in Aitutaki may meet some resistance from tour operators, but will likely not harm tourist satisfaction levels. It could be argued that overseas snorkelers regarded bread feeding as superfluous only because they had already been satisfied by the proximity of abundant fish during the cruises. Whether their opinion on banning bread feeding would change if they had encountered less fish when snorkeling remains to be tested in controlled experiments. In practice the link between bread feeding activities and tourism satisfaction is driven by tourists' behaviors and expectations, which are often to see high numbers of fish. Tourists' satisfaction in Australia, Thailand and Malaysia was directly related to fish abundance and taxonomic richness (Moscardo et al., 2001; Topelko, 2007; Salim and Mohamed, 2014). Arguably, sustainable tourism activities provide a high-quality experience for visitors, which encourages them to be concerned about the conservation of the observed animals (Higginbottom et al., 2001). In the Cook Islands, environmental sustainability already constitutes a constraint to tourism growth, which in turn places a high priority on the protection of the environment in order to support tourism (Mellor, 2003).

Recommendations

In light of these findings, this study suggests regulation of artificial feeding practices, supporting conservation measures to protect fish communities and functions in Aitutaki lagoon or elsewhere, being subject to local management priorities. This study highlights a difference between long-term and short-term

effects of bread feeding on fish assemblages. The following recommendations are given:

Initially, restrictions to bread feeding activities could be issued in the form of guidelines and rules that allow local tour operators to supply bread strictly (i) at designated feeding sites, (ii) using appropriate food types (Murray et al., 2016; Birnie-Gauvin et al., 2017), (iii) providing limited food amounts per person and boat (Great Barrier Reef Marine Park Authority, 1994; Murray et al., 2016), and (iv) at unpredictable times (Murray et al., 2016).

In lieu of a ban, it would be relevant to (1) work on transferring the perceptions of snorkellers to operators of snorkeling tours, (2) inform tour operators and dive guides on how the bread may impact fish behavior and function, and (3) involve education programs for tourists (Wiener et al., 2009; Patroni et al., 2018). Environmental education during tourism activities will result in positive attitudes of visitors toward wildlife conservation (Higginbottom et al., 2001), and may thus assist in a voluntary reduction of feeding (Bessa et al., 2017a). Lastly, pressure to feed wild animals may, in many places, come from tourists rather than from tourism operators. Avenues of non-scientific communication (i.e., tourism magazines, airline magazines, signs, flyers) to educate visitors could be helpful worldwide. On coral reefs, further research should aim to improve the understanding of long-term harmful effects of this previously overlooked activity on ecosystem health and on feeding behaviors of more fish species. In addition, potential indirect cascading effects of unconsumed bread on reef benthos, e.g., in terms of oxygen consumption and nutrient release, should also receive attention (Turner and Ruhl, 2007; Brookhouse et al., 2013).

These recommendations were delivered, and are relevant for, the currently-developed Aitutaki Management Plan. The continuous management of touristic activities in the reef requires active participation of governments, tour operators, scientists, and local communities in order to ensure its long-term ecological sustainability and incentives for conservation (Hawkins et al., 1999; Trave et al., 2017). The results of the current study suggest that no major impacts on tourism-dependent livelihoods are expected if the activity was modified by regulating the artificial feeding of fish. These findings underline the potential for sustainable management interventions in the form of reduced fish feeding activities in the Cook Islands.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

NP and SB conceptualized and designed this study with input of SF. NP procured funding and conducted the field experiment and stakeholder interviews with the support of RS and SL. This study took place within the frame of the project Resilience of South Pacific coral reef social-ecological systems in times of global change (REPICORE) led by SF. NP and SB performed the statistical analysis of the data. NP and SB led the writing of the manuscript with input of SF. All authors approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00145/full#supplementary-material

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REVIEW
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The Potential to Improve the Sustainability of Pelagic Fisheries in the Northeast Atlantic by Incorporating Individual Fish Behavior Into Acoustic Sampling

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With the increased uncertainty introduced through climate change and fishing pressure, having accurate estimates of fish biomass is essential for global ecosystem and economic health. Acoustic surveys are an efficient way to determine population size for pelagic species in the Northeast Atlantic (NEA), but acoustic population estimates still contain uncertainty and are difficult for some species. For example, Atlantic mackerel (*Scomber scombrus*) is one of the most valuable fisheries in the NEA and is not monitored acoustically, as mackerel lack the swim bladder that provides the strongest acoustic echo (target strength) at common assessment frequencies. For all pelagic species, and especially for mackerel, behavior is a source of variation in acoustic measurements and therefore in population estimates. Behavior is mediated by both extrinsic and intrinsic factors, such as the environment and the life history of the fish. In turn, behavior affects the density of the shoal and the tilt angle of the fish relative to the survey vessel, affecting their target strength, which affects the biomass estimate. Some fish may also undergo an anti-predator response to survey vessels, changing their behavior in response to the survey. Understanding these behaviors and incorporating them into acoustic stock assessment methods can improve the accuracy of population estimates. Individual-based models (IBM) of fish shoals provide a pathway for incorporating behavior into acoustic methods. IBMs have been used extensively to build theoretical models of fish shoals, but few have been successfully tested in lab or field conditions. As computational power and monitoring technology improve, modeling the collective behavior of pelagic fishes will be possible. Novel, interdisciplinary approaches to data collection and analysis will help translate theoretical IBMs to the fisheries science domain. Beyond acoustic stock assessments, this approach can be used to investigate knowledge gaps in the effects of fisheries-induced evolution and the potential for range shifts under climate change. Further work to synthesize existing

models and incorporate field data will help determine how environmental, ecological, physiological, and anthropogenic factors, often affecting both behavior and acoustic surveying, are interconnected. Moving from theoretical models to practical applications will be a valuable tool in tackling the uncertainty that accompanies further fisheries exploitation and warming oceans.

Keywords: Atlantic mackerel, pelagic fisheries, fish shoaling, fisheries acoustics, individual-based models (IBM), collective behavior

INTRODUCTION

As fishing pressure and climate change intensify, so does the need for well-informed and standardized fisheries management. Ineffective management could lead to ecosystem collapse and widespread food shortages (Scheffer et al., 2005; Srinivasan et al., 2010). Effective management, in addition to well-crafted legislation and incentives, must be based on the most accurate possible estimation of fisheries stock size (Burgess et al., 2017; Zimmermann and Werner, 2019). In the Northeast Atlantic (NEA), small pelagic fishes, such as Atlantic mackerel (*Scomber scombrus*), Atlantic herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*), horse mackerel (*Trachurus trachurus*), and capelin (*Mallotus villosus*) are high-value catches, representing 37% of global fisheries landings (Alder et al., 2008). Fished for both human consumption and animal feed, their large shoals mean low effort for commercial fisheries (Biseau, 1998). They are also essential to the pelagic and benthic ecosystems, transferring energy from low-trophic plankton to predators such as larger fish, seabirds, and marine mammals (Essington et al., 2015).

The population size for the majority of these species is assessed with acoustic surveys, an efficient and effective method for estimating stock size, especially when combined with trawls to determine the finer-scale population dynamics such as age and condition (Massé, 1996; Georgakarakos et al., 2011). All acoustic stock estimates are, however, an estimate, and while huge advances in technology and fisheries science have reduced the bias inherent in the method, there are limits to how much information can be gleaned from an acoustic survey. The behavior of fish, and how that affects the density recorded by the echosounder, can complicate the final biomass estimate (Fréon et al., 1993).

Behavior affects all assessments for gregarious fishes and models of shoaling behavior can be adapted to any of these species. Including behavior is especially important for developing an acoustic protocol for monitoring Atlantic mackerel, which form large shoals and lack the swim bladder that provides the strongest acoustic echo at the commonly-used frequencies (Simmonds and MacLennan, 2005; Korneliussen, 2010). Mackerel is one of the most valuable, and most controversial, pelagic fisheries species. Mackerel distributions are largely mediated by temperature. Therefore, their range may expand poleward and into deeper waters with increasing temperatures (Dulvy et al., 2008; Hughes et al., 2015; van der Kooij et al., 2016; Ólafsdóttir et al., 2019). The shift in mackerel distributions precipitated a dispute over the total allowable catch (TAC) for the NEA, a region shared by the European Union, Norway, Iceland, and the Faroe Islands (Hughes et al., 2015; Jensen, 2015; Spijkers and Boonstra, 2017). These disputes were worsened by decreases in other fish catches, such as blue whiting (Jensen, 2015). With climate change, the ranges of pelagic fishes may shift (Pecl et al., 2014), potentially creating conflict (Spijkers and Boonstra, 2017) and economic impacts (Hughes et al., 2015).

Reducing the uncertainty in mackerel stock assessments will require extensive and standardized evaluation of their spatial distributions, population size, and behavior. The estimates of NEA population size are based on surveys of mackerel egg biomass, catch-at-age data, and tagging and recapture, all of which are subject to biases and error (Tenningen et al., 2011). For example, a 2005 International Council for Exploration of the Seas (ICES) report on acoustic and aerial surveys for mackerel in the North Sea produced an abundance estimate that was lower than the fishery catch (ICES, 2005; Scoulding et al., 2017). Until 2014, there was no standardized quantitative assessment criteria between the agencies assessing the NEA stock, contributing to uncertainty in the calculation of the total stock biomass (ICES, 2014). Because of this uncertainty, ICES, who reviewed the NEA mackerel stock, recommended a 20% reduction in catch levels as a "precautionary buffer" (ICES, 2014).

Improvements in acoustic techniques and novel approaches incorporating individual behavior, however, are providing a pathway to monitoring mackerel acoustically (Scoulding et al., 2017), reducing the possibility that the stock will be overfished before monitoring catches up with the current state of the population. While there are many avenues for improving acoustic monitoring, one possibility is to use models of collective fish behavior to inform density estimates. While this is a theoretical approach, it provides ample opportunities for research that bridges theory and practice and brings the broad bodies of work in ethology and acoustics to bear on a new problem. This approach could inform all species management processes, with the most impact for species like mackerel.

FISHERIES ACOUSTICS AND BEHAVIOR

Acoustic Survey Techniques

Acoustic surveys serve as the basis for population estimates and stock assessments for many species, informing effective fisheries management. The population size of gregarious fishes is difficult to estimate because of their large geographic ranges and dense shoals. Before 1960, fish abundance estimates relied on catch per unit effort (CPUE) data collected from commercial

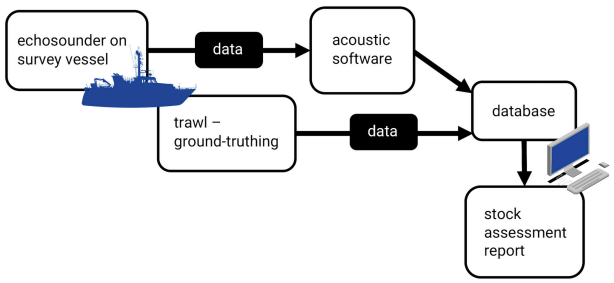

FIGURE 1 | Acoustic stock assessment workflow, from data collection with an echosounder and ground-truthing with trawl data to data processing and report generation.

fisheries, which was biased by the constant improvements in commercial fishery technology and the lack of an accurate relationship between CPUE and stock size (Gunderson, 1993). In the 1970s, catch-at-age and cohort analyses based on scientific trawl data became more popular, initiating the move to fisheries-independent assessments. These methods were more accurate, but were subject to bias from erroneous age estimates and the mortality coefficients used in the analysis (Gunderson, 1993). There is still uncertainty in fisheries-independent assessments, however, and they are entirely dependent on the data collected during scientific surveys (Mesnil et al., 2009).

Acoustic surveys, conducted along transect lines, are an expedient option for estimating populations, as they can cover large areas in short timeframes and estimate density with low effort (**Figure 1**). They also provide information on species absence, highlighting distribution changes and migration patterns (Georgakarakos et al., 2011). Acoustic surveys are carried out with echosounders, which consist of a transmitter that produces a burst of energy at a particular frequency, passed through a transducer that converts this energy to acoustic energy (sound). This acoustic pulse is emitted in a focused beam that can propagate through water (Simmonds and MacLennan, 2005).

Modern fisheries survey vessels are equipped with echosounders that run on one or multiple frequencies (commonly from 18 to 333 kHz) and are used for estimating fish biomass and distribution, along with zooplankton populations, oceanographic processes, and other applications (Demer et al., 2017). The data from the echosounder are processed with software that infers the species present and the approximate biomass from shoal shape, location, and behavior (Reid and Simmonds, 1993; Scalabrin, 1996). Species identification is based on descriptive factors for each species, determined by their acoustic resonance on various frequencies (target strength) in various orientations and conditions, determined experimentally (Nakken and Olsen, 1977; Simmonds and MacLennan, 2005; Korneliussen, 2018). The echosounder software uses algorithms based on predictive neural networks and Bayesian networks to identify species (Georgakarakos et al., 2011). These identifications are ground-truthed by fishing a target shoal and recording species present and relative and total biomass (Georgakarakos et al., 2011). The trawls also provide data on the size, sex, life stage, and condition of the fish. The accuracy of these algorithms determines the accuracy of the density estimates. Simulated backscatter from virtual shoals indicates how bias in estimates of shoal properties can vary with an interaction of detection range and shoal density (Trygonis and Kapelonis, 2018). Hence, algorithms can be confounded by shoaling behavior (Fréon et al., 1992; Scalabrin, 1996; Godø et al., 2004; Hensor et al., 2005; Lopez et al., 2012) and physiological differences between fish species (Blaxter and Batty, 1990; Misund, 1993; Misund and Beltestad, 1996; Scalabrin, 1996).

The essence of collective behavior is that the group is more than just a collection of individuals and fisheries acoustics perceive the behavior of the shoal as a whole, rather than an aggregate of separate individual signals. Collective behavior facilitates feeding, reproduction, and predator avoidance and can vary between species and with environmental conditions (Rieucau et al., 2014; Handegard et al., 2017). Shoals of fish, defined as a group engaged in social behavior beyond resource exploitation and following one direction, and schools of fish, the same following one speed and approximately less than a body length between individuals, are common in the open ocean (Pitcher, 1983; Delcourt and Poncin, 2012; Rieucau et al., 2014). These dense groups introduce variation and therefore uncertainty into acoustic population estimates (Fréon et al., 1993). The echosounder software performs a series of calculations that are based on "single target detector" algorithms that sort through the acoustic echoes of the group to filter out the echoes from individuals (Georgakarakos et al., 2011). These algorithms perform best in low-density, monospecific conditions. Therefore, larger shoals, where the signal-to-noise ratio is lower, can introduce bias where the algorithms can fail to reject multiple echoes from the same individual (Georgakarakos et al., 2011). Density varies both between shoals and within individual groups, with holes and density nuclei shifting in time (Lopez et al., 2012). While ground-truthing with trawls can confirm species composition and provide other biological details, especially important for multi-species shoals (Massé, 1996), overall density is hard to verify, as much of the backscatter from fish depends on their distance from and angle relative to the acoustic beam, in addition to numbers (De Robertis and Handegard, 2013; Trygonis and Kapelonis, 2018).

Incorporating Behavior Into Acoustic Assessments

Though predation risk is often seen as the main driver for fish aggregations, shoal dimensions and intra- and inter-shoal density can depend on multiple other behavioral and environmental factors. These include the geographical distances traversed, motivation of the fish (seeking food or seeking safety), reproductive stage, position within the water column, time of day, oxygen levels and consumption, and water flow (**Tables 1**, **2**). The factors affecting individual behavior and hence shoal structure can be considered as imposed on the shoal (extrinsic variables like time of day) or originating from the biology of the fish (e.g., feeding state). Incorporating these variables into surveys of fish abundance is difficult because some of the same variables

TABLE 1 | Extrinsic sources of variability in individual behavior that may affect the overall shape and density of a shoal and therefore acoustic measurements, where they are mentioned in the literature, and the specific effects of these variables, if stated.

Category	Variable	Specific effect
Environmental	Water flow	Mediates maximum size of the shoal (Fu, 2016)
	Temperature	Changes food distribution (Nonacs et al., 1998)
		(Tien et al., 2004)
		Thermoclines (Rieucau et al., 2016)
	Salinity	Pycnoclines (Rieucau et al., 2016)
	Time of day	Light levels (Rieucau et al., 2014, 2016; Quera et al., 2016; Lee et al., 2019)
		Diel migration (Knudsen et al., 2009)
	Substratum	Changes food availability (Hensor et al., 2005)
		Conspicuousness of predators (Hensor et al., 2005)
	Currents	(Tien et al., 2004)
	Oxygen levels	(Tien et al., 2004; Rieucau et al., 2014)
	Depth	Higher visibility and more coordination closer to the surface (Nøttestad et al., 2016a; Quera et al., 2016)
Ecological	Predation stress	Mediates maximum size of the shoal (Fu, 2016)
		Oblong shape with individuals attempting to hide behind those in front (Hemelrijk and Hildenbrandt, 2008)
		Swimming speed (Nonacs et al., 1998)
		Spacing – decreased nearest neighbor distance (Tien et al., 2004)
	Food distribution	Mediates maximum size of the shoal (Fu, 2016)
Anthropogenic	Vessel presence/noise	Predatory response (Fréon et al., 1993)
		Swimming speed (Mitson and Knudsen, 2003; Godø et al., 2004; Lopez et al., 2012; Bruintjes et al., 2016)
		Vertical movement (Mitson and Knudsen, 2003; Bruintjes et al., 2016)

TABLE 2 | Intrinsic sources of variability in individual behavior that may affect the overall shape and density of a shoal and therefore acoustic measurements, where they are mentioned in the literature, and the specific effects of these variables, if stated.

Category	Variable	Specific effect
Physiological	Body size	Intra-shoal position, largest individual takes foremost position (Pitcher et al., 1985)
	Tilt angle	Not found
	Perceptive ability	Sensing neighbors (Pitcher et al., 1985; Herbert-Read, 2016).
	Reproductive stage	(Rieucau et al., 2014)
	Condition	Not found
Behavioral	Feeding state (hungry or sated)	Intra-shoal position (Pitcher et al., 1985; Nonacs et al., 1998)
		Behavior the individual or group is engaged in affects swimming speed (Nonacs et al., 1998; Herbert-Read et al., 2011)
	Distance traveled	(Rieucau et al., 2014)
	Experience	Leadership – maintaining heightened environmental awareness, especially on migration paths (Krause et al., 2000b; Reebs, 2000)
		Memory and forgetfulness (Quera et al., 2016)
	Leadership	Direction of the shoal (Krause et al., 2000b)

that affect fish behavior also affect the acoustic surveying process (**Table 3**).

Acoustic survey technology and analysis are continually improved, but still include assumptions about behavior that introduce bias into the abundance estimates. Target strength calculations assume even distributions within shoals and often only account for variation in the length of the fish (Hazen and Horne, 2003). In reality, further variation introduced from uneven densities within the shoal and biased recording of the edge of a larger group can lead to incorrect abundance estimates (Simmonds and MacLennan, 2005). Just as intra-shoal density is not consistent, the body size and condition of fish within the shoal may not be evenly distributed. The fish on the edge of a shoal may differ physiologically and behaviorally in important ways. Some fish have been shown to sort themselves by body size (Pitcher et al., 1985) and individuals on the edge may be hungry and seeking food, rather than seeking safety in the center of the shoal (Rieucau et al., 2014).

In addition to boundary effects and physiological variation, behavior affects the orientation of the fish relative to the echosounder beam. This tilt angle of the fish affects the target strength, as the orientation of the fish affects which tissues are along the acoustic beam and different tissues have different target strengths. Tilt angle is especially important for species without swim bladders, where other tissues (i.e., the backbone) provide the best acoustic echo (Hazen and Horne, 2003; Simmonds and MacLennan, 2005). Experimental determinations of target strength from scenarios where the fish are held in a fixed-position or in fish cages cannot replicate the complex conditions of the open ocean and large shoals. Therefore, tilt angle *in situ* remains an important and elusive behavioral determinant of acoustic abundance estimate accuracy (Reid and Simmonds, 1993; Fernandes et al., 2016).

Vessel Avoidance

Beyond more static environmental and behavioral factors, some research suggests that fish perceive the survey vessel as a threat and undergo avoidance behaviors, though improvements in the acoustic profile of vessels has mitigated this issue. Fréon et al. (1993) reported that the low-frequency noise from some vessels causes avoidance behavior that can reduce shoal density by 40–90% in some studies, but only weak or no reaction in others.

TABLE 3 | Potential sources of variability in the acoustic survey process (beyond standard calibration settings accounting for local conditions and vessel/echosounder capacity), if found in the literature, and the specific effect, if stated.

Category	Source of variation	Specific effect
Environmental	Water flow	Not found
	Temperature	Not found
	Salinity	Not found
	Time of day	Density and organization of the shoal (Simmonds and MacLennan, 2005)
		Tilt angle (Simmonds and MacLennan, 2005)
	Substratum	Not found
	Currents	Not found
	Oxygen levels	Not found
	Depth	Compression of swim bladder (Knudsen et al., 2009)
		Measurements less accurate at the surface and directly above the seabed (Godø et al., 2004; Simmonds and MacLennan, 2005; Nøttestad et al., 2016a)
		May affect tilt angle, especially with changing light levels (Simmonds and MacLennan, 2005)
Ecological	Predation stress	Not found
	Food distribution	Not found
Anthropogenic	Vessel presence/noise	Vessel avoidance (De Robertis and Handegard, 2013)
		Vessel avoidance (Simmonds and MacLennan, 2005; Georgakarakos et al., 2011)
	Trawling	Size and condition selection during trawling (Slotte et al., 2007)
Physiological	Body size	Uncertainty in body size (Simmonds and MacLennan, 2005; Georgakarakos et al., 2011)
	Tilt angle	Angle of the fish to the vessel presents different target strength (Simmonds and MacLennan, 2005; Georgakarakos et al., 2011; De Robertis and Handegard, 2013; Fernandes et al., 2016)
	Perceptive ability	Not found
	Reproductive stage	Not found
	Condition	Body condition and tissue density changes target strength (Simmonds and MacLennan, 2005)
		Fish caught in trawls may be of lower relative condition if healthier fish can avoid the net (Slotte et al., 2007)
Behavioral	Feeding state (hungry or sated)	Not found
	Distance traveled	Timing of surveys around fish migrations (Simmonds and MacLennan, 2005; Georgakarakos et al., 2011)
	Experience	Not found
	Leadership	Not found

There is continued evidence to both support and refute avoidance behavior in various species and scenarios (Fernandes et al., 2000; Mitson and Knudsen, 2003; Knudsen et al., 2009). High noise can disrupt the social behaviors that fish rely on for survival and reproduction and can affect individuals' ability to coordinate their movements by interrupting the transfer of information through the lateral line, such as their neighbors' position. Noise can also affect other sensory inputs, such as vision and olfaction (Herbert-Read et al., 2017). This communication interference, combined with possible effects on stress, injury rate, feeding rate, predator avoidance, and swimming behavior, can lead to lower catch rates, especially when bottom trawling.

Fish may avoid the path of the vessel, horizontally or vertically, changing their tilt angle relative to the acoustic beam (Mitson and Knudsen, 2003; De Robertis and Handegard, 2013; Bruintjes et al., 2016; Brehmer et al., 2019). Changes in tilt angle from diving or surfacing to avoid the vessel affects the backscatter of the shoal, causing the signal to change with the orientation of the fish to the vessel, rather than a change in shoal density or distribution (Fréon et al., 1993; De Robertis and Handegard, 2013). In addition, the expulsion of air from the swim bladder when diving can affect the backscatter; in herring, a dive from 50 to 90 m results in an 11% reduction in target strength (Knudsen et al., 2009; De Robertis and Handegard, 2013). Laterally, vessel avoidance can also reduce the likelihood of a shoal being detected by the echosounder, the magnitude of which depends on whether the change in position happens before or after the fish have been measured by the echosounder (De Robertis and Handegard, 2013). Trawl avoidance may also affect the biological sampling during research cruises; Slotte et al. (2007) found that research trawls contained smaller, more immature, and possibly "weaker" fish than the catch from commercial trawlers. Therefore, the biological data used to determine the shoal composition and therefore population structure may also be biased by avoidance behavior (Slotte et al., 2007).

The effect that vessel avoidance has on population estimates depends on how stock assessments are used. While vessel avoidance introduces bias into the stock assessment pipeline, this only becomes an issue when the assessment is used as an absolute representation of population, or if the inclusion of bias varies between years (De Robertis and Handegard, 2013). The magnitude of response also depends on the type of vessel and the hydrographic conditions, such as time of day, physiological state, and predation risk. The introduction of noise-reduced vessels has lessened the impact of noise (Fernandes et al., 2000), though vessel avoidance remains a source of bias (Georgakarakos et al., 2011; De Robertis and Handegard, 2013).

Difficult Fish to Sample Acoustically – Northeast Atlantic Mackerel

While swim bladders provide the strongest acoustic echo for most fishes, Atlantic mackerel (*Scomber scombrus*) lack a swim bladder, meaning that acoustically measuring their population size is difficult at the most common acoustic frequency (i.e., 38 kHz; Korneliussen, 2010). While the large shoals that mackerel form mean they are easily found, determining density is difficult. The

mackerel egg survey was the only source of fisheries-independent data for the NEA mackerel stock for a long time, but changes in the distribution of mackerel eggs and in the timing of spawning affect the survey's accuracy (Slotte et al., 2007; van der Kooij et al., 2016). Acoustic or sonar monitoring is the preferred way to carry out fisheries-independent surveying, so research has been carried out in an effort to update and parameterize the existing framework to work for mackerel.

Multifrequency acoustics can be used to identify mackerel, combining frequencies ranging from 18 to 364 kHz. The backbone provides the highest target strength at 200 kHz, instead of the standard 38 kHz (Gorska et al., 2005; Korneliussen, 2010; Fernandes et al., 2016). Even with an expanded frequency range, the target strength of mackerel is low and, therefore, correct identification of species is even more important. For example, the incorrect identification of herring as mackerel at these frequencies would overestimate the abundance by 20 times (Fernandes et al., 2016). Additionally, while estimating the correct tilt angle is important for all fish species, in mackerel, it is essential for correctly estimating abundance (Hazen and Horne, 2003; Fernandes et al., 2016). The difference in target strength for mackerel with a tilt angle of 1° vs. 15°can double the abundance estimate (Scoulding et al., 2017). When expanded over the survey area, this can have a considerable effect on the total estimates of density, as in 2005, when the mackerel abundance estimate for the North Sea was lower than the catch for the fishery (ICES, 2005; Scoulding et al., 2017). For all pelagic fishes, but especially mackerel, novel techniques to determine how behavior affects density and orientation are essential to improving stock assessment techniques and therefore estimates of population size.

Along with multifrequency acoustic surveys, the algorithms for differentiating mackerel from other species, such as capelin and sandeel (*Ammodytes marinus*) have been successful (Korneliussen et al., 2016). With these improvements, estimates for the stock in Norway are determined acoustically while fish are aggregating in the feeding grounds before migrating south to spawn (Korneliussen and Ona, 2004; Slotte et al., 2007). A method for the acoustic monitoring of mackerel has not, however, been implemented across the NEA region. Issues with vessel avoidance due to mackerel's swimming speed may introduce bias into the sample of mackerel in research trawls. Slotte et al. (2007) suggest that mackerel exhibit size-dependent trawl avoidance, as the age, length, and condition of mackerel caught in the slower and smaller research trawls was significantly lower than the fish caught during purse seining in the same area. The acoustic surveys carried out in the Norwegian Sea may also be possible because of the behavior of the mackerel, grouped into schools, predominately in the top 40 m, whereas their behavior changes and may be more difficult to measure acoustically at other points in their migration (Godø et al., 2004; van der Kooij et al., 2016). While some opportunistic sampling has been successful in identifying mackerel, such as the work conducted by van der Kooij et al. (2016) during the North Sea International Bottom Trawl Survey, there is still no overarching method. Developing a protocol will require extensive work to determine how the behavior of mackerel varies across their migration route and how these behaviors affect their acoustic properties.

MODELING COLLECTIVE BEHAVIOR

Determining How Fish Move and Behave With Individual-Based Models

Many commercial species are gregarious, forming aggregations to serve a particular purpose, such as facilitating mating, increasing foraging efficiency, or mitigating risk from predators (Rieucau et al., 2014; Reuter et al., 2016). One method for improving stock assessments is to decrease the assumptions made about the behavior of individual fish within the shoal. Though predation risk is often considered the main driver of aggregations, changes in the dimensions and density of the school can depend on a variety of factors (**Table 1**).

Developing a quantitative description of how individual fish interact within a group is essential for understanding how animals behave (Gautrais et al., 2012), yet there are few species whose collective behavior has been effectively quantified and the definitions of behaviors and modeling methods vary across the literature. Modeling collective behavior depends on quantifying the relationships between individuals, balancing biological reality and theoretical simplicity. Quantification is generally based on measuring the basic dimensions of the group and determining the degree of cohesion. Measurements of cohesion can be the mean distance to the center of the aggregation or the distance between individuals (Delcourt and Poncin, 2012).

Incorporating behavior into models of fish density can be achieved with individual-based models (IBMs)[1], which model the interactions of individual agents within an environment with a simple set of rules. In addition to modeling collective behavior, IBMs and particle models have been used to model fish distributions with environmental factors, such as for mackerel (Boyd et al., 2018) and capelin (Barbaro et al., 2009a,b). Before IBMs, most movement ecology used "state-variable models," which do not incorporate location and assume that each individual has equal influence on the others (Huston et al., 1988). With IBMs, the interactions between individuals are local; an individual is affected only by the other individuals and the environment with which it comes in contact, facilitating modeling of variance on the small scale (Huston et al., 1988). IBMs also include individual variability and stochastic processes, allowing the actions of individuals to build the behavior of the group as a whole (Reuter et al., 2016).

An IBM consists of three aspects: (1) the individual agents, including their attributes and behavior, (2) the relationships between the agents: how they are connected and how they interact, and (3) the environment (Macal and North, 2010). The fundamental assumption of an IBM is that all individuals are self-contained and uniquely identifiable. Older versions of IBMs required the individuals to be identical, but newer methods allow for heterogeneous individuals whose goals,

[1]Individual-based models are also called agent-based models and are related to particle models.

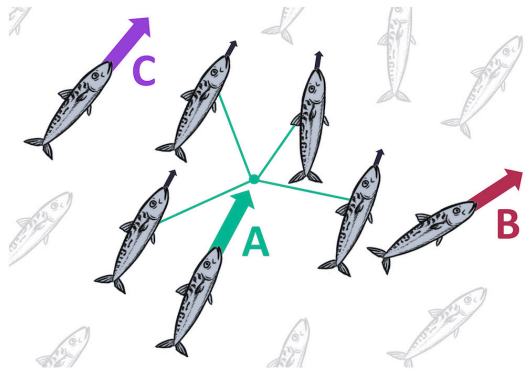

FIGURE 2 | Interaction rules that form the basis of a "Boids" model (Reynolds, 1987), often used in collective behavior IBMs. Rules are **(A)** attraction to mean position of nearest neighbors; **(B)** avoidance of other individuals at close proximity; **(C)** alignment with neighbors.

behaviors, and resource loads can vary (Huston et al., 1988; Macal and North, 2010). Additionally, the individuals must be autonomous: programmed behaviors must not curtail their independent decision-making. Individuals also have a state that can vary over time and that is subject to their environment (Macal and North, 2010).

Fish shoal IBMs have generally been based on three rules: attraction to, separation at a minimum distance from, and alignment with neighbors to establish collective behavior (**Figure 2**; Couzin et al., 2002; Tien et al., 2004; Hensor et al., 2005; Hemelrijk and Hildenbrandt, 2008; Quera et al., 2016). These models are based on the Boids model, developed by Reynolds (1987), which follows this three parameter framework. While these models create a theoretical, cohesive shoal, they include huge assumptions, such as constant speed, large perception ranges, and small school sizes (Couzin et al., 2002; Hemelrijk and Hildenbrandt, 2008).

Improvements to this basic model have included changing the rules to be based on cohesion, separation, and alignment zones instead of set limits (Tien et al., 2004; Hemelrijk and Hildenbrandt, 2008), and incorporating a blind zone behind each "fish" to represent the sensory capabilities of vision and the lateral line (Hemelrijk and Hildenbrandt, 2008; Rountree and Sedberry, 2009). These models can be expanded to include different behavioral states, such as food-seeking or safety-seeking (Pitcher et al., 1985; Nonacs et al., 1998; Krause et al., 2000a,b; Reebs, 2000), presence of a threat (Tien et al., 2004), leadership (Huth and Wissel, 1992; Krause et al., 2000b), methods for information transfer through the shoal (Ward et al., 2011; Rieucau et al., 2016), and environmental conditions such as thermoclines, pycnoclines, and light levels (Fu, 2016; Rieucau et al., 2016). While the specific effects of these variables on collective behavior *in situ* are not fully-understood, IBMs are a useful tool for modeling shoaling behavior, even with spatial heterogeneity (Reuter et al., 2016).

Validating IBMs for Fish Behavior

Many shoaling IBMs are purely theoretical, and while there have been a number of studies of collective behavior under lab and controlled field conditions, such as aquaculture pens, few studies have attempted to validate their models using open field data. These *in situ* studies are necessary to fully understand collective behavior, but moving from theoretical models to a replication of real-world systems is difficult to undertake (Krause et al., 2000a; Lopez et al., 2012). First, while humans are adept at distinguishing collective patterns in both simulated and real video, machines are not always as accurate (Butail et al., 2013). Additionally, most research has focused on a single species, outside of its ecological context. That context can be important; for example, species from high-predation habitats have been shown to form larger, tighter groups, evidence that predation pressure may shape collective behavior (Ioannou, 2017). There is ample evidence that factors such as predation affect group dynamics, but it remains unclear how these behaviors emerge from the group's decision-making process. For example, Ioannou (2017) modeled killifish behavior in the lab and the field and found that their shoaling model could not handle the thousands individuals in naturally-occurring shoals, let alone explain their behavior. Ioannou (2017) also found that the substratum likely had an effect on the fishes' behavior because the type of substrata was tied to food availability and the visibility of predators. The number of extraneous biotic and abiotic factors in the field made predicting movement difficult (Hensor et al., 2005).

Many emergent group behaviors can be understood and modeled without a thorough understanding of the underlying rules. However, comprehension of the rules governing individual interactions is important for understanding the evolution of social behaviors and the conditions that affect them (Mann, 2011). It is well-accepted that complex group behaviors derive from simple rules, but the details of the interactions, i.e., whether there is a leader or the number of neighbors an individual interacts with, are unknown for most groups (Lukeman et al., 2010; Herbert-Read et al., 2011). It is not enough to simulate collective behavior; any model needs to be compared to real behavior (Lukeman et al., 2010). Inferring interaction rules from data is often done by correlating measurable aspects of individual behavior and interactions with neighbors (Mann et al., 2013).

One of the complications with comparing a theoretical model to empirical data is that the theoretical models rarely incorporate the environment and also rarely represent the entirety of a fish shoal. Many others focus on either individual behaviors, such as speed and direction changes, or collective phenomena, rather than both. Various studies have determined quality-of-fit and model parameters through Bayesian statistics (Mann, 2011; Lopez et al., 2012; Mann et al., 2013; van der Vaart et al., 2015). This method requires the central assumption that fine-scale behavior leads to group behavior and therefore one can be used to test the other. Different individual rules can result in the same collective behavior, deemed IBMs' "Achilles heel" by Eriksson et al. (2010), and therefore small-scale dynamics can be more useful in determining interaction rules (Mann, 2011). Bayesian paradigms are best-suited to deal with the uncertainty inherent to IBMs because Bayesian inference uses a probability distribution to determine the model parameters, rather than absolute values (Mann, 2011). Additionally, Bayesian methods allow researchers to examine many competing hypotheses,

while avoiding over-fitting (Mann et al., 2013). Other methods for assessing theoretical models are through artificial neural networks, which were used by Herbert-Read et al. (2011) to tease out the influence of social cues vs. environmental topography on individual movement. The authors found that while their model may have represented the experimental data effectively, it would not necessarily accurately depict group behavior under all circumstances, a point also made by Katz et al. (2011) when looking at the effect of predator detection on collective behavior. Katz et al. (2011) found that while the model could reproduce the patterns observed, the response in the lab is likely less dynamic than in the real system.

Balancing Complexity and Parsimony in Collective Behavior Models

Replicating an open ocean scenario requires the incorporation of both behavioral and environmental variables, but there is a balance between the most "accurate" model and an effective one. While leadership (Huth and Wissel, 1992; Krause et al., 2000b; Lopez et al., 2012) and memory (Huth and Wissel, 1992; Couzin et al., 2002; Lopez et al., 2012; Biro et al., 2016) are important aspects of collective behavior and determining decision-making pathways, does their inclusion in a collective behavior model have an impact on the practical applications for collective behavior models, i.e., in the acoustic monitoring of fish shoals? Lopez et al. (2012) state that while IBMs have had some experimental success in linking individual behaviors to school-wide properties, they are unlikely to accurately reproduce experimental data because they fail to produce experimental speed distributions. The applicability of models based on experimental conditions may also depend on the size of the shoal. For example, Huth and Wissel (1994) successfully reproduced the basic structure of a fish school for 20 and 100 fish, concluding that the same model would be applicable to schools of 1000 or more. Is that a valid assumption?

Additionally, there are biological and environmental factors to consider when comparing models to data *in* and *ex situ*. On a fundamental level, not all fish have the same sensory capabilities, and there are effects of time of day, water dynamics, prey availability, predation risk, etc. in the open ocean. Random variation as a stand-in for some of these variables can be included in the model, as in Huth and Wissel (1994), but this approach may introduce further bias. With the inherent complexity, the "best" model answers the question asked; as we know, while all models may be wrong, some are useful (Wasserstein, 2010).

An important area for research would be to reduce the complexity of the variables listed in **Tables 1**, **2**. It should be possible for several research programs to replicate the response of shoals to extrinsic and intrinsic factors. It is plausible that the mechanisms that affect shoal characteristics have aspects in common across environmental and biological drivers. Further research would be to reduce the apparent complexity to a limited number of empirically justified processes. For example, the responses to temperature, flow and salinity could all be special cases of a response based on (for example) leadership. An individual-based framework, linked to field data, has the potential to make these types of syntheses, moving toward an understanding of what extrinsic and intrinsic processes affect acoustic data collection. For example, Trygonis and Kapelonis (2018) use a static, spatially random representation of shoal density, but recognize that dynamic, realistic descriptions of the internal structure of shoals are needed to refine signal algorithms.

Implications of Behavior for Acoustics – Atlantic Mackerel

For mackerel, the *in situ* conditions that affect collective behavior include their ontogeny, foraging ecology, and reaction to predators. Mackerel are gregarious forage fish, at high risk for predation (Nonacs et al., 1998), and environmental factors govern the route of foraging and spawning migrations, as well as the dynamics of the shoal. Foraging mackerel are usually found close to the surface, with their geographical and vertical movements mediated by temperature (Hughes et al., 2015; Nøttestad et al., 2016a). Nøttestad et al. (2016a) found all mackerel schools in water above 6°C, with the majority found between 7 and 11°C, a temperature tolerance lower than the 8°C found in previous studies. Mackerel stay above the thermocline where warmer, stabilized water masses trap nutrients, phytoplankton, and zooplankton. The higher light levels may also help them detect prey and the warmer waters may facilitate efficient swimming (Nøttestad et al., 2016a). As mackerel are temperature-sensitive, their distributions have shifted with climate change, following increased thermally-acceptable habitat, but the relationship between mackerel and temperature is not straight-forward. The fisheries catch has also become more dispersed, moving further offshore to areas of deeper water (Hughes et al., 2015). Temperature and plankton concentrations affect swimming speed as well, with areas with high plankton concentrations and low temperatures found to be home to the largest fish, swimming the slowest (Nøttestad et al., 2016a). Mackerel migratory behavior has also been shown to be affected by currents; rheotaxis is likely due to the influence on the lateral line and changes in the inertia of the shoal (Godø et al., 2004).

Another consideration for field studies of mackerel behavior is their predator avoidance strategy, if the shoal senses the survey vessel or trawler as a threat. One fisher stated that after trawlers had passed through an area, the mackerel were "all flighty," that "they lie on the bottom to feed instead of swimming in midwater," making them harder to fish (Purvis, 2002). Within the literature, however, there is conflicting evidence about whether mackerel respond to vessels as predators, as with most fisheries species (Fréon et al., 1993; Fernandes et al., 2000; Slotte et al., 2007). Nøttestad et al. (2016b) found no change in mackerel acoustic readings before and after trawling, but Godø et al. (2004) had previously found that vessels may affect their behavior and suggest reducing vessel speed when surveying. Mackerel may also respond to the net while trawling, with some evidence that they dive to avoid it, mixing with herring near the seabed (Fernandes et al., 2000; Slotte et al., 2007). With their weak target strength, correct identification of a mackerel shoal is essential, and this

mixing could have major effects on the total biomass estimate. Further investigations into their behavior are necessary.

POSSIBLE FUTURE RESEARCH

Parameterizing IBMs for Acoustic Research

Much of the work on modeling collective behavior has been theoretical, but the insights from these models, when validated with empirical data, demonstrate that they are a useful tool for determining overall shoal characteristics such as density and orientation and how these characteristics change depending on conditions. No studies, however, have attempted to apply these models to acoustic surveys or to how the collective behavior of pelagic fish may change along their migration path. This is a rich avenue for research, as behavior is a major source of variation in acoustic stock assessments (**Table 3**). Properly parameterized and applied, IBMs could be used to reduce sources of bias such as uncertainty in tilt angle and density variations, especially for mackerel and other gregarious species. IBMs may also provide more information on whether behavior changes in response to the survey vessel, or between acoustic sampling and trawling, by providing statistical descriptors of shoal shape that can be related to individual behaviors such as nearest neighbor distance and polarization (Huth and Wissel, 1992; Gautrais et al., 2012).

IBMs provide a framework for testing environmental and behavioral factors that would be near impossible to replicate *in situ*. As the fundamental rules governing collective behavior are well-understood, there is scope to test both intrinsic and extrinsic effects on shoals to determine what changes to the environment or to the animals may affect shoal shape (**Tables 1**, **2**) and acoustic surveys (**Table 3**) and whether these effects are independent or linked. A clear taxonomy of these factors may not be possible, but focusing on the connections between individual behavior and acoustic surveying will help build hypotheses that can be tested with theoretical models and limited data collection. There is a wealth of empirical data to be collected on whether the same conditions, such as bathymetry and oceanography, change behavior to a degree that is reflected in acoustic surveys (**Tables 1**, **3**). Similarly, experimental work is needed to test if behavioral conditions such as leadership and the differences between foraging and evasive behaviors affect shoal shape in acoustic surveys, even at a small scale (**Tables 2**, **3**). IBMs have been used successfully to model the spatial and temporal variation in mackerel populations (Boyd et al., 2018). This research could be expanded further by incorporating behavioral changes across migration, i.e., between foraging, spawning, and traveling between grounds, to predict the approximate vertical position and density of shoals along the migratory path.

Improvements in Technology for Testing Theoretical Models

The practical side of testing theoretical models is also increasingly feasible, as monitoring, tracking, and computing resources improve and become more accessible. Investigating the individual behavior of fish in the open ocean and efficient and accurate analysis of the data collected requires novel uses of and advancements in these technologies. Technology for monitoring and assessing pelagic fish in the field ranges from consumer-level cameras to 3-D sonar and does not need to be highly technical to be effective. Fernandes et al. (2016) used small video cameras to determine the tilt angle of mackerel during surveys. The small cameras did not disturb the mackerel and the fish were shallow enough to be clearly visible on video. More advanced technologies are also being used, such as multibeam sonar, used by Tenningen et al. (2015) to determine the backscatter and density of herring and mackerel during purse-seine capture to determine how they responded to the net.

Further improvements in data collection include three-dimensional video equipment and analysis techniques and automated tracking technology (Butail et al., 2013; Nath et al., 2019) for individuals in video. The vanguard of collective behavior research are using approaches seemingly out of science fiction, such as creating photorealistic virtual environments for zebrafish (*Danio rerio*) to test leadership and social interactions (Stowers et al., 2017). Additionally, cloud computing is increasingly accessible for individuals and institutions, allowing for more robust models and further parameterization and testing (Michener and Jones, 2012). With these technological improvements come myriad opportunities to turn theoretical models into practical tools for fisheries assessment.

Applying Behavioral Modeling to Other Important Questions

IBMs may also be useful in approaching more complex and theoretical questions about how behavior affects fisheries science, such as whether fish behavior has evolved with fishing pressure. There is evidence to suggest that humans have exerted considerable selective pressure on fisheries species through direct intervention, such as the escape of selectively-bred fishes from aquaculture (Hutchings and Kuparinen, 2020). While the evidence for indirect intervention through fishing is less clear, the theoretical basis for genetic change under "predator" and prey interactions is clearer (Hutchings and Kuparinen, 2020). For example, shoals facilitate information transfer and Macdonald et al. (2018) found that the age of individual herring in a shoal can affect the migration path and organization of the shoal. Further, Hollins et al. (2019) found that the vulnerability of minnows to trawling depended on anaerobic capacity when the fish were swimming with familiar conspecifics, but there was no effect in an unfamiliar shoal. These studies suggest that collective behavior and experience has an additional effect on both spatial distribution and fisheries capture. While collective memory and information transfer have been questions explored in theoretical modeling studies (Couzin et al., 2002; Giardina, 2008; Lopez et al., 2012; Ioannou, 2017), the applications to fisheries and stock assessments have not been clearly laid out.

Another important avenue for behavioral research is the effect of climate change on shoaling. Environmental conditions such as temperature, water flow and currents, salinity, and oxygen levels can affect shoaling behavior (**Table 1**; Nonacs et al., 1998; Tien et al., 2004; Rieucau et al., 2014, 2016) and the influence

of these factors is likely to vary under climate change. While shifts in the spatial distribution of important fisheries species, such as mackerel, has been investigated (Hughes et al., 2015; Boyd et al., 2018; Ólafsdóttir et al., 2019), there has not been an overall synthesis of how climate change may affect behavior and, in turn, how those behavioral changes will affect larger-scale spatial distributions.

CONCLUSION

The body of theoretical modeling works spans over four decades and many disciplines, including mathematics, physics, medicine, ecology, and cognitive science. From models of pathogen transmission across aquaculture sites (Alaliyat et al., 2019), to testing theories of democratic consensus with fish shoals (Couzin et al., 2011), collective behavior modeling has been hugely useful. Simple theoretical concepts have been effectively applied to complex, real-world problems. The same approach is possible for fish behavior in stock assessments. Making predictions on how extrinsic conditions affect shoal shape and density will require further synthesis of existing models and deliberate inclusion of variables that affect acoustic monitoring, as many of the factors affecting behavior are likely interdependent. This research can improve our knowledge of and therefore capacity to manage the commercially-valuable pelagic species in the Northeast Atlantic, especially for mackerel. With climate change and increasing global demands for fish, improvements to fisheries assessment are imperative if we want to ensure a stable and productive future for our oceans.

AUTHOR CONTRIBUTIONS

SW drafted the manuscript. SW and MJ revised the manuscript.

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Toward New Ecologically Relevant Markers of Health for Cetaceans

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Multiple stressors caused by human-induced disturbances can affect the foraging opportunities of cetaceans, potentially depleting their energy stores, and ultimately impact survival and reproductive success. Currently, blubber thickness and lipid composition is used as measure of health and nutritional status in cetaceans. This assumes that blubber functions in the same manner as adipose tissue in terrestrial mammals. However, cetaceans have evolved to have thickened blubber which serves as thermoregulation, buoyancy and energy store. In addition, blubber is composed of several layers and regions that have different physiological functions. We currently lack a clear understanding of how blubber biology contributes to maintaining energy status in cetaceans and several studies show blubber thickness, and composition in some body regions, is an inappropriate measure of health. Before new markers of health can be identified, we need to understand how environmental stressors influence blubber biology and particularly unravel its complex signaling roles with other organs. Currently, we do not understand how changes in energy status drive changes in health in cetaceans, and eventually population dynamics. This review synthesizes recent developments in cetacean blubber biology to propose potential directions to develop novel cetacean health markers.

Keywords: cetaceans, blubber thickness, health, PCoMS, PCoD

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INTRODUCTION

Cetaceans underwent critical morphological and physiological adaptations to their anatomy and energy metabolism as they transitioned from a terrestrial to an aquatic lifestyle (Parry, 1949; Scholander et al., 1950). This included the loss of hind limbs, sensory adaptations for navigation and foraging, and changes to the respiratory system to allow for prolonged and deep dives (Berta et al., 2015). Blubber thickening provided insulation (Berta et al., 2015) and opened opportunities to store energy and deal with more sporadic foraging opportunities (Williams et al., 1993, 2001; Vasseur and Yodzis, 2004). Fat stores not only play a role in maintaining energy balance, but also play a crucial signaling role to other organs to regulate energy metabolism (Trayhurn and Beattie, 2007; Ye, 2011). There are indications that some of these signaling functions have changed during the evolutionary trajectory of these species (Ball et al., 2017; Derous et al., 2019). Crucially, these adaptations impact the ways in which individuals decide to invest in reproduction and define their abilities to survive under varied environmental pressures.

As the conservation relevance of sub-lethal stressors (e.g., noise, contaminants, prey limitation) caused by anthropogenic disturbances becomes more important for cetaceans, management frameworks are being developed to estimate the cumulative impact of sub-lethal stressors that

can affect survival and reproduction and therefore population trajectory (National Academies of Sciences, Engineering, and Medicine, 2017). The Population Consequences of Multiple Stressors (PCoMS) are mediated by the impacts of physiological and behavioral changes associated with exposure to those stressors on the health of individuals (National Academies of Sciences, Engineering, and Medicine, 2017). Health in this framework is seen in an ecological context; that is, it encompasses the physiological systems key to enable individuals to survive and reproduce. Energy metabolism, rather than acute immune responses for example, is therefore key to understanding this ecological health status. The framework uses blubber thickness as a measure of health to relate the cumulative behavioral and physiological impacts of anthropogenic stressors to an individual's demographic contribution (Pirotta et al., 2015). Ecologically relevant indicators of health are therefore crucial to understand how different stressors affect survival and reproduction and hence population dynamics in cetaceans. Early attempts to use ecological proxies for the notion of health, such as body condition, have had mixed results to inform PCoMS (New et al., 2014; Pirotta et al., 2015). Indeed, it was recently suggested that using blubber thickness alone is providing a limited view of cetacean ecological health (Kershaw et al., 2019).

We need to determine how multiple stressors are integrated in the energy metabolism of the targeted species at a molecular and cellular level to understand how they affect health. For example, response to stress is centrally regulated by the hypothalamic-pituitary-adrenal axis (HPA) and signals to mobilize energy from stores to maintain the exercising muscles and the brain (Romero and Wingfield, 2016). This allows for a rapid response and optimizes survival from immediate threats. However, long-term stress causes structural changes to the adrenal gland (Clark et al., 2006) and can cause deterioration or even death in marine mammals (Cowan and Curry, 2008). Stressors may affect energy metabolism of cetaceans to such a level that it could have detrimental effects, even after the stressor is removed. We are currently facing a knowledge gap between health and energy metabolism in cetaceans, and how they mediate potential metabolic constraints faced during periods of exposure to stressors.

We therefore need to understand the physiological systems involved in energy metabolism in cetaceans. We know that adipose tissue in all mammals, blubber in cetaceans, plays a critical role in energy metabolism not only as an energy store, but also as an emitter of regulatory signals. The majority of cetacean blubber biology studies have focussed on lipid composition (Kershaw et al., 2019), hormone profiling (Boggs et al., 2017, 2019; Kershaw et al., 2017), persistent organic pollution and contamination (Montie et al., 2008; Fair et al., 2010; Kucklick et al., 2011; Pinzone et al., 2015; Zhan et al., 2019), and morphology (Montie et al., 2008). A few have focussed on the role of blubber and its link to health status/reproductive success in cetaceans (Miller et al., 2011; Christiansen et al., 2013, 2014; Irvine et al., 2017). Here, we review how this existing information is relevant to the PCoMS challenge and what future directions are needed to better qualify cetacean health in an ecologically relevant manner.

TERRESTRIAL MAMMALS' ENERGY STORES AND CONDITION OF HEALTH

In terrestrial mammals, the size of energy stores is a classical body condition and health proxy (Barnes, 1984; Markusfeld et al., 1997; Morfeld et al., 2016). From studies with species such as rodents and humans, we know that adipose tissue serves as an energy storage and is involved in regulating metabolism by producing several signaling molecules (adipokines) such as leptin (Trayhurn and Beattie, 2007; Ye, 2011). Adipose tissue can be categorized into two main types based on the position: visceral and subcutaneous fat. Excessive visceral fat is associated with numerous metabolic disorders including insulin resistance and cardiovascular diseases in humans, rodents and canine pets (Mathieu et al., 2010; Thengchaisri et al., 2014) while subcutaneous fat does not have such a detrimental effect on health (Gabriely et al., 2002). The secretion of leptin is in proportion to the amount of adipose tissue and is therefore a key peripheral signal to communicate energy status to other organs. Mammalian reproduction is sensitive to the state of energy stores and leptin secretion plays a role in maintaining reproductive function during adulthood (Williams et al., 2002; German, 2006; Sam and Dhillo, 2010; Yan et al., 2011; Nahar et al., 2013; Pantasri and Norman, 2014; Morfeld and Brown, 2016).

CETACEANS' ENERGY STORES AND CONDITION OF HEALTH

Blubber Thickness and Reproductive Cycle

The amount of adipose tissue in cetaceans has also been used as an indicator of health and reproductive success (Miller et al., 2011; Christiansen et al., 2013, 2014; Irvine et al., 2017). These energy stores seem to vary depending on strategies for financing the costs of reproduction. Stores of income breeders (e.g., bottlenose dolphins, *Tursiops truncatus* and sea lions, *Zalophus californianus*) stay relatively constant throughout the year, while those of capital breeders (e.g., humpback whales, *Megaptera novaeangliae* and elephant seals, *Mirounga spp.*) vary with reproductive class and migratory stages (Irvine et al., 2017). For example, pregnant humpback whales have higher relative energy stores than non-pregnant females and males (Irvine et al., 2017). In addition, larger pregnant females had relatively larger energy stores compared to smaller pregnant females (Irvine et al., 2017). In North Atlantic right whales (*Eubalaena glacialis*), blubber thickness depends on reproductive cycle; it is thickest 3 to 6 months prior to pregnancy and thinnest during lactation (Miller et al., 2011). The blubber was thickest in pregnant North Atlantic fin whales (*Balaenoptera physalus*) compared to other reproductive classes (Williams et al., 2013). This indicates that, like for terrestrial mammals, energy stores are needed for gestation and lactation as these are energetically very costly (Iverson, 2009). In addition, smaller individuals may experience higher levels of energetic stress during the migration fast (Irvine et al., 2017). In minke whales

(*Balaenoptera acutorostrata*) blubber volume was associated with fetal investment (Christiansen et al., 2013). Fetus length was reduced for those female minke whales with a poorer body condition, suggesting that they reduce their energic investment in fetus growth to optimize their own survival (Christiansen et al., 2014). In North Atlantic fin whales, a decline in pregnancy rate in breeding age females is associated with low blubber thickness (Williams et al., 2013). In North Atlantic right whales it has been suggested that during periods of low prey availability, early term abortion could be a mechanism to save energy (Knowlton et al., 1994).

Blubber Thickness and Nutritional Stress

The blubber of North Atlantic right whales is thinner in years with low prey availability (Miller et al., 2011). Inter-annual variability in blubber thickness associated with prey availability was also observed in North Atlantic fin whales (Williams et al., 2013). The blubber mass of harbor porpoises (*Phocoena phocoena*) was lost quickly when they were disturbed, losing approximately 4% of initial body mass after 24 h disturbance (Kastelein et al., 2019).

Blubber thickness is one of the attributes contributing to insulation against the cold besides the lipid content and lipid composition (Iverson, 2009). Smaller cetacean species would require an increased metabolism for heat production (Iverson, 2009). Hence, smaller cetaceans are therefore more susceptible to changes in their prey availability, and thus starvation, as demonstrated by the rapid decline in body mass of harbor porpoises (Kastelein et al., 2019). The inner most layer of blubber in harbor porpoises has characteristics (both structure of fat cells and gene expression of UCP1) associated with brown adipose tissue, which plays a key role in thermoregulation and heat production in some land mammals (Hashimoto et al., 2015). In bowhead whales (*Balaena mysticetus*), however, blubber thickness did not vary with seasons or life stages (Ball et al., 2015), and similar results are found in other species including sperm whales (*Physeter macrocephalus*) (Evans et al., 2003; Ruchonnet et al., 2006; Caon et al., 2007; Koopman, 2007; Gómez-Campos et al., 2011). Interestingly, larger cetaceans such as bowhead and sperm whales seem to lack functional proteins of UCP1, one of the key genes related to heat production (Keane et al., 2015). Hence, the evolution on a species level may have ecological implications of how blubber is used during periods of starvation, the cost of thermoregulation and the deleterious effects it may have on health. Indeed, smaller aquatic animals are constrained for thermoregulatory costs while larger aquatic animals have limitations on feeding efficacy (Gearty et al., 2018). We should therefore place blubber thickness in the context of how it may affect reproduction and if, as an ecological health indicator, it is relevant to demographic contributions of a specie. Using blubber thickness alone is providing a limited view of cetacean ecological health (Kershaw et al., 2019) and thus using blubber thickness as an ecological health proxy might be flawed in many species.

Blubber Thickness and Body Condition

Blubber thickness as a marker of body condition in cetaceans has its limitations (Kershaw et al., 2019). In sperm whales, blubber thickness was positively related to total length but there was a lack of relationship with age, sex or reproductive success (Evans et al., 2003). In addition, blubber lipid content was not related to blubber thickness in these stranded sperm whales. This is in agreement with data from dorsal blubber samples from stranded ziphiids and balaenopterids where the lipid content of the blubber and blubber thickness provided little information on overall body condition (Kershaw et al., 2019). In striped dolphins (*Stenella coeruleoalba*), blubber thickness did not differ between reproductive classes and nutritional condition (Gómez-Campos et al., 2011). In two mass strandings of rough-toothed dolphins (*Steno bredanensis*), the dorsal blubber thickness was not different although clear differences were found in body condition measured by body mass index between euthanized and rehabilitated animals (Karns et al., 2019). However, differences were found in the lateral and ventral blubber thickness of these animals (Karns et al., 2019). Depending on biopsy site, the blubber thickness indeed varies in the same animals and this depending on the length and cause of death (**Figure 1**).

Hence, using blubber thickness alone in some cetaceans as a health marker may not reflect whether individuals are in negative energy status or not. In addition, in a meta-analysis of stranded male harbor porpoises with different causes of death only 50% of the variation in body mass/length^2 ratio could explain the body condition while model validation for ventral blubber thickness was very poor (Kershaw et al., 2017). Therefore, blubber thickness might indeed be a poor index of condition in harbor porpoises as well as other species (Read, 1990; Evans et al., 2003; Ruchonnet et al., 2006; Caon et al., 2007; Koopman, 2007; Gómez-Campos et al., 2011). Kershaw et al. (2017) argued that muscle mass may be used as fuel during periods of starvation as blubber has other functions such as thermoregulation and buoyancy as a consequence of secondary adaptations to life in water. Fat may also be stored within the muscle and although no significant changes were found in blubber between reproductive classes of North Atlantic fin whales, the adult females do appear to store more fat in their tail muscles (Lockyer et al., 1985). Lockyer (2007) also argues that it is critical to understand each species energy metabolism to understand how fat storage is linked to reproductive success and health (Lockyer, 2007). More than a decade later, we still lack a good physiological understanding of how health/reproduction/energy stores are regulated in the majority of cetaceans. We therefore first need to understand (1) how the different layers of blubber function, (2) what triggers lipid deposition, and (3) how this is related to ecological health.

Functionality of the Different Blubber Layers

Blubber can be divided into different layers, with the outer layer mainly used for structural support and inner layer for energy storage. For example, the adipocytes of healthy porpoises in the outer layer of blubber were smaller than inner blubber adipocytes. Starved porpoises, however, had fewer, smaller adipocytes in the inner layer blubber, suggesting a possible

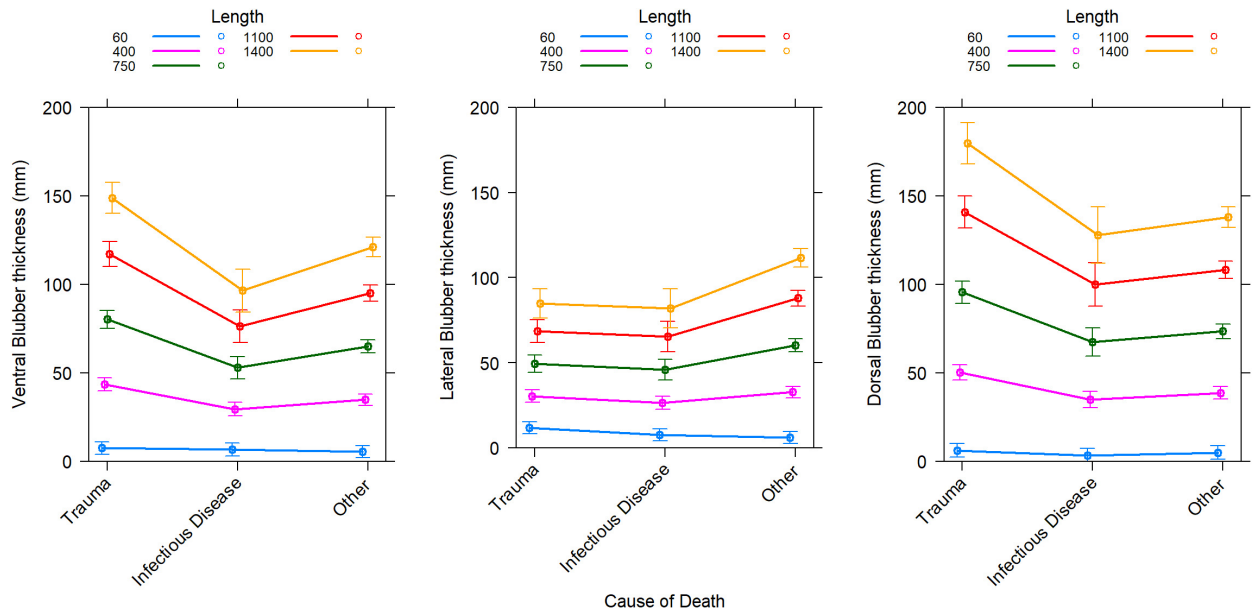

FIGURE 1 | Predicted change in blubber thickness at three locations along the mid-body depending on the cause of death for Odontocetes categorized in 4 taxa occurring more often in strandings in Scotland (bottlenose dolphins, harbor porpoises, pelagic delphinids, sperm and beaked whales). Individuals that died from trauma can be expected to have "typical" blubber thickness (unchallenged) for their population. Predictions are from the best general mixed-effect linear model for each blubber location which includes an effect of body length (Length in cm) depending on the effect of cause of death (Trauma, Infectious disease, or other) and random effects of taxa and year of stranding in taxa. Marginal coefficients of determination are 0.72, 0.65, and 0.78, respectively for the ventral, lateral, and dorsal blubber thickness models. Conditional coefficients of determination are 0.79, 0.75, and 0.83, respectively for the ventral, lateral, and dorsal blubber thickness models. Error bars are 95% confidence intervals. Historical stranding data (since 1991) from the Scottish Marine Animal Stranding Scheme (database available at https://www.strandings.org/cgi-bin/smass/map.pl and previously published by Kershaw et al., 2017).

combination of adipocyte shrinkage and loss (Koopman et al., 2002). Interestingly, the adipocytes of the deepest layer of the blubber in lactating dolphins were significantly smaller compared to pregnant animals (Montie et al., 2008). This suggests that lactation is energetically more costly for these animals and more stored fat is being used to meets these metabolic demands. In addition, lipid content differed between the blubber layers of fin whales, yet the composition of the top layer was not different between reproductive classes of the whales (Aguilar and Borrell, 1990). Levels of cortisol (i.e., stress hormone) in stranded harbor porpoises showed a clear difference in concentration with the inner layer having a higher concentration compared to the top layer (Kershaw et al., 2017). A study using five parameters (i.e., lipid percent and classes, contaminant concentrations and profiles, fatty acid profiles) to assess body condition found that results varied depending on the layer sampled in beluga (*Delphinapterus leucas*) and killer whales (*Orcinus orca*) (Krahn et al., 2004). Hence, classical measures in superficial biopsy samples may not be relevant health proxies.

Regulation of Lipid Deposition

In our classical view of mammalian energy metabolism, hormonally regulated lipid storage/deposition depends on the interaction between an individual's physiological needs and environmental changes. A key regulatory hormone is leptin, which is involved in regulating food intake and energy metabolism depending on fat mass via key neuropeptides in the hypothalamus region of the brain (Friedman, 2019).

Leptin gene expression changed drastically depending on the migratory stage of bowhead whales (Ball et al., 2017). Leptin expression in mature bowhead whales differed between the outer and inner blubber layers, and for the inner layer leptin changed significantly according to season. Blubber thickness, however, did not vary in bowhead whales with season or life stage. This is likely due to the adipocyte cell size reducing rather than their number combined with an increase in structural fiber density (Ball et al., 2015). As leptin and binding to its receptor seems to be highly conserved, the modification in leptin functions observed in these animals seems to therefore stem on its regulatory mechanism. The results of Ball et al. (2017) indicated cetaceans may be departing from the classical mammalian model of leptin regulation of energy metabolism, and temporary leptin resistance during migration may be a mechanism to reduce the anorexigenic effects of leptin. In addition, Ball et al. (2017) speculates that the unusual large differences in seasonal leptin levels is likely a signal to induce a physiological response to change feeding habits or start migration, rather than a measure of total lipid stores as is the case in typical mammalian energy metabolism.

Therefore, whale foraging mechanisms may have evolved to compensate for large size being limited by prey availability, posing questions about satiation mechanisms in which leptin is key in other mammals. These large animals may face some

metabolic constraints on their energy metabolism based on the energy cost for thermoregulation and feeding efficiency (Gearty et al., 2018; Goldbogen et al., 2019).

Genes related to triacylglycerol synthesis and lipolysis processes were positively selected in cetaceans compared to terrestrial mammals (Wang et al., 2015) and indeed, a large portion of positively selected genes in cetaceans are involved in energy metabolism (Nery et al., 2013). Positive gene selection in energy metabolism-related biological pathways suggests these genes may have been positively selected to adapt to a glucose-poor diet and it is unlikely that fat depots signaling function in the same manner as in terrestrial mammals. Specifically adiposity is not likely to have the deleterious health consequences known in terrestrial mammals (Derous et al., 2019). For example, while low blubber thickness negatively impacted pregnancy rate in North Atlantic fin whales, larger than normal blubber thickness was still associated with the same rate of pregnancy as that of typical healthy animals (Williams et al., 2013). This is in stark contrast with land mammals where both reduced and increased fat mass (signaled by leptin) leads to reduced reproductive success (Caprio et al., 2001). Hence, cetaceans may not face a metabolically constrained upper limit of the amount of fat they can store but the evolutionarily increase in body-size of whales does seemed to be constrained by prey availability (Goldbogen et al., 2019). In a land mammal, large volume of adipose tissue triggers inflammatory responses and can lead to metabolic dysfunctions at a physiological level (Mantovani et al., 2002). In cetaceans, key genes related to inflammation are positively selected in such a way that fat deposits signaling may not be as limited by inflammation, metabolic dysfunctions and reproduction (Derous et al., 2019). These phylogenomic studies indicate that due to evolutionary constraints associated with secondary adaptations to life in water, we cannot expect adipose signaling to interact with energy metabolism in cetaceans like it does in the classical mammalian model. We therefore need de novo studies of the role of adipose signaling in cetacean appetite regulation and reproductive investment.

TOWARD NEW MARKERS OF HEALTH – OMICS APPROACH

We can now characterize many thousands of genes, metabolites and proteins associated with phenotypic traits and this is key to the discovery of health biomarkers in human diseases (Abu-Asab et al., 2011; Hasin et al., 2017; Karczewski and Snyder, 2018; Peña-Bautista et al., 2018; Blencowe et al., 2019). To date, we still lack a detailed understanding of whole genome dynamics associated with changes in energy status in cetacean blubber and the consequences for cetacean cellular biology (Kershaw et al., 2018; Misra et al., 2019). However, recent attempts have been made to elucidate how metabolism of cetaceans is regulated by using an omics approach (Kershaw et al., 2018; Misra et al., 2019). Proteomics data from full depth blubber subsamples from dead-stranded harbor porpoises identified 295 proteins mostly involved in cell function and metabolism (45%), immune response and inflammation (15%) and lipid metabolism (11%) (Kershaw et al., 2018). Blubber metabolomics analysis of stranded bottlenose dolphins compared to skin biopsies indicated, unsurprisingly, a clear role of blubber in fatty acid metabolism and ketogenic amino acids. In addition both tissues were involved in urea cycle, nucleotide metabolism, amino acid metabolism, glutathione metabolism among others (Misra et al., 2019). Although these studies give us insight into the metabolome/proteome, it is hard to conclude the role of blubber in health status. There is a need to unravel the complex signaling mechanisms in blubber and to understand how environmental stressors influence blubber biology and signaling.

CONCLUSION

Blubber thickness has previously been used in cetaceans as a measure of their energy stores and thus their health. However, using blubber thickness alone may provide a limited view of cetacean's ecological health. For example, blubber thickness measured at three locations of varies species and varies causes of death seems to lead to differs in conclusions in terms of how their energy stores are reflective for their health. These conclusions related to blubber thickness is based on the assumptions that cetaceans are using their fat stores in a similar manner as terrestrial mammals. Based on empirical data and the lack of experimental data, it is unclear if this is indeed the case. For example, while a clear decrease in morphometric body condition of juvenile and adult humpback whales was observed at different time points (from 18.8% to −8.1%; and from 8.6% to −3.4%, respectively), this was not reflected by a change in outer layer blubber lipid concentration (Christiansen et al., 2020). We therefore urge to move toward interdisciplinary research to try to understand how these animals are regulating their energy stores (e.g., different positions and different layers) and if we can find novel markers that are more reflective of their energy state. The evolution of metabolic pathways shape mammalian physiology and may impact the ways in which cetaceans "decide" to invest in reproduction and define their abilities to survive under varied environmental pressures. These changes therefore have the scope to alter the way individuals make biological decisions about reproduction investment given their energetic metabolic state. Food availability is more clustered in time and space and thermoregulatory challenges are acute, externalizing some motivational processes. This will have ecological implications of how blubber is used during periods of starvation and the cost of thermoregulation. Relying on prey limitations to guide satiation may have advantages to ensure the maintenance of blubber and reduced stochasticity in its dynamics to help maintain its thermoregulatory advantages. For example, leptin in cetaceans is likely a signal to change feeding habits or start migration rather than a measure of total lipids stores. This has profound implications for the way energy metabolism status influences reproduction and survival, which we do not understand clearly at the moment. In addition, energy metabolism is also regulated by the microbiome and changes in composition could have an

effect on signaling molecules related to appetite, energy uptake and storage, and energy expenditure (Heiss and Olofsson, 2018). We need innovative management tools to assess the impact of PCoMS on the conservation of key species like cetaceans. However, to achieve this there is a need to move toward interdisciplinary research as the current knowledge gap requires an integration of ecological insights and de novo molecular biology analyses using systems biology approaches.

AUTHOR CONTRIBUTIONS

DD and DL contributed to the design and concept of the manuscript. DD wrote the manuscript. DL performed the statistical analysis and made the figure. AB and ND provided the intellectual input. MD organized the database. All authors contributed to manuscript revision, read, and approved the submitted version.

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Connecting Crabs, Currents, and Coastal Communities: Examining the Impacts of Changing Ocean Conditions on the Distribution of U.S. West Coast Dungeness Crab Commercial Catch

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Dungeness crab (*Cancer magister*) is one of the most lucrative fisheries on the United States (U.S.) west coast. There have been large spatial and temporal fluctuations in catch, which reflect the interconnected influences of the coupled natural-human fishery system. Changing ocean conditions are likely to further alter the magnitude and distribution of Dungeness crab catch, the impacts of which will propagate ecologically and through the social systems of fishing communities. Therefore, the effect of changing ocean conditions on U.S. west coast Dungeness crab catch per unit effort (CPUE) was used as an interdisciplinary case study to examine the susceptibility, a metric that integrates Dungeness crab reliance and social vulnerability indices, of coastal communities to changes in the fishery. Statistical models indicated that ocean conditions influence commercial CPUE 3–5 years later and that CPUE is likely to decline in the future as ocean conditions change. In particular, sea surface temperature scenarios for 2080 (+1.7 and +2.8°C) reduced Dungeness crab CPUE by 30–100%, depending on fishing port latitude. Declines in Dungeness crab CPUE were greater for southern port communities than for northern port communities under both scenarios – demonstrating greater exposure at the southern end of the species range. We show that U.S. west coast communities are differentially susceptible to a decline in Dungeness crab catch, with Washington communities being at least five times more susceptible than California communities. Our overall assessment showed varying levels of risk (a combination of exposure and susceptibility) for Dungeness crab fishing ports that do not necessarily align with regional or fishery management boundaries.

Keywords: Dungeness crab, climate change, species distribution, ocean conditions, fisheries, coupled natural-human system

INTRODUCTION

Fisheries of the United States (U.S.) west coast are coupled natural-human systems that cross state borders, and integrate private and public sectors. They involve complex relationships between coastal socio-economics, resource management, and environmental factors. The integral role of humans in fishery systems has been formally recognized with a shift toward ecosystem-based management in natural resource programs (ORAP, 2013). In addition, social science research has begun to address vulnerabilities in fishing-reliant communities (Norman et al., 2007; Himes-Cornell et al., 2016; Moore et al., 2019). However, few studies employ the interdisciplinary techniques necessary to understand and address complex problems, like climate change, involving fisheries (except see Ekstrom et al., 2015; Mathis et al., 2015).

The consequences of changing ocean conditions due to climate change are already being experienced across fishery systems (Ritzman et al., 2018; Young et al., 2019). The impacts include, but are not limited to, decreased ocean production, altered food-web dynamics, and shifted species distributions (Hoegh-Guldberg and Bruno, 2010). While there are uncertainties in the spatial and temporal dimensions of future ocean conditions, there are clear trends toward a changing ocean in the California Current System (CCS) (Bograd et al., 2002; Snyder et al., 2003; Bograd et al., 2008; Gruber et al., 2012; Sydeman et al., 2013; Gentemann et al., 2017; Holsman et al., 2019). In particular, sea surface temperature (SST) is expected to increase both globally and within the CCS throughout the 21st century (Holsman et al., 2019). Under the relatively conservative RCP 4.5 W/m^2 radiative forcing scenario, the CMIP5 multi-model ensemble predicts a 1.7 $\pm$ 0.4°C increase in SST within the CCS by 2080, but other scenarios (e.g., RCP 8.5 W/m^2) predict up to a 2.8 $\pm$ 0.6°C SST increase by 2080 (reviewed in Jewett and Romanou, 2017). With changing SST and air temperature, other ocean conditions are predicted to change, including upwelling (Upw), physical spring transition (STI), and the way in which these local ocean conditions correlate with basin-scale indexes such as the Pacific Decadal Oscillation (PDO), El Niño Southern Oscillation (ENSO), and North Pacific Gyre Oscillation (NPGO) (Bograd et al., 2002; Bakun et al., 2015; Jacox et al., 2016; Litzow et al., 2020). Oceanographic changes within the next few decades will likely have substantial and cascading implications for ocean systems, fisheries, and coastal communities (Jones et al., 2015; Yen et al., 2016). Distribution shifts have already been documented in species found between 30 and 60°N, and many observed shifts have been correlated with global temperature increases (reviewed in Lenoir and Svenning, 2015). Despite prior expectations, species responses to climate change have not been uniform and species distribution shifts have occurred at different rates and directions (e.g., Perry et al., 2005; Nye et al., 2009; Pinsky et al., 2013; Cheung et al., 2015). Marine species, in particular, show considerable variation in the rate and direction of shifts due to the complexity of changing ocean conditions. This complexity results in considerable spatial variation in the magnitude and direction of ocean condition changes and, ultimately, species have tracked closely with local-scale differences (Pinsky et al., 2013). Understanding the distribution and abundance of marine species is necessary for implementing appropriate fishery management strategies and assessing the potential resilience of a fishery to environmental changes (Ritzman et al., 2018).

Therefore, we aimed to elucidate the impact of changing ocean conditions on coastal communities through the lens of a socio-economically important fishery in the CCS. In this study, we focused on commercial catch of Dungeness crab (*Cancer magister*) delivered to fishing communities in Washington, Oregon, and California. Currently, Dungeness crab is the most lucrative single species fishery on the U.S. west coast, generating about $200 million per year (Rasmuson, 2013; PSMFC, 2014). Potential impacts associated with climate and oceanographic changes and a resulting shift in the magnitude and distribution of Dungeness crab catch in the CCS, are expected to propagate through ecological and social systems, affecting policy, fishing industries and the greater well-being of many U.S. west coast communities. Major fishing ports for Dungeness crab on the U.S. west coast range from large cities like San Francisco, California to smaller, natural resource dependent communities like Port Orford, Oregon (NOAA, 2017). Some of these areas may be more reliant on the Dungeness crab industry than others, particularly where catch represents a considerable proportion of economic input to the community (PFMC, 2017).

Changes in ocean temperatures and currents may impact survival and dispersal of Dungeness crab larvae in the CCS, and subsequently the magnitude and distribution of commercial catch along the U.S. west coast. The 3- to 4-month pelagic larval stage of Dungeness crab is the most vulnerable life stage, and the crabs become increasingly resilient to environmental factors, like temperature, as they develop into adults (Ebert et al., 1983). In addition to thermally induced physiological effects on crab larvae, there can also be indirect effects, due to changing ocean currents that are correlated with changes in SST in the CCS (Botsford and Lawrence, 2002; Shanks et al., 2010; Shanks, 2013). Therefore, it is possible that the cumulative effect of increasing SST on larval Dungeness crab will alter the abundance and distribution of adults available for harvest within the CCS.

Management of Dungeness crab is atypical compared to other U.S. west coast fisheries because total allowable catch determinations are not based on calculations for sustainable yield and do not incorporate a formal stock assessment (Davis et al., 2017). Instead, managers estimate that the majority (>90%) of legal-sized adult (approximately 4 years of age) male crab are harvested every year (Botsford, 1984; Higgins et al., 1997; Armstrong et al., 2003; Rasmuson, 2013). Even with these uncertainties, the biological condition of the Dungeness crab stock is considered to be healthy based on sustained catch over the past 30+ years (Helliwell, 2009; Richerson et al., 2020). However, there have been large spatial and temporal fluctuations in historical commercial catch of Dungeness crab along the U.S. west coast over the past four decades that reflect

the interconnected influences of biological, environmental, and social variability (reviewed in Rasmuson, 2013).

Using an interdisciplinary framework, we investigated how changing ocean conditions affect commercial catch of Dungeness crab and associated fishery communities of the U.S. west coast. Through the process of four steps, our analysis utilized both existing and novel metrics for exposure and susceptibility in the Dungeness crab coupled natural-human system. We defined the potential "exposure" of fishing communities to altered Dungeness crab catch due to changing ocean conditions via the first two steps. First, (1) we determined the spatial and temporal relationship between various ocean conditions and Dungeness crab commercial catch along the CCS from 1981 to 2017. Then, (2) this relationship was used to examine the magnitude of change in Dungeness crab catch for U.S. west coast port communities resulting from two ocean condition scenarios. Next, (3) we assessed the degree to which changes in Dungeness crab commercial catch may impact 18 fishery-reliant CCS communities (**Figure 1**) by defining a novel "susceptibility" score, which incorporated existing indices for fishery reliance and social vulnerability. Finally, (4) we considered the overall picture of "risk" to coastal communities via a qualitative assessment of the combination of exposure and susceptibility.

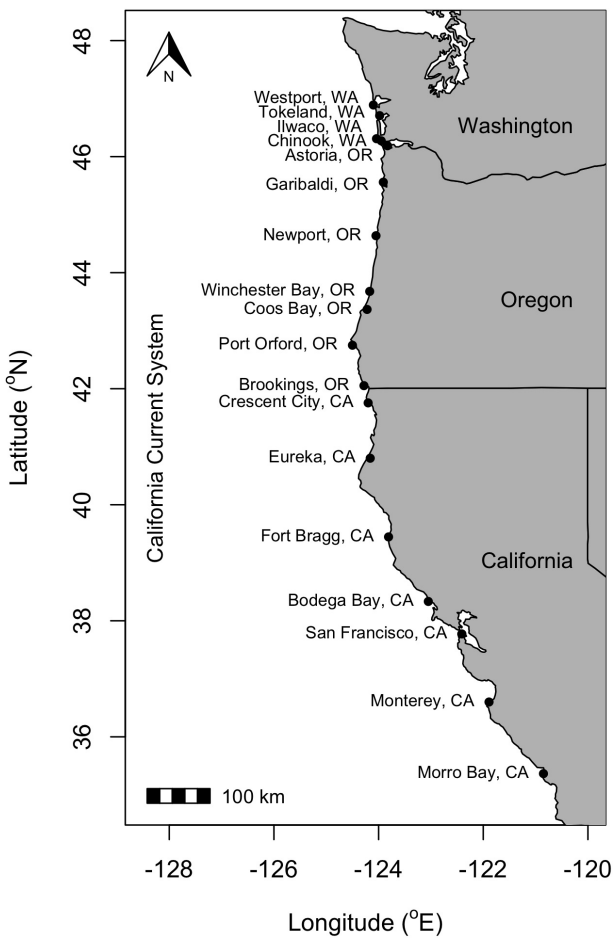

FIGURE 1 | Map of the 18 major U.S. west coast port communities considered in this study within the Washington, Oregon, Northern California, and Central California management units. See **Table 4** for port latitudes and management regions.

MATERIALS AND METHODS

Data were obtained from multiple state, federal, and academic sources (**Supplementary Table S1**). All analyses were performed in R (v.3.5.0, R Core Development Team, 2018). The data and analyses are described in greater detail below.

Commercial Catch per Unit Effort

We gathered historical Dungeness crab commercial catch data (1981–2017) within the CCS for major U.S. west coast fishing ports (two Washington regions, seven Oregon ports, and seven California ports) (**Supplementary Table S1**). To normalize commercial catch, we calculated an estimated catch per unit effort (CPUE) by dividing the weight in kilograms (kg) of annual port or region Dungeness crab commercial catch by the number of Dungeness crab fish tickets (i.e., state department of fish and wildlife landing receipts) reported at each location in each year. Additionally, the proportional distribution of CPUE among U.S. west coast ports for each year was determined by dividing each port's annual CPUE by the total annual CPUE across all ports. Analyses by ODFW (2014) and Richerson et al. (2020) found that fish tickets served as an adequate estimate of effort when compared to logbooks. Limited access and availability of fishery logbooks across all states and years necessitated estimation of CPUE in this way.

Ocean Conditions

A time series of the ocean conditions occurring within or affecting the CCS was compiled for 1977–2017 based on our hypotheses about the impact of ocean conditions on Dungeness crab survival and dispersal (**Table 1**, **Figure 2**, and **Supplementary Table S1**). Four basin-scale ocean condition indices were used in this study: PDO (sum of monthly averages January through June), NPGO (sum of monthly averages January through June), Multivariate ENSO Index (MEI; sum of monthly averages January through June), and Southern Oscillation Index (SOI; sum of monthly averages January through June) (**Figure 2**, left column). In addition, four latitude-specific measurements were used for 2- or 3-degree latitude increments, including: SST (average of January through June), upwelling (Upw; sum of daily Bakun upwelling index during the April through August upwelling season), spring transition index (STI; day of year), and northward Ekman transport (EkTrans; sum of monthly averages January through June) (**Figure 2**, right column). We used the northward component of EkTrans (metric tons second^{-1} kilometer^{-1}) to indicate the relative strength of the California Current, with negative values indicating southward flow (Nelson, 1977). Most of the ocean condition metrics were summarized for January through June (**Table 1**) because CCS Dungeness crab are planktonic larvae during that time, which is hypothesized to be the life history stage most impacted by ocean

TABLE 1 | List of ocean conditions analyzed for their relationship to Dungeness crab commercial catch per unit effort (CPUE) across the U.S. west coast, description of how the ocean condition value was summarized for analysis, and its hypothesized effect on CPUE.

Ocean condition	Summary value	Hypothesized effect: *greater CPUE will be associated with a lagged effect of:*
Pacific Decadal Oscillation (PDO)	Sum of January–June monthly averages	Stronger negative PDO (Shanks, 2013)
North Pacific Gyre Oscillation (NPGO)	Sum of January–June monthly averages	*None* (Shanks et al., 2010)
Multivariate El Niño Southern Oscillation Index (MEI)	Sum of January–June monthly averages	*None* (Shanks et al., 2010)
Southern Oscillation Index (SOI)	Sum of January-June monthly averages	*None* (Shanks et al., 2010)
Sea Surface Temperature (SST)	Average January–June (2° latitude increments from 36°N to 48°N)	Lower SST (Botsford and Lawrence, 2002)
Upwelling (Upw)	Daily sum from April-August (3° latitude increments from 36°N to 48°N)	Stronger Upw (Shanks, 2013)
Spring Transition Index (STI)	Day of year (3° latitude increments from 36°N to 48°N)	Earlier STI (Shanks and Roegner, 2007)
Northward component of Ekman Transport (EkTrans)	Sum of January-June monthly averages (3° latitude increments from 36°N to 48°N)	More negative northward component of EkTrans (Shanks, 2013)

A citation for the basis of the hypothesized effect is included.

conditions (Botsford et al., 1989; Botsford and Lawrence, 2002; Rasmuson, 2013).

Spatial and Temporal Analyses of Ocean Conditions and Commercial Catch

Generalized additive mixed models (GAMM) were used to assess the spatial and temporal relationship between ocean conditions and commercial Dungeness crab CPUE along the U.S. west coast. To allow for the spatially variable effects of ocean conditions on Dungeness crab CPUE and to account for simultaneously testing the effects of ocean conditions at multiple locations, we applied a variable coefficient GAMM (VC_GAMM) framework. The VC_GAMM allows for variable model intercepts and variable linear relationships between the response and the design variable (Bacheler et al., 2009; Bartolino et al., 2011). These formulations are ideally suited to test for the presence of either spatially (e.g., Ciannelli et al., 2012) or temporally (e.g., Litzow et al., 2019) variable relationships between ocean conditions and indices of fish productivity or abundance. Dungeness crab span a large distributional range, thus the effect of ocean conditions on catch is likely to be spatially variable across latitude. This outcome could have important societal implications because some fishing communities may be more exposed to changing ocean conditions and associated impacts on fisheries than others. Therefore, our analyses compared two GAMM formulations: one with linear and spatially fixed effects of ocean conditions on Dungeness crab CPUE (stationary GAMM) and another with locally linear and spatially variable effects of ocean conditions on CPUE (VC_GAMM) depending on the port or region of commercial catch (n = 16). The two model formulations are nested and thus can be compared using a likelihood-ratio (LR) test, which tests the null hypothesis that the likelihood of the unconstrained (i.e., VC_GAMM) and constrained (i.e., stationary GAMM) model formulations are not significantly different from each other (Litzow et al., 2019). The two model formulations can also be compared based on the Akaike information criterion (AIC), which is a metric of model performance that accounts for both likelihood of the model parameters and complexity of the model parameterization.

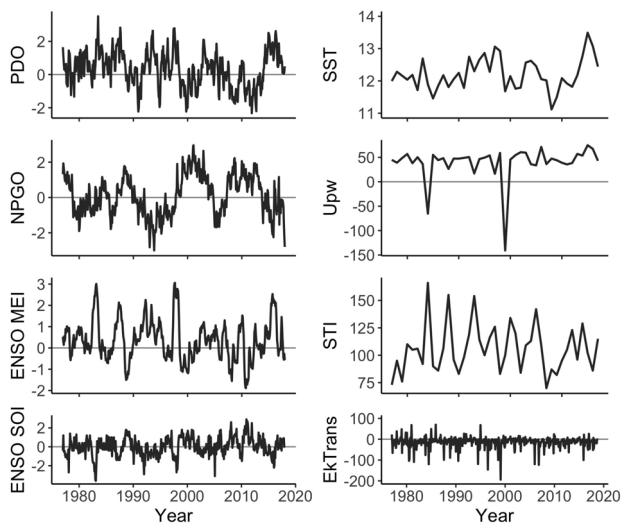

FIGURE 2 | Ocean conditions measurements from 1977 to 2017. Regional factors (PDO, ENSO SOI, ENSO MEI, and NPGO) are monthly index values. Local factors (EkTrans, SST, Upw, and STI) are shown, for example, at 45°N. Northward EkTrans (value × 10 = metric tons second^{-1} kilometer^{-1}) are shown as monthly values. SST (°C), Upw (meters^3 second^{-1} per 100 m of coastline), and STI (day of year) are annual values.

The GAMM and VC_GAMM were built using the R packages 'mgcv' (v.1.8-28; Wood, 2017; Wood, 2019) and 'nlme' (v. 3.1-139; Pinheiro et al., 2019). The CPUE data were natural log transformed to meet the assumption of normality. The summarized ocean conditions were then lagged 3, 4, and 5 years in accordance with published literature that Dungeness crab are caught in the CCS fishery at about age four (Botsford, 1984; Johnson et al., 1986). For each of the eight ocean conditions, we fit 26 models of latitudinally fixed (i.e., stationary GAMM) and latitudinally variable (i.e., non-stationary VC_GAMM) effects for all three time lags (3, 4, and 5 years). Each ocean condition was considered separately and the suite of 26 models for each ocean condition included all possible combinations of stationary and/or non-stationary effects at one or multiple time lags

(**Supplementary Table S2**). The general formulations for each model type were:

Stationary GAMM:

$$y_{t,lat} = \alpha_{lat} + \beta_1 \cdot OC_{(t-3)} + \beta_2 \cdot OC_{(t-4)} + \beta_3 \cdot OC_{(t-5)} + \varepsilon_{t,lat}$$

Variable Coefficient GAMM:

$$y_{t,lat} = \alpha_{lat} + \beta_{1lat} \cdot OC_{(t-3)} + \beta_{2lat} \cdot OC_{(t-4)} + \beta_{3lat} \cdot OC_{(t-5)} + \varepsilon_{t,lat}$$

Where $y_{t,lat}$ is Dungeness crab CPUE at year '*t*' and port latitude (*lat*). *OC* is one of the eight ocean condition indices listed in **Table 1**, at the three examined time lags (3, 4, and 5 years). Each β term is the linear coefficient of the lagged *OC* variable, and α_{lat} is the model intercept. In the VC_GAMM, model coefficients (α_{lat} and β terms) are assumed to be spatially variable according to a smooth function of *lat*. In the stationary GAMM formulation, only the model intercept α_{lat} is assumed to be spatially variable, while β terms are fixed. It is necessary for both formulations to allow for spatially variable intercept α_{lat} to account for the overall trend of greater Dungeness crab catch at higher latitudes. The error term ($\varepsilon_{t,lat}$) is assumed to be temporally autocorrelated at lag = 1: $\varepsilon_{t,lat} = \partial + \Phi\ \varepsilon_{t-1,lat}$. Including a temporally autocorrelated error structure ensures that potential temporal trends in the model residuals does not bias estimates in the uncertainty of model parameters. For each model, the parameter Φ was assessed to determine if an autocorrelation error variable should be included.

The best model for each ocean condition was chosen based on LR tests and AIC. The model with the lowest AIC value was chosen as the best model if it was the reduced (simpler) model. However, if the model with the lowest AIC value was the more complex model, it had to be significantly different (LR test, $p < 0.1$) from the reduced model to be chosen as the best model. If the more complex model was not significantly different, then the reduced model was chosen.

Changing Ocean Conditions and Exposure to Reduced Commercial Catch

The CMIP5 multi-model ensemble of the International Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) predicts that SST will increase by 0.3°C decade^{-1} through the end of the century (Jewett and Romanou, 2017; IPCC, 2018). Therefore, to assess the exposure of CCS port communities to reduced Dungeness crab commercial due to changing ocean conditions, we estimated changes in Dungeness crab CPUE across U.S. west coast ports in relation to expected SST changes in the CCS. Change in Dungeness crab CPUE was estimated based on the predictions determined from the SST VC_GAMM and two SST scenarios (**Table 2**) using the predict function in the 'mgcv' R package (Wood, 2019). The percent change in predicted versus current Dungeness crab CPUE defined the "exposure" component of our framework. We focused the exposure metric on SST because of the high explanatory power of SST on Dungeness crab CPUE and the degree of confidence on the projected range of SST increase in the CCS (Jewett and Romanou, 2017).

TABLE 2 | Possible future (2080) sea surface temperature (SST) scenarios for the California Current System (CCS) based on the IPCC AR5.

Warming Scenario	Radiative Forcing Trajectory	Value
Moderate	RCP 4.5 W/m^2	+1.7°C
High	RCP 8.5 W/m^2	+ 2.8°C

Values represent the predicted change in CCS SST relative to the 1976–2005 average based on each Representative Concentration Pathway (RCP).

Reliance and Social Vulnerability of Fishery-Dependent Communities

To determine the impact of a change in Dungeness crab CPUE (exposure) on fishery dependent coastal communities along the CCS, we first assessed the current importance of Dungeness crab to these communities by utilizing existing indices for reliance and vulnerability. The National Oceanic and Atmospheric Administration designed frameworks to evaluate fishery reliance and engagement of coastal communities (Norman et al., 2007; Jepson and Colburn, 2013). In response to recent fishery closures, the frameworks were adapted to produce indices specific to the Dungeness crab commercial fishery (K. Norman and A. Varney, personal communication; NOAA, 2017; Moore et al., 2019). Dungeness crab commercial fishery reliance indices for 2015 from 64 U.S. west coast communities were shared with our team (**Supplementary Table S1**; Norman and Varney, personal communication; NOAA, 2017; Moore et al., 2019). Of these communities, the major Dungeness crab commercial fishing ports from California (7), Oregon (7), and Washington (4) were selected (**Figure 1**). Reliance indices were used to determine the quantitative importance of the Dungeness crab fishery to each coastal community and were based on the following information: Crab catch (pounds) per capita, crab revenue (USD) per capita, and count of crab processors per capita. Although reliance indices were calculated for only 1 year, the total Dungeness crab catch in the CCS in 2015 (1.92×10^7 kg) was similar to the average catch from 1981 to 2017 (1.90×10^7 kg) (based on Pacific Fisheries Information Network annual data; **Supplementary Table S1**).

A multi-point social vulnerability analysis in 2014 provided information on the current overall socio-economic stability of each coastal community (**Supplementary Table S1**; Varney, 2018). Social vulnerability refers to the socioeconomic and demographic factors that determine a community's ability to withstand hardships and is commonly used in risk assessment. In this case, we used social vulnerability to assess the level of disruption that would occur in a community given an interference in the lucrative Dungeness crab fishery. Community Social Vulnerability Index (CSVI) was calculated for all U.S. west coast communities using the following information: Metrics of personal disruption, population composition, poverty, labor force, housing characteristics, housing disruption,

and retiree migration (Varney, 2018). CSVI values were rescaled to be positive.

Coastal Community Susceptibility to a Change in Dungeness Crab CPUE

To determine the relative degree to which a change in Dungeness crab CPUE could impact coastal communities, we combined Dungeness crab-specific fishery reliance indices with CSVI into a novel "susceptibility" score. Our susceptibility score for each community was calculated as the product of CSVI and reliance. CSVI encapsulates the relative ability of communities to weather hardships, where lower indices indicate a community that is less vulnerable in the face of an unwanted event due to its social well-being. The reliance index denotes the per capita presence of the Dungeness crab fishery in the community relative to other communities, which expresses how important the fishery is to the economic and social well-being of the community. The value of the product, susceptibility, was used to represent the vulnerability of a community, scaled by reliance on Dungeness crab and is a quantitative representation of the degree to which each community would be influenced by a change in Dungeness crab CPUE. Communities that are both heavily reliant on Dungeness crab and socially vulnerable would have high susceptibility scores, highlighting the scaling effect of these two properties. In contrast, communities with either high vulnerability and low reliance on Dungeness crab, or low vulnerability and high reliance on crab would have similar susceptibility scores. Finally, a community with both low reliance and vulnerability, would be the least susceptible because they are generally resilient to change, and a change in the Dungeness crab fishery would not have a large impact on the community. The compounded risk for each community was examined by comparing the exposure to a change in Dungeness crab CPUE under increased SST scenarios with a region-specific susceptibility score. Although exact terminology differs, similar approaches have been adopted in other recent studies examining the exposure-vulnerability of coastal communities to changing ocean conditions (e.g., Ekstrom et al., 2015; Mathis et al., 2015).

RESULTS

Relationship Between Ocean Conditions and Dungeness Crab Commercial Catch

Commercial Catch per Unit Effort

From 1981 to 2017, Dungeness crab commercial catch within 16 major ports/regions of the CCS varied annually (total U.S. west coast mean catch = 985,183 kg; **Figure 3**). Standardized catch (kg of crab landed per number of fish tickets), or CPUE, also varied annually (**Figure 3** and **Supplementary Figures S1–S4**). As a result, there was variation in the annual proportional distribution of CPUE along the CCS (defined as each port's percent of the total U.S. west coast CPUE) (**Figure 4**). Total U.S. west coast CPUE was significantly correlated with total U.S. west coast catch (Pearson's $r = 0.92$, $p < 0.001$).

Spatial and Temporal Analyses of Ocean Conditions and Commercial Catch

The results of the stationary GAMM and non-stationary VC_GAMM and selected models are listed in **Table 3** and described below. There was support ($R^2_{adj} = 0.54$, LR test:

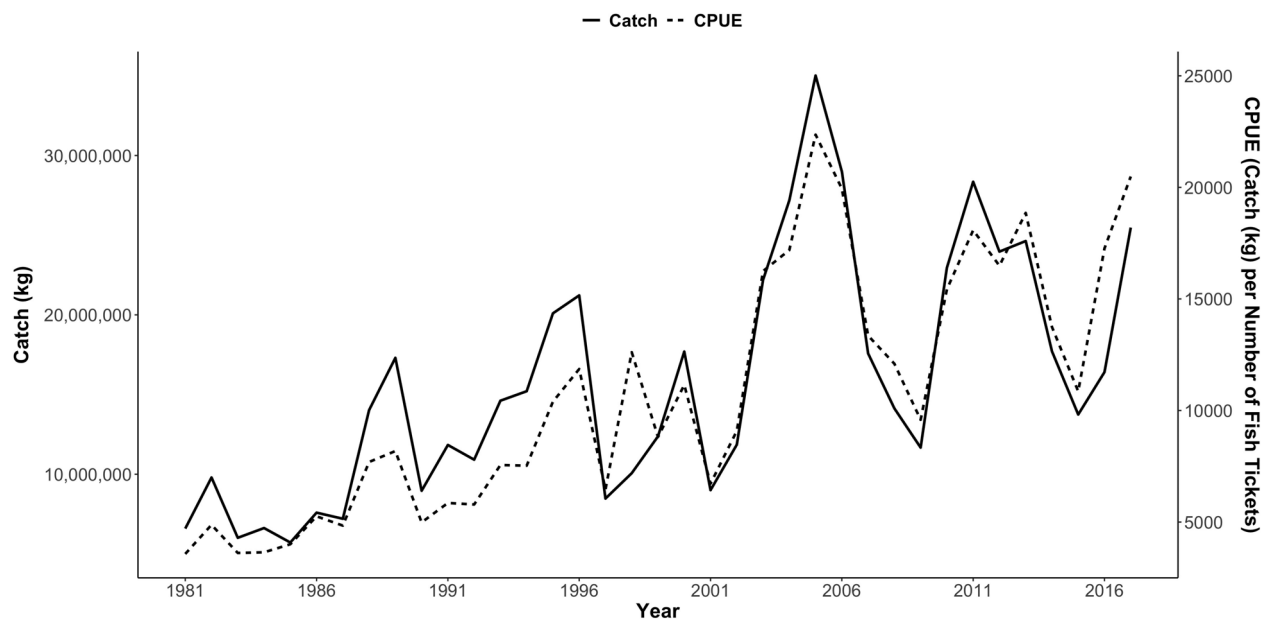

FIGURE 3 | Total commercial catch of Dungeness crab in kilograms (kg) per year (solid line) and catch per unit effort (dashed line) from 1981 to 2017 for the U.S. west coast, including 16 ports/regions in Washington, Oregon, and California. Catch per unit effort (CPUE) was calculated as kg caught per number of fish tickets per year. Data were provided by WDFW 2018, ODFW 2018, and CDFW 2018. **Supplementary Figures S1–S4** show CPUE by port for each region.

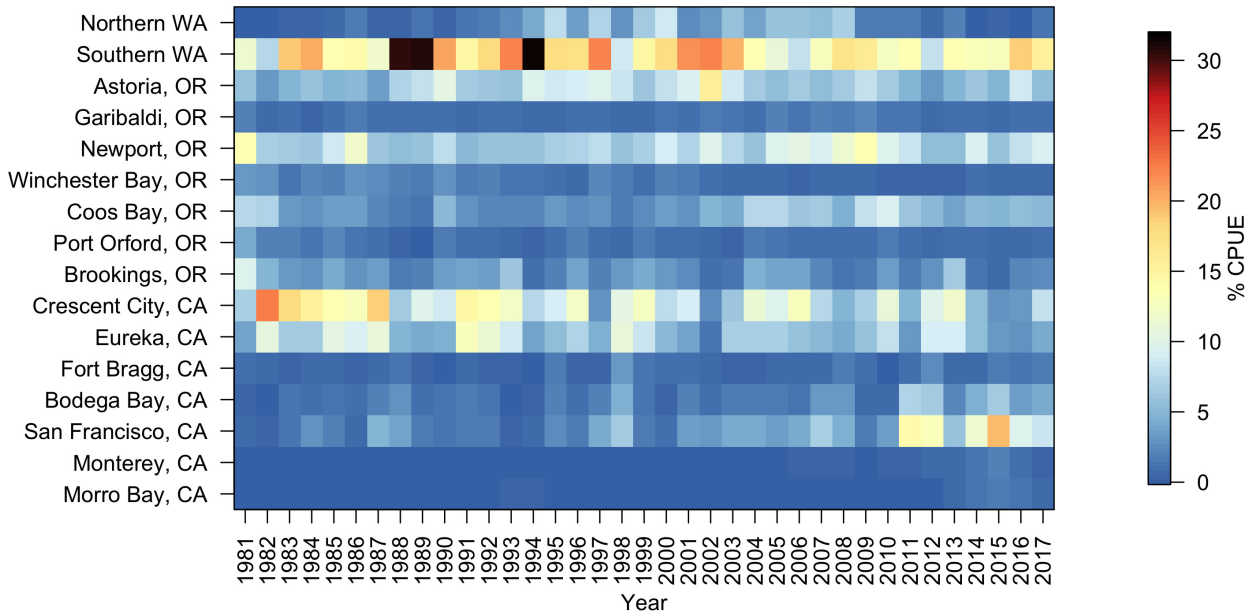

FIGURE 4 | Percent of total Dungeness crab commercial catch per unit effort (CPUE) landed annually in 16 U.S. west coast ports from 1981 to 2017. Warm colors indicate a high percentage of the total annual CPUE and cool colors indicate a low percentage of the total annual CPUE. Total annual CPUE was calculated as kilograms caught per number of fish tickets per year. Ports correspond to those shown in **Figure 1** and latitudes are listed in **Table 4**.

$p = 0.09$) for a model of Dungeness crab ln(CPUE) along the U.S. west coast that includes a spatially (latitudinally) homogeneous effect of PDO lagged by 4 years and a spatially variable effect of PDO lagged by 5 years (**Supplementary Figure S5**). At a 4-year lag, there was an inverse relationship between Dungeness crab ln(CPUE) and PDO (coefficient: −0.029). Furthermore, at a 5-year lag the coefficient ranged from −0.042 to −0.0085, and was a stronger negative correlation at southern latitudes compared to northern latitudes (**Supplementary Figure S5**).

There was support (R^2_{adj} = 0.50, LR test: p = 0.06) for a model that includes a spatially homogeneous and positive effect of NPGO lagged by 4 (coefficient: 0.173) and 5 (coefficient: 0.068) years (**Supplementary Figure S6**). There was support (R^2_{adj} = 0.46, LR test: p = 0.07) for a model that includes a spatially homogeneous and negative effect of MEI lagged by 3 and 5 years (coefficient: −0.12 at both lags) (**Supplementary Figure S7**). In addition, there was a spatially variable effect of MEI lagged by 4 years and the coefficient ranged from −0.206 to 0.065, indicating a strong negative relationship at northern latitudes and a weak positive relationship was observed at southern latitudes (**Supplementary Figure S7**). The effect of ENSO was also examined using SOI and support was found (R^2_{adj} = 0.47, LR test: p = 0.14) for a model that includes a spatially homogeneous effect of SOI lagged 3, 4, and 5 years (**Supplementary Figure S8**). This model indicates a positive relationship between ln(CPUE) and SOI lagged by 3 years (coefficient: 0.142), 4 years (coefficient: 0.067), and 5 years (coefficient: 0.145).

Consistent with other temperature-related oceanic indices (e.g., PDO), there was support (R^2_{adj} = 0.51, LR test: p = 0.02) for a model that includes a spatially homogeneous and negative effect of SST lagged by 3 (coefficient: −0.110) and 4 (coefficient: −0.269) years and a spatially variable effect of SST lagged by 5 years (**Figures 5A,B**). At lag 5, the coefficient ranged from −0.443 to −0.582 and was stronger at southern latitudes than northern latitudes (**Figure 5C**).

There was support (R^2_{adj} = 0.43, LR test: p = 0.05) for a model that includes a spatially variable effect of Upw lagged by 5 years (coefficient range: $-1.12e^{-5}$ to $4.04e^{-5}$; **Supplementary Figure S9**). There is a stronger, positive relationship at southern latitudes and a weaker, negative relationship at northern latitudes. On the other hand, there was limited support for a model of STI (R^2_{adj} = 0.42, LR test: p = 0.46) with a spatially homogeneous and negative effect lagged by 3 years (coefficient: $-7.73e^{-4}$; **Supplementary Figure S10**). There was also limited support (R^2_{adj} = 0.45, LR test: p = 0.77) for a model of that includes a weak and positive relationship between ln(CPUE) and the northward component of EkTrans lagged by 3 years (coefficient: $7.72e^{-4}$; **Supplementary Figure S11**).

Exposure: Change to Dungeness Crab Commercial Catch Under SST Scenarios

Predictions for a +1.7 or +2.8°C increase in CCS SST indicated that Dungeness crab ln(CPUE) along the U.S. west coast would decrease under these two scenarios (**Figure 6A** and **Supplementary Table S3**). This change was latitudinally variable and a larger decrease in ln(CPUE) was found for southern latitudes than northern latitudes. The +1.7°C SST scenario decreased ln(CPUE) by 30–90%, depending on latitude, and the +2.8°C SST scenario decreased ln(CPUE) even more dramatically (45–100%; **Figure 6B**). Therefore, there was greater exposure (i.e., a larger decrease

TABLE 3 | Selected models of individual ocean conditions lagged 3, 4, or 5 years and Dungeness crab commercial catch per unit effort ln(CPUE) along the U.S. west coast, including the adjusted R^2 and delta Akaike information criterion (AIC) for each model.

Ocean condition	Model*	R^2_{adj}	Delta AIC
Pacific Decadal Oscillation (PDO)	$y_{t,lat} = \alpha_{lat} + \beta_1 \cdot PDO_{(t-4)} + \beta_{2lat} \cdot PDO_{(t-5)} + \varepsilon_{t,lat}$	0.54	0
North Pacific Gyre Oscillation (NPGO)	$y_{t,lat} = \alpha_{lat} + \beta_1 \cdot NPGO_{(t-4)} + \beta_2 \cdot NPGO_{(t-5)} + \varepsilon_{t,lat}$	0.50	19
Multivariate El Niño Southern Oscillation Index (MEI)	$y_{t,lat} = \alpha_{lat} + \beta_1 \cdot MEI_{(t-3)} + \beta_{2lat} \cdot MEI_{(t-4)} + \beta_3 \cdot MEI_{(t-5)} + \varepsilon_{t,lat}$	0.46	39
Southern Oscillation Index (SOI)	$y_{t,lat} = \alpha_{lat} + \beta_1 \cdot SOI_{(t-3)} + \beta_{2lat} \cdot SOI_{(t-4)} + \beta_3 \cdot SOI_{(t-5)} + \varepsilon_{t,lat}$	0.47	39
Sea Surface Temperature (SST)	$y_{t,lat} = \alpha_{lat} + \beta_1 \cdot SST_{(t-3)} + \beta_2 \cdot SST_{(t-4)} + \beta_{3lat} \cdot SST_{(t-5)} + \varepsilon_{t,lat}$	0.51	49
Upwelling (Upw)	$y_{t,lat} = \alpha_{lat} + \beta_1 \cdot Upw_{(t-5)} + \varepsilon_{t,lat}$	0.43	43
Spring Transition Index (STI)	$y_{t,lat} = \alpha_{lat} + \beta_1 \cdot STI_{(t-3)} + \varepsilon_{t,lat}$	0.42	48
Northward component of Ekman Transport (EkTrans)	$y_{t,lat} = \alpha_{lat} + \beta_1 \cdot EkTrans_{(t-3)} + \varepsilon_{t,lat}$	0.45	31

*The best model for each ocean condition was selected based on Likelihood Ratio tests and AIC. *Model abbreviations: y, ln(CPUE); t, year; lat, latitude; α, to intercept; β, ocean condition coefficient, and ε, error (includes auto-correlation at lag 1 and a random term).*

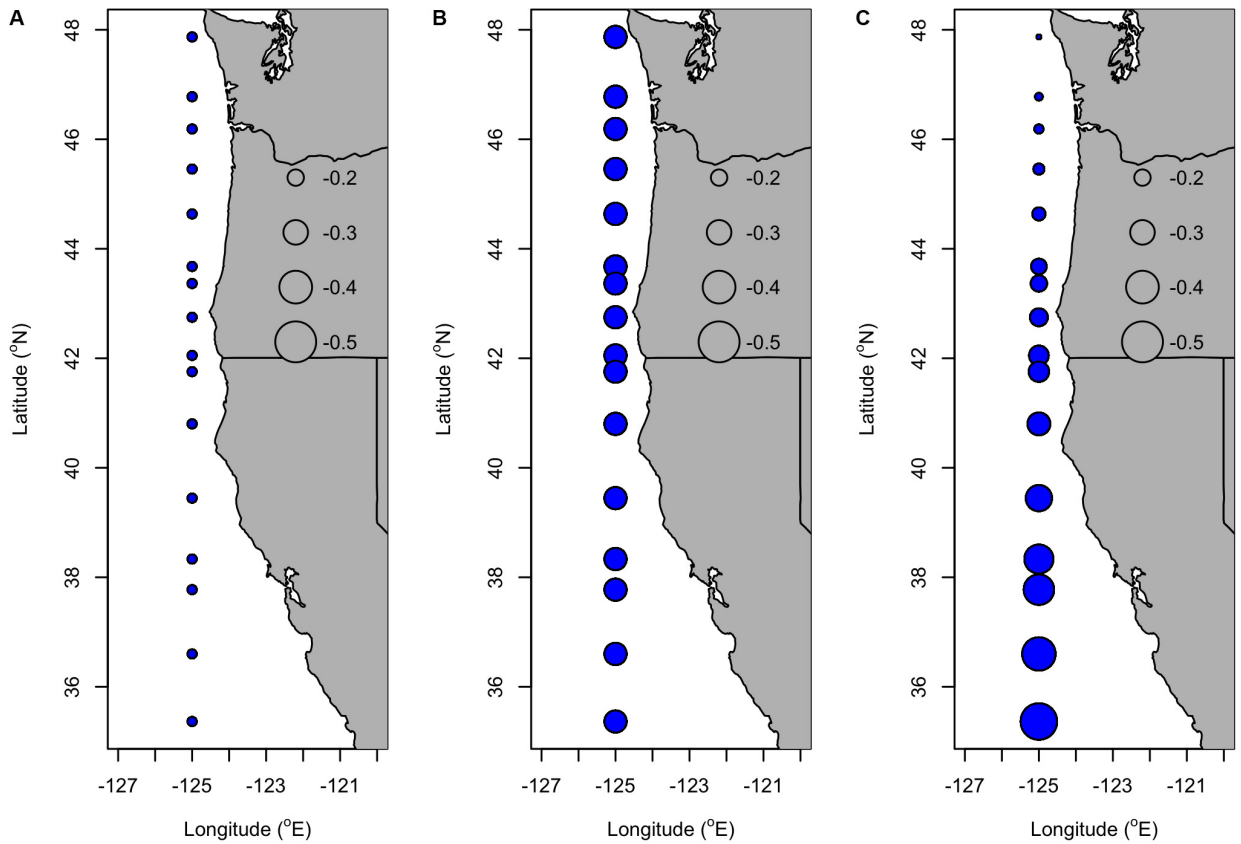

FIGURE 5 | Coefficients of SST lagged by **(A)** 3 years, **(B)** 4 years, and **(C)** 5 years in the selected VC_GAMM of Dungeness crab commercial ln(CPUE) along the U.S. west coast (**Table 3**). The latitude of ports corresponding to each of the circular symbols are listed in **Table 4**. Blue symbols represent negative coefficients and the size of the symbol scales with the magnitude of the coefficient.

in CPUE due to increased SST) at the southern end of the species range.

Risk for Coastal Communities

Quantitative Importance of Dungeness Crab to Coastal Communities

Because paired CPUE data and socio-economic indices (reliance and CSVI) were not available for all 18 selected coastal communities, we divided them into four regions that reflect the U.S. west coast fishery management divisions: Washington, Oregon, Northern California, and Central California. Compared to all communities across the CCS, Westport, Washington was an outlier with a very high Dungeness crab reliance index (**Table 4**). Regardless of inclusion or exclusion of Westport, Washington port communities had the highest reliance on the Dungeness crab fishery, followed by Oregon, Central California, and Northern California (**Table 4** and **Figure 7**). When social vulnerability was compared between the four

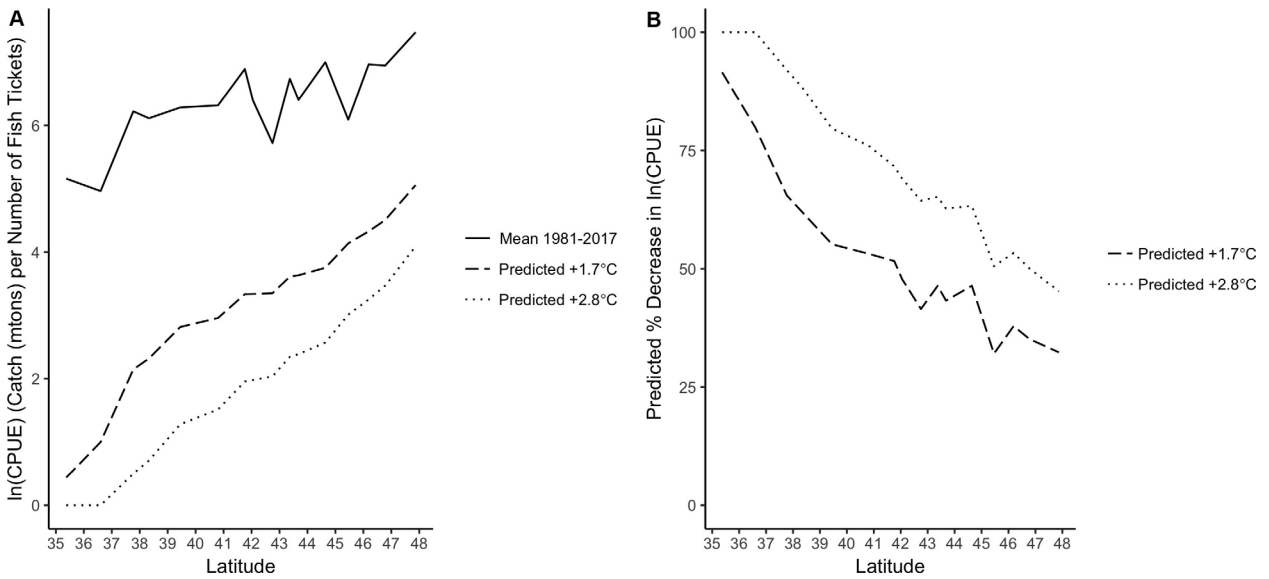

FIGURE 6 | (A) Mean Dungeness crab ln(CPUE) along the U.S. west coast from 1981 to 2017 (solid line) and VC_GAMM predicted CPUE along the U.S. west coast under two future SST scenarios: +1.7°C (dashed) and +2.8°C (dotted). **(B)** VC_GAMM predicted percent decrease in Dungeness crab ln(CPUE) by latitude along the U.S. west coast based on two future SST scenarios: +1.7°C (dashed) and +2.8°C (dotted).

U.S. west coast regions, Oregon had the highest CSVI, followed by Washington, Northern California, and Central California (**Table 4**).

Coastal Community Susceptibility and Risk to Changing Dungeness Crab CPUE

The calculated susceptibility score (product of reliance and CSVI) and the percent decrease in Dungeness crab CPUE under future SST scenarios shows that the overall risk of a shift in Dungeness crab CPUE is moderate to high across the CCS, depending on the level of SST warming (**Table 4**). Below, we discuss these results specific to each management region.

Washington port communities

Predictions from the SST VC_GAMM indicated that the northern portion of the CCS Dungeness crab fishery is the least exposed to a change in CPUE due to changes in SST (32.31–50.08% decrease in CPUE, depending on latitude and SST scenario; **Table 4**). The four Washington port communities exhibited high reliance on the Dungeness crab fishery (mean reliance = 9.72), likely due to low human populations (reliance is calculated per capita) and high Dungeness crab catch. Furthermore, social vulnerability of the Washington communities ranked second highest of the four CCS regions examined (mean CSVI = 11.17). Given high reliance and high CSVI, Washington had the highest regional susceptibility score regardless of whether Westport was included or excluded (mean including Westport = 113.58, mean excluding Westport = 66.72). Although exposure is lower for Washington than southern management regions, high susceptibility of the ports in this region indicates higher overall risk that Washington coastal communities would be negatively impacted by a decrease in Dungeness crab CPUE from changing ocean conditions.

Oregon port communities

The SST VC_GAMM predicted higher exposure of Oregon Dungeness crab CPUE to SST changes than for Washington (32.05–69.07% decrease in CPUE, depending on latitude and SST scenario; **Table 4**). The seven Oregon port communities exhibited wide variability in reliance on the Dungeness crab fishery and CSVI. Examining the region as a whole, reliance of Oregon communities ranked second highest (mean reliance = 2.51) and social vulnerability ranked second highest of the four CCS regions (mean CSVI = 11.59). Combining reliance and CSVI, the susceptibility of Oregon communities was second highest of the four CCS regions (mean susceptibility = 29.30). Similar to Washington, high susceptibility scores reflected the socio-economic importance of Dungeness crab in Oregon port communities, particularly in small, natural resource-based communities like Port Orford and Winchester Bay. Oregon had a lower susceptibility score than Washington, but greater exposure indicates that the risk of this region to a change in Dungeness crab CPUE from changing ocean conditions is still relatively high.

Northern California port communities

Northern California port communities showed higher exposure to changes in CPUE predicted by the SST VC_GAMM than Washington or Oregon (51.64–79.62% decrease in CPUE, depending on latitude and SST scenario; **Table 4**). The three Northern California communities had the lowest reliance on the Dungeness crab fishery (mean reliance = 0.48) and the highest social vulnerability score (mean CSVI = 12.50). Taken together, however, the susceptibility of this region ranked lowest of the four CCS regions (mean susceptibility = 6.31). Despite having greater exposure than Washington or Oregon, northern California communities may be at lower risk to a decrease

TABLE 4 | Reliance index, community social vulnerability index (CSVI), susceptibility score, and predicted percent decrease in ln(CPUE) by port and by region (NOAA, 2017; Varney, 2018).

Region	Port community	Latitude	Reliance score	CSVI	Port susceptibility	Region susceptibility	% Decrease in ln(CPUE) (+1.7°C)	% Decrease in ln(CPUE) (+1.7°C)
Washington	Westport	46.89	21.15	12.01	254.17	66.72*	32.32	33.72
	Tokeland	46.71	5.78	12.36	71.41		35.13	
	Ilwaco	46.31	7.65	12.34	94.43			
	Chinook	46.28	4.3	7.98	34.31			
Oregon	Astoria	46.19	0.73	9.64	7.03	29.30	37.87	42.17
	Garibaldi	45.56	3.03	13.53	41.01		32.05	
	Newport	44.62	1.18	10.47	12.33		46.38	
	Winchester	43.68	9.06	9.78	88.64		43.24	
	Coos Bay	43.38	0.54	11.54	6.24		46.37	
	Port Orford	42.75	2.62	17.58	46.06		41.48	
	Brookings	42.07	0.44	8.6	3.78		47.82	
Northern California	Crescent City	41.77	0.57	14.81	8.49	6.31	51.64	53.34
	Eureka	40.79	0.13	10.74	1.38		53.19	
	Fort Bragg	39.44	0.76	11.94	9.06		55.19	
Central California	Bodega Bay	38.32	8.95	4.57	40.86	12.07	62.06	74.74
	San Francisco	37.73	0.01	6.11	0.06		65.5	
	Monterey	36.6	0.08	6	0.49		79.85	
	Morro Bay	35.37	0.92	7.49	6.87		91.53	

*See **Supplementary Table S1** for reliance and CSVI data sources. Susceptibility was calculated as the product of reliance and CSVI. Red indicates higher scores and blue indicates lower scores. Percent decrease in ln(CPUE) was predicted using the SST VC_GAMM with a +1.7°C future scenario. *The Washington region mean susceptibility score excludes Westport because of its status as an outlier, with an anomalously high reliance index.*

in Dungeness crab CPUE due to low susceptibility – driven primarily by low reliance.

Central California port communities

The southernmost Dungeness crab ports had the greatest exposure to CPUE changes due to SST increases, according to the VC_GAMM (62.06–100.00% decrease in CPUE, depending on latitude and future SST scenario; **Table 4**). Large human populations within central California and generally lower Dungeness crab catch likely resulted in lower reliance on the fishery (mean reliance = 2.38). Furthermore, the overall social vulnerability within this region is also low compared to other CCS regions (mean CSVI = 6.04). The overall susceptibility of the central California region to decreased Dungeness crab CPUE was low (mean susceptibility = 12.07). Despite high exposure for the southern portion of the CCS, central California coastal communities exhibit low risk of being negatively impacted by a decrease in Dungeness crab CPUE due to changing ocean conditions. Although the overall risk of a distribution shift to central California is low, it is also important to consider ports individually. For instance, Bodega Bay has high susceptibility and exposure. Therefore, this specific port is at a much higher risk to a change in Dungeness crab CPUE compared to other ports in the same region.

DISCUSSION

The impacts of climate change on marine systems will alter ecosystem-scale functions including productivity, food web and disease dynamics, and species distributions (Hoegh-Guldberg and Bruno, 2010). Many of these changes are already occurring in the CCS (Snyder et al., 2003) and our analyses indicate that changing ocean conditions could impact the abundance and distribution of commercial catch of the socio-economically important Dungeness crab. These effects will not be confined to the Dungeness crab fishery, but will impact many economically important fisheries on the U.S. west coast and globally. In particular, studies have projected a greater than 10% reduction in catch potential for continental U.S. exploited fisheries by mid-century (Cheung et al., 2010; Barange et al., 2014). Although global fishery assessments are critical to our understanding of climate change, there is also value in addressing fine-scale impacts at the level of individual fisheries. Our study provides a framework for evaluating an individual fishery and the risks for the communities that rely on it, and will be useful when adapting fisheries management strategies in response to climate change.

Importance of Ocean Conditions for Dungeness Crab

Statistical analysis of Dungeness crab CPUE and ocean conditions identified a mix of relationships that were lagged by 3–5 years. This finding upholds previous work and confirms the importance of favorable ocean conditions, such as negative PDO and positive SOI indices, for promoting larval crab survival and transport in the CCS (Botsford and Lawrence, 2002; Shanks et al., 2010; Shanks, 2013). We found support for a mix of latitudinally stationary and non-stationary models, indicating that the influences of various ocean conditions on Dungeness crab CPUE are spatially variable, and are likely specific to different time lags. However, U.S. west coast fishery management often operates under the assumption that harvestable-sized

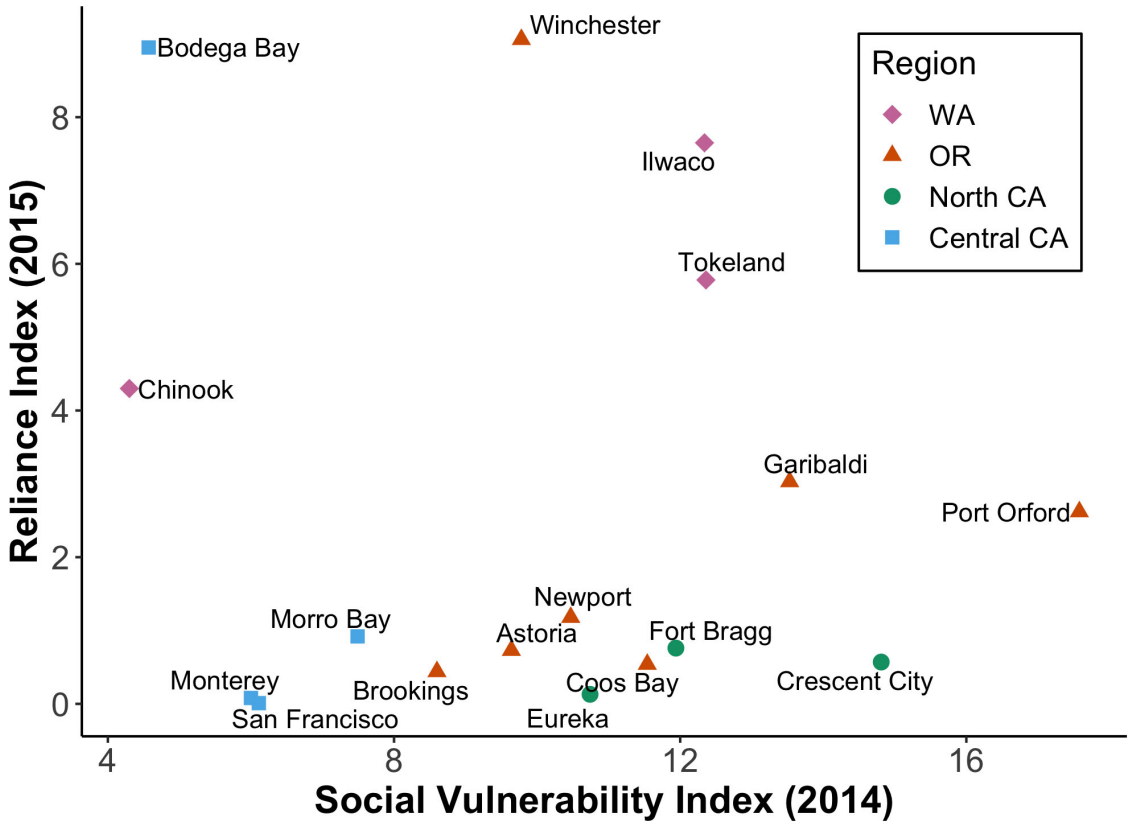

FIGURE 7 | Dungeness crab reliance index for 2015 versus social vulnerability (CSVI) for 2014. Reliance scores consider per capita engagement in the Dungeness crab fishing industry, while CSVI indicates the overall vulnerability of a community. This figure excludes Westport, WA, which had anomalously high reliance and moderate vulnerability (**Table 4**).

Dungeness crabs are age 4 (Rasmuson, 2013). This analysis suggests that the relationship between ocean conditions and Dungeness crab commercial harvest may be more dynamic and could explain inaccuracies in commercial catch projected using only larval abundance 4 years prior (i.e., Shanks et al., 2010).

Overall, we found that the models explaining the largest amount of variance were those with PDO, SST, and NPGO, individually. Consistent with our findings, negative PDO conditions during the vulnerable early life history stages of Dungeness crab, and other exploited marine fish, have been shown to increase survival to harvestable size (Mantua et al., 1997; Botsford and Lawrence, 2002; Shanks, 2013). Although SST can be correlated to large scale ocean conditions, like PDO, most previous work on Dungeness crab has not explicitly examined SST (except see Botsford and Lawrence, 2002). However, our analysis indicates a strong, negative relationship between Dungeness crab CPUE and lagged SST. In addition, we identified a positive relationship with NPGO, which was unexpected given that Shanks et al. (2010) found no correlation between NPGO and Dungeness crab larval recruitment. However, this newly identified association corroborates other indications that, since the late 1980's, NPGO has had a greater influence on regional physical and biological variables in the North Pacific Ocean (Di Lorenzo et al., 2008; Litzow et al., 2020), including novel impacts to salmon (Kilduff et al., 2015) and seabirds (Schmidt et al., 2014). The lack of strong support for models of STI and EkTrans was also contrary to our expectations given previous work of Shanks and Roegner (2007) and Shanks (2013). Although we did find support for an upwelling model, the influence of Upw was spatially variable and indicated a greater dependence of southern Dungeness crab CPUE to onshore advection of larvae and upwelling-fueled primary productivity (Shanks, 2013).

While we focus on the SST model for the purpose of determining exposure of CPUE to changing ocean conditions, it is important to recognize that SST is closely correlated with other climate-related phenomena. For example, increasing SST is likely to increase occurrences of hypoxic events (Grantham et al., 2004; Chan et al., 2008) and algal blooms that release domoic acid in the CCS (McKibben et al., 2017). These SST-related phenomena have already had detrimental ecological and socio-economic consequences for the Dungeness crab industry and are likely to influence future abundance, distribution, and accessibility of Dungeness crab along its entire range. Hypoxia causes mass mortality events in adult and juvenile Dungeness crab (Grantham et al., 2004). Harmful algal blooms that release domoic acid result in the bioaccumulation of the neurotoxin in Dungeness crab and other shellfish (Schultz et al., 2013),

leading to fishery closures due to the risks of human consumption (Trainer et al., 2007). The occurrence of domoic acid events on the U.S. west coast are expected to increase with warmer ocean conditions (McKibben et al., 2017). Ocean acidification is also expected to negatively impact Dungeness crab, primarily through indirect effects via shellfish prey species (Marshall et al., 2017), but Bednaršek et al. (2020) found that larval crabs are already experiencing exoskeleton dissolution under present acidification levels. The lack of sufficient time series precluded our ability to explore the relationship between ocean acidification, hypoxia, and Dungeness crab. Similar to the impact of ocean conditions considered in this study, the impacts of these climate-related phenomena are likely to vary spatially and temporally. Therefore, further analyses are needed to determine how these complex events will shape the future of the U.S. west coast Dungeness crab industry and other important fisheries.

Exposure of the CCS to Ocean Condition-Driven Changes in Dungeness Crab Catch

Our analysis showed that increasing SST in the CCS would decrease U.S. west coast CPUE of Dungeness crab with larger decreases in CPUE projected for the RCP 8.5 W/m^2 radiative forcing scenario (+2.8°C) compared to RCP 4.5 W/m^2 (+1.7°C). Decreases in CPUE would likely be caused by a shift in offshore distribution and accessibility of Dungeness crab to the fishing industry. However, the decrease in CPUE may not be monotonic along the coast, as the best model included a non-stationary effect of SST at a 5-year lag. Under both warming scenarios, our model found greater exposure of Dungeness crab CPUE to SST for southern latitude ports than northern latitude ports and indicates the possibility for a northward distribution shift of U.S. west coast Dungeness crab. Furthermore, there may be regional differences in the rate of SST warming, which could accentuate a northward distribution shift.

There is a generally good consensus that SST will increase in the CCS (IPCC, 2018) and other studies have also used SST to project or analyze species movements under climate change (e.g., Pinsky et al., 2013; Yen et al., 2016). It is less clear how large scale ocean-atmosphere climate patterns, such as PDO and NPGO, will shift in the future (Newman et al., 2016). In addition, local-scale differences in shelf dynamics could cause important spatial variability in temperature and upwelling (timing and strength). These uncertainties are not captured in our models. Reported changes in coastal winds and upwelling are spatially variable and have not resulted in a clear intensification of upwelling (Bakun et al., 2010; Sydeman et al., 2014). This spatial variability may explain why there was less support for the models of Upw and STI. However, the importance of upwelling dynamics in driving Dungeness crab dynamics, as well as other important fishery species, is well documented (Barth et al., 2007; Shanks and Roegner, 2007) and the relationship between climate, upwelling, and Dungeness crab is an important avenue for future investigation. Recent advances in upwelling index calculations may further elucidate the importance of upwelling (Jacox et al., 2018). Overall, Dungeness crab are affected by a variety of oceanic conditions and our findings highlight important implications of a changing ocean for fishing communities involved in the Dungeness crab industry.

Importance of Dungeness Crab to Coastal Communities

Economically valuable fisheries provide a direct link between changing ocean conditions and communities. U.S. west coast communities showed varying levels of social vulnerability and reliance on the Dungeness crab fishery that did not necessarily align with regional or management boundaries. Combining these metrics into a susceptibility score allowed us to determine that the risk of a change in Dungeness crab distribution or availability is unequal, with generally greater consequences for northern communities.

Given the projected decrease in Dungeness crab catch with increased SST, communities with the greatest potential for exposure were those in the central California management region. Although the likelihood of communities such as Morro Bay and Monterey experiencing a reduction in catch of Dungeness crab was relatively high, their overall susceptibility was low. On the other hand, Bodega Bay had higher reliance on the Dungeness crab fishery and was the most susceptible of the central California communities.

Oregon and Washington were less exposed to changes in Dungeness crab catch due to increased SST compared to California. However, many of these communities showed high social vulnerability and, ultimately, higher susceptibility. Therefore, the risk of reduced Dungeness crab catch would likely be more detrimental to communities in Oregon and Washington. As noted above, Bodega Bay, California represents a potential exception to this pattern. In addition, communities across the CCS have already been impacted by other climate-related phenomena and the subsequent management responses, including closures for the presence of domoic acid in crabs and hypoxia-related mass mortality of adult crab. Expected increases in the potency, duration, and occurrence rate of harmful algal blooms in marine systems (Gobler et al., 2017) point to increased domoic acid-related fishery closures across the U.S. west coast (McKibben et al., 2017). These closures can be economically damaging and may be the most immediate threat from changing ocean conditions to the Dungeness crab industry and associated coastal communities (Ritzman et al., 2018; Moore et al., 2019).

One caveat of this discussion is the fact that CSVI captures overall vulnerability of the "community of place" and is not specific to participants in the commercial fishing industry, which represents the "community of interest" (McMillan and Chavis, 1986; Nasar and Julian, 1995). Our analysis has captured only the potential risk for the larger community, but it is likely that individual community members would be differentially impacted depending on their connection to the fishery. For instance, fishermen and others directly involved in the fishing industry may experience more impacts than the larger community. This limitation also applies to other recent studies of exposure-vulnerability analyses of fisheries (e.g., Ekstrom et al., 2015; Mathis et al., 2015), but has not received much attention

in the literature due to the challenges of characterizing sub-community level impacts (PFMC, 2017). Furthermore, socio-economic indices may not adequately capture intricate natural-human connections woven into fishing communities (Lavoie et al., 2018). However, by calculating a susceptibility score, we are able to apply the notion of vulnerability specifically to the relative importance of Dungeness crab in each community. This provides a general picture of how communities might be differentially susceptible to a change in the Dungeness crab fishery and may be useful for anticipating the needs of individual communities in the face of declining catch potential.

Study Limitations

In general, it is analytically challenging to capture the effect of individual ocean conditions on marine species due to the myriad of interacting physical and biological factors, variability in ocean conditions at multiple spatial and temporal scales, and often limited data on the distribution and abundance. Given these complexities and limited data on certain important ocean conditions, our modeling approach allowed us to describe historical trends and project CPUE under increased SST scenarios, but lacks mechanistic explanation for these changes. In the absence of mechanistic understanding, our projected future changes in CPUE with increased SST are based on the assumption that underlying mechanisms are linear and will continue unchanged into the future. However, synergies between temperature, ocean acidification, and hypoxia have been shown to alter the thermal tolerance of marine species (Pörtner et al., 2005). If the relationship between CPUE and SST has an energetic basis, then there are likely to be non-linearities and thresholds in the response of Dungeness crab to temperature. For example, Metzger et al. (2007) showed that elevated CO_2 concentrations dramatically reduced the heat tolerance of edible crabs (*Cancer pagurus*).

For this analysis, we had to limit our inference to that of Dungeness crab CPUE due to the lack of available information about the actual offshore abundance and distribution of crab. Management of Dungeness crab does not include a formal stock assessment and adequate spatial information captured in fishing vessel logbooks is not available for all regions along the U.S. west coast. Without consistent logbook information, it is difficult to estimate fishing effort across all three states. Therefore, we standardized catch across ports and years using fish tickets following ODFW (2014). We assumed that if fishermen delivered crab to a port close to where it was caught, then an estimate of Dungeness crab commercial CPUE across U.S. west coast ports would be reflective of offshore abundance and distribution along the coast. A recent analysis of the Dungeness crab fishery logbooks and fish tickets by Richerson et al. (2020) found that delivery port was a good proxy for offshore catch area in Oregon. In addition, total catch was a good indication of the abundance of legal-sized male crabs (Richerson et al., 2020). Thus, a change in the magnitude or distribution of CPUE across ports could indicate a change in the offshore abundance or distribution of Dungeness crab associated with ocean conditions.

Although our data covered 36 years, some ocean condition factors operate on longer time scales. For instance, the data only spanned two major oscillations in PDO, which may have limited our ability to effectively describe the relationship between PDO and CPUE. Other ocean conditions not included in this analysis, due to insufficient data, may also contribute to Dungeness crab survival and distribution along the U.S. west coast, including hypoxia and ocean acidification. Such data could improve our mechanistic understanding of changes in Dungeness crab CPUE. These limitations reiterate the value of collecting long-term data series related to the success of socio-economically important fisheries under climate change.

Socio-economic data in our analysis were temporally limited and represent only a snapshot of each community. Indices obtained were based on 2014 (CSVI) and 2015 (Dungeness crab reliance) and may not be a comprehensive representation of the community condition from 1981 to 2017; however, these data represent warm ocean years in the CCS that may be common in the future (Cavole et al., 2016; Moore et al., 2019). In particular, 2015 was an anomalous year with the presence of "The Blob" of warm water in the N.E. Pacific Ocean (Kintisch, 2015; Di Lorenzo and Mantua, 2016; McCabe et al., 2016) and significant commercial fishery closures due to the presence of domoic acid (Ritzman et al., 2018). Future work should evaluate whether and how communities have historically fluctuated in their social vulnerability and reliance on fisheries and, furthermore, what community scenarios may be observed in the future. Long term data of reliance and vulnerability would allow for a more complete evaluation of community susceptibility, risk, and adaptive capacity.

Future Directions

Climate change is creating scenarios that are environmentally, ecologically, and socially novel. We found that decreased Dungeness crab catch from increasing ocean temperature has the potential to greatly impact fishery participants and U.S. west coast communities. In addition, substantial risks to the Dungeness crab fishery exist from other climate-related phenomena (e.g., domoic acid, hypoxia, and ocean acidification) that often co-occur with temperature. This study provides a valuable framework for understanding the social and ecological impacts of one important fishery in a single analysis, however, we recognize that this examination is insufficient to capture the full risk of climate change on U.S. west coast communities. For instance, many exposure-vulnerability analyses suffer from limited understanding of social and ecological adaptive capacity, particularly the timescales over which they operate. The social-ecological context of marine fisheries provides a particularly promising avenue for exploring adaptive capacity and untangling the complexity of coupled natural-human systems. There is great potential for future work to understand the possibility for resilience and adaptation in both coastal communities and target species. Among other social factors that contribute to adaptive capacity, flexibility to change strategies (Cinner and Barnes, 2019) is particularly salient to fishery systems where catch diversification (Kasperski and Holland, 2013; Cline et al., 2017) and the ability to adapt the distribution of fishery effort to track target species' distributions as they move with climate (Perry et al., 2005) can reduce economic risk. Successful adaptive

fishery management in a time of ocean change should rely on an understanding of projected fishery changes as well as the risks to coastal communities across the species' current and future ranges.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors contributed to the conceptualization and design of the study. CM and EL obtained the fishery and environmental data and performed the analysis. AS and AJ obtained the social data and performed the analysis. CM, EL, AS, KS, and AJ wrote and revised the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00401/full#supplementary-material

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Advancing Through the Pandemic From the Perspective of Marine Graduate Researchers: Challenges, Solutions, and Opportunities

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The ongoing COVID-19 pandemic has brought about a new social and academic reality to researchers worldwide. The field of marine science, our own topic of interest, has also been impacted in multiple ways, from cancelation of laboratory and field activities to postponement of onboard research. As graduate researchers, we have a time-sensitive academic path, and our current situation may constrain our academic future. At the same time, the pandemic demands revised strategies to deal with the ongoing difficulties and tackle similar future situations. In this perspective, we have gathered information on the challenges, solutions and opportunities for graduate researchers in the field of marine science by (1) discussing the relevant short-, long-term challenges caused by the pandemic, (2) providing feasible immediate and near-future solutions, (3) compiling opportunities (courses, scientific events, academic positions), and (4) creating a shared social media account to make the available information on new opportunities more accessible. With this, we hope to add to the efforts to advance the academic career of marine graduates during this harsh period.

Keywords: coronavirus pandemic, early career researchers, career, opportunities, marine science and technology

INTRODUCTION

Decision-makers, practitioners and economists have been discussing the actions needed to overcome our current situation with the ongoing COVID-19 pandemic. At the same time, researchers have also started to assess the consequences of this period on scientific development (Inouye et al., 2020). The recent editorial by Corlett et al. (2020) provides an overview of the current situation and expected impacts for biodiversity conservation, highlighting that it is premature to predict overall impacts in the field. Meanwhile, researchers are already facing the consequences of the pandemic and many early career researchers enrolled in their graduate programs are also

experiencing career-related issues as well as negative psychological impacts. As graduate researchers in marine science coming from multiple different fields from around the globe, we explore some of the ongoing problems and future challenges faced by ourselves and our peers due to the pandemic and propose immediate and long-term actions to tackle them. As there is the possibility of additional isolation periods (Kissler et al., 2020), finding and implementing solutions can help to move forward the academic career of graduate researchers. Although this pandemic has already impacted the lives of millions of people and proved to be a colossal challenge in many sectors of society, versatility and creativity can also bring forth opportunities for those working in marine science.

IMMEDIATE DIFFICULTIES AND LONG-TERM CHALLENGES FOR MARINE GRADUATE RESEARCHERS

Marine graduate researchers, also included in the definition of early career ocean professionals, are directly impacted by COVID-19 in both the short- and long-term. The most immediate interruption has been the closing of university campuses worldwide, preventing students from physically attending classes, which have either been canceled or transferred to an online format. While online classes allow students to continue their studies, home-based learning has logistical requirements, including steady internet and a reliable computer, commodities not always available. Scientific work has been limited with either temporary closure of laboratories or limited work effort due to staff limitations and delays in equipment flow, with direct impacts on long-term laboratory experiments (Servick et al., 2020). Fieldwork has also been considerably restricted and sampling efforts, such as collecting time-sensitive data or use of valuable ship-time, have been postponed. This is especially problematic for marine science graduates, as fieldwork usually demands great logistic planning (e.g., equipment preparation, tide periods, and vessel availability), resulting in a considerable investment of time and financial costs. Moreover, cancelation or postponement of conferences represents a missed opportunity for graduate researchers to learn about advancements in their fields, discuss their research, and consolidate and expand their networks. As an example, the International Coral Reef Symposium, which is held every 4 years, had to be postponed, affecting the discussions about the research on this highly impacted ecosystem.

Graduate researchers in marine science are facing a reality where options that had been available before the pandemic cannot be taken into future consideration, as they are employed on short-term contracts with restricted deadlines. Supportive responses from universities and research foundations vary, with best-case scenarios involving project and salary extensions[1,2] and cash handouts[3] as immediate alternatives. Individuals at the planning stage of their research strategy may also consider eliminating fieldwork to produce a more realistic approach. This could be especially damaging to researchers pursuing shorter graduate degrees, as well as to those relying on time-sensitive academic visas. Ultimately, graduate students may also feel difficulties in completing their tasks and dissertation work, which can persist into their future academic career.

When considering long-term impacts, we can expect to see repercussions on scientific work, funding, and international collaborations. Continued delays in fieldwork will result in gaps in time-series data, while long-term impacts on the economy will affect the financial support of scientific investigations, and lead to either redirection or removal of research funding (Corlett et al., 2020). Indeed, many data collecting efforts on marine science involve public financing, which is presently at stake. Health and safety protocols must also be updated or restructured following current restrictions and precautions, especially for outdoor activities (e.g., diving, field samplings) and potential contact with others. One of the most substantial impacts, however, may be on networking. Social interactions in conferences are especially fruitful for early career researchers (Günther et al., 2015), and provide an invaluable opportunity to publicize one's findings and even lead to an increase in citations (Funk et al., 2012). Face-to-face conversation, accordingly, is more likely to reduce ambiguity and facilitate positive interactions than computer-mediated communication (Okdie et al., 2011) when interacting with other researchers during scientific events. While the canceling or delaying of conferences may appear to be only a short-term problem, it is just the beginning of a more severe issue where interactions for international collaboration may need to be rethought. We may now be facing changes in how we incorporate highly beneficial social interactions with other researchers.

The personal lives of each researcher can also affect their academic performance. We must also acknowledge that children in home-schooling and the (lack of) division of household chores during the pandemic can disproportionately take a heavier toll on women, thus contributing to an increase in gender inequality in science (Staniscuaski et al., 2020; Viglione, 2020). It is important to take into account the lack of psychological structure to confront the pandemic and loss of motivation. Indeed, mental health disorders can increase among the student community during this period (Zhai and Du, 2020), worsening something that was already problematic (Levecque et al., 2017; Andrews et al., 2020). Fortunately, universities worldwide are enabling free online counseling resources to students coping with stress and anxiety during this period[4,5,6]. Uncertain times such as these affect each individual uniquely, and it is complicated to measure and consider each case individually. An unexpected interference during one's research can result in negative impacts on their future career, independent of the research topic. Even upon

[1] https://www.bundesregierung.de/breg-en/search/meldung-zeitvertraeg-1742262

[2] http://www.fapesp.br/14080

[3] https://www.japantimes.co.jp/news/2020/05/19/national/japan-approves-cash-handout-students-coronavirus/#.XsWz5mhKi00

[4] https://www.imperial.ac.uk/counselling/

[5] https://www.wits.ac.za/ccdu/personal-counselling-/covid-19-emotional-health-resources/covid-19-support/

[6] https://www.uottawa.ca/wellness/covid-19/support-from-home

completion, it is uncertain if there will be job opportunities and whether disturbances during the pandemic may have impacted the researcher's qualifications. Research-associate positions are naturally highly competitive and the pandemic's economic fallout may impact job-searching after graduation[7].

ACTIONS TO ENSURE GRADUATE RESEARCHERS DEVELOP IN THIS PERIOD

Considering that marine graduate researchers will inevitably be affected by the pandemic in multiple ways, we need to move forward and consider, "What can we do now?". The following section explores some possible actions that universities, funding agencies, supervisors and graduates could apply to tackle these challenges. We show priority points that may substantially help marine graduate researchers and advance their work now and after this pandemic.

Re-scheduling of Research Projects and Grants

Funding agencies and universities will need to consider as early as possible changes in research projects, international academic exchange periods, and grants to accommodate delays caused by the pandemic. While a case-by-case analysis may be adopted, an extension for all graduates is considered to be fair and allow graduate researchers to protect their private information (e.g., concerning their mental health). Some research areas may not have been directly affected (e.g., those working with computer modeling and possessing the necessary equipment/resources at home), but others relying on field or laboratory work may need extensions to conclude their research (Inouye et al., 2020). When possible, graduate researchers have modified their investigations to be online-based as a directive from their supervisor, but this is highly dependent on the study area. However, there are aspects of research that are not as flexible. In that sense, it is also essential that supervisors or funding bodies adjust their expectations to this new reality. Many marine graduate researchers will be unable to deliver the expected results, but with the right guidance they can adapt their projects to fit the allocated time and ultimately produce significant scientific outcomes.

Supporting Online Conferences and Working Group Meetings

Scientific gatherings will undoubtedly be severely affected for the duration of the pandemic. Such events are an essential part of an academic career, providing an environment where researchers with shared interests are incentivized to communicate and collaborate. For instance, conferences offer an opportunity to interact with well-known senior researchers, and the chance for early career scientists to "put themselves out there", promote partnerships and find potential job positions (Günther et al., 2015). Given the present difficulty in hosting gatherings dependent on physical attendance, we suggest that instead of postponing or canceling events, organizing committees should instead aim to facilitate online meetings. Yet, we understand that in-person conferences should not be permanently replaced by online events, given the former offer unique opportunities with several networking benefits for young researchers (Günther et al., 2015; Gopalan et al., 2018).

Coming up with online alternatives will initially be difficult. Therefore, we propose short pre-recorded sessions and symposia/workshops/webinars (1–2 h each) spread out over several weeks to accommodate attendants from different backgrounds. Spacing out sessions would also ensure that more people are able to participate. As for the necessary online resources, one possible solution is through online repositories, capable of storing large amounts of data in the form of posters and video files. Attendants unable to participate at specific times could join dedicated group chats to answer any questions pertaining to their work/discussion topic.

Finally, these events also have the advantage of being far less costly, with the possibility of being available free of charge or at a reduced fee. When offering online services as a substitute for real-life presentations, scientific meetings can: (1) offer the opportunity for new research to be discussed and advanced; (2) become even more inclusive to early career researchers who would be financially unable to travel to the event location in the first place and (3) reduce carbon emissions due to travel and general transportation. For instance, conference attendance can correspond to 35% of the carbon footprint during a doctoral degree (Achten et al., 2013).

Using Existing Technologies to Foster Collaboration During Quarantine

Periods of social isolation may still continue in the near future. To overcome this problem in a short-term time scale, research groups must take advantage of the many online tools available to communicate and collaborate. Supervisors should facilitate communication between all laboratory members via remote group meetings but also provide an environment for consistent one-to-one discussions with their students. There are many free and easy to use cloud-based instant messaging alternatives, like Whatsapp and Telegram. More advanced tools (e.g., Slack and Mattermost) enable the creation of a laboratory workspace, as well as setting teams for each project[8]. Regular video meetings are encouraged to guarantee that work is still being carried out within expectations (see Powell, 2020 for more tips on inclusiveness). For this, there is a myriad of software, like Skype and Google Meet.

A second step is implementing tools to enable collaborative work during isolation. Teams can use cloud edition to work on documents and data analysis. Indeed, there is already an effort to turn marine data publicly available online and to create platforms for cloud analysis of marine data (e.g., Míguez et al., 2019). It is also possible to implement project-management tools that help to organize and accompany the

[7]https://www.thecrimson.com/article/2020/4/24/harvard-coronavirus-gsas-job-prospects/

[8]https://www.nature.com/articles/d41586-019-01375-4

workflux of a project (some interesting tools are Trello, Asana and Basecamp, all providing a free version). A combination of these solutions, from communication to project management, can increase productivity during this period and enable projects to remain on track. These tools can improve laboratory work even after the pandemic, bringing together other benefits to make research more open and inclusive (Powell, 2020). However, the mentioned solutions imply that graduates have access to the necessary tools – computer, smartphone, and internet access – which may not be trivial in many parts of the world. Universities and marine research centers have to find ways to guarantee basic technological access to graduate researchers to enable remote working.

Ensuring Academic Development Through Online Classes and Courses

Classes and courses constitute an essential part of the academic pathway of graduate researchers. To overcome campus closure, universities can adopt online classes. Indeed, many universities are already offering online classes through web-conference tools or in video format. This is essential if we want to keep providing the knowledge basis for marine graduates. However, we have to take into account that there might be issues with this format. First, universities have to ensure that students have access to the internet. Although this incurs costs for universities, this is a critical point if we want to avoid deepening social inequity in science, and is achievable as already demonstrated[9]. Second, making the switch to online classes is challenging and demands teachers to use different strategies (Gewin, 2020). Finally, many aspects of courses may be lost during this period, such as practical or field-based classes, important components for those in marine science. In that sense, lecturers have to find alternatives, for example videos of shipboard sampling practices and analytical procedures.

On the other hand, online classes provide unique opportunities to share knowledge beyond the university; departments, for example, can share their classes to a broader community via video platforms. This can even enhance public awareness about ocean-related topics. Additionally, online classes enable inviting guest researchers from different parts of the world to teach a specific subject or to participate in a discussion without additional costs to the university. So, although online classes can prove challenging at first, they have a great reward potential. Graduates can also help to improve online classes by offering feedback to their departments and lecturers. Thankfully, while the retraining of academic staff could well become a necessity, universities should strive to offer open courses on online teaching, as some free initiatives are already taking place[10,11].

While capacity building initiatives and programs worldwide will continue as key strategies to promote development of marine science and ocean health (Schmidt et al., 2019;

TABLE 1 | Online repositories of resources for marine graduate researchers (examples below).

Organization	What is offered	Web page
CJB Network	Advertise academic/job positions, courses	https://www.cjbnetwork.com/
Climate and Ocean: Variability, Predictability and Change (CLIVAR)	Offer and advertise academic/job positions, courses, scientific events	http://www.clivar.org/
EUROMARINE (European Marine Research Network)	Advertise academic/job positions, courses, scientific events	http://www.euromarinenetwork.eu/
Future Earth	Offer and advertise scientific events, advertise academic/job positions	https://futureearth.org/networks/knowledge-action-networks/ocean/
IMBeR (Integrated Marine Biosphere Research)	Offer courses academic/job, positions, scientific events,	http://www.imber.info/
MARINE-B (MArine Research Information NEtwork on Biodiversity)	Advertise academic/job positions, courses, scientific events	https://listserv.heanet.ie/cgi-bin/wa?A0=MARINE-B
MarineTraining.eu	Advertise courses	http://www.marinetraining.eu/
NF-POGO Alumni Network for Oceans (NANO)	Advertise academic/job positions, courses, scientific events	https://nf-pogo-alumni.org/about/opportunities/
NOAA (National Oceanic and Atmospheric Administration)	Offer courses	https://coast.noaa.gov/digitalcoast/about/
OTGA (Ocean Teacher Global Academy)	Offer courses	https://classroom.oceanteacher.org/
Ocean Oculus	Advertise courses, academic/job positions, scientific events	https://www.oceanoculus.com/news-from-the-sea/ocean-opportunities
Ocean Training Partnership	Offer and advertise courses	http://www.oceantrainingpartnership.org/current-training
OpenChannels	Offer and advertise academic/job positions, courses, scientific events	https://www.openchannels.org/
POGO (Partnership for Observation of Global Ocean)	Offer courses	http://www.ocean-partners.org/training-education
SEVENSEAS Media	Advertise academic/job positions	https://sevenseasmedia.org/ocean-jobs/
The Academy by DHI	Offer courses, scientific events	https://www.theacademybydhi.com/

[9]https://jornal.usp.br/institucional/usp-distribui-mais-de-2-mil-kits-internet-para-estudantes-com-necessidades-socioeconomicas/

[10]https://www.futurelearn.com/courses/teach-online

[11]https://www.coursera.org/learn/teach-online

Stammer et al., 2019), an emphasis on virtual-oriented strategies should now be taken into account. We compiled in **Table 1** some important repositories for courses, academic/job positions and scientific events (webinars, conferences) of current and near-future relevance for marine graduate researchers. Apart from the mentioned sources, online shared repositories (e.g., Gradworksheet – jobs, volunteer, travel grant and scientific databases opportunities, https://bit.ly/gMar20Fron; Ocean webinars, https://bit.ly/yMar20Fron) and massive open online course providers such as edX[12], Coursera[13], and FutureLearn[14] are also relevant resources for graduate researchers.

Creating Online Groups for Young Researchers in Marine Science

Given the suspension or slowing down of research activities, many researchers are, when possible, optimizing their time by working on the theoretical aspects of their subject, building capacities/skills (e.g., GIS, coding) and developing project ideas with colleagues from their network. Online groups on social networks (e.g., Marine Biologist network and job postings)[15], and other platforms allow us to bring together researchers from all over the world to discuss issues and challenges, and share opportunities. This dynamic of exchange and sharing could lead in the short and medium term to collaborative research in marine science.

[12]https://www.edx.org/

[13]https://www.coursera.org/

[14]https://www.futurelearn.com

[15]https://www.facebook.com/groups/39975981246

OPPORTUNITIES TO MARINE SCIENTISTS ARISING FROM THIS NEW REALITY

As all members of society, marine graduates are concerned primarily with their health, their families and the impacts of the pandemic on their career. If the marine science community is able to implement solutions to thrive despite this situation, we can also look forward to emerging opportunities. First of all, this period can generate new vocations and interest in education and research in marine science, as the general public have been made aware of the links between biodiversity conservation and human well-being. Several efforts have arisen to better understand the impact of COVID-19 in our coastal and marine environments, including citizen science (for example the eOceans initiative)[16]. Marine scientists have become more involved in public outreach by sharing their knowledge with the public via webinars[17]. This pandemic has reinforced the need for collaboration through virtual research environments across all aspects of marine science. Regarding research, this period may also encourage further development and potential academic positions in certain sectors of marine science. Marine organisms have demonstrated

[16]https://www.eoceans.co/project-covid19

[17]https://www.forbes.com/sites/farahqaiser/2020/03/24/10-ways-scientists-can-help-during-the-covid-19-coronavirus-pandemic/#46bf8130a901

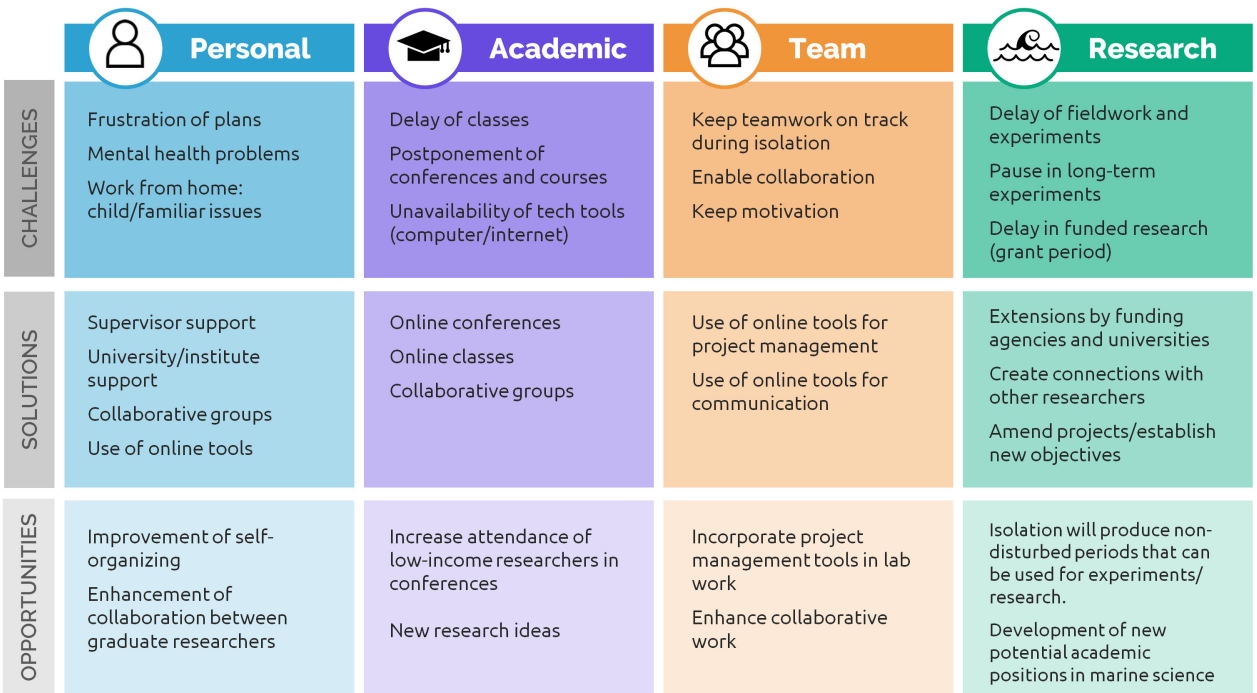

FIGURE 1 | Challenges, solutions, and opportunities for graduate researchers in marine science.

a vast potential as a source for several pharmaceuticals mainly due to their range of specific secondary metabolites (Lindequist, 2016). Reduction or absence of anthropogenic disturbances may also promote an ideal opportunity for studies on marine wildlife behavior and ecology[18] (Bates et al., 2020). Reduced number of tourists, lower levels of noise pollution, boat-generated waste and recreational fishing, for instance, may allow research on the pressures faced by the marine environment, the efficacy of marine protected areas, and on baselines for non-disturbed periods (e.g., Rolland et al., 2012).

CONCLUDING THOUGHTS

The COVID-19 pandemic has changed the world. As the pandemic period continues and other isolation periods are expected, we propose solutions that can be adopted by institutions, supervisors, and graduates to overcome this situation. Apart from the importance of showing immediate and expected challenges, solutions and opportunities (summarized in **Figure 1**), it is crucial to keep updating the list of technologies and strategies to deal with future similar situations. Graduate researchers are important actors in the marine science research community, being considered, for instance, to be at the core of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) (Intergovernmental Oceanographic Commission [IOC], 2019). Although there are aspects that we may not have taken into account, this article covers the main topics identified among our peers. We should also mention that several of these recommendations can be applied to other segments of science, and not necessarily confined to marine science and graduate researchers.

Many, if not all, of these challenges will require a joint effort of all involved in marine science research. As a contribution to the community, we are launching a Twitter account (Marine Graduate Opportunities – @mar_opps) as a repository for opportunities for graduates in marine science, hoping the information will be used for other early career researchers at different levels. The community is also encouraged to post and share opportunities on social media via #marineopps, which may be reposted in our account. Despite being a small contribution, we hope it will add to the efforts to advance the academic career of marine graduates during this period. We believe that if we work together, we can still grow in spite of this great challenge.

[18] https://www.theguardian.com/environment/2020/apr/27/silence-is-golden-for-whales-as-lockdown-reduces-ocean-noise-coronavirus?CMP = share_btn_tw

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

JP and SP conceived and designed the perspective. All authors contributed equally to the writing and critically revised the text.

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ORIGINAL RESEARCH
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Engaging More Effectively With Visitors to Coastal Regions for Improved Management Outcomes: Insights From the Ningaloo Coast, Australia

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A key component of successful coastal management efforts is an effective communication and engagement strategy focused on raising awareness of a region to different stakeholders to encourage more pro-environmental behaviors. Accordingly, in recent times there has been a proliferation of research focused on improving engagement and communication with different users of the coastal environment. Despite this effort, a paucity of evidence is available to guide better communication and engagement with visitors (i.e., tourists). Addressing this knowledge gap is critical given the adverse impacts of current global coastal tourism on ecosystem health, and projected future increases in coastal tourism. Using a case study of the Ningaloo Coast World Heritage Area (WHA) in Australia, we contribute toward filling this gap by identifying visitors' perception of the region and their self-reported and intended pro-environmental behaviors. We also identify the types of information they access and trust, and explore whether different message framings on the value of the WHA influence visitors' intended pro-environmental behavior. We determine that although visitors to the Ningaloo Coast WHA are optimistic about the future sustainability of the region, they have low understanding of the rules and regulations in place to support its management. Further, we find that visitors consider tourism to be a serious threat to the future of the region. However, most participants in our study considered the quality of their *own* environmental behavior to be high, and thus not contributing to these threats, although this did differ by gender. Finally, we highlight that visitors to the Ningaloo Coast WHA, for the most part, obtain their knowledge of the region during their visit, primarily through local signage and visitors centers. We discuss the implications of these results, and highlight future considerations for coastal managers when developing visitor-focused communication and engagement strategies.

Keywords: communication, message framing, trust, World Heritage Area, coral reef, tourism

INTRODUCTION

Coastal ecosystems are among the most productive globally, providing a range of critical goods and services that underpin societal well-being and prosperity (Barbier et al., 2011). The services that these ecosystems provide include, for example, food, shoreline protection from storm surges, income from tourism, and numerous cultural and spiritual benefits (UNEP, 2006; Cracknell, 2019). As such, coastal ecosystems are an essential component of the basic global life support system for more than 40% of the world's population (Seto, 2011; Neumann et al., 2015). However, despite their value and importance to humanity, increased direct pressures from a growing population (e.g., through coastal development), as well as other anthropogenic sources of pressure (e.g., from climate change), threaten the long-term persistence of these ecosystems and the services they provide (Halpern et al., 2008). Accordingly, the development and implementation of effective and integrated coastal management strategies that reduce human pressures and maintain societal benefits is critical for ongoing societal well-being.

A critical component of any successful coastal management strategy is an effective stakeholder communication and engagement program (Stephenson et al., 2019). Communication and engagement efforts underpin stakeholder awareness about the value of an ecosystem and the current rules and regulations in place to protect it (Kelly et al., 2019). Through increased understanding, stakeholders are more likely to accept and abide by the rules and regulations that are in place, thus fostering pro-environmental behaviors (Jolls et al., 1998). However, while in theory this is achievable, on a practical level establishing communication and engagement strategies capable of influencing people's behaviors are difficult to achieve. This is partly due to the challenges associated with developing messages that can be salient across the broad diversity of worldviews, beliefs and values held amongst and between different groups of stakeholders (Dean et al., 2019). Further, the logistics of communicating across wide geographies and large numbers of stakeholders often also necessitates linear (i.e., one-way or top-down) modes of communication (Stocklmayer, 2013), which are likely to be less effective than those founded upon two-way engagement processes.

Recognizing these difficulties in stakeholder communication and engagement has led to an increased research focus on identifying improved ways to more effectively engage with diverse groups of stakeholders, in oftentimes remote or geographically spread coastal regions. For example, in Australia, MacKeracher et al. (2018) investigated the extent to which different user groups associated with the Great Barrier Reef trusted information from five different sources: research institutions, non-government organizations, the primary management agency (the Great Barrier Reef Marine Park Authority), industry groups, and friends, family, and co-workers. They found that the extent to which people trusted information from different sources differed between stakeholder groups, suggesting a need for more tailored communication protocols for engaging diverse groups in achieving environmental stewardship. Similarly, Dean et al. (2019) examined the effectiveness of different types of message frames (e.g., environmental, economic, lifestyle) in engaging and influencing different segments of the community in relation to the sustainable management of Moreton Bay in southeast Queensland. Finally, Cvitanovic et al. (2018) demonstrated how an understanding of the diverse perceptions and values held by community members can help local decision-makers develop a more nuanced and targeted communication and engagement strategy within the Ningaloo Marine Park in northern West Australia, potentially leading to improved social and environmental outcomes. These three case studies are only a sample of growing research in this space, but also highlight some more recent efforts to improve understanding on how to engage with diverse stakeholders in coastal regions.

Despite this recent progress, however, significant knowledge gaps remain. In particular, with much research to date focused on understanding how to improve communication and engagement with community members (i.e., permanent residents), there is a paucity of evidence available to guide communication efforts with visitors (i.e., non-permanent) to coastal regions. Addressing this knowledge gap is critical, given the adverse impacts of current global coastal tourism on ecosystem health (e.g., Hall, 2001; Davenport and Davenport, 2006; Machado et al., 2017), as well as the projected future impacts to coastal ecosystems from increased tourism (e.g., Boavida-Portugal et al., 2016). This study seeks to contribute to addressing this knowledge gap, and investigates the case study of the Ningaloo Coast World Heritage Area (herein, referred to as the Ningaloo Coast WHA, or the WHA) in Western Australia, Australia.

We selected the Ningaloo WHA as a case study for several reasons. First, the Ningaloo Coast is globally marketed as a premier tourist region; between the years 2016–2018, the average annual number of visitors to Exmouth (the largest settlement along the Ningaloo Coast) was approximately 159,900 individuals (Tourism Western Australia, 2019a,b). Second, the Ningaloo coast is home to the world's largest fringing coral reef and is unique in that, to date, the reef state is relatively pristine in comparison to other sites where reefs have been heavily impacted by multiple pressures, including tourism (e.g., Great Barrier Reef). Globally, there is extensive evidence of impacts from tourism on coral reefs (e.g., via direct habitat destruction associated with activities such as snorkeling and scuba diving, e.g., Renfro and Chadwick, 2017), through increases in local levels of eutrophication (e.g., Wong et al., 2019), or by increasing the prevalence of coral disease (Lamb et al., 2014). Finally, the Ningaloo coast is among the most comprehensively studied coastal ecosystems worldwide, as a result of the support of the AUD$36 million Ningaloo Research Program (Cvitanovic et al., 2016), which ran from 2006–2011 and included 40 individual research projects across the broad domains of biodiversity, physical environment, socio-economics and human-use. The Program included extensive research on the socio-economics of tourism in the region (Jones et al., 2011), thus providing a baseline of information on visitor behaviors in the region that serves to guide the development, design and implementation of this study. Thus, in light of these three reasons, the Ningaloo Coast WHA represents a suitable case study to begin to

understand the broad objectives of this study as specified above. Thus, building on these, the specific aims of this study are to (i) elucidate visitors' broad perceptions of the Ningaloo Coast WHA and their environmental behaviors while visiting the area, (ii) determine how visitors to the Ningaloo Coast WHA access information and their levels of trust in these different information sources, and (iii) understand what types of message framings are likely to be most effective in eliciting pro-environmental behaviors among visitors to the region.

MATERIALS AND METHODS

Study Site

The Ningaloo Coast World Heritage Area is a 604,500 hectare (∼1,500,000 acre) marine and terrestrial property stretching over more than 300 km along the Western Australian coast. It was inscribed onto the World Heritage list on the 24th of June, 2011 under two of the World Heritage Outstanding Universal Value Criteria:

(vii) – to *contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance*; and

(x) – *to contain the most important and significant natural habitats for in situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation*.

The primary terrestrial feature of the Ningaloo Coast is the extensive Karst system and network of underground caves and watercourses of the Cape Range National Park (Allen, 1993), which support a diversity of highly specialized species, including the Blind Gudgeon (*Milyeringa veritas*) and Blind Cave Eel (*Ophisternon candidum*) which are both also endemic to the region. Above ground, the Ningaloo Coast WHA includes the Cape Range Peninsula, which belongs to an arid ecoregion recognized for high levels of endemism and species richness, particularly for birds and reptiles. The coastal and marine portion of the WHA nomination comprise a diversity of habitats including the intertidal system and rocky shores, lagoon, reef, open ocean, and the continental slope and shelf. These waters are renowned for whale sharks (*Rhincodon typus*) with annual aggregations in the region reaching an estimated 300–500 individuals (Wilson et al., 2001), as well as manta rays (*Manta alfredi*), dugongs (*Dugong dugon*), multiple species of whales and turtles, and numerous other species (Storrie, 1998). Much of the coastal and marine area along the coastline is offered protection via the Ningaloo Marine Park; the park was first established in 2004 and was expanded in 2011 to cover the entire Ningaloo Reef Area.

In addition to its natural beauty, the Ningaloo Coast WHA supports two permanent human settlements, the largest of which is Exmouth, with a permanent residential population of approximately 2,600 individuals. The smaller town of Coral Bay, which lies 150 km south of Exmouth, has a permanent population of 200 residents. The economies and ongoing viability of both towns are dependent upon the tourism sector, although the area is also a key service point for the offshore oil and gas industry. Outside of the townships of Exmouth and Coral Bay, the coastline contains several pastoral leases that are managed by long-term leases with grazing rights. Many of these properties also accommodate tourists via the provision of campsites (Smallwood et al., 2013).

The Western Australian Department of Biodiversity, Conservation and Attractions (DBCA) has primary responsibility for the management of the Ningaloo Coast WHA, and is supported by an independent State-Cabinet appointed Ningaloo Coast World Heritage Advisory Committee (from herein referred to as "the Committee"). The Committee provides advice to Commonwealth and State Environment Ministers and other managing agencies on the protection, conservation and management of the natural world heritage values. The Committee also serves to represent the view point of the local and broader community and circulate information on key matters relevant to the WHA throughout the community. Committee members are chosen for their diversity and ability to represent community interests, and thus have knowledge and/or background in areas such as tourism, planning, indigenous heritage, conservation and scientific expertise relevant to the protection and conservation of the WHA.

The DBCA are, therefore, also the primary agency responsible for communicating the World Heritage values of, and the rules and regulations associated with, the management of the WHA to local communities and visitors. This is achieved in numerous ways and through various mediums, for example, through local signage positioned throughout the WHA, via the Milyering Discovery Centre (a visitors center in Cape Range National Park), via social media (e.g., Facebook and Instagram), and through the DBCA regional Facebook account, to name a few. Local Government also play an important and complementary role in communicating about the WHA to community members and visitors, for example, via the recent construction of the Ningaloo Visitor Centre in Exmouth, which was undertaken by the Shire of Exmouth. Thus, close collaboration between DBCA, the Committee and local government is important and a key focus in the region.

Survey Design and Implementation

The logistical challenges associated with a study such as this included: obtaining a sufficiently large sample size, the geographic spread and remoteness of respondents and the difficulty of eliciting information from holidaying visitors (who are unlikely to want to spend a long period of time contributing to scientific research). As such, a relatively short quantitative survey, that would be implemented in the main visitor hubs, was considered the most suitable approach for addressing the first two aims of this study (Bryman, 2012) [i.e., (i) elucidate the broad perceptions of visitors about the Ningaloo Coast WHA and their environmental behaviors while visiting the area, and (ii) describe how visitors to the Ningaloo Coast WHA access information and their levels of trust in different information sources]. The quantitative survey questionnaire was developed by drawing upon and adapting previous studies aimed at understanding the perceptions of stakeholders within World Heritage Areas (e.g.,

Marcotte and Bourdeau, 2006; Jimura, 2011; Song and Kim, 2019), and in relation to environmental issues more broadly (e.g., Jones et al., 2011; Kim et al., 2011; van Riper et al., 2012).

To increase the efficiency of the survey, and reduce the time needed for completion and thus, maximize potential participation, the majority of questions were presented to respondents as a statement. The respondents were asked to indicate how strongly they agreed or disagreed with each statement on a 10-point Likert scale, where a score of 1 indicated that the respondent strongly disagreed with the statement, and a score of 10 indicated that the respondent strongly agreed with the statement (following Cvitanovic et al., 2018). Using this scale, there is no mid-point; a score of 5 indicated that the respondent slightly disagreed with the statement, while a score of 6 indicated that the respondent slightly agreed with the statement. Prior to implementation, the survey was piloted by members of the research team who were not involved in its design, as well as members of the Ningaloo Coast World Heritage Advisory Committee and staff employed within the local management agency (the Western Australian Department of Biodiversity, Conservation and Attractions). Based on feedback from these groups, the survey was further refined to remove ambiguity and increase clarity and ease for the respondent. The final survey instrument used in this study can be found in **Supplementary Appendix I**.

To address the third aim of this study – (iii) understand what types of message framings are likely to be most effective for eliciting pro-environmental behaviors among visitors to the region – we adapted the methodology outlined by Dean et al. (2019) to examine how the framing of information might impact visitors' understanding and perceptions. Framing, in its broadest sense, refers to how particular aspects and/or phrases within a message are accentuated to make that information more persuasive (Chong and Druckman, 2007; Nisbet, 2009). By doing so, theory suggests that the way in which information is presented (i.e., the frame) influences how people perceive and process that information for themselves, and also influences their individual behavior (Chong and Druckman, 2007).

Building upon an example of how the Ningaloo Coast WHA is commonly described by the local management authorities (i.e., our framing control – see **Supplementary Appendix II**), we developed four alternate frames following the language used by Dean et al. (2019). Our first framing was a *factual environmental message*, which focused on talking about the environmental uniqueness of the region, and the importance of a healthy ecosystem for the region. Building on this, the second frame developed was a *moral environmental message*, which sought not only to focus on the uniqueness of the region, but also to highlight the broad moral foundations underpinning its protection. The third message was an *economic message*, focused on emphasizing the economic importance of the region for human well-being, and the ways in which economic benefits are dependent on having a healthy ecosystem. The final message framing tested was a *lifestyle message*, which emphasized the social importance of the region.

Each of these five different framings were included in different versions of survey instrument (see **Supplementary Appendix II**). Following Dean et al. (2019), a framing message (e.g., 1, 2, 3, 4, or 5) was placed as text at the start of the survey to allow testing for the influence of the frame on the responses for the proceeding questions (i.e., the questions that investigated (i) perceptions and environmental behaviors, and (ii) information access and trust). Further to this, the frame was repeated at the end of the survey. The aim of repeating the framing message was to test two other aspects. First, it allowed us to investigate how *reflective* the message was of the respondent's own perception of the WHA. Second, it allowed us to test how *comprehensive* the framing was (i.e., was it a framing that the respondent might use themselves). These two aspects would help to contextualize the influence of the framing on (i) and (ii), and also to understand whether the influence of framing is "unconscious" or simply as a result of the frame reflecting the respondent's values.

The survey was conducted *in situ* at multiple sites along the Ningaloo Coast, but was concentrated in the areas surrounding Exmouth and Coral Bay, over 2 weeks during July and August 2019. July and August fall within the peak tourist season for the region, coinciding with Australian School holidays and key tourist drawcards such as the opportunity to swim with whale sharks and humpback whales. Three members of the research team (RK, HF, and TvS) implemented the survey questionnaire. To ensure a random sample of respondents, the interviewers positioned themselves in visitor hubs (e.g., outside shopping centers, alongside boat ramps, within local visitor centers, etc.) in both Exmouth and Coral Bay (following Cvitanovic et al., 2018). We tested the data for interviewer bias and found there to be no statistical difference in the survey responses between the three interviewers. The five different versions of the survey described above (i.e., with the different frames) were randomly distributed between the three researchers to avoid any researcher bias. The researchers randomly approached people as they walked past. Once a respondent had self-identified as a visitor to the region and indicated their willingness to participate, they were provided with the study information sheet and invited to complete the survey questionnaire. As part of the survey questionnaire, a range of demographic information was collected (and subsequently anonymized) for each respondent, including: interview location (Coral Bay or Exmouth), country of origin (and if in Australia, city/town of origin), age, gender, and the length of visit to the region. Ethical permission to conduct this research was approved by Australian National University Human Ethics Research Committee (Protocol number 2019/424).

Data Analysis

In total, 163 visitors to the Ningaloo Coast WHA took part in the study: 33 completed the survey using the control message frame, 31 using the *factual environmental* message frame, 36 using the *moral environmental* message, 31 using the *economic message* frame, and 32 using the *lifestyle message* frame. Respondents ranged in age from 19 to 85 years old; 68 males (41%), 91 females (56%), and 4 who chose not to identify a gender. Ten respondents were solo travelers, 69 with a partner, 19 with friends, and 61 with family. International respondents represented 24% of the sample population (n = 41) and spanned 17 different countries. Of the Australian participants, 36% (n = 59) were from other parts of

Western Australia, mostly from Perth (n = 32), the capital of Western Australia, approx. 13 h drive south of Exmouth.

Data were entered into Microsoft Excel, and the software package "R" (version 3.2.0) was used for the data analysis. We used simple statistical tests of difference to test whether the mean scores for each question were from a single population (t-test for continuous variable or Chi square tests for categorical variables). We test for differences in the answers given by groups of people characterized by different demographics (i.e., male/female, visitor origin, age-group). We consider p-values of 0.05 as significant as we have a reasonably large sample size of 163 (but see Boos and Stefanski, 2011; Wasserstein and Lazar, 2016; McShane et al., 2019 for debate on the use of p-value).

RESULTS

Visitor Perceptions and Behaviors in Relation to the Ningaloo Coast WHA

Survey results show that respondents of this study have a very high level of awareness that the Ningaloo Coast is a WHA, and that they strongly agree that it deserves to be designated as a WHA (**Table 1**). However, results also show that visitors to the region have a lower awareness about the boundaries of the WHA, the rules and regulations in place to protect the WHA, and the management agency charged with the protection of the WHA (**Table 1**). Further, while results showed that visitors to the region would have come irrespective of the WHA designation, all respondents strongly supported the need for management actions focused on preserving and protecting the environmental sustainability and cultural heritage of the region (**Table 1**).

Results also show that visitors generally found that the Ningaloo WHA lived up to their expectations, was in good condition, and that it was well managed (**Table 2**). In general, respondents were optimistic about the long-term future of the region (**Table 2**), although many respondents also indicated concern about its long-term viability. In particular, visitors to the region showed concern about the potential impacts of climate change and plastic pollution to the WHA (**Table 2**). These concerns were largely in relation to the marine environment, with less concern shown about the condition and future of the Karst system and underground caves (**Table 2**).

When asked about their own behaviors whilst visiting the Ningaloo Coast WHA, the results indicate that respondents of this study believe that they generally behave in an environmentally responsible manner and also encourage others to do so (**Table 3**). Respondents indicated that they did not litter or interfere with the animals, and generally do not go off the designated roads (**Table 3**). When respondents were asked about the environmental behaviors of other visitors to the region, or residents of the region, results show that they believed that both residents (mean 7.59, SD 1.75) and visitors (mean 6.85, SD1.84) behave in an environmentally responsible manner in the WHA, although visitors were perceived to behave slightly less responsibly. Interestingly, however, this result was lower than for their self-assessed behavior (mean 9.20, **Table 3**).

When asked about their intended future behaviors while visiting the Ningaloo WHA, respondents indicated that they would seek to minimize their individual impact, but were less sure if they might be able to influence the behavior of others (**Table 3**). In fact, they were less sure that they even had the ability to find actions (and carry them out) to help protect the Ningaloo Coast WHA. In general, they were also unsure if they were able to communicate the importance of responsible behavior to others in the region.

Statistical differences in the perceptions and behaviors of study respondents varied according to where the visitors originated from, the type of group they traveled in, their age, their gender, and the length of their stay as discussed in the next sections.

The Origin of Respondents

Respondent understandings of the WHA differed between groups of people and were dependent upon their place of origin (i.e., WA, interstate, or overseas; see **Table 1**). Specifically, people from WA were more aware of all aspects related to the WHA, including the locations of the boundaries of the WHA ($p = 0.001$), the management agency for managing the WHA ($p < 0.001$), and the rules and regulations in place to protect and conserve the WHA ($p = 0.001$). Respondents from other Australian States or Territories were slightly better informed than people from overseas, who had the lowest levels of awareness. Another statistically significant difference associated with the origin of the visitors was related to the importance of tourism as a threat to the WHA; people from overseas perceived threats associated with tourism to pose a greater risk to the region than the Interstate and WA visitors ($p = 0.0256$; **Table 2**).

Travel Party

Data analysis shows WA visitors to the Ningaloo Coast WHA tended to travel in family groups (55%) more than visitors from overseas (29%) or interstate (25%). Visitors

TABLE 1 | Visitors' awareness and understanding of the Ningaloo Coast WHA and its management.

Visitor origin (n = 160)*	Awareness of WHA Mean (SD)	Awareness WHA boundaries Mean (SD)	Awareness managing authorities Mean (SD)	Awareness rules and regulations Mean (SD)	Deserves WHA status Mean (SD)
West Australia (n = 60)	9.64 (1.35)	7.44 (2.51)	6.64 (3.04)	7.64 (2.30)	9.27 (1.81)
Interstate (Aus) (n = 59)	8.78 (2.83)	5.50 (3.00)	4.13 (2.77)	6.19 (2.81)	9.37 (1.81)
Overseas (n = 41)	8.73 (2.61)	5.79 (3.30)	3.94 (3.11)	5.68 (3.26)	9.55 (1.51)
All respondents	9.05 (2.41)	6.27 (3.03)	5.03 (3.20)	6.56 (2.92)	9.35 (1.84)

*Scores are based on a Likert scale between 1 (representing strongly disagreed) and 10 (representing strongly agreed). *Three respondents did not identify their origin.*

TABLE 2 | Visitors' perceptions of the Ningaloo Coast WHA, and concerns for its future.

Visitor origin (*n* = 160)*	WHA lives up to expectation Mean (SD)	WHA is in good condition Mean (SD)	WHA is well Managed Mean (SD)	Optimistic for future of WHA Mean (SD)	Concern – increasing tourism Mean (SD)	Concern -climate change Mean (SD)	Concern – Pollution Mean (SD)	Concern – oil and gas sector Mean (SD)	Concern for Marine Environment Mean (SD)	Concern for Karst system Mean (SD)	Concern for Terrestrial Environment Mean (SD)
West Australia (*n* = 60)	9.15 (1.47)	8.26 (1.60)	8.28 (1.72)	7.77 (2.22)	7.02 (2.76)	7.85 (2.79)	8.58 (1.97)	7.56 (2.59)	7.68 (2.49)	6.58 (2.94)	7.32 (2.45)
Interstate (Aus) (*n* = 59)	8.98 (1.45)	7.88 (1.77)	8.04 (1.80)	7.98 (1.97)	6.92 (2.67)	8.14 (2.54)	8.64 (1.90)	8.11 (2.14)	7.60 (2.40)	6.89 (2.61)	6.96 (2.67)
Overseas (*n* = 41)	9.31 (1.03)	8.42 (1.61)	8.39 (1.80)	8.03 (2.07)	8.37 (2.14)	8.50 (2.00)	8.71 (2.19)	7.84 (2.43)	8.17 (2.23)	6.66 (2.97)	7.24 (2.99)
All respondents	9.13 (1.36)	8.11 (1.76)	8.18 (1.85)	7.87 (2.15)	7.34 (2.62)	8.08 (2.52)	8.64 (1.98)	7.80 (2.40)	7.75 (2.41)	6.70 (2.80)	7.17 (2.66)

*Scores are based on a Likert scale between 1 (representing strongly disagreed) and 10 (representing strongly agreed). *Three respondents did not identify their origin.*

TABLE 3 | Visitors' behaviors within the Ningaloo Coast WHA.

Visitor origin (*n* = 160)*	*My* env responsible behavior (mean SD)	Encourage *others* env responsible behavior Mean (SD)	*My* littering behavior Mean (SD)	Pick up *others* litter Mean (SD)	*My* interfering with animals Mean (SD)	*My* staying on the road Mean (SD)	Intention minimize my impact Mean (SD)	Intention influence others behavior Mean (SD)	*My* ability to help protect Mean (SD)	Intention to take action to protect Mean (SD)	Intention communicate responsible behavior Mean (SD)
West Australia (*n* = 60)	9.15 (1.16)	9.22 (1.13)	9.80 (0.71)	8.67 (2.11)	8.68 (2.67)	8.63 (2.56)	9.55 (0.96)	8.41 (2.42)	8.21 (1.97)	8.38 (2.16)	8.20 (2.26)
Interstate (Aus) (*n* = 59)	9.42 (1.34)	9.51 (1.26)	9.77 (0.98)	8.14 (2.37)	9.53 (1.42)	8.93 (2.51)	9.64 (1.08)	7.98 (2.38)	7.67 (2.52)	7.82 (2.25)	7.48 (2.42)
Overseas (*n* = 41)	8.88 (1.67)	8.82 (1.93)	9.86 (0.43)	7.63 (2.97)	9.19 (2.01)	9.29 (1.78)	9.48 (1.20)	8.38 (1.82)	7.89 (2.39)	7.81 (2.49)	7.67 (2.52)
All respondents	9.20 (1.35)	9.25 (1.40)	9.81 (0.77)	8.22 (2.45)	9.13 (2.12)	8.89 (2.37)	9.56 (1.07)	8.22 (2.28)	7.95 (2.28)	8.05 (2.27)	7.78 (2.39)

*Scores are based on a Likert scale between 1 (representing strongly disagreed) and 10 (representing strongly agreed). *Three respondents did not identify their origin.*

from interstate and overseas traveled predominately with their partners (59% and 44% respectively). Visitors from overseas had the highest proportion of solo travel (15%). There are some differences between the types of travel party in terms of their understanding and perceptions of the Ningaloo Coast WHA. For example, the sustainable management of the WHA was more important to people who traveled individually (p = 0.001, their mean score was 9.90 as opposed to 9.35 for all respondents). Preserving the cultural heritage of the Ningaloo Coast World Heritage Area was also more important to solo travelers (p = 0.030, their mean of 10 as opposed to 8.94 for all respondent). Solo travelers were also more concerned than other travelers about the terrestrial environment (flora and fauna) in the Ningaloo Coast WHA (p = 0.041, average was 7.17).

Visitors who traveled with friends to the Ningaloo Coast WHA were most likely to state that the region did not live up to their expectations as much as it did for example, for family groups (who were most satisfied) (p = 0.035). Visitors who traveled with friends also had a lower score to the question: "while visiting the region, I never interfered with animals (marine or terrestrial)" than the other travel party types on average, but this was not statistically significant. They did have a significantly lower score in terms of their intentions to minimize the impacts that their actions have on the condition of the Ningaloo Coast WHA (p = 0.034) than the other travel party types on average. In terms of their behavior, most respondents generally believed they behaved in an environmentally responsible way. However, respondents of this study who were traveling with their partners felt that they behaved on average more responsibly that those who traveled with friends (p = 0.042). Friends also had a lower score for their littering behavior (9.3 as opposed to an average of 9.8 for the whole group) but this was not statistically significant.

Age Group

Around one third of overseas visitors were less than 25 years old, corresponding to having a larger number of solo visitor respondents and respondents travelling with their partners. In contrast, almost half of the interstate visitors were between 45 and 65 years of age but these respondents also traveled mostly with their partners. 42% of the people from WA were between 25 and 45 years old (which corresponds to this visitor group traveling more as families).

When looking at the relationship between respondent age and level of concern for the WHA, younger people (< 25), not unexpectedly, had a higher concern for the effect of tourism (p = 0.006), oil and gas (p = 0.028), and climate (p = 0.003). These younger people were generally more concerned about the marine (p = 0.089) and terrestrial flora and fauna (p = 0.078) of the WHA than other age-groups, but this was not statistically significant at 0.05. Respondents aged over 65 years of age had the lowest concern for all the different environmental and sectoral use pressures. For instance, young people's score for concern about increasing tourism threatening the condition of the Ningaloo Coast WHA was 8.4, whilst only 6.6 for people over 65. Furthermore, younger people were also less likely to believe that visitors behaved in an environmentally responsible way in the Ningaloo Coast WHA (but with p = 0.063 this was not statistically significant). However, despite having higher levels of concern, these young people were the least to likely to pick up litter if they saw it in the WHA of any other groups (again with p = 0.086 this was not statistically significant).

Gender

There were slightly more female than male survey respondents (56% were female) but the gender ratio was similarly even within the three visitor groups. When looking at the influence of gender on the perceptions and behaviors of study respondents while visiting the Ningaloo Coast WHA, differences were evident. Specifically, females were significantly more aware of the rules and regulations associated with the WHA than males (p = 0.037). It was also more likely for females to say that the WHA designation was their main reason for visiting the region (p = 0.014). Similar to the results reported for younger visitors (section "Age Group"), females were more concerned about climate impacts than males (p = 0.038), and the impact of oil and gas (p = 0.027). Although the mean score is still greater than 5, females were less likely to indicate they behaved in an environmentally responsible way while in the Ningaloo Coast WHA or to have encouraged others (for example friends/family) to engage in an environmentally responsible way while visiting the Ningaloo Coast WHA (p = 0.009 and p = 0.019 respectively).

Where Do Visitors to the Ningaloo Coast WHA Get Their Information From, and What Information Sources Do They Trust?

Results show that there was surprisingly low respondent agreement that they actively sought information before they visited the WHA (a score of 6.45; **Table 4**) with approximately one third of respondents indicating they did not seek information (a score less than or equal to 5). However, if people did search for information prior to their arrival, they felt that this information was mostly informative and easy to find. Perhaps as may be expected, visitors originating from overseas were more likely to actively seek information about the Ningaloo WHA before visiting the region. On arrival to the WHA, respondents of this study confirmed that they were able to easily locate good information about the WHA (**Table 4**).

Prior to visiting the WHA, respondents to our survey stated that they mostly obtained their information from websites (**Table 5**). However, once they had arrived and were visiting the WHA, the respondents primarily received information from the visitor centers: 86% interstate, 63% WA and 68% overseas respondents went to the visitor centers during their visit to the Ningaloo Coast WHA. In regards to levels of trust in this information, respondent trust was higher for information from the visitor center before the visit, and for signs and the visitor center during the visit. The respondents' levels of trust in the different sources of information did

TABLE 4 | Visitors' information seeking and trust in that information about the Ningaloo Coast WHA.

Visitor origin (*n* = 160)*	Before visit find info Mean (SD)	Before visit good info Mean (SD)	Before visit easy find info Mean (SD)	After arrival good info Mean (SD)	After arrival easy find info Mean (SD)	Would like more info Mean (SD)
West Australia (*n* = 60)	5.78 (3.66)	5.80 (3.52)	6.00 (3.80)	7.41 (2.85)	7.47 (2.89)	6.12 (3.54)
Interstate (Aus) (*n* = 59)	6.44 (3.38)	6.29 (3.45)	5.93 (3.68)	7.91 (2.53)	7.70 2.53)	6.28 (3.27)
Overseas (*n* = 41)	7.51 (3.16)	6.73 (3.31)	7.00 (3.31)	7.54 (2.97)	8.02 (2.56)	6.95 (3.22)
All respondents	6.45 (3.49	6.21 (3.46)	6.25 (3.62)	7.65 (2.75)	7.72 (2.66)	6.38 (3.38)

*Scores are based on a Likert scale between 1 (representing strongly disagreed) and 10 (representing strongly agreed). *Three respondents did not identify their origin.*

not differ before or during their visit (**Table 6**) [e.g., of the 86% interstate respondents who went to the visitor center for information, their level of trust in this information was very high (9.25)].

Does Message Framing of the Ningaloo Coast WHA Description Influence Visitors' Perceptions and Behaviors?

The five different ways in which the Ningaloo Coast WHA area was described (i.e., framing it in terms of environmental values (with or without moral statements) or in terms of economic or social (lifestyle) values) did not influence the way respondents answered the different survey questions. The average scores for agreeing with the accuracy of the description that was given to people were generally quite high (average score of 8.81 for all respondents, SD 1.59). However, there were some minor differences between respondent groups in the level of their agreement with the different frames (but note that sample sizes are small for some groups); e.g., respondents from overseas tended to have a higher level of agreement with the description (i.e., frame) that was presented to them (average score of 9.35), and in particular, these respondents from overseas tended to agree with the environmental frame (**Table 7**).

Further, the respondents agreed they would use the description (i.e., the frame that had been presented to them) to describe the WHA to their friends and family (average score for all respondents 8.14, SD 2.11). There were only some minor differences in this scoring; specifically, respondents tended to agree more with the *lifestyle* framing and the *moral environmental* statement than with the other message frames (i.e., the scores were all greater than 5 and there was less spread in the scores; see **Figure 1**).

Thus, the framing had no effect on people's agreement with the accuracy (or potential use) of the description of the WHA. This may be because the framing was too subtle, and the respondents did not respond to the difference (i.e., no noticeable treatment effect) or, that the people generally agree with all the different types of framing. The latter would mean that economic, lifestyle, and environmental values are not perceived to be incongruous with the WHA.

DISCUSSION

The effective engagement of stakeholders in protecting and conserving coastal regions is critical for the long-term maintenance of natural and cultural heritage values, and positive societal well-being effects have been associated with these sustainability outcomes. Owing to the link between sustainability outcomes and engagement, there has been an increase in the number of scientific studies seeking to understand how to engage with often diverse stakeholder groups including different sectors, residents and visitors (e.g., Cvitanovic et al., 2018; MacKeracher et al., 2018; Dean et al., 2019). In popular coastal areas, the number of visitors can add significantly to local numbers and put pressure on natural resources; thus, engagement with this group is key. However, a paucity of evidence about how best to engage with visitors to coastal areas to achieve sustainability outcomes remains. To contribute toward filling this gap we used a case study of the Ningaloo Coast WHA in Australia, to identify visitors' perception of the region and their self-reported and intended behavior. We identified the types of information they access and trust, and whether or not different message framings could potentially influence visitor's environmentally sustainable behaviors. Here, we discuss our results in further detail, with a specific focus on their implications for coastal management and improved visitor engagement.

Within our study, there was a strong awareness among visitors that the Ningaloo Coast is a WHA, which our results suggest is likely a result of the extensive signage along the coastal driving route and information provided at the beaches and visitors centers. Further, our results revealed that, based on their *in situ* experience within the region, visitors believed that the region deserves to be a WHA. Accordingly, they supported the need for management and preservation of the natural and cultural heritage values of the region.

Whilst the results of this study revealed that visitors generally support the WHA, our results also suggest that they did not have a deep understanding of the WHA. For example, visitors who took part in our survey indicated that they were largely unaware of who was responsible for managing the WHA, and they were not familiar with the rules and regulations in place to protect the WHA. These results are perhaps unsurprising, as holiday-makers are more likely to focus on their leisure activities than on regulatory and management aspects in place to ensure the conservation and protection of the values. However, an understanding of why protection measures are in place (and who manages these and how) can be linked to better long-term conservation outcomes. For example, even for people who do not reside in an area and who are transient, low awareness has implications for WHA outcomes, particularly when such individuals do not feel "connected" or "attached" to the place that

TABLE 5 | Types of information accessed by the different types of visitors prior to their arrival.

Visitor origin (*n* = 160)*	Website proportion of visitor group (average trust score)	Social media proportion of visitor group (average trust score)	Friends proportion of visitor group (average trust score)	Family proportion of visitor group (average trust score)	Visitor center proportion of visitor group (average trust score)	Signs proportion of visitor group (average trust score)	TV documentary proportion of visitor group (average trust score)
West Australia (*n* = 60)	0.73 (8.82)	0.18 (7.18)	0.50 (8.87)	0.30 (9.44)	0.42 (9.40)	0.23 (9.29)	0.10 (9.17)
Interstate (Aus) (*n* = 59)	0.68 (8.11)	0.29 (6.24)	0.47 (7.71)	0.12 (7.71)	0.46 (8.98)	0.14 (9.38)	0.20 (7.17)
Overseas (*n* = 41)	0.71 (7.86)	0.37 (6.93)	0.34 (8.93)	0.05 (9.00)	0.49 (9.30)	0.10 (8.25)	0.02 (9.00)
All respondents	0.71 (8.29)	0.27 (6.59)	0.45 (8.45)	0.17 (8.96)	0.46 (9.21)	0.17 (9.19)	0.12 (7.89)

*The figures show the proportion of visitors of that groups that accessed the information and the average trust at which they scored that information. Trust scores are based on a Likert scale between 1 (representing no trust) and 10 (representing high levels of trust). *Three respondents did not identify their origin.*

TABLE 6 | Types of information accessed by different types of visitors after their arrival.

Visitor origin (*n* = 160)*	Website proportion of visitor group (average trust score)	Social media proportion of visitor group (average trust score)	Friends proportion of visitor group (average trust score)	Family proportion of visitor group (average trust score)	Visitor center proportion of visitor group (average trust score)	Signs proportion of visitor group (average trust score)	TV documentary proportion of visitor group (average trust score)
West Australia (*n* = 60)	0.20 (7.92)	0.03 (9.00)	0.12 (9.43)	0.08 (7.60)	0.63 (9.24)	0.07 (8.88)	N/A
Interstate (Aus) (n = 59)	0.22 (7.85)	0.07 (6.00)	0.10 (8.17)	0.03 (6.00)	0.86 (9.25)	0.25 (9.86)	N/A
Overseas (*n* = 41)	0.22 (8.33)	0.15 (7.00)	0.17 (9.14)	0.05 (10.00)	0.68 (8.96)	0.17 (9.29)	N/A
All respondents	0.21 (8.00)	0.07 (7.00)	0.12 (8.95)	0.06 (7.78)	0.73 (9.18)	0.23 (9.32)	N/A

*The figures show the proportion of visitors from each groups who accessed the information, as well as and the average trust at which they scored that information. Trust scores are based on a Likert scale between 1 (representing no trust) and 10 (representing high levels of trust). *Three respondents did not identify their origin.*

they are visiting (van Putten et al., 2018). Thus, while the current study provides insights into place-related aspects of "sense of place" within the Ningaloo region it was outside of the scope of our research design to explore these directly. We, therefore, suggest that future research is needed to more comprehensively understand the specific variables (not only related to place, but also the person and process – see van Putten et al., 2018) that can build and foster place attachment among visitors to the region (Gurney et al., 2017).

Despite not having a strong understanding of the regulatory and management measures currently in place to protect the values of the WHA, our results suggest that visitors to the region are optimistic about the future sustainability of the region. This optimism, in part, likely reflects the reported positive perceptions that visitors had regarding the current condition of the region during their visits. The positive perceptions in the Ningaloo region, as reported here, however, are at odds with visitor feelings of "reef grief" in the Great Barrier Reef region on the east coast of Australia (Marshall et al., 2019). The pressures on the Great Barrier Reef and its consequent decline have had much publicity, and this shared detailed (and negative) information is leading the public into this grief (Marshall et al., 2019). Our optimistic results are perhaps unsurprising, given that visitors with "less knowledge" tend to be more satisfied with reef and environmental health (Leujak and Ormond, 2007), and the Ningaloo coast receives significantly less national and international media attention than the Great Barrier Reef. However, even the positive perceptions of the Ningaloo WHA reported by visitors who took part in this study were tempered by current environmental projections; e.g., because of climate change (Jones, 2019) and development (Boavida-Portugal et al., 2016). We expand on this finding in the next section.

Optimism, Tourism, Gender, and Self-Reported Behavior

In our study, the results suggest that visitors are optimistic about the future of the WHA, but simultaneously are concerned about several threats in the future, including those associated with climate change and local pollution. In particular, in the case of the Ningaloo WHA, we found that young people and females are most concerned, a result that has also been partly reported elsewhere (Van Liere and Dunlap, 1980; Davidson and Freudenburg, 1996). Although the perceived average concern about the impact of tourism was lower than for instance, climate change and pollution, four out of five people also agreed that tourism poses a threat[1]. Ironically, however, while respondents in this study did recognize tourism as a threat to the region, most considered the quality of their *own* environmental behavior to be high (i.e., they feel as though they exhibit good environmental behaviors that do not pose a threat to the WHA). In contrast, results suggest that visitors feel as though the behavior of *others* was less environmentally friendly.

Care must be taken when interpreting and comparing the result from self-reported behavior and other-reported behavior (Chao and Lam, 2011), because self-reporting can be prone to exaggeration and over reporting of pro-environmental behavior (Kormos and Gifford, 2014), for instance, due to social desirability bias (e.g., Ewert and Galloway, 2009). Nevertheless, from our results we hypothesize that from a psychological perspective, visitors to the WHA perceive themselves to be responsible for desirable outcomes but not responsible for undesirable ones. In doing so, they transfer the responsibility of undesirable outcomes to others (i.e., a blame shift; Lozano and Laurent, 2019) and thus, legitimize their own actions. Moreover, in such situations people tend to be overconfident in their own behavior and their ability to do the right thing (i.e., the overconfidence effect; Dunning et al., 1990).

Interestingly, and somewhat unexpectedly, there was also a gender dimension in our study to the respondents' own perceived environmental behavior and that of other visitors, which contradicts previous research. Since the origin of environmental behavior literature, there has been much observational evidence to suggest that women are more worried about the environment than men, and that this is reflected in their greater levels of pro-environmental behavior (e.g., Stern et al., 1993; Davidson and Freudenburg, 1996; Ramstetter and Habersack, 2019). However, females in our study self-rated their own environmental behavior as lower (i.e., less environmentally friendly) than men – which would be counter to the observational evidence (e.g., Lam and Cheng, 2002; Wallhagen et al., 2018). Given that our study was not specifically designed to test for such gender differences we do not have adequate evidence to explain these findings, however, we posit that females may under-report the adequacy of their own behavior for gender related reasons. We posit this because females in this study were also less confident that they would be able to influence the environmental behavior of others. Irrespective of which, subsequent research is needed to comprehensively understand these results, the drivers of these findings, and the associated implications for the management of coastal regions.

Visitor Access to Information and Trust in Information Sources

The ways in which individuals access (and the extent to which they trust) different sources of information has implications for their behaviors and actions (MacKeracher et al., 2018). In terms of accessing information, our results somewhat interestingly suggest that most visitors to the WHA start their search for information during, and not prior to visiting, the WHA (i.e., most information about the conditions of the region, and associated management measures are obtained *in situ*). Further, our results suggest that these *in situ* sources of information, including local signage and visitor centers, are considered more trustworthy that other sources of information, such as websites. Indeed, this reflects previous studies about the importance of visitor information centers for engaging with and educating visitors partaking in tourism activities (e.g., Ballantyne et al., 2009).

These findings have important implications for the management agencies responsible for developing and

[1] 1 out of those 4 visitors in fact strongly agreed, i.e., score of 10 on the Likert scale.

TABLE 7 | Scores of the five different framing messages (n = 160*), which did not influence respondents' answers to the survey.

Framing	WA visitors Average score (SD) sample size	Interstate visitors Average score (SD) sample size	Overseas visitors Average score (SD) sample size	Grand Total Average score (SD) sample size
A Base case	9.10 (1.91) n = 10	8.77 (1.36) n = 13	8.50 (1.20) n = 8	8.75 (1.50) n = 32
B Environmental	7.91 (1.04) n = 11	8.50 (2.76) n = 10	10.00 (0.00) n = 9	8.71 (1.85) n = 31
C Moral environmental	9.00 (1.18) n = 14	8.10 (3.18) n = 10	9.64 (0.50) n = 11	8.94 (1.88) n = 36
D Economic	9.17 (0.94) n = 12	8.38 (1.50) n = 13	8.67 (1.37) n = 6	8.74 (1.29) n = 31
E Lifestyle	8.42 (1.78) n = 12	9.00 (1.08) n = 13	9.67 (0.52) n = 6	8.90 (1.37) n = 31
All responses	8.73 (1.44) n = 59	8.58 (1.98) n = 59	9.35 (0.98) n = 40	8.81 (1.59) n = 161

*Scores are based on a Likert scale between 1 (representing strongly disagreed) and 10 (representing strongly agreed). *There was a total of 3 non-responses to this question.*

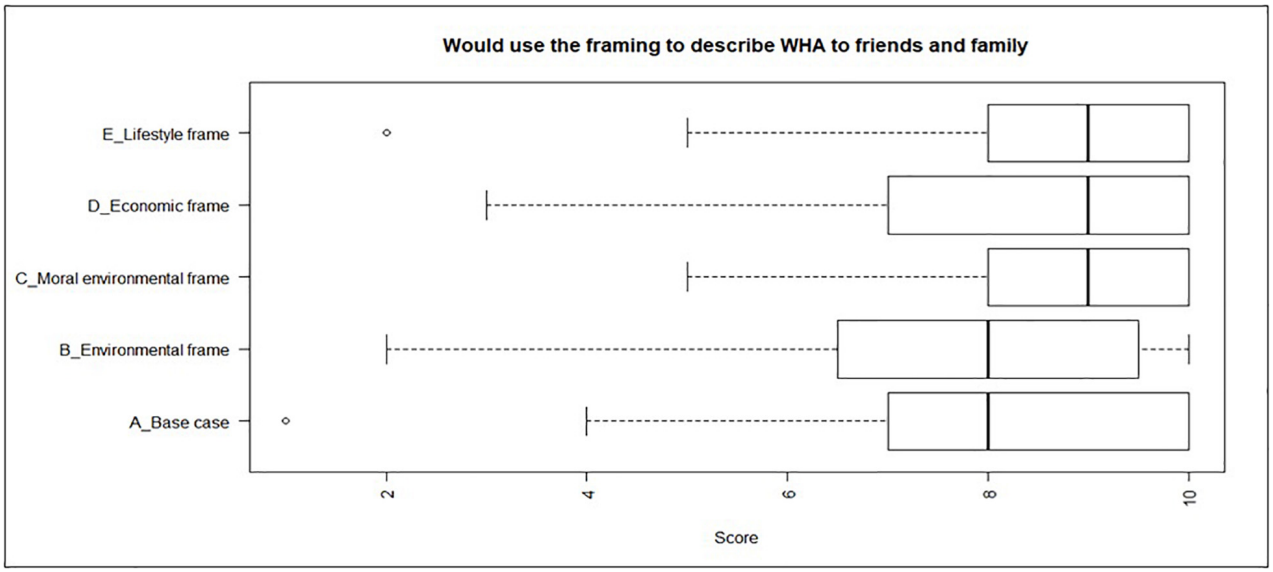

FIGURE 1 | Level of agreement (where 1 is strongly disagree and 10 is strongly agree) by survey respondent (n = 163) with the different four message frames (i.e., short statements used to describe the Ningaloo Coast WHA that accentuate certain aspect to make the information more persuasive). The four frames highlighted environmental values of the WHA [without moral statements (B) or with moral statements (C)] or in terms of economic (D) or social (lifestyle) values (E), and a base case in which a neutral description of the Ningaloo Coast WHA was given (A).

implementing communication and engagement strategies aimed at visitors. Firstly, they highlight the need to regularly update local signage and visitor information centers. Particularly in relation to signage, this can be problematic as such information sources are very static (i.e., not easily updated as new information comes to hand), and also prone to destruction such as graffiti and other forms of vandalism (Patrick, 2003). Similarly, updating exhibits and other communication tools within visitor centers can be labor intensive (in terms of planning and design) and costly (in terms of the financial resources required). Thus, our findings highlight the need for management agencies to adequately maintain (i.e., keep clean) and update local signage and visitor centers as new information comes to hand.

Further, and as previously mentioned, some visitors to the WHA were unsure if they had the ability to carry out actions to help protect the WHA, or communicate the importance of responsible behavior to other visitors. This may indicate a potential lack of confidence in their own knowledge of (i) how to behave in an environmentally responsible manner themselves and (ii) what issues might require action in the WHA, or perhaps this is simply a reflection of their perception that it is not their responsibility to communicate this. Irrespective, these findings suggest that signage and visitor centers located within coastal regions should be focused on helping raise awareness among visitors as to the type of pro-environmental actions that individuals can take to reduce their impacts while improving local sustainability.

Framing of Information About the Ningaloo WHA

There were no statistically significant differences between message framings for the intended pro-environmental behavior response variables. This result is not completely unexpected as evidence of the effect of framing (especially in the context of environmental frames) is mixed and inconsistent. The manipulations used in this study comprised of an emphasis

frame (for terminology refer to Chong and Druckman, 2007), and an associated benefit or efficacy pertaining to that frame. Although these are not necessarily competing frames, recent research has shown that in more complex framing environments, the framing effect can be diminished (Nisbet et al., 2013; Detenber et al., 2018).

In the case of the Ningaloo WHA, these findings may mean that economic, lifestyle, and environmental values are not perceived to be incongruous with the Ningaloo Coast. This type of information is important for managers and local decision makers because balancing environmental, social and economic objectives can be very difficult in areas where tourism is a major local economic activity (Wight, 1993). Our results could also be an indication of the current management success in achieving all these objectives in the eyes of visitors to the area, although future research is required to state this with certainty. Further, these findings may suggest that all of the message frames used in the present study were considered acceptable by those who completed the survey. Thus, future studies are needed to determine any intricacies of this possible result, for instance, local residents' perceptions on this issue versus that of the visitors. We suggest that future studies on message framing, either in the Ningaloo WHA or elsewhere, may also benefit from having participants explicitly compare and rank all framings in order of which best reflects/resonates with their individual views (e.g., via methods such as analytical-pared hierarchy).

However, as highlighted above, it is also likely that the respondents did not have enough personal understanding about the WHA to critique the information (i.e., the framing) that was provided to them. Thus, no difference in how the respondents understood and agreed with the five frames was observed. This result then reveals how visitors to the WHA trust in the information that is provided to them, and emphasizes the important role of the visitor centers in providing visitors with information and enabling them to understand (i) the uniqueness of the WHA, and (ii) the rules and regulations that are in place to protect it, particularly as the results revealed that respondents were not very well aware of the regulations at all. Framing effects can be difficult to isolate but it is understood that there are conditions that can result in more effective communication (Druckman and Lupia, 2017). The consistently high scores recorded in this study suggest that combining a framed message with a statement emphasizing a benefit could potentially aid in eliciting more intended pro-environmental behaviors among visitors to the WHA, and is certainly worth exploring in future research.

CONCLUSION

The long-term maintenance of natural and cultural heritage values within coastal regions requires effective engagement of visitors (i.e., tourists) in protecting and conserving coastal regions. Via a case study of the Ningaloo Coast WHA in Australia, we found that strong support for management and preservation of the natural and cultural heritage values of the Ningaloo Coast, combined with a high level of optimism about the future sustainability of the region, was prevalent among visitors. We also found that visitors to the Ningaloo coast recognize that tourism is a threat to the region, but they felt that their own environmental behavior did not contribute to that threat, and that the behavior of others was less environmentally friendly.

This study emphasizes the importance of visitor information centers and local signage for engaging and educating visitors partaking in tourism activities in coastal regions and World Heritage Areas. Key to such engagement will be adequate resourcing from local governments and other key agencies. Information centers, such as those in the Ningaloo Coast WHA, will need to equip visitors with adequate and salient information that can enable visitors to understand the uniqueness and value of the WHA, as well the rules and regulations that are in place to protect it. Effective information sharing and education is also required to ensure the long term pro-environmental behavior of visitors transient in the region, and to foster visitors' place attachment, similar to residents.

DATA AVAILABILITY STATEMENT

The datasets generated for this study will not be made publicly available: In accordance with our ethics approval to protect the anonymity and confidentiality of all project participants.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the ethical permission to conduct this research was approved by Australian National University Human Ethics Research Committee (Protocol number 2019/424). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CC, EP, and TG conceived the study, designed the survey design, interpreted the data, and drafted the manuscript. RK, HF, and TS helped refine the survey, undertook the field-work, and contributed to writing the manuscript. MM and NB assisted with data analysis and interpretation, and contributed to writing. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00583/full#supplementary-material

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frontiers in Marine Science

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The Blue Economy–Cultural Livelihood–Ecosystem Conservation Triangle: The African Experience

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The concept of Blue Economy (BE) is recognized as central for sustainable development that incorporates socio-economic benefits and ecological conservation. However, in Africa, much of the emphasis on BE is placed on economic gains; as a result, traditional livelihoods and small-scale local operations are outcompeted by international corporations and government initiatives, with little or no regard for social inclusion and environmental sustainability. We argue that successful BE initiatives in Africa accentuate the involvement of local communities and promote sustenance of the natural ecosystem. We define success in terms of the sustainability balance among ecological, social and economic aspects. Drawing on extensive expert experiences, observational data and literature review of case studies across the African continent, we highlight two critical findings. First, large scale BE initiatives prioritize economic gains at the expense of environmental degradation and the exclusion of local communities. Second, using the full spectrum sustainability (FSS) evaluation, we show that successful BE interventions considered ecological, economic, socio-cultural and institutional objectives. Drawing on these case studies, we propose the adoption of a collaborative framework which amalgamates the top-down and bottom-up approaches to BE management. Achieving the goal of successful blue growth in Africa is now even more challenged by the implications of COVID-19 on the BE sectors. Reimagining and rebuilding a resilient BE in Africa post-coronavirus will require a strong political commitment to promoting a balance between economic, social and environmental benefits in line with the African Union's Agenda 2063 and the United Nations' Sustainable Development Goals.

Keywords: Agenda 2063, collaborative blue management, ecosystem conservation, social equity, ocean economy

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INTRODUCTION

"Blue Economy" or "Oceans Economy" is increasingly being proposed by scholars and policy makers as a useful concept for conserving the world's ocean and the inherent resources (UNECA, 2016, 2018; Au-Ibar, 2019; Wenhai et al., 2019; Lee et al., 2020). Rapidly resonating with many countries, demonstrated by its prominent positioning on national development agendas, the

concept of the Blue Economy (BE) was first highlighted at the United Nations Conference on Sustainable Development held in Rio de Janeiro in 2012 (UNCTAD, 2014). At the backbone of the BE lies the need for "improved human wellbeing and social equity, while significantly reducing environmental risks and ecological scarcities" (UNEP., 2015) thus placing the society, economy and environment at the core of the discourse.

Recent work by Wenhai et al. (2019) examines various definitions of BE using global case studies and summarizes it as a "macro-economy" concept that encompasses "every aspect of national and global governance, economic development, environmental protection and sustainability and international communication." Further, some key players view BE as a blueprint for promoting economic development along with ecological conservation aimed at poverty reduction (AU, 2015; UNECA, 2016). For example, the concept of BE was defined by The World Bank United Nations Department of Economic Social Affairs (2017) as "comprising the range of economic sectors and related policies that together determine whether the use of oceanic resources is sustainable."

The United Nations Conference on Trade and Development (UNCTAD) defines BE as the economic and trade activities that focus on the ocean-based marine environment, associated biodiversity, ecosystems, species, and genetic resources whilst ensuring conservation (UNCTAD, 2014). While multiple players acknowledge the role of BE in socio-economic development and environmental sustainability, inherent complexities exist in its interpretation despite the urgent need to transition to a more sustainable blue growth pathway which addresses threats to the environment and economic and human security (Voyer et al., 2018a; Okafor-Yarwood et al., 2020). BE is mostly divided into economic, environmental, and social components with the aim of bringing the three categories together. However, the economy is often given priority in policies and development debates whereas environmental conservation and social equity are often marginalized. This holds true for many African states where the idea of the BE often appears to be restricted to generating revenue by any means necessary from a capitalistic viewpoint, with very little, if any, consideration for the benefits to local communities or environmental conservation (Masie and Bond, 2018; Childs and Hicks, 2019). It is imperative to incorporate the needs and concerns of local communities in the conception and implementation of current and future BE projects as their contributions will be central to achieving social equity and reducing environmental risks. As such, we define a successful BE in the African context as one that emphasizes the interconnectedness of economic development, local community inclusion and environmental sustainability without prioritizing one aspect over the other.

In Africa, while blue growth makes substantial contributions to the economy through various sectors, the potential of BE has yet to be fully recognized (UNECA, 2016). The prospects of BE to influence Africa's economic growth was first highlighted in the African Union Integrated Maritime Strategy (AIMS) 2050 (AU, 2012; Adewumi, 2020) and advanced with the adoption of the African Charter on Maritime Security and Safety and Development in Africa (or the Lomé Charter) by the African Union Assembly in 2016 (AU, 2016). As set out by the African Union's Agenda 2063, the BE is perceived as the continent's future because its benefits extend beyond the shores of coastal states and create opportunities for adjacent landlocked communities and countries (AU, 2015).

The goal of BE parallels the guiding principles of the green economy which center on "improved wellbeing and social equity, while significantly reducing environmental risks and ecological scarcities" (UNEP., 2015). In Kenya, for example, the Green Economy Strategy and Implementation Plan (2016–2030) emulates these guiding principles by promoting a low-carbon, resource-efficient and inclusive socio-economic transformation (Government of Kenya, 2016). Kenya is not an exception as many African states have increasingly mainstreamed green economy strategies into institutional performance targets (Georgeson et al., 2017). These experiences are being applied in the implementation of the BE. However, blue growth in Africa remains mostly unattainable as sustainable exploration of the sea is undermined by inadequate knowledge and technological capacity, combined with limited investment in the BE sectors. With this in mind, it becomes clear that African nations will not develop what they do not understand and therefore blue growth becomes even more elusive and remains at the subsistence level of our ancestors.

Nevertheless, some strides have been made in selected sectors of Africa's BE, which currently contributes an annual value of US$1 trillion to Africa's economy (UN, 2020). The fisheries sector makes a significant contribution to the food and income security of millions of Africans (De Coning and Witbooi, 2015). The sector contributed $US24 billion, or 1.26% of the GDP of all African countries, in 2011 (de Graaf and Garibaldi, 2014). However, the ability of Africa's fisheries to contribute to the sustainable development of its people is undermined by overexploitation, including illegal, unreported and unregulated (IUU) fishing by local and distant water fishing vessels (Carney, 2017; Belhabib et al., 2020; Okafor-Yarwood and Belhabib, 2020). de Graaf and Garibaldi (2014) estimate that 25% of all the marine catches in the continent are made by non-African states, resulting in the loss of US$3.3 billion potential earnings, which in turn may impact food and economic security. This is a significant amount when compared with the US$0.4 billion earned by African countries from fisheries agreements without taking into account the US$2.3 billion lost through IUU fishing in West Africa alone (de Graaf and Garibaldi, 2014; Doumbouya et al., 2017; Grun, 2019; Okafor-Yarwood, 2019). To meet the growing demand for food and economic security, African states are increasingly investing in aquaculture (Harris, 2011; Chan et al., 2019; Obiero et al., 2019). Compared to global figures, Africa contributes the least of any continent to total global aquaculture production, yet the continent's aquaculture sector is growing faster than anywhere in the world, and accounts for 8% of the 12.3 million Africans employed in the fisheries sector (Obiero et al., 2019).

Further, Africa's rich oil fields and the prospects for offshore discoveries have transformed it into an important player in the global oil production and resource extraction. Four coastal states, Algeria, Egypt, Nigeria, and Libya, possess 91.5% of the continent's proven oil reserves. However, Africa's hydrocarbons are predominantly extracted by international

corporations and most of the crude oil is refined outside the continent. Consequently, the benefits do not always stay in the host communities and there is little regard for environmental sustainability (Okafor-Yarwood, 2018; Okafor-Yarwood et al., 2020). Nigeria and Angola, the first and second largest oil producing countries in the continent, import over 80% of their fuel due to lack of domestic refineries (Steffani, 2011; Ogbuigwe, 2018; Graham, 2019). The quest for harnessing the resources in their marine environment is also driving non-oil producing states on the continent to explore offshore hydrocarbons, with Senegal and Mauritania set to join the league of oil producing states by 2022 (EIU, 2019) and Mozambique to follow by 2024 (Zawadzki, 2019).

Maritime transportation and shipping is another promising sector in the continent. The sector was developed at an exponentially increasing rate by European empires in the mid-nineteenth century, making it possible to exploit their colonies (Debrie, 2012; Bickford-Smith, 2016). The maritime transportation and shipping sector continues to play a vital role in the continent's trade such that over 90% of Africa's imports and exports are conducted by sea (AU, 2012). Despite the large volume of trade via the sea, the continent only accounts for 2.7% of global trade value, 7% of global seaborne trade and 5% of maritime import and export by volume (UNCTAD, 2018). With the launching of the operational phase of Africa Continental Free Trade Area (AfCFTA), investment in relevant infrastructure would create jobs for Africans and facilitate intra-Africa trade. Today, this accounts for only 17% of African exports, compared to Asia and Europe's 59 and 69%, respectively (Cloete, 2019; Chimbelu, 2019).

The continent's diverse marine ecosystems, consisting of beaches, coral reefs, and wildlife among others, presents untapped tourism opportunities that would support local economies while advancing conservation. Small island nations such as Seychelles, Cabo Verde, and Mauritius derive 62, 43, and 27%, respectively, of their GDP from the tourism sector (UNCTAD, 2017) which signifies the importance of investing in this sector for socio-economic development. Notably, the lack of investment in relevant infrastructure, and security threats at sea such as piracy and armed robbery, have hindered the advancement of the tourism sector in West, Central, and East African regions (UNEP and WIOMSA, 2015; Okafor-Yarwood, 2020).

Finally, marine renewable energy is increasingly growing on the continent. The presence of the Indian and Atlantic Oceans provide an opportunity to exploit enough energy to meet the demand for electricity on the continent (UNEP, 2011). The prospect of Ocean Thermal Energy Conversion (OTEC) in Africa dates back to 1956, with an initial attempt of a 3MW open-cycle plant for Abidjan, Côte d'Ivoire (Cummins, 2011). African countries may have viable OTEC resources within their 200-Nautical Mile Exclusive Economic Zones (Asian Development Bank, 2014; IRENA, 2014). In addition, the capacity of Africa's wave energy is estimated at 3,500 Wave Energy TWh/yr (Smith et al., 2011; Hafner et al., 2018) and many countries are keen to explore ocean energy. For example, Ghana has installed and operationalised a wave energy array with 400 Kilowatt (KW) of capacity, while South Africa has identified a coastal spot for the Stellenbosch Wave Energy Converter (SWEC) (World Energy Council, 2016). Governments in Africa have signed Memoranda of Understanding (MoU) with several leading renewable energy project development firms to design their OTEC capacity (Grad, 2014; NIOMR, 2020). However, while blue power generation gives a promising picture for Africa's BE, limited progress has been made to actualise the vision of a continent powered by blue energy, thus challenging the process of upscaling the BE.

Recognizing the significance of BE as the "next frontier" for Africa's development in its Agenda 2063 of the "Africa we want," the African Union (AU) declared that the Blue Economy is "Africa's Future" (UNECA, 2016). The AU declaration aligns with the global development plans, through Goal 14 of the Sustainable Development Goals (SDGs) 2030, which focuses on life below water specifically "to conserve and sustainably use the world's oceans, seas and marine resources" (UN, 2016). By developing a successful BE, Africa's coastal and island nations will be a step closer to achieving SDG 14, which is strongly connected to other SDGs (Okafor-Yarwood, 2019; Obura, 2020).

Managed properly, the BE is key to ensuring the sustainable development of the African people by 2063. However, one inherent problem noticeable in the monitoring, benefits sharing, and implementation of projects related to the ocean economy is the top-down management approach which often leads to further exclusion of coastal communities (Sowman et al., 2011; Gaymer et al., 2014; Sowman and Sunde, 2018; Isaacs and Witbooi, 2019) resulting in limited economic input into local economies and destruction of traditional livelihoods (Pereira, 2011; Belhabib et al., 2020; Okafor-Yarwood and Belhabib, 2020). Given the dependence of coastal communities on marine resources, stakeholder conflict often arises between development, industry, government and communities (Kadagi et al., 2020). There is also a lack of human and financial resources for monitoring which increases the risk of development paying little to no attention to environmental degradation due to emphasis on generating revenue (Okafor-Yarwood, 2018, 2019; Belhabib et al., 2020).

The literature is replete with approaches for addressing challenges arising from the management of natural resources, especially in relation to coastal and fisheries governance. Much of these studies have proposed frameworks pointing to the need for an integrated approach that combines the top-down and bottom-up approaches (Christie, 2005; Curtin and Prellezo, 2010; Fulton et al., 2014; Butler et al., 2015; Jones and Stephenson, 2019; Stephenson et al., 2019b). Though more emphasis is given to the ecological objectives and less on the economic, social, cultural and institutional facets (Jones and Stephenson, 2019; Stephenson et al., 2019a), these guiding principles can be a useful tool for assessing the outcome of BE projects as either successful or unsuccessful, through the lenses of their ecological, economic and social outcomes (Curtin and Prellezo, 2010; Benson and Stephenson, 2018).

Our paper sets out to address two critical objectives: (i) assess the performance of government, corporate and community blue initiatives against societal, economic and environmental

metrics, and (ii) propose a collaborative engagement framework that can guide and support the development of the African BE that combines the top-down and bottom down blue management approaches.

MATERIALS AND METHODS

To examine successful BE in Africa, we defined important gaps in the context of our own experiences and knowledge. The paper drew on experiences and discussions between co-authors who found that most examples of BE initiatives in the continent failed to prioritize ecological sustainability, and social equity, thus excluding the needs of coastal communities.

We do not aim to produce a comprehensive evaluation of ecological, economic and social equity for BE initiatives in Africa, but this may be a recommended approach for assessing the success of current and future BE interventions. This would also involve something that is beyond the scope of this work: a thorough analysis of case studies taking into account a complex variety of information sources which are not necessarily accessible to the general public, involve different scales, the time frame of a given BE initiative, contexts and applications. We instead make use of published literature, reports, observational data and extensive expert experiences to examine perceived success in light of the BE objectives. Despite the limitations of the ethnographic observation method, such as bias in the analysis of data, the method allows the researcher to study people in their native environment, understand things from their perspective and learn things that the observed might have been unwilling to discuss in an interview (Baker, 2006; Clark et al., 2009; Bryant, 2015).

Success was defined in terms of the sustainability balance among ecological, social and economic aspects. We adopted the full spectrum sustainability (FSS) approach described by Jones and Stephenson (2019) (**Table 1**) to express balance or imbalance. We selected various African case studies which are well documented with information from a variety of accessible sources and compared them using a desktop FSS framework. We then matched indicator information mentioned in the literature with sustainable objectives and allocated either a tick for a mention and overall positive perspectives, a cross for mentions and negative perspectives or NM for "no mention" (**Supplementary Table S1**).

Following our evaluation of unsuccessful and successful projects, we explored three types of management approaches to recommend possible blue governance frameworks that integrate local communities.

In the remainder of this section, we examined unsuccessful and successful community-based and government-led BE interventions which allowed us to critically review and recommend possible frameworks for participation of coastal communities. Following the review of existing literature, we adopted the integrated or collaborative management approach described in various studies (Schelhas et al., 2001; Butler et al., 2015; Keen et al., 2018) as the outcomes aligned with the FSS and our argument for a successful BE in Africa.

AN ASSESSMENT OF BLUE PROJECTS IN AFRICA

An estimated 25 percent of Africa's population live 100 km within the shoreline (Celliers and Ntombela, 2015). The figure is much higher in West and East Africa, where over 40% of the population lives in coastal areas (Obura et al., 2017; Okafor-Yarwood, 2019). Given the significance of the marine environment and the resources that lay beneath it to the livelihoods of the African people, one of the biggest challenges to a sustainable BE would be achieving a balance between inclusivity, ecological conservation and economic development.

Ocean-based development activities related to Africa's BE range from community-based enterprises to large scale initiatives operated by governments and private sectors. Our evaluation of various BE case studies based on the FSS approach is twofold. First, we use examples to demonstrate the characteristics of unsuccessful BE which focuses on economic gains against the backdrop of ecological conservation and social reciprocity for local communities who struggle to achieve general wellbeing (**Figure 1**). Second, we highlight successful examples of BE projects that incorporate the FSS approach (**Figure 1**).

Unsuccessful BE Examples

Recognizing that blue growth is a crucial factor in Africa's new economic paradigm, we argue that development initiatives must account for the potential implications arising from the exclusion of community needs and social objectives. For example, selected BE projects have led to the displacement or extinction of fishing communities along the coast. In addition, the expansion of the offshore oil and natural gas sector through exploration and new infrastructures combined with pollution and climate change may further diminish marine fisheries, especially where there is a lack of coherent and effective governance frameworks (Okafor-Yarwood et al., 2020). Some examples of the challenges faced by local communities are explored in the ensuing case studies.

Port of Kribi Project, Kribi, Cameroon

The Government of Cameroon embarked on infrastructure development in the maritime and shipping sector to enhance the national economy and improve the livelihoods of coastal communities. One example of such commitment is the Kribi deep-water port project, recognized among China's biggest port investment projects anywhere in the world, the largest deep-water port in West Africa, and aimed at easing congestion to the harbor in Douala (EIU, 2017). While the investment in the Kribi Port would bring about economic development in Cameroon, it comes at a huge cost to coastal communities and the environment. In particular, the 300 inhabitants of Mbode in Lolabe, whose village had to be destroyed for the port to be built, received little or no compensation for their land (Schenkel, 2018). In addition, the clearing of the forest in the project areas has implications for local biodiversity, as it has resulted in the direct loss and the fragmentation of ecosystems (Romain et al., 2017).

The people affected, many of whom are fishers and farmers, have lost their traditional fishing grounds and farmlands, and

TABLE 1 | Summary of full spectrum sustainability (FSS) for assessment of BE activities in Africa, adapted from Jones and Stephenson (2019).

Full-spectrum sustainability category	Sustainable objectives	Example indicators
Ecological	Productivity and trophic structure	Recruitment dynamics, indigenous knowledge
	Biodiversity	Species assemblage structure, biodiversity indicators, indigenous knowledge
	Habitat and ecosystem integrity	Pollution, habitat restoration, ecological indicators, indigenous knowledge, maintenance of ecological services
Economic	Viability and prosperity	Human demographics, capacity building, technical assistance
	Sustainable livelihoods	Livelihood index, financial empowerment, ownership
	Distribution of access and benefits	Equity, the inclusion of marginalized groups, women, youth and indigenous communities, ownership
Social and Cultural	Health and wellbeing	Social factors, social development, quality of life
	Sustainable communities	Social capital, social structure
	Ethical practices	Rights of people, respect for indigenous practices and traditions
Governance and Institutional	Legal and policy support	Legal support for indigenous people, favorable people-centered policies
	Governance structure	Organized groups, multi-sectoral involvement, the involvement of indigenous people
	Cooperation and accountability in decision process	Collaboration, accountability, the involvement of indigenous people, use of indigenous knowledge

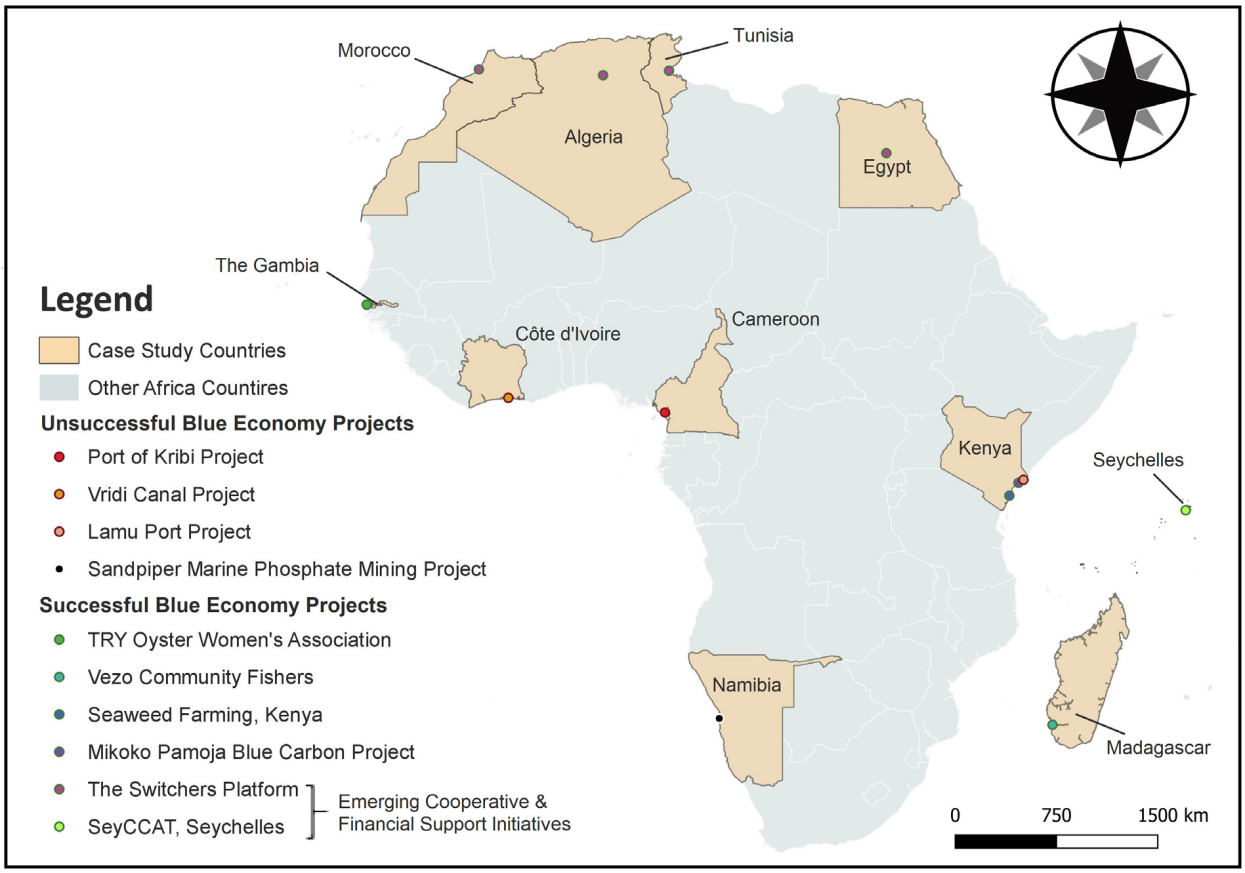

FIGURE 1 | Map of Africa, with Figure citation for the case study areas highlighted.

must now invest in expensive fishing equipment to fish elsewhere and/or seek an alternative source of livelihood. It has been reported that the villagers affected by the Kribi Port Infrastructure development were compensated and a special town built for them (Benkenstein, 2014). In reality, the promise of a better life has eluded many of the villagers, as they note that they struggle to make ends meet in their current location. Some members of the Mbode village have noted that though they were compensated, the compensation was far from what was initially agreed with the government, especially concerning land allocation, provision of housing and other basic amenities such as water and electricity (Okafor-Yarwood et al., 2020). They further claim that since the process of relocation started in 2011, nothing concrete has been achieved and many members of the community have relocated to different parts of the town, rather than the proposed site which is far removed from the comfort they once enjoyed (personal observation by I.O-Y).

The general view is that community members had hoped that the investment in the Kribi Port infrastructure would improve their socio-economic wellbeing, which has not been the case. Instead, they have lost their farmland, traditional fishing grounds and their ancestral homes. For the women, the eviction from Mbode means that they no longer have access to the lands they once farmed, or get as much fish to sell, since their husbands have either abandoned the fishing trade out of frustration or are not catching as much as they used to (personal observation by I.O-Y).

The narrative is similar in other communities across Lolabe. In Batanga, residents were displaced from their ancestral land and relocated to a different site some 6 km away, without any provision or consideration for the ancestral graves and other sites of social and cultural significance (Assembe-Mvondo, 2019). Also, the deforestation induced by the development project has destroyed other human habitats such as the Bagyeli and Baka indigenous people in rubber plantation sites, with livelihoods, places of worship and other cultural activities of pygmy populations destroyed with no regard for social safeguards (Assembe-Mvondo, 2019; Pemunta, 2019).

Though the Kribi deep seaport and the infrastructure associated with it would boost the Cameroonian economy when completed, the impact of the project in contributing to environmental degradation and depletion of the natural forest must not be ignored (Romain et al., 2017). The impact of the Port project on the Congo Basin, home to the second-largest tropical rain-forested area on earth (Tyukavina et al., 2018) calls for serious concern. Specifically, the cutting of trees began in late 2010, and by the time the project will be completed in 2035, it is projected that tens of thousands of hectares of the jungle will be cleared (Bax, 2018). The impact on the Congo Basin is worth highlighting due to its significance for biodiversity, serving as a home to important species including the critically endangered Pangolin and Lowland Gorilla (Tyukavina et al., 2018; Nforngwa, 2019). Deforestation associated with the felling of trees for the construction of the Port infrastructure, such as roads, threatens biodiversity. It exposes already endangered habitats to many threats, as they become easily accessible to poachers.

The completion of the Kribi deep water port in 2018 has led to further deforestation as there is now access to some of the most sought-after wood for the Asian market. In May 2018, a single Vietnamese ship was said to have loaded an estimated 10,000 cubic meters of wood from the Port of Kribi, which is an estimated 450 trucks load of logs (Colgan, 2018). During a visit to Kribi in October 2019, it appears the deforestation has increased substantially, as over 50 truckloads of logs were counted en route Yaoundé to Kribi (personal observation by I. O-Y).

Ultimately, the port infrastructure provides an opportunity for local development, as well as improving the economy of Cameroon. However, the implications for biodiversity, cultural preservation and the livelihood of the communities also have to be taken into account. In particular, given the Congo Basin's "role in regulating rainfall patterns across other parts of the continent, [the] continued [deforestation] could exacerbate insecurity of freshwater and food supplies for some of Africa's most vulnerable populations" (Bergen, 2019). One thing that must not be ignored, therefore, is the potential for such development projects to result in further animosity against the central government, something that Cameroon and its neighboring state, Nigeria, have experienced over the perception of political exclusion and unequal economic development in Anglophone Cameroon and the Niger Delta of Nigeria, respectively (Okafor-Yarwood et al., 2020).

Unfortunately, the narrative of the unsustainable approach to blue projects highlighted in Cameroon is replete across the African continent. For example, coastal communities are forcefully evicted or face eviction in Angola, Garside and Burke (2020) Kenya, Njunge (2019), Senegal, Grun (2019), and Guinea-Conakry, Philippe (2019), which brings about increased uncertainty due to the loss of traditional fishing grounds and ancestral homes, to make room for real estates, roads and port infrastructures respectively.

Vridi Canal Project, Abidjan, Côte d'Ivoire

The narrative is similar in Côte d'Ivoire, where the expansion of port infrastructure in Abidjan, through the widening of the Vridi canal, has negatively impacted communities living adjacent to it. The Vridi canal has been expanded and deepened from the previous maximum draft of 12 m and a Twenty-foot Equivalent Unit (TEU) capacity of 3,500 to a draft of up to 16 m and 10,000 TEU capacity. The project, which started in 2015 and was inaugurated in 2019 (Budd Group, 2019; Port Authority, 2019) is aimed at accommodating more container ships, improving the maritime transport and shipping industry, and thereby transforming the Port of Abidjan into a major maritime transport hub in West Africa (Kobri and Dosso, 2019).

The surrounding areas of the Vridi canal have been hit by coastal erosion which is attributed to the cumulative effect of climate change (Addo et al., 2011; Zamblé, 2011; Sink, 2016; Dahir, 2017; Kemper, 2017; Vitousek et al., 2017). However, some local residents explicitly associate the recent coastal erosion with human causes, in particular the expansion of the Vridi canal. The residents note that the enlargement of the canal led to the diversion of sea currents to the eastern part of the canal, causing destruction of homes, places of worship and businesses. Although residents have been urged by the government to move away from the coast to avoid being affected by future erosion events, they

claimed that they have received little to no support from the state to rebuild their homes and businesses (personal observation by I.O-Y). While there are no current scientific studies that link the expansion of the canal to the recent erosion, previous studies connect human activities to erosion in the Abidjan area. In fact, scholars have linked previous coastal erosion to the construction of the Vridi canal in the 1940s. Odada (2013) argues that beach erosion on the east of Vridi canal has intensified since its opening in 1950. Similarly, Abe and Affian (2012) show the construction of the canal, which began in 1943, resulted in the accumulation of sediment[1] on the western part and the erosion of the Port-Bouët coastline (which is located in the eastern part) by up to 3 m per year. The coastal retreat induced by the port facilities has severe consequences on livelihoods, as it leads to the destruction of properties and reduction of constructible space (N'Doufou et al., 2015).

The expansion of the Vridi canal and the resulting modernization of Côte d'Ivoire's port would bring about economic development and perhaps an improvement of the welfare of coastal communities. At the same time, the project exposes the countries' population to environmental risks, and loss of livelihoods. The cost of coastal degradation in Cote d'Ivoire in 2017 was estimated at US$2 billion, close to 5% of the country's GDP (The World Bank, 2019) which counteracts any economic gains made from the development of coastal infrastructure should coastal degradation continue to escalate. Therefore, coastal states must ensure that the impact of future BE initiatives are assessed to incorporate the views of coastal communities, especially those likely to be affected by such developments. In essence, we argue that future BE initiatives should consider adopting the FSS approach, which takes into account the ecological, economic, socio-cultural, government and institutional perspectives.

Lamu Port Project, Kenya

The Government of Kenya initiated the Lamu Port Project in 2012 to provide a transhipment hub for the East Africa region (Wël, 2012; Nduire, 2018). The project is one of the key components in the Lamu Port South Sudan Ethiopia Transport (LAPSSET) corridor which consists of the construction of 32 Deep Sea Berths and several infrastructures, originating in Lamu, intended to link East, Central and North Africa. The LAPSSET corridor is identified as an integrative infrastructure priority for East Africa Community (EAC) Vision 2030. It includes several highway roads, a causeway, and an oil pipeline between Lamu Port and Kenya's Oil Fields in Turkana Basin, and a standard gauge rail network that connects the Southern Agricultural Growth Corridor of Tanzania (SAGCOT), and the Maputo Development Corridor (MDC) (Kabukuru, 2016).

The port, which is currently not fully operationalized, was designed to ease the congestion in transportation and improve Kenya's connection with its landlocked neighbors, thereby boosting Kenya's regional and global competitiveness in the transhipment business. However, some local residents have raised an alarm over their lack of involvement in the planning and implementation process. Other reports point to the lack of sensitization of communities on the effect of the Lamu project on their socio-economic wellbeing (Sena, 2012). While fishing is important to the food and economic security of communities in Lamu, several reports denote a decline in the number of fishing grounds due to dredging activities which negatively impact livelihoods. In addition, the dredging has altered the diversity of fish species and the ecosystem at large. Destruction of habitats such as mangroves and coral reefs have been reported. In 2018, for instance, the court ruled that more than 4600 fishers would be affected by the LAPSSET project stating that:

> "Murky waters due to [the] effects of dredging and the destruction of the coral reefs and mangrove forests, have already affected the population and location of the fish" (Njunge, 2019).

This is true as many residents have raised concern about the decline in fish catches as noted by a 46-year-old fisher:

> "I used to get 40 kilogrammes in one catch but since the exercise started, I cannot get even 15 kg. The fishmongers don't want to understand when you raise the price because they will tell you they have the option of buying cheaper imported fish" (Njunge, 2019).

The loss of fishing grounds combined with decline in fish catches is likely to undermine the livelihoods of Lamu residents who have a long history of fishing. The Lamu Archipelago, particularly Old Town Lamu which dates back from the 14th century, has been known as a tourist destination and was designated as a UNESCO World Heritage Site in 2001 (Njunge, 2019).

Several residents have also highlighted the implications of Lamu Port for the surrounding habitats and resources, including far-reaching ecological, cultural, economic and social destruction. Activities such as sand mining and dredging for the port contributes to destruction of the ecosystem as stated by a 47-year-old dhow maker and snorkeling guide:

> "The water around where we used to take tourists for snorkelling started becoming dusty after the dredging started and the coloured fish species disappeared" [...] You either take them deeper in the ocean, which is very dangerous, so most of them opt not to snorkel in Lamu" (Njunge, 2019).

A 2019 court ruling instructed the Kenya Ports Authority (KPA) to pay the fishers US$17 million in compensation to be made within a year. However, KPA appealed the ruling resulting in the suspension of the compensation (Business Reporting Desk, 2019). This example points out to the inherent complications of such developments which fail to meet the expectations of the communities.

Though the Lamu Project presents an example of a BE initiative poised to enhance global shipping, the negative externalities borne by the communities may outweigh the benefits. As the Kenyan coastline is changing to accommodate

[1]Sedimentary accumulation is a natural process that involves the long-term deposition of sand to the shorelines/beaches to make up for the amount lost by erosion (Szmytkiewicz and Zalewska, 2014).

such large-scale infrastructure, innovative methods of compensation need to be developed to ensure that communities are not left impoverished by such projects. There is an urgent need for African states to initiate adequate monitoring programs to identify the impacts of current and future BE projects in a timely manner. Monitoring and evaluation require enforcement of regulatory and policy frameworks to ensure the environment and people are not adversely disadvantaged at the expense of economic development.

The Sandpiper Marine Phosphate Mining Project, Namibia

The Namibian government authorized the mining of phosphates within its EEZ in 2011 in an area believed to be the largest identified marine phosphate deposit in the world (NAMPHOS, 2012). The project aimed to push Namibia as a global market front-runner in rock phosphate production, with an envisaged steady-state production of three-million tons a year of phosphate concentrate product over an initial mine life of 20 years, including a 2-year ramp-up period (Odendaal, 2020). It is estimated that Sandpiper Marine Phosphate Mining would generate N$730 million (∼US$40 million) a year while fully operational (Odendaal, 2020).

However, the project, led by the Namibian Marine Phosphates (Pty) Ltd. (NMP), has not been in operation since 2012 because of a lack of transparency as well as concerns about serious impacts on the marine environment and the fisheries. Specifically, the proposed exclusion zone of 23 × 9 km would impact key commercial fishing grounds for hake, horse mackerel and monkfish which would have serious effects on livelihoods and environmental conservation (Midgley, 2012; Mensah, 2017; Menges, 2018). In an October 2012 press release, the founder of the World Future Council, Jakob von Uexkull, voiced concerns about the future of Namibian fisheries should the planned Sandpiper marine phosphate mining project be allowed to go ahead (World Future Council, 2012). He posited:

> "The risks of the project are incalculable and potentially devastating, as it is the first time phosphate would be mined at sea anywhere in the world. Application of the precautionary principle is critical in this instance if we are to protect our oceans."

Despite many concerns raised by activists and environmentalists over the years, Namibia's Environmental Commissioner in September 2016 gave out an environmental clearance certificate to NMP to commence mining operations (Immanuel, 2016). Following the issuance, three associations representing the Namibian fishing industry launched legal action against the commissioner for granting the environmental clearance certificate, resulting in the reversal of the award certificate in November 2016 (Shapwanale, 2016). Since then, there has been a back-and-forth legal tussle between the NMP and the Namibian authorities with no lasting solution in sight.

The prospects of this project to Namibia's economy may be far-reaching, however, it expedites environmental degradation and undermines livelihoods. Further, the associated impacts on the environment and conflicts between stakeholders is a critical precursor to the success for the Sandpiper Marine Phosphate Mining project as an example of developing the BE. Thus, calls attention to power imbalances that exist in the top down approach to BE management whereby the contributions of local stakeholders are rarely considered.

Balancing community needs, cultural preservation, and ecological function is a growing challenge in the quest for a successful BE for many states (Roberts and Ali, 2016; Keen et al., 2018). Though some efforts have been made to draw attention to the competing interests in exploring the economic potential of oceans, community needs are increasingly marginalized from decision-making processes (Bennett, 2018; Pauly, 2018). Therefore, addressing Africa's 'next frontier' for economic development must prioritize features of social equity and environmental sustainability. A successful BE framework presents a viable opportunity for many communities that rely on ocean resources as a source of livelihoods and food security but faces the risk of poor and disjointed governance efforts which underrate the importance of communities (Bennett et al., 2019; Roy, 2019).

Neglecting to consider community needs jeopardizes human, social, economic, and cultural security, and therefore undermines inclusivity and sustainable development as discussed in the aforementioned case studies. What the foregoing discussion suggests is that the increasing failure to acknowledge the role of local communities within the African BE debate leads to a stand-still in socio-economic development as evidenced in the examples presented above. We assert that the mainstreaming of the BE agenda with community needs requires a process that challenges the normative governance and economic mindset which isolates ecological sustainability and the needs of local resource users. Imbalances in power dynamics as exhibited in top-down management often leads to the marginalization of local communities in the decision-making process, which accelerates the potential for conflicts (Voyer et al., 2018b; Kadagi et al., 2020; Lee et al., 2020; Okafor-Yarwood, 2020).

The Niger Delta provides a prime case study that underscores the immediate and long-term implications of excluding the interests of local communities since oil exploration started in the 20th century (Obi and Rustad, 2011). The alliance between the government and multinational corporations has mostly focused on maximizing and protecting oil revenues while paying little attention to the under-representation of communities and environmental conservation in the Niger Delta (Maiangwa and Agbiboa, 2013; Okafor-Yarwood, 2018). This has fuelled a rise in militant groups who claim to represent the needs of communities, resulting in conflict between the oil multinational corporations and the state, as well as insecurity that has extended to neighboring countries (Onuoha, 2013; Obi, 2014; Ali, 2015; Oyewole et al., 2018; Okafor-Yarwood et al., 2020) threatening the economic development of the entire region.

The Niger Delta example highlights the implication of adopting a management framework that fails to consider the connection between the BE sectors and the SDGs. Primarily, the BE sectors contribute significantly to the SDGs: income (SDG 8) from the sale of fish (SDG 14) addresses food and nutrition security issues (SDGs 1 and 2), pays for health care and education

(SDGs 3 and 4), and reduces inequalities (SDG 10) (Un General Assembly, 2014; Okafor-Yarwood, 2019; Obura, 2020). The SDGs epitomize the United Nations pledge of "no human left behind," emphasizing the need to address imbalances in attaining the collective benefit to the economy, society, and environment (Un General Assembly, 2014; Okafor-Yarwood, 2019). The negative impact of the BE projects on local communities cast doubt on the ability of countries to attain the related SDGs by 2030. If the BE cannot offer real benefits to the local people, maintaining the monolithic approach to benefit sharing will increasingly prove difficult. Thus, the integration of local communities in the BE paradigm is required to address the short-comings and allow social inclusivity and engagement.

Undoubtedly, blue growth is underpinned on a resource base which is susceptible to human-driven changes such as increased pollution, alteration of coastal ecosystems and overfishing which limits the ability for ocean resources to contribute to the realization of the SDGs and the AU's Agenda 2063 of the "Africa we want." Yet, the discussions about issues of ocean development are mainly centered around economic motives with less consideration for the communities in the management or co-management of those resources. Success in the BE calls for the participation of coastal communities to ensure that social contracts are of mutual benefit to all stakeholders (Boutilier and Thomson, 2011; Bennett et al., 2018). Achieving success would require transparency in the management of BE and building the capacity of communities to leverage the field for multiple stakeholders.

In the remainder of this paper, we explore the successful community-based and government-led BE interventions which allow us to critically review and recommend possible frameworks for the management of BE projects in Africa.

Successful Blue Economy Examples

The first global conference on the sustainable BE was held in Kenya in 2018. The purpose of this conference was to contribute to a successful ocean economy. Its thematic session on an inclusive BE is of particular relevance as it presents a vision of what success may look like from the perspective of local communities (SBEC, 2018). Successful examples of BE in Africa tend to be people-centered and work to overcome the marginalization of women, youth, and indigenous communities. Successful examples also incorporate co-management models that enhance ownership, participation, and mutual benefits among stakeholders, build knowledge and technical capacity, accelerate financial empowerment, and use indigenous knowledge (SBEC, 2018). Using the FSS approach as a measure for success and authors' extensive experiences, we outline some well-documented projects that demonstrate key lessons for the success of BE in Africa.

TRY Oyster Women's Association, the Gambia

In the Gambia, the community of Karmalloh started the TRY Oyster Women's Association (TRY) in 2006, which eventually became an NGO linked to The Gambia-Senegal Sustainable Fisheries Project (Ba Nafaa) (Lau and Scales, 2016). In 2012, TRY became the first women's association in Sub-Saharan Africa to be granted exclusive use rights to a fishery under the Cockle and Oyster Fishery Co-Management Plan for the Tanbi Wetlands National Park, between the Gambian Department of Parks and Wildlife, the Department of Forestry, the National Environment Agency and the Department of Fisheries. TRY aimed to address the "connected challenges of unemployment and coastal degradation" (UNDP, 2013). It has led to reduced pressure on the mangrove environment and increased cooperation between groups of oyster harvesters and in turn has contributed to the reduction of tensions among local groups and integration of migrant communities (Lau and Scales, 2016). Success in this example was partially attributed to (i) building trust and confidence among stakeholders, (ii) consultation among women harvesters at local to national level, (iii) integrated programmes that delivered tangible short-term benefits while making progress toward achieving longer term goals, and (iv) adaptive management based on indigenous knowledge and other scientific approaches (UNEP., 2015).

Vezo Community Fishers, Madagascar

In 2004, the Vezo community of fishers, a small isolated and poor community in southwest Madagascar, created a locally managed BE initiative that addressed the need for a sustainable octopus fishery, given the general decline in catches (Langley, 2006). The establishment of locally managed marine areas (LMMAs) was supported by government policies which allowed local communities to use traditional laws and indigenous knowledge to govern temporarily through measures such as permanent closures which resulted in the recovery of octopus stocks (Cripps and Gardner, 2016). Blue Ventures, the Wildlife Conservation Society, World Wide Fund for Nature and the Madagascan Marine Research Institute provided necessary technical and material support to enable local management. Early involvement of seafood export companies, Copefrito and Murex, was also critical as they became the main buyers of octopus and paid a premium rate for stocks from temporary closures, thus supporting the value chain and sustainable management of the fishery. This example shows that fishers, private sector seafood companies, government and non-governmental agencies can work together to successfully manage natural resources, resulting in the sustainment of livelihoods, economy and biodiversity (Westerman and Benbow, 2013; UNEP., 2015; Cripps and Gardner, 2016).

Mikoko Pamoja, Kenya

Mikoko Pamoja (Mangroves together), based in Gazi Bay in Kenya, is the first mangrove Payment for Ecosystem Services (PES) project in the world which seeks to restore and conserve mangroves, degraded by years of legal and illegal cutting, through the sale of carbon credits. The community received technical support in restoration of the mangrove forests and also in carbon quantification through scientists from the Kenya Marine and Fisheries Research Institute (KMFRI) in Mombasa. The project is accredited by the Plan Vivo system and standards to trade in 3000t CO_2. Mangroves are referred to as Blue Forests and they have been documented to contain six times the carbon sequestration potential of terrestrial forests (Huxham et al., 2015;

Huff and Tonui, 2017). Mangrove forests also offer additional ecosystem support services such as the provision of nursery grounds for important fish species and coastal protection services (Huff and Tonui, 2017; Murungi, 2017; Das, 2020).

Under this project, about 117 hectares of natural and planted mangrove forests are under a co-management regime where communities safeguard the forests and its resources. The carbon credits produced by the project are sold on the international voluntary carbon market through a charity known as the Association for Coastal Ecosystem Services (ACES). The carbon verification is done through Plan Vivo. Benefits from the credits are used to support various community needs in the Gazi village (Huff and Tonui, 2017).

The Mikoko Pamoja blue carbon project is run by the community based Mikoko Pamoja Community Organisation in partnership with the KMFRI and in collaboration with Earthwatch[2]. Since its inception in 2014, this community-led initiative incorporates mangrove rehabilitation and PES to ensure co-management and benefits sharing. This project provides a successful example of cooperation between multiple stakeholders including the local communities, state agencies, and non-governmental organizations (Huff and Tonui, 2017; Murungi, 2017).

An important aspect of this endeavor is the fact that it provides financial benefits for conservation and the work is currently promoting the national dialogue for inclusion of blue carbon from mangroves in the Kenyan Nationally Determined Contributions (NDCs). According to the Africa Blue Economy Strategy, NDCs form an essential component of the BE (Au-Ibar, 2019) and projects such as these lend themselves to providing conservation benefits and securing critical areas of biodiversity even as the drive for large developments are promoted by African governments.

Seaweed Farming, Kenya

In 2001, seaweed farming started out as an experiment to determine site suitability for the growth of commercial seaweeds in Kenya (Wakibia et al., 2006). The aim of the work was to explore the potential of seaweeds as a possible means of improving the livelihoods of local villagers. The village of Kibuyuni, in the south coast of Kenya, was one of the study sites and seaweed farming has taken root in this community. Technical support was provided through the Kenya Marine and Fisheries Research Institute (KMFRI) under the World Bank-funded Kenya Coastal Development Project (KCDP) which improved the efficiency of seaweed farmers (Nyundo, 2017). Seaweed farming is linked to the provision of income generating and employment opportunities for the community. A better education for the children of farming families is also one of the benefits related to higher incomes (Personal observations by NIK and JU; Mirera et al., 2020; Odhiambo et al., 2020). In addition to economic gains, community members note that the development of seaweed farming has paralleled the conservation of mangrove forests through planting of hundreds of mangrove seedlings hence improving the health of fish stocks by providing refugia and breeding grounds (Personal observations by NIK and JU; Mirera et al., 2020; Odhiambo et al., 2020).

The farming is mostly undertaken by women and the process is moving toward commercialization with over 50 farmers participating in the project (van Wyk, 2015; Hurtado and Msuya, 2017; Walker, 2018; ODINAFRICA, 2020). The Kenyan Blue Economy Committee in 2019 provided support for value addition to produce branded juice, salads, soaps, and shampoos from this unique ocean product. One of the aims of such ventures is to promote value addition and enhance benefits to coastal livelihoods through establishment of processing plants (Wells et al., 2010; Msuya et al., 2014). The provision of production energy for such plants is a critical factor for upscaling village-level industries that seek to exploit the BE. The demand for energy is on the rise and this is shown by the electrification efforts in African nations (Au-Ibar, 2019). A large proportion of these nations depend on hydroelectric power, which is increasingly being impacted by climate variabilities leading to a renewed focus on sustainable blue energy in the form of wind, wave and tidal energy as well as algal biofuels (Elegbede et al., 2017).

This case study provides a template to accentuate the importance of involving local communities through capacity building and partnerships with government institutions such as KMFRI. The availability of training ensures that communities gain adequate skills relating to the production of better-quality seaweed. In reference to the FSS approach, the seaweed farming in Kenya shows that not only are communities internally motivated to diversify their livelihoods but they are also taking responsibility for environmental sustainability as evidenced by the conservation of mangroves.

Emerging Cooperative and Financial Support Initiatives

There are also examples of cooperative and financial support initiatives which aim to directly benefit small and micro enterprises run by local communities. Seychelles is a leader in BE development and has established funding streams for small businesses which are also aimed at individual citizens. The Seychelles Conservation and Climate Change Adaptation Trust (SeyCCAT) influences the way in which funds are distributed across Seychelles, through a competitive grant process aiming to "support the design and implementation of sustainable-use marine protected zones; empower the fisheries sector with robust knowledge and capacity to improve governance, sustainability, value, and market options; and nurture new business models to secure the sustainable development of Seychelles' fisheries"[3]. In the Mediterranean region (Tunisia, Egypt, Algeria, Morocco), The Switchers platform[4] started within the framework of the EU-funded SwitchMed programme (2012–2018) and was developed by the Regional Activity Centre for Sustainable Consumption and Production (SCP/RAC) which acts under the Mediterranean Action Plan, an organization that belongs to the United Nations Environment Programme. In 2019, Switchers became an independent initiative aiming to

[2]https://earthwatch.org

[3]https://seyccat.org

[4]https://www.theswitchers.eu

provide support services to individuals and small businesses in an effort to "contribute to sustainable and fair consumption and production models" of "green and circular businesses," and this led to the development of the Switchers Support Programme which provides a variety of services including support for business model development and for access to finance[4]. These examples show that support initiatives which are designed to become independently run by local communities tend to become successful. The success of these initiatives may depend on (i) their ability to deliver clear benefits for career development of individuals, particularly through blue entrepreneurship involving small and micro enterprises, (ii) their production practices, and (iii) their alignment with fair and environmentally sustainable consumption. However, as these initiatives progress, more information needs to be collected from a variety of sources, including from affected individuals and communities, in order to make adequate assessments.

FRAMEWORK APPROACH FOR A SUSTAINABLE BLUE ECONOMY

To achieve a successful BE, African states need to work on enhancing the political will to support the institutional capacities for economic growth and environmental responsibility while mutually reinforcing social inclusion. Given the contributions of marine resources, and the impact of depleting resources on livelihoods, integrating watershed management and collaborative networks would go a long way in reconciling coastal demands, protecting critical habitats and promoting the resilience of coastal residents.

The management of marine and coastal resources in the context of BE entails three approaches: the top-down, the bottom-up or the collaborative approach.

The terms "top-down" and "bottom-up" as used here imply formal authority and community resource users, respectively, while collaborative is the combination of the top-down and bottom-up approaches (Sievanen et al., 2011; Gaymer et al., 2014; Butler et al., 2015). These frameworks can potentially provide the basis for attaining the promise of a successful BE that is inclusive and accommodates ecological sustainability. In view of the FSS approach as the basis for a successful BE in the African continent, the ensuing sections explore the top-down, bottom-up and collaborative blue management frameworks to make a case for why current and future BE initiatives should consider approaches that meet the FSS criteria for success.

Top-Down Blue Management

Top-down blue management considers a vertical resource management approach that begins from the top, the governmental level, down to the community level. This is also known as a single-sided organizational structure used for conserving and managing environmental resources (Basco-Carrera et al., 2017). This kind of blue resources management leads to centralized planning and control by non-local communities, particularly the government, with little to no involvement of local resource users in the planning and implementation stages (Simane and Zaitchik, 2014). The one-sided power dynamics usually allows the enforcement of national and international policies and agreements without the presence of local communities as effective contributors to the decision-making process (Simane and Zaitchik, 2014).

Implemented correctly, the top-down management approach can be a useful tool for creating widespread and immediate changes, primarily because the government is central to instituting behavioral change through policy implementation and enforcement. The establishment of a larger open ocean marine protected area is a classic example of the top-down approach working as a standalone tool for achieving a broader marine conservation objective (Jones, 2012; Gaymer et al., 2014). While top-down blue management may have good intentions for local communities, there are similarities in the unsuccessful examples where there is an inherent failure to empower marginalized individuals and communities. Bridging the social gaps between stakeholders and the resources across different levels of governance is required as noted in the FFS evaluation (**Supplementary Table S1**) and our examples of unsuccessful BE initiatives in Africa. Three critical points on the setbacks of a top-down blue management require highlighting. First, high-level or central interests which are largely focused on economic gains and limited social and environmental responsibility may not align with the immediate needs of local communities (e.g., food, income, shelter, and education). Second, central governance may prioritize profit gains with minimal emphasis on the sustenance of the natural resources compared to local communities which constantly interact with their environment and embrace voluntary stewardship and conservation. Third, emphasis on central governance of blue resources is likely to encounter conflicts between resource users and multi-level stakeholders which often leads to a failure to improve livelihoods and worsening ecological sustainability as highlighted in examples of unsuccessful BE projects.

Bottom-Up Blue Management

In contrast, bottom-up blue management, as viewed by many, can be a viable alternative that allows local communities to be actively involved in the decision-making process and management of marine resources (Butler et al., 2015; Chen et al., 2020). The formalization of community involvement in environmental management is driven by past failings of "top-down" approaches which gave less attention to active community participation (Fraser et al., 2006; Gaymer et al., 2014).

As Chavis and Wandersman (1990) suggest, community-based approach to development is vital for "improving the quality of the physical environment, enhancing services, preventing crimes, and improving social conditions." Failure to engage the community can in turn undermine the overall quality of the environment and result in instability. This is true for the Niger Delta region where the failure to bring about social equity and ecological sustainability in the development of the hydrocarbon industry has driven select community members to illicit activities such as pipeline vandalization and kidnapping/armed robbery at sea undermining environmental sustainability and state security

(Okafor-Yarwood, 2018, 2020). It should be noted that the authors do not propose a bottom-up blue management as an alternative to the functions and role of the government. Instead, we posit that active engagement of communities is central to the sustainable use of ocean resources in line with previous studies that emphasize participation of communities in the development of long term, proactive and localized social innovations (Simane and Zaitchik, 2014; Mackenzie et al., 2019).

The bottom-up blue management approach can work as a standalone solution to conservation whereby adoption of policies can be influenced through behavioral change, in that individual actions can have a massive effect when embraced by a large number of people. Importantly, the participatory process whereby all stakeholders are equally involved in the policy development and implementation allows them to take ownership of the process (El Asmar et al., 2012). The TRY Oyster Women Associate initiative in The Gambia discussed in section 3.2.1, exemplifies the significance of the bottom-up approach to a successful BE, whereby social equity and ecological sustainability are achieved through community effort.

While the bottom-up approach is critical to achieving a successful BE, the top-down contributions from the state in the form of institutional contributions is equally important (Baker and Mehmood, 2013) especially in the African context. Two drawbacks may arise from a focus on bottom-up blue management. First, communities may fail to integrate the contributions of higher-level decision making which may limit diverse experiences, knowledge and expertise to improve the design, implementation and scaling-up of BE initiatives. Second, power constraints arising from a lack of centralized decision making in the bottom-up management can impede access to resources such as funding opportunities which may undermine the robustness and sustenance of BE initiatives. Given these complex interactions within top-down and bottom-up blue management systems, consideration should be given to the amalgamation of both approaches in the development of African's BE as will be discussed in the ensuing section.

Collaborative Blue Management

This framework entails the integration of the top-down and bottom-up approaches. It involves multi-level actors and stakeholders in the process of the BE development, from goal-setting to evaluation of the outcome, and in turn, bridges the gaps between top-down or bottom-up approaches (Schelhas et al., 2001; Butler et al., 2015; Keen et al., 2018). The collaborative approach can be time-consuming and expensive to implement (Bodin, 2017). In some cases, collaborative blue management can be challenged by limited assurance on the long-term engagement of multi-level stakeholders and divergence of interests which make it difficult to meet the common goal (Hind et al., 2010; Bodin, 2017). However, collaborative management provides a sense of belonging and ownership, eliminates mutual misunderstandings and creates transparency in resource sustainability practices (Vodden et al., 2005; Keen et al., 2018; Støttrup et al., 2019). These traits seem to be missing in the current discourse on BE as depicted in the various examples of unsuccessful BE.

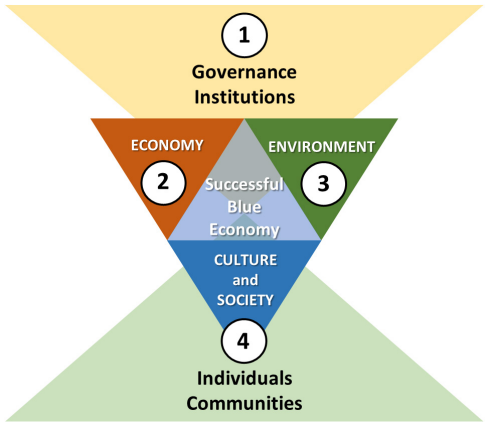

FIGURE 2 | Representation of the blue economy triangle (comprising culture and society, economy and environment); the top-down policy-driven and bottom-up community-led approaches needed for a successful blue economy; and the four key components of sustainability: (1) governance and institutions, (2) economy, (3) environment, and (4) culture and society.

In line with Wagner and Fernandez-Gimenez (2009); Bodin (2017) the authors agree that the collaborative approach does not lead to automatic success in the management of resources. Therefore, for BE initiatives to be deemed successful, they must achieve tangible outcomes and address ecological, economic, socio-cultural and institutional objectives as shown in **Table 1** and **Figure 2**. It follows that for the collaborative approach to be successful in the context of Africa's BE, then, it must give voice to the local communities and provide necessary education and capacity building which is critical for their participation. Additionally, factors such as the scale and impact of a particular blue project must be considered to allow managers and the relevant stakeholders to enforce regulations and monitor the progress.

Now more than ever, the devastating disruption of the Novel Coronavirus (COVID-19) on the socio-economic outlook of the BE sectors across the globe provides an excellent opportunity for coastal states in Africa to rebuild their BE as a source of economic recovery and resilience in case of future pandemics (UNCTAD, 2020). Re-imagining a BE for African states post-COVID-19 urgently calls for a renewed sense of awareness and recognition that achieving a successful BE in the African context requires inclusiveness and social equity considerations to deliver economic and environmental governance outcomes. In light of the potential for African states to realize recovery and resilience, we emphasize the use of the FSS evaluation in the current and future BE initiatives.

CONCLUSION

The paper has reviewed eight case studies of BE projects across the African continent. The findings from unsuccessful BE projects show that while the governments of the respective countries have the right intentions about developing their ocean

economies, emphasis is placed predominantly on economic outcomes, with limited attention given to social equity and ecological sustainability. Our evaluation of the successful community- and government-led case studies based on the FSS approach underscores the significance of multi-sectoral involvement in achieving ecological, economic, socio-cultural and institutional objectives.

Examining the performance of BE initiatives in Africa along with identifying applicable governance frameworks is critical to realizing the overall goal of current and future BE projects. We show that incorporating the top-down and bottom-up blue management approaches is central to strengthening economic development while considering social equity and ecological conservation. Recognizing the complexities in the collaborative management framework, we emphasize the need for capacity building and education to facilitate the involvement of local communities.

Our work contributes to the African BE discourse through the adoption of the FSS evaluation as a measure for the performance of BE initiatives. This provides a structure for African states, private and public institutions to assess the key indicators for ensuring the success of current and future BE initiatives. Our emphasis on the adoption of a collaborative blue management approach creates a recipe for multi-level engagement that has greater potential to spearhead a successful African BE. There is a lesson to be learned about the interconnectedness between African communities and nature based on the various case studies. Therefore, the future of BE in the continent lies on the ability of the governments to think beyond the economic gains and consider the needs of communities. The evidence of negative impacts of COVID-19 on blue economic sectors – declining tourism earnings, food and economic insecurity combined with a fall in commodity prices – presents a considerable challenge which demands re-imagining and re-building the BE post-pandemic (FAO, 2020; UNCTAD, 2020). Our discussion on the role of a collaborative blue management approach contributes to processes to rebuild communities and develop measures for the recovery and resilience of Africa BE post-coronavirus. COVID-19 has also taught us that nature is resilient and can recover in a very short time. Therefore, studies on the state of the environment post-COVID-19 are much needed to provide guidance on the recovery trajectories especially in areas with large scale BE developments projects.

Undoubtedly, further research is needed to understand the extent to which the FSS evaluation and collaborative blue management approach would work in other contexts. For coastal states in the African continent to benefit from BE as the "new frontier" for economic development, there is an urgent need for a functional institutional governance framework. This framework should ensure that all actors in the BE sector focus on achieving an equitable and sustainable BE in Africa, for Africans. Therefore, to truly embrace the BE and achieve the promise of sustainable development for the African people as enshrined in the Agenda 2063 of the African Union, the development of the BE must incorporate social equity and ecological conservation.

DATA AVAILABILITY STATEMENT

The datasets generated for this study will not be made publicly available: The article is based on the review of peer-reviewed articles and the gray literature, including personal observations, and experiences from the authors.

ETHICS STATEMENT

The Kribi Port (Cameroon) and Vridi Canal (Côte d'Ivoire) case studies involving human participants were reviewed and approved by the United Nations Office on Drugs and Crime (UNODC) Regional Office for West and Central Africa. Written informed consent to participate in this study was provided by the participants, their legal guardian/next of kin, or the relevant stakeholders.

AUTHOR CONTRIBUTIONS

IO-Y conceived the idea. NM, IO-Y, and NK contributed to the methodological framework. IO-Y and NK contributed equally to the writing of the manuscript. JU and IA contributed to the introduction and case studies. IA produced **Figure 1**. NM contributed to the case studies and produced **Figure 2** and **Supplementary Table S1**. IE contributed to the management framework section and formatted the references. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00586/full#supplementary-material

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Experiences With Governance in Three Marine Conservation Zoning Initiatives: Parameters for Assessment and Pathways Forward

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In this perspective paper, we examine the challenges of governance in three marine conservation settings where rights, access to resources and zoning intersect with changing social and ecological conditions: (1) Tsitsikamma Marine Protected Area in South Africa; (2) Marine Protected Area of the Northern Coast of São Paulo (APAMLN) in Brazil; and (3) Gwaii Haanas National Marine Conservation Area Reserve in Canada. Many MPAs and related zoning initiatives are located adjacent to coastal communities that rely on marine and coastal resources for their livelihoods. Thus, processes of zoning must often address local use of natural resources which can be perceived by decision-makers and regulators as problematic. Our analysis highlights how conservation zoning intersects with the perception of diverse stakeholders regarding a range of governance dimensions, including: (1) levels of participation and compliance; (2) the clarity of zoning and conservation objectives; (3) livelihood impacts and benefits; (4) evidence of ecological and conservation benefits; and (5) the influence on sense of place. Pathways forward to address the challenges of governance associated with zoning include the importance of co-producing knowledge for more robust zoning outcomes, and situating zoning processes in a co-management context in which power and authority are more evenly distributed.

Keywords: marine protected areas, zoning, governance, perceptions, rights

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PROBLEM CONTEXT AND CONCEPTUAL OVERVIEW

Globally, marine protected areas (MPAs) are an established strategy to conserve the biodiversity and habitats associated with oceans and coasts (Jones, 2014; Day et al., 2019). Such strategies are important as nations aim to meet the Aichi targets and those that will emerge in the post-2020 Global Biodiversity Framework (Visconti et al., 2019). There are a variety of MPA categories, most of which have different levels of regulation to define the rules for access and multiple use zones (see IUCN categories and their management objectives – Dudley, 2008). How we evaluate the effectiveness of these conservation initiatives and zoning strategies with reference to both social and ecological outcomes is an important challenge for all MPA categories (Berkes, 2010; Ban et al., 2013; Sowman and Sunde, 2018; Naidoo et al., 2019). Zoning is a spatial planning process for marine protected areas and conservation efforts generally, and observations about their efficacy

are crucial to long term success (Charles and Wilson, 2009). Here, we refer to zoning as the process of spatially delineating which actors and stakeholder groups have rights to access a marine area and its resources, guided by the normative goal of sustainability (Day et al., 2019).

We draw attention to issues of MPA governance literature and practice in several ways. Our analysis draws attention to issues of participation – who is involved and how, and the critical role of perceptions of those engaged in or affected by zoning initiatives (Mascia, 2004; Cinner et al., 2009; Pollnac and Seara, 2011; Di Ciommo and Schiavetti, 2012; Voyer et al., 2012; Bennett et al., 2020). We also discuss the implications of zoning for the individuals and/or communities that access or interact with valued ecological habitats (Villa et al., 2002; Gurney et al., 2016; McNeill et al., 2018). Understanding how different groups use and rely on an area for their livelihoods and cultural needs is particularly important in countries that have high levels of poverty, unemployment and food insecurity (Jones et al., 2017). The social impacts from creating an MPA, for example, that do not adequately consider adjacent community needs and rights, nor effectively engage them in the process of zone development, will further exacerbate situations in developing countries where limited capacity undermines governance processes and where there is a high level of dependence on natural resources (World Bank, 2017; McNeill et al., 2018). As a result, zoning interventions are often contested with regard to their socio-economic and ecological objectives (Bennett and Dearden, 2014; Voyer et al., 2014; Ban et al., 2019), with implications for the success of marine protected area networks and conservation outcomes.

Assessing the effectiveness of marine protected areas and conservation initiatives has a long history (Bennett and Dearden, 2014; Larrosa et al., 2016). For example, Pomeroy et al. (2005) developed a framework to evaluate MPAs that includes a range of socio-economic, biophysical and governance criteria. Similarly, Jones et al. (2013) focused on the role of institutional "incentives" as important evaluative criteria drawing attention to the economic, interpretative, legal, knowledge and participative dimensions of marine conservation. Bennett and Dearden (2014), in contrast, have emphasized the importance of governance attributes as a way to understand MPA effectiveness, such as enabling policies, setting clear targets and objectives, fostering participation and relationships, adequately addressing capacity for participation, and providing appropriate tenure and rights over resources and ecosystems. Further, Gill et al. (2017) and Scianna et al. (2019) have emphasized that effective and equitable management of MPAs requires adequate staff and budget capacity for compliance and ecological success.

We outline a general framework for our assessment of zoning interventions and governance challenges across our case study sites (**Table 1**). Specifically, this framework synthesizes key insights from the literature that are relevant for our cases, and that allow us to draw lessons from different social-economic and governance contexts, highlighting some key commonalities and insights that may inform other practices and experiences.

LEARNING FROM THE FIELD

We analyze three case studies that reflect different issues with governance, drawing attention to who is involved and how the respective zoning initiatives are implemented (see **Table 2**). These cases studies were chosen opportunistically and reflect our experience in different geographic settings. However, a key criteria in selecting the cases is the potential to show variation of opportunities and challenges across different governance regimes, zoning types, and policy and socio-economic settings. Further, our analysis draws on data that has been generated from a wide range of semi-structured interviews with key stakeholders (community, government, management authority, and non-government), focus groups and workshops with diverse stakeholders and reviews of relevant literature (see for example Muhl, 2016, 2019; Berdej et al., 2017; Dias and Armitage, in press). We draw in particular on perceptions of those directly involved in these cases, noting that the perceptions of zoning by local people affect their levels of support and the legitimacy of the conservation initiative. We address each of the cases in turn.

Marine Protected Area of the Northern Coast of São Paulo (APAMLN) – Brazil

The marine protected area from the northern coast of São Paulo State (APAMLN) in Brazil is a state-level MPA created in 2008

TABLE 1 | Framework for comparative assessment of zoning and governance outcomes.

Key parameter	Selected issues related to zoning
Participation, collaboration and compliance	• Level of or presence/absence of meaningful participation and engagement • Regulated as well as informal opportunities for participation and engagement • Clarity of roles of different stakeholders
Clarity of objectives	• Emphasis on social and economic as well as ecological objectives • Communication of objectives to stakeholders • Relationships among objectives and guiding principles for conservation • Synergy among objectives
Livelihood benefits	• Implications of zoning for stakeholders in terms of access and resources needed for livelihoods • Consideration of differential livelihood implications for different groups (e.g., Indigenous, non-Indigenous)
Ecological and conservation benefits	• Clear evidence of ecological benefits, outcomes from zoning (habitat, species protection) • Incorporation of ecological knowledge of diverse groups in clarifying conditions (e.g., increase, decrease in stocks)
Sense of place	• Implications of zoning on maintaining, disrupting place attachment • Recognition of identity of adjacent communities to spaces, places subject to zoning • Potential influence of zoning and regulatory requirements on place, culture and customary resource practices (e.g., sharing)

TABLE 2 | Overview of case study areas.

	Marine protected area of the northern coast of São Paulo (APAMLN)	**Gwaii Haanas**	**Tsitsikamma**
IUCN category	VI: Protected area with sustainable use of natural resources	V: Protected Landscape/Seascape	II: National Park
Size of area, location	Situated in the northern portion of the coast of São Paulo, Brazil with a total area of 3,160 km^2	Situated at the southern end of Haida Gwaii, an archipelago off the north pacific coast of Canada, with a total area of 5,000 km^2	Situated on the border of the Western and Eastern Cape Provinces in southern South Africa, with a total area of 186 km^2
Socio- economic features	Ubatuba, Caraguatatuba, Ilhabella and São Sebastião: 320,000 inhabitants with 300–1,500 additional inhabitants along the coast Local livelihoods based on small-scale fisheries and tourism.	Haida Gwaii: 4,320 inhabitants Gwaii Haanas is important for fishing, Haida traditional use, education and tourism.	Koukamma municipality: 40,663 inhabitants. Average household income is between USD1384 to USD2697 per month. Unemployment in the area is at 50%. Reliance on natural resources
Responsible authority and governance context	State government: Manager in-chief + management council (50% Civil society, 50% governmental organizations)	Archipelago Management Board (AMB) with equal representation from the Haida Nation and DFO and Parks Canada.	South African National Parks under the Department of Environment, Forestry and Fisheries (DEFF)
Information on zoning / Zoning types	Five zones: small-scale (e.g., fisheries coordinated with state and federal level regulations on seasonal closures and gear restriction), intensive and extensive use, a no-take area and geobiodiversity protection in which the extraction of natural resources is not allowed, but other uses are (e.g., maritime traffic, tourism).	Three sectors: Restricted, strict protection and multiple use. Haida traditional use permitted in all zones.	No-take (80%) with three coastal control zones (20%) restricted to registered community members only
Timeline/key events,	2010 – Participatory assessment to inform management plan. 2013 – Process begins to create MPA management plan 2016 – Process halts 2018 – Zoning of the MPA – ongoing with increasing participatory input.	1985 – Gwaii Haanas declared a Heritage Site by Haida Nation 2010 – Gwaii Haanas Marine Agreement signed and Marine Conservation Reserve established 2014 – Process begins to create the Land-Sea-People Management Plan 2018- The Gwaii Haanas Land-Sea-People plan implemented	1964 – Proclamation of the Tsitsikamma MPA 1976 – 1978 Fishing is reduced to a three kilometer zone 2000 – MPA is declared "no-take" 2007, 2015 – Attempts to rezone the park for controlled access for local fishers 2016 – The MPA is rezoned to have three controlled coastal zones for fishing with strict regulations.

that encompasses the marine area of the northern coastal portion of the state of São Paulo. The region is characterized by a jagged coastline, including estuaries and mangroves, hundreds of sandy beaches, rocky shores and more than 40 coastal islands with a total area of 3,160 km^2 (São Paulo, 2008). As a multiple use MPA (Brazil, 2000), it has a mandate to protect marine ecosystems and regulate human activities within the area. The rights of traditional peoples (i.e., the *Caiçaras*) to use natural resources and the territory is legally guaranteed. This MPA is divided into three marine and island sectors (Cunhambebe, Maembipe, and Alcatrazes), across four municipalities, making it challenging from a jurisdictional perspective.

Even though the MPA was created in 2008, it still lacks a management plan. The purpose of the MPA is to regulate economic (e.g., tourism, industrial fisheries, nautical infrastructure) and traditional activities (e.g., small-scale fisheries). A lack of financial resources and personnel, political instability and a history of conflict between environmental authorities and coastal communities has led to setbacks in implementation of the MPA. Additionally, reduced participation of coastal communities, and lack of clear goals and roles has further exacerbated issues with the management of the MPA. In 2010, a process was initiated to assess key stakeholders, local uses of the marine area and other relevant information to inform the management plan and zoning of the MPA. Currently, a draft of the zoning plan is being discussed with stakeholders and it includes five zones. The zones are categorized as: small-scale, intensive and extensive use, geobiodiversity protection and "no-take" areas. Despite increased efforts to engage the community in the zoning process, participation has been low overall (especially among youth), despite the relevance of the changes to future livelihoods.

A current lack of legitimacy and accountability with regards to the zoning process is linked to a participatory plan that is frequently interrupted, highly dependent on political will and, in many situations, lacks resources to proceed effectively (see also Seixas and Berkes, 2004). The MPA is currently developing the management plan and zoning process. However, as of 2018, this process gained an important ally, a local movement comprised of Indigenous people (Traditional Peoples Forum – from Ubatuba, Paraty, and Angra dos Reis). Additionally, participatory processes in the region are being mediated by researchers, calling for accountability of stakeholders (Seixas et al., 2017).

Gwaii Haanas – Canada

The Gwaii Haanas National Marine Conservation Area Reserve is situated at the southern end of Haida Gwaii, an archipelago off the north-pacific coast of Canada. Gwaii Haanas is 5000 square kilometers and is co-governed with reference to the Gwaii Haanas Gina Waadluxan KilGulGa (Talking about Everything) Land-Sea-People management plan (Council of the Haida Nation and Government of Canada, 2018).

The Gwaii Haanas area was originally designated in 1985 as a Haida heritage site by the Haida Nation. In 1987, the site was further designated a National Park by Canada and British Columbia through the South Moresby Memorandum of Understanding. The Gwaii Haanas Agreement was signed in 1993 and set the groundwork for co-management of the protected area through a partnership between the Haida Nation and the Government of Canada (Gwaii Haanas Agreement, 1993; Gwaii Haanas Marine Agreement, 2010).

The Gwaii Haanas National Marine Conservation Area Reserve is now co-governed through the Archipelago Management Board (AMB), which consists of three representatives from the Haida Nation and three representatives from the federal government (two from Parks Canada and one from the Department of Fisheries and Oceans Canada). The management plan was created in partnership and with support from a marine planning team from the Council of Haida Nation, Parks Canada and Fisheries and Oceans Canada technical staff, and involved extensive consultation over a 4 year period (Council of the Haida Nation and Government of Canada, 2018).

Gwaii Haanas is divided into multiple zones with different levels of protection. There are four terrestrial and three marine zones to protect ecological and cultural areas of importance while ensuring sustainable livelihoods. The three marine zones are designated as restricted access, strict protection and multiple use. Forty percent of the marine reserve is "strict protection" and "restricted access." "Restricted access" only allows for conditional research. "Strict protection" prohibits extractive activates, although boat access and anchoring for educational, tourism and recreational activities is permitted. The remainder of the marine zone is "multiple use" and allows for specific marine activities. Haida traditional use is permitted in all terrestrial and marine zones, consistent with the Constitution of the Haida Nation and section 35 of the Constitution Act (Canadian Constitution Act, 1982; Haida Nation Constitution, 2014). Gwaii Haanas is considered an important area for fishing, Haida traditional use, education and tourism, with an average of 2500–3000 people visiting per year (Council of the Haida Nation and Government of Canada, 2018).

From a governance perspective, the context for the Gwaii Haanas National Park Reserve is unique, and potentially well-suited to deal with the complexity in the system. Specifically, the AMB sets the direction for how the Gwaii Haanas Management Plan will be applied to help manage the area from the mountain peaks to the seabed (including fisheries i.e., herring) as an interconnected ecosystem. Decisions are made on a consensus basis and are binding with the Haida Nation and the Crown having shared decision making power. The strength of the co-governance body can be seen in the joint Haida Nation-federal announcements, for example, to prohibit all "bottom contact" fishing in the marine reserve. Although challenges still exist, the management plan has set a positive and strong foundation for the future conservation of the area (Jones et al., 2017).

Tsitsikamma – South Africa

The Tsitsikamma National Park MPA stretches for 60 kilometers along the Western Indian Ocean. It has a rugged coastline with steep cliffs and sandy beaches. The Tsitsikamma MPA is managed by South African National Parks (SANParks), the conservation management authority, which is overseen by the Department of Environment, Forestry and Fisheries (DEFF).

The Tsitsikamma MPA was created in 1964 and is the oldest MPA in South Africa. In South Africa, MPAs created prior to 1994 under the Apartheid regime disregarded local communities' rights to the coast and in some cases removed or restricted access, with no consultation. Therefore the MPA has been disputed since its creation. The Tsitsikamma MPA was proclaimed a strict "no-take" zone from 2000 following the collapse of some South African line fishery stocks (Chadwick et al., 2014). However, the adjacent communities perceived the area as being closed from 1978 when most of the coastal area was zoned as closed for fishing and physical access, except for a small section of three kilometers, and with the rest of the park zoned as "no-take" (Muhl, 2016). Rezoning was attempted in 2007 and 2015, but was not successful because of ongoing stakeholder disputes.

In December 2016 the Tsitsikamma MPA was rezoned from a "no-take" MPA to a partially open protected area with the aim of finally addressing historical exclusion and to provide managed access and benefits to adjacent communities. The rezoning allows for managed access for recreational fishing only by local community members and only in three designated coastal control zones (20% of the park) on specific days (four times a month) and according to a set of regulations (i.e., only certain species allowed to be caught, with set quotas) (DEAT Protected Areas Act No. 57 of 2003 Regulation 2016:40511). The remainder of the park (80%) is a "no-take" MPA, with strict fines in place. To fish in the coastal control zones, community members must live in or adjacent to the MPA and register as anglers. They are required to have a standard recreational fishing permit and need to register as a Tsitsikamma community angler at the conservation management authority office (Protected Areas Act No. 57 of 2003 Regulation 2016:40511).

From a governance perspective the 2016 MPA rezoning process has been challenged because of the speed in which it took place and the lack of consultation. Marine and social scientists who had historically been involved in extensive research in the area, NGO representatives and vulnerable community members who had historic ties to the coast were not consulted and do not deem the open areas appropriate for fishing access. Additionally, the conservation management authority under instruction from the then Department of Environmental Affairs (now DEFF) had only 5 days to legally implement the rezoning initiative. As a result, the participation processes about the rezoning only engaged the leadership of the Tsitsikamma Angling Forum (TAF), a sub-set of anglers that is not representative of all subsistence

angling interests. This lack of participation among diverse stakeholders has led to a range of issues and ongoing conflicts.

ZONING, PERCEPTIONS AND THE CHALLENGE OF MARINE GOVERNANCE

In the sections below, we assess how the zoning initiatives in these cases intersect with insights about their effectiveness and impact. We focus in particular on perceptions about zoning, and draw specific attention to issues of collaboration and participation, clarity of objectives associated with zoning, livelihood implications, local understanding surrounding conservation and ecological benefits, and the relationship among zoning changes and sense of place (**Table 1**).

Participation, Collaboration and Compliance

The manner in which coastal actors (e.g., fishers, tourism operators) participate in zoning processes, and their expectations about levels of engagement or collaboration, have a significant influence on their views of zoning impacts and effectiveness (see also Cvitanovic et al., 2014; Dehens and Fanning, 2018). Here we define engagement and collaboration as the participatory processes through which trust is developed among coastal actors and in ways that promote knowledge sharing for collective action. Collaboration and effective engagement requires participants who have knowledge of the marine space and who can contribute meaningfully to a zoning process that can address socio-economic and conservation goals (Voyer and Gladstone, 2017). In the context of MPAs and allied zoning initiatives, meaningful participation ultimately fosters equal power among stakeholders groups to ensure fairness and legitimacy (Bennett and Dearden, 2014).

In the APAMLN, for example, managers are attempting to engage fishing communities (including Indigenous fishing communities) that use the area to establish the zoning process. A key obstacle to effective participation, however, has been the inappropriate use of communication tools. For instance, MPA staff prepared a pilot zoning plan to receive input from fishers, but they made this plan only available via the host MPA website. This is an inappropriate context as many community members do not have internet access. The process of participation has faced other setbacks too, such as misunderstandings regarding which laws apply in the territory (such as national and state regulations) and what is regulated by the MPA (e.g., special zones for biodiversity conservation). Moreover, the MPA is governed by a manager in chief and a management council consisting of community representatives. However, the participation of the council is unclear. Specifically, it is not clear if the council participates in decision making, or whether it participates in a primarily consultative role only. In the zoning process, this uncertainty manifests in a lack of understanding about how much the input from fishers and other community actors will be considered after the consultation phase.

In the Tsitsikamma case, participation and consultation did not occur among stakeholder groups despite the importance of the decisions being made about zoning and access for adjacent communities. In fact, the exclusion of certain groups (e.g., community representatives from all villages) led to the rezoning being perceived by many as illegitimate, further compounding enforcement and compliance challenges. The complex history of the Tsitsikamma MPA (**Table 2**) and the creation of the MPA has meant that there is still "poaching" that occurs in the park as the rezoning has not been perceived as effective in addressing their livelihood needs. As is the case of many MPAs, Tsitsikamma included, compliance is difficult to assess as it has an element of subjectivity that requires critical reflection. For example, local fishers perceive themselves as rightly having customary access to the area while park authorities view local fishers as disregarding the law (and therefore poachers).

In the Gwaii Haanas case, the extended consultation period, collaboration across partners and equal power sharing among the Haida Nation and the Crown (i.e., federal government) within the AMB has led to a zoning arrangement that is generally accepted, enforced and regarded as legitimate. Of particular note, there were many commercial fishing interests that were effectively engaged in the zoning process despite the potential costs associated with reduced access to fisheries and other marine resources.

Clarity of Objectives

One of the critical challenges confronting marine conservation initiatives involves the effort to balance multiple objectives – social, economic and ecological (Pomeroy et al., 2005; Jones, 2014). Most marine conservation efforts are initiated as an effort to meet ecological objectives (e.g., habitat protection, species protection), and yet there is often significant uncertainty among adjacent communities as to why those objectives are prioritized and how they might coexist with material needs and cultural objectives. For example, in Tsitsikamma, the objectives of the zoning process have long been a source of confusion, with limited information given to coastal communities and even fewer opportunities for communication and meaningful engagement with decision makers as noted above. As a result, local people do not understand or accept the conservation objectives of the zoning intervention, and perceive the managing authority as failing to account for their own needs (cultural, social, and economic).

This situation in the Tsitsikamma case stands in sharp contrast to Gwaii Haanas, where a set of guiding principles situated in Haida culture were used in conjunction with ecosystem-based management principles to inform the zoning consultation initiative. Specifically, these principles were used to guide goals, objectives and indicators for innovative use across both scientific and local knowledge practices to promote legitimacy. In the APAMLN, the experiences were more mixed. This MPA established five zones to define the activities permitted (see **Table 2**), and six "areas of interest," in which management programs for specific purposes (e.g., conservation, sustainable tourism) should be implemented. These zones and areas of interest are well described in the official documents; however, the rationale behind this arrangement has not been effectively discussed with those affected by them. Moreover, when

establishing the zoning objectives for the MPA, state and federal laws that apply to fishing are still in place (e.g., seasonal closures of shrimp and mullet fishing, the banning of certain fishing gear). These overlapping regulatory arrangements reflect competing objectives and can enhance confusion as to what rules may be modified, and how they relate to different fisheries.

Livelihood Benefits

Zoning processes inevitably affect the livelihoods of individuals and communities, primarily in terms of access to resources (Sowman, 2015). How people experience these impacts has significant implications for the perceived legitimacy of zoning efforts in marine conservation initiatives. In Gwaii Haanas, for example, the zoning process is embedded in a broader effort to maintain traditional access to marine resources and in a manner that is consistent with the Constitution of the Haida Nation, and section 35 of the Constitution Act. As a result, the outcomes of the zoning process are generally viewed as positive and supportive of longer-term efforts to maintain the cultural connection Haida peoples have with the sea. The zoning process in the APAMLN is less clear in terms of the implications for livelihoods, as other laws and regulations also apply in the territory and may restrict access of small-scale fishers. Despite the fact that the APAMLN permits sustainable use, many fishers observe the zoning process as restricting their access to key fishing grounds. On the other hand, some community members, usually those more engaged in the MPA meetings, recognize opportunities to collaborate and to demonstrate their needs (e.g., in terms of gear or access to specific habitats). Arguably the most challenging situation emerges in the context of Tsitsikamma, where the implications of the loss of direct access to the coast for adjacent communities has been profound (Faasen and Watts, 2007). Many community members report a significant loss of livelihoods and an impact in food security (Muhl, 2016) which more recent rezoning efforts have failed to address (Muhl, 2019).

Ecological and Conservation Benefits

Marine conservation initiatives are typically aimed at protecting critical habitat, species of significant ecological value and/or representative ecosystems (Jones, 2014). Secondary ecological and conservation benefits may also include the preservation of contexts for scientific research. However, the extent to which these ecological and conservation benefits are achieved has much to do with the location and design of zoning efforts (Gurney et al., 2016). Perceptions of these zoning efforts and their ultimate ecological outcomes is therefore a critical dimension of governance effectiveness. For instance, the Tsitsikamma zoning process failed to incorporate the knowledge of local fishers about the status of stocks or levels of fishing effort, thus undermining the opportunity to clarify the conservation benefits behind the original zoning initiative. This failure to clarify the ecological and conservation benefits (given the livelihood impacts generated) was a fundamental reason why the rezoning was seen as unsuccessful, and it exacerbated feelings of mistrust of the managing authorities among local communities. In contrast, the process in Gwaii Haanas management has been more proactive in articulating the conservation and ecological benefits of zoning. Specifically, the zoning process has deliberately integrated conventional scientific understanding of ecological values with insights and local knowledge from the Haida people. This has led to zoning outcomes that reflect shared perspectives of what is ecologically valuable and of conservation importance, while respecting the cultural imperative of the Haida to harvest marine resources.

Sense of Place

How individuals and communities are impacted by marine conservation initiatives that are connected to places and spaces of importance will have significant implications for marine

TABLE 3 | Summary of key lessons learned.

Key dimension	Key lessons
Participation, collaboration and compliance	• MPAs need to reflect the priorities of Indigenous and traditional communities, in addition to conservation objectives (i.e., zoning processes) • Levels of participation not necessarily aligned with good decision-making outcomes unless core social and economic outcomes are considered • Collaboration and negotiated decision-making across stakeholder groups (including youth) will enhance legitimacy and thus lead to improved governance outcomes
Clarity of objectives	• Public policy (e.g., overlapping protected area regulations) can confuse how people view the objectives of the protected area zoning • Involving groups who will be affected by policy changes in negotiating, defining and implementing objectives will lead to increased understanding surrounding MPA zoning
Livelihood benefits	• MPA implications for local livelihoods need to be meaningfully considered by authorities, given the future implications of livelihood change among different stakeholder groups (e.g., youth) • Collaboration round tables that enable communities and conservation authorities provide a basis to clarify and negotiate livelihood needs (e.g., in terms of gear or access to specific habitat zones)
Ecological and conservation benefits	• Conservation benefits are undermined if they fail to address the underlying socio-economic factors or provide alternate livelihood benefits in accordance with local norms • Location and design of zoning efforts need to be cognisant and address conservation objectives associated with the original zoning initiative
Sense of place	• Place attachment is an important (but often overlooked) driver of perceptions different stakeholders may have about zoning processes • Engaging fishers in community science (such as in monitoring critical places and spaces) and fostering Indigenous-led research can allow for shared recognition of conservation interventions and highlight connections to place engagement • Enhancing and including local knowledge, and fostering local participation in tourism and resource management practices, can improve local sense of place and zoning outcomes

conservation outcomes (Larson et al., 2013). In particular, the influence of zoning on place attachment – the emotional bonds formed between an individual and a geographic context – can influence how people discern the effectiveness of marine conservation efforts and their willingness to collaborate in governance processes. Both in Brazil and in South Africa there is a strong sensitivity within the community that their identity is tied to the sea, and that the subsequent loss of access to the sea is akin to undermining their history as "people of the sea." For instance, in Brazil, the *Caiçara* people are a traditional group that inhabits the south and southeast coast of Brazil. Their traditional livelihoods are based on small-scale fisheries, small-scale agriculture and hunting (Diegues et al., 2000). *Caiçara* people also possess a strong sharing culture as expressed through their collaborative fishing practices and a strong attachment to the territory (Hanazaki et al., 1996). Yet, environmental regulations and restrictions in the use of resources in traditional territories are an issue in Brazil and has affected the zoning process in the APAMLN. This situation compounds the opinion of communities that traditional rights and place attachment were already undermined by the initial establishment of the MPA.

In South Africa, many community members have voiced a sense of loss of their identity and culture. The rise in crime rates and increased prevalence of substance abuse has also been attributed to the loss of access to the coastline as a result of the zoning process (Faasen, 2006; Williams, 2013; Muhl, 2016). In Gwaii Haanas, the management plan has been designed to maintain and foster a place connection between the Haida to their cultural and ecological heritage. Specifically, the management plan maintains access and allows for traditional use while ensuring long-term sustainable conservation for future generations.

LESSONS LEARNED AND PATHWAYS FORWARD

The expansion of marine protected areas (MPAs) and the zoning approaches associated with them generate diverse governance challenges. In this paper, we have analyzed the experiences with zoning in three unique case studies. From these different contexts, we have highlighted several commonalities and revealed pathways forward that may inform other practices and experiences in different contexts (**Table 3**). These lessons and pathways illustrate the influence of the socio-economic and policy contexts on perceptions about zoning, and ultimately, governance outcomes in MPAs.

As the lessons from these cases reveal, efforts to improve perceptions and long-term effectiveness of zoning will benefit from knowledge "co-production" and a participatory co-management approach. First, a co-production process can be an effective mechanism to identify plausible and feasible zones, particularly in places where there may be more significant contestation. Such "co-produced zones" will have common agreements on achievements, and help to clarify what is being accomplished and how it is measured. However, we need to be cognisant of capacity issues and allocate appropriate time frames when "co-producing zones." In this regard, community science (i.e., increased collaboration and participation in research and monitoring – see Charles et al., 2016) can help to support co-production processes, especially where Indigenous groups and their knowledge can have a central role in zoning efforts (e.g., as in the example of *Caiçara* people in the Brazil case). Of note, engaging youth and addressing their perspectives on future livelihood opportunities provides an important pathway to move forward with regard to knowledge co-production and community science.

Second, a process to co-produce zoning arrangements will likely only work when power is effectively shared, as in the case of the AMB in Gwaii Haanas. Recommendations for improved co-management of MPAs are not novel, yet there remains a reticence to make the necessary shifts. Ceding decision making control in a way that equitably distributes power is an important precondition to improve zoning and is the basis for a transparent and collaborative process. As the case of the APAMLN shows, the lack of trust in decision-making criteria in upper governance levels, and lack of clarity on whether the management council has a consultative or deliberative role, causes mistrust and undermines collaboration with communities. Communities perceive and experience the lack of power in decision making (with consequences for their traditional territory or livelihoods), and this has negative long-term implications with regards to zoning initiatives.

CONCLUSION

The expansion of MPAs and other conservation measures in response to the post-2020 biodiversity conservation framework will generate diverse governance challenges. Examining the zoning processes associated with conservation and protection efforts is crucial as they influence the access and rights of communities adjacent to marine resources. We have highlighted in this perspective piece a suite of governance parameters around which stakeholders may perceive an array of challenges and opportunities with zoning, including levels of participation, clarity of objectives, impacts and benefits (ecological, livelihood) and sense of place. Moving forward, strategies to address these perceptions will require greater attention to processes of knowledge co-production and power-sharing to better ensure positive social and ecological outcomes.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article are protected for confidentiality purposes as per ethics agreements. Requests to access the datasets should be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Faculty of Science Research Ethics Committee,

University of Cape Town and Office of Research Ethics, University of Waterloo. The participants provided their informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

E-KM coordinated this effort and contributed information for two of the three case studies. AE contributed information for one of the three case studies. DA edited and provided a high-level overview of the manuscript and critical guidance. All authors provided input, edited and contributed with text.

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An Interdisciplinary Approach for Valuing Changes After Ecological Restoration in Marine Cultural Ecosystem Services

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Ecological restoration in marine ecosystems is considered strategic to recover environmental conditions and ecosystem services. However, the traditional single-discipline perspectives followed for analyzing the results of both restoration projects (focused in the analysis of biophysical changes) and valuation of ecosystem services (focused in economic valuation), do not provide useful theoretical frameworks when working with cultural ecosystem services, where socio-economic and environmental components are complexly interrelated. We propose an interdisciplinary approach for analyzing changes in cultural ecosystem services in restored marine ecosystems, based on the DAPSI(W)R(M) framework and following a social-ecological system approach. Our methodology considers environmental, social and economic elements that may be contributing to changes in the provision and demand for cultural ecosystem services in restored ecosystems. Our approach was tested in the Nerbioi estuary, a system that, after the implementation of a wastewater treatment plant at the end of the 20th Century, changed from being one of the most polluted estuaries in Europe to a nearly recovered system. Based on previous studies that have analyzed partial components of the restoration process and of the recreational ecosystem services, here we provide an interdisciplinary picture of the changes occurred in the last 25 years, directly linking the management measures adopted to an increase in human well-being. In the applied methodology, the three discipline domains (social, economic, and environmental) transcend each other to provide a new holistic view, completely different from what one would expect from the addition of the parts. In conclusion, this interdisciplinary approach provides a systematic framework for studying changes in cultural ecosystem services in restored systems, with a practical application for valuing human benefits as outcomes of marine restoration projects.

Keywords: ecological restoration, cultural ecosystem services, multiple values, social-ecological systems, marine blue spaces, integrated valuation

INTRODUCTION

Marine and coastal systems, through ecosystem services, provide many benefits to humans, contributing to our well-being (Barbier, 2017) and health (Borja et al., 2020). However, the overexploitation of resources and unsustainable environmental practices are generating the loss of biodiversity and degradation of ecosystems, which compromises the capacity of the natural systems to provide ecosystem services (Carpenter et al., 2006, 2009; Díaz et al., 2006; Outeiro et al., 2017). While the demand for ecosystem services continues to increase (Liu et al., 2010), their current global loss threatens human well-being.

Ecological restoration emerged as the most promising solution to recover natural assets and ecosystem services in human-degraded ecosystems (Elliott et al., 2007; Benayas et al., 2009), being an international priority for the coming decade, promoted by United Nations under the 'Decade on Ecosystems Restoration' (Cooke et al., 2019; Waltham et al., 2020). Ecological restoration encompasses *"all the activities which seek to upgrade and improve the damaged area, recreate what had been destroyed, recover its use and restore its biological potential"* (Bradshaw, 2002). Restoration of natural assets is recognized to improve biodiversity and contribute to achieving the good ecological status (Bullock et al., 2011; Everard, 2012). Also, it can be a first step to reverse declining trends in ecosystem services (Gómez-Baggethun et al., 2019). In the marine realm, where interactions between ecosystem and society are strong (Abelson et al., 2016), positive changes in ecological status after restoration actions could lead to an increase of provision of ecosystem services.

Despite the generally accepted idea of the possibility of recovering marine ecosystem services through ecological restoration, the few practical examples lead to important gaps between theoretical knowledge and practical verification (Abelson et al., 2016). Indeed, most studies for valuing the consequences of restoration projects analyze the changes in biophysical variables, but little attention is paid to the cascading changes in ecosystem services.

The consideration of the relationship between ecological restoration and marine ecosystem services in policies and management decisions is also scarce. In European legislation, ecological restoration is included in the two main Directives for the protection of aquatic biodiversity and environments: the Water Framework Directive (WFD; 2000/60/EC) and the Marine Strategy Framework Directive (MSFD; 2008/56/EC) (Borja et al., 2010b). Ecological restoration is considered as one of the ways to achieve the objectives of both directives: The objective of the WFD is *"to achieve good ecological status for all water bodies by 2015* (now, 2021) *and avoid deterioration, supporting the adoption of protection and restoration measures on aquatic ecosystems*"; for the MSFD, the main objective is *"to establish a framework to achieve or maintain good environmental status in the marine environment by 2020."* Regarding marine ecosystem services, these are only mentioned in the MSFD, under the term "goods and services," but with no clear objectives associated to those.

The little consideration of ecosystem services in these policies and, consequently, in management decisions, is related to little comprehension of the interactions between biophysical and social elements that are required to provide ecosystem services (Carpenter et al., 2009; Costanza et al., 2017). Consequently, the critical role of marine ecosystem services for human well-being remains out of the spotlight, leaving them without clear protection measures and their true value remaining outside important economic decision-making processes (Millennium Ecosystem Assessment, 2005; Carpenter et al., 2009; Liu et al., 2010). From the three types of ecosystem services (i.e., provision, regulation-maintenance and cultural) considered by the Common international Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018), changes are relatively easily tracked for provisioning and regulating-maintaining services. However, the analysis of change in cultural services is more complex. As cultural services are the "non-material outputs of ecosystems that affect physical and mental states of people", analyzing changes also from a social perspective (e.g., user's behavior, perceptions, etc.) is mandatory (see Borja et al., 2020).

In this study, we study the consequences of ecological restoration projects in marine cultural ecosystem services. From a social-ecological system approach (Ostrom, 2007, 2009), we propose a way to perform an integrated valuation of marine cultural ecosystem services in restored areas, including environmental, social and economic factors in an interdisciplinary perspective.

VALUATION OF ECOSYSTEM SERVICES AFTER RESTORATION: FROM SINGLE-DISCIPLINE STUDIES TO MULTIDISCIPLINARY STUDIES

Ecological restoration success can be evaluated through changes in the provision of ecosystem services (Bullock et al., 2011; Borja et al., 2015). Furthermore, some authors consider ecosystem services valuation as a crucial step to evaluate the success of the investments done in restoration (Carpenter et al., 2009; De Groot et al., 2013).

Traditionally, valuations of ecological restoration and ecosystem services have been done following single-discipline perspectives. Ecological restoration success has been studied mainly through the analysis of changes in biophysical conditions (Martin and Lyons, 2018), while valuation of ecosystem services has been done focusing on monetary values (Gómez-Baggethun et al., 2010, 2014; Jacobs et al., 2017). Adopting the traditional single-discipline perspective to study the consequences of restoration in ecosystem services provides a partial and incomplete picture of the reality. Firstly, because restored ecosystems are part of complex systems, where strong interactions occur between nature and society (Abelson et al., 2016). Secondly, because valuation of ecosystem services should consider their multiple values domains (i.e., environmental, social and economic) (De Groot et al., 2002; Wang et al., 2013).

In recent years, scientists have advocated for applying social-ecological system concepts to ecological restoration and ecosystem services studies (Hobbs et al., 2011; Nassl and Löffler, 2015). The social-ecological system approach allows the establishment of linkages between people and nature, with emphasis on the idea that humans are part of nature (Berkes and Folke, 1998). This approach is especially relevant when the sociocultural part of the services (e.g., the cognitive processes involved such as emotions, perceptions, experience, local knowledge) has to be analyzed (Palomo et al., 2016).

Also, it is increasingly accepted that an integrated valuation approach is the most appropriate when working with ecosystem services (Gómez-Baggethun et al., 2014; Bark et al., 2016). The multiple and diverse elements involved, as well as the complex relationships between them, require the integration of multiple disciplines to study environmental, social and economic aspects of ecosystem services, consistently with the nature of the problems being analyzed (Liu et al., 2010; Costanza et al., 2017). This approach contemplates the multidimensional identity of ecosystem services (Martín-López et al., 2014) and advocates for a valuation perspective that combines the three ecosystem services valuation domains (i.e., environmental, social and economic domains) (Gómez-Baggethun et al., 2014) to support decision-making processes (Jacobs et al., 2016). It provides a more accurate valuation of ecosystem services than single-discipline approaches, and therefore, contributes to secure the sustainability of complex social-ecological systems in the long term.

Consequently, an integrated valuation of restoration should incorporate values of the three domains of ecosystem services (Martin and Lyons, 2018). Despite this clear prerequisite, there are still few examples of studies that followed a multidisciplinary approach to value the multiple domains of marine ecosystem services (Garcia Rodrigues et al., 2017) and even less studies focusing on valuation of changes in ecosystem services after restoration. In February 2020, a search in Web of Science (WoS) identified a total of 185 articles published in the period 1997-2019 with the searching terms TS = ("integra* valu*") AND TS = ("ecosystem service*"). The first article was published in 2002. When the "marine" term was added to the search [AND TS = (marine OR coast* OR sea)], the results were reduced to 21, being the first article published in 2013. The combination of restoration with integral valuation of ecosystem services resulted in a total of 22 articles TS = ("integra* valu*") AND TS = ("ecosystem service*") AND TS = (restoration). The introduction of the marine term [AND TS = (marine OR coast* OR sea)], reduced the results to 2. This shows that there is a clear delay in research in marine ecosystem services compared to terrestrial ecosystems, and even more when it comes to research in recovery of marine ecosystem services in restored ecosystems.

The knowledge gaps regarding the relationships and interactions of the multiple elements involved in the provision of ecosystem services, and the few practical examples that could help to fill those gaps, make research in ecological restoration and valuation of ecosystem services a priority for marine research. The interdisciplinary study of ecosystem services in restored marine ecosystems, which considers their three valuing domains, should be incorporated in the existing narrative (including legislation) of marine management.

ANALYSIS OF MARINE CULTURAL ECOSYSTEM SERVICES: COMBINING THE SOCIAL-ECOLOGICAL SYSTEM APPROACH WITH THE DAPSI(W)R(M) FRAMEWORK IN AN INTERDISCIPLINARY PERSPECTIVE

Any management measure in the complex marine environment needs to consider the interactions between ecosystem components and users, analyzing the key biophysical and socioeconomic aspects involved in it.

The DAPSI(W)R(M) framework, presented by Elliott et al. (2017), is a problem structuring framework, used in marine management to study, in an holistic way, the causes, consequences and responses to change. The DAPSI(W)R(M) framework comes from the development of the DPSIR (Drivers-Pressures-State-Impact-Response) framework, which has frequently been used to explain the degradation and posterior ecological restoration processes on marine ecosystems (OECD, 1993; Patrício et al., 2016a).

The DAPSI(W)R(M) framework is explained in detail in Elliott et al. (2017). In short, it considers that basic human needs (Drivers - D) are achieved through human activities (A). These human interventions create pressures (P) that lead to environmental alterations in the system (State changes - S). State changes can have an impact (I) on the environment (e.g., biodiversity) and societal welfare (W) (e.g., human benefits obtained through ecosystem services). In order to address the pressures, state changes and/or impacts created from a certain human activity, the society needs to adopt management measures [Response using Measures – R(M)]. Successful measures would prevent state changes and impacts on welfare and could also have a positive effect on other marine-based activities. The DAPSI(W)R(M) framework could represent a single activity, but as maritime activities are interconnected (e.g., the pressure generated by one activity could negatively affect other activity); the relations between the different activities can be represented by nesting several DAPSI(W)R(M) frameworks between them (Atkins et al., 2011; Elliott et al., 2017).

The evolution of DPSIR into DAPSI(W)R(M) allowed the incorporation of the ecosystem services concept to the framework, as Welfare matches with the human benefits obtained from ecosystem services. For highlighting how marine systems are social-ecological systems, the DAPSI(W)R(M) can be represented inside two main spheres: the environmental and socioeconomic spheres (see **Figure 1**). This representation helps to explain how impact (as degradation or as restoration processes) can have consequences for human well-being (in the form of ecosystem services).

Hence, here the perspectives of the three domains (environmental, social and economic) transcend each other

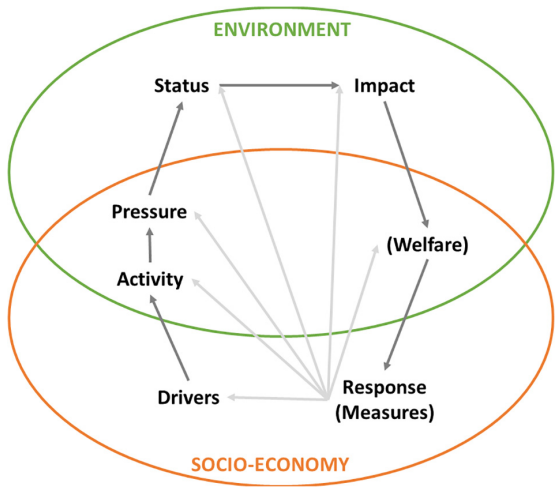

FIGURE 1 | DAPSI(W)R(M) framework inside environment and socio-economy spheres. "Activity," "Pressure," and "Welfare" are part of both socio-economy and environment spheres, as complex links between environmental and social elements are needed to carry out activities, and to obtain welfare (understood as human well-being); furthermore, activities generate pressures that are placed on the ecosystems. The environmental sphere contains "Status" and "Impacts," as both allude to environmental elements. The socio-economy sphere contains the "Drivers" and "Response (Measures). "Response" in the form of management "Measures" can be adopted to change or remove "Drivers," "Activities," "Pressures," "Status," "Impacts," and/or "Welfare" (these links are represented in light gray to indicate that they are optional, as not all of them have to happen together).

to form a new integrated approach, completely different from what one would expect from the addition of the parts.

INTEGRATED VALUATION OF CULTURAL ECOSYSTEM SERVICES IN RESTORED MARINE ECOSYSTEMS

The match between Welfare, in the DAPSI(W)R(M) framework, and the human benefits obtained from ecosystem services (Elliott et al., 2017), highlights the important role of social and environmental components in the provision of ecosystem services. Indeed, in **Figure 1**, Welfare is in both the environmental and the socio-economic spheres, matching the idea that benefits underpinned by ecosystem services are the result of complex combinations and interactions between natural components (i.e., natural capital) and human components (Chan et al., 2012b; Costanza et al., 2014, 2017).

The non-material character of the benefits provided by cultural ecosystem services makes them more difficult to study. Therefore, the analysis of the cultural ecosystem services is more approachable when focused on the human-ecosystem relationship that makes the benefits possible, instead of in the actual outcome or benefit.

When the objective is to study the changes in marine ecosystem services (e.g., after an ecological restoration process), apart from analyzing changes in environmental conditions, it is important to analyze if changes in social, economic and political aspects have happened, as these aspects also shape the benefits obtained from cultural services (Chan et al., 2012a). In other words, the evaluation of changes in Welfare (as described in DAPSI(W)R(M) framework) or human benefits after restoration should be done following an integrated valuation of ecosystem services. An integrated valuation is the one that considers environmental, social and monetary aspects (Villegas-Palacio et al., 2016) involved in the delivery of human benefits from ecosystem services.

Considering these ideas and based on the model designed by Kulczyk et al. (2018) for recreational ecosystem services, we present an interdisciplinary approach for studying the changes in cultural ecosystem services after restoration (**Figure 2**).

This model attends to both supply and demand side of ecosystem services (Burkhard et al., 2012). The supply side, or the capacity of a particular area to provide ecosystem services (Burkhard et al., 2012), has two main components, environmental base and supporting elements. Environmental base or natural capital includes environmental elements (i.e., physical-chemical and biological elements) that have a direct effect in the provision of specific ecosystem services. For example, in the recreational services of an estuary, the fish abundance

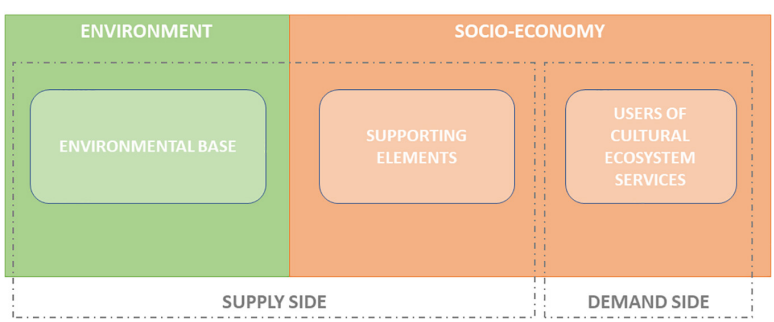

FIGURE 2 | Supply and demand sides of cultural ecosystem services. To obtain human welfare, [W in DAPSI(W)R(M)], the environmental elements (i.e., ecosystem services) need to interact with supporting elements (i.e., infrastructure) and cultural ecosystem services' users (recreationalists). Adapted from Kulczyk et al. (2018).

could be one of the key environmental elements. It is important to highlight that, from the ecosystem services' perspective, the improvement of the general conditions does not imply that the conditions required for specific human activities are also improved. Therefore, each ecosystem service studied in each case study requires to select the more appropriate elements that constitute their environmental base. The second part of the supply side are supporting elements, which include those general or specific recreational facilities that potentially can have an effect in cultural ecosystem services. For example, in a touristic beach, supporting elements can be the road network, aquatic sports facilities and other services (e.g., showers, toilets, platforms for access of disabled people), which affect the capacity of the area to provide recreational services.

Regarding the demand side, it focuses on the users (or consumers) of cultural ecosystem services. The objective is to understand the current use of the services, collecting information on users' perceptions, behavior, and values (e.g., monetary) associated to the benefit. In order to check if use has changed due to environmental changes, historical data will be collected (e.g., number of users before and after restoration). A key aspect when analyzing changes in ecosystem services in a restored ecosystem is to analyze changes registered in both the supply and demand sides. Only when changes in the service demand are proved to be related to changes in the environmental base, will we be able to confirm that changes in ecosystem services are an outcome of ecological restoration measures.

Hence, the integrated valuation will be completed when: (i) the capacity and supply of ecosystem services has been evaluated; (ii) the users' demand is set, through their perceptions and behavior toward the services provided by the ecosystem; and (iii) the monetary (or non-monetary) values of the benefits are determined, completing the chain of the three domains to evaluate if the restoration of a marine system has resulted in a recovery of the environmental values and socio-economic benefits.

PRACTICAL EXAMPLE OF THE INTERDISCIPLINARY APPROACH: THE NERBIOI ESTUARY

Description of the Ecosystem and Restoration Processes Under the DAPSI(W)R(M) Framework

The Nerbioi estuary is located in the inner Bay of Biscay, on the coast of the Basque Country, Spain (**Figure 3**). Nine municipalities are located along the two banks of the estuary, including the city of Bilbao, and comprise a total population of 695,020 inhabitants in 2019[1].

From the mid-19th Century, the urbanization, industrial (i.e., mining, steel and chemical industries), and port developments caused a deep change in the estuarine morphology and degraded its environmental health status. In the second half of the 20th Century, the Nerbioi estuary became the most polluted estuary in northern Spain and one of the most polluted in Europe (Cearreta et al., 2000). The continuous discharges of untreated urban and industrial wastes caused the accumulation of pollutants and the organic enrichment of the sediments and the water column, the reduction of the concentration of dissolved oxygen in the water column (with episodes of hypoxic and anoxic conditions in the inner estuary) and the general degradation (even absence) of the biological communities (Belzunce et al., 2001, 2004b; Gorostiaga et al., 2004; Borja et al., 2006).

Also, the intense development of urban, industrial and port activities in the estuarine banks, in need of space for placing their infrastructures, transformed the estuary into a narrow navigable tidal channel (Cearreta et al., 2004), with a clear differentiation of two zones: the inner part, a highly stratified channel of 15 km length, that crosses the city of Bilbao; and the outer part, also known as the "Abra," a semi-enclosed coastal embayment of 30 km^2 (Leorri et al., 2008; Irabien et al., 2018).

In 1979, the Sanitation Scheme was approved by the local authorities, with the aim to restore the esthetics, sanitary and ecological conditions of the estuary, and to achieve a water quality standard of 60% oxygen saturation (Pascual et al., 2012). The Nerbioi's recovery has been gradual, responding to three milestones (Borja et al., 2010a): (i) in 1990, the implementation of the Wastewater Treatment Plant (WWTP) of Galindo, with physical and chemical treatments; (ii) in 1996, the closure of the highly polluting iron and steel industry "*Altos Hornos de Vizcaya*" (AHV); and (iii) in 2001, the addition of the biological treatment in the WWTP. The closure of industries, the WWTP implementation, and the limitations imposed by more restrictive environmental policies caused a decline of metals, organic compounds and fecal pollution inputs into the estuary, reducing the pollutant concentrations in estuarine waters and sediments (Belzunce et al., 2004b,a; García-Barcina et al., 2006; Borja et al., 2016; Irabien et al., 2018). This resulted in the recovery of, among others, benthic communities (Borja et al., 2006) and demersal fishes (Uriarte and Borja, 2009), as reflected in the increase of the general biological value within the estuary (Pascual et al., 2012).

Despite the many scientific publications confirming that the general environmental conditions in the estuarine waters have improved after restoration, how the adopted restoration measures caused changes in ecosystem services has not been studied until recently (Pouso et al., 2018c,b, 2019b). These studies focused on specific values of ecosystem services (i.e., social or economic), but this is the first attempt to evaluate, following an integrative approach, how cultural ecosystem services recovered in the restored Nerbioi estuary.

To understand this process (how ecosystem restoration may translate into ecosystem service improvement), the degradation and restoration processes of Nerbioi estuary, presented above, have been conceptualized using the DAPSI(W)R(M) framework (**Figure 4**), differentiating between Drivers vs. Activity, Impact vs. Welfare, and Response vs. Measures.

In order to understand how aquatic restoration activities in the Nerbioi estuary may affect human well-being, two recreational activities have been selected for applying the framework: bathing

[1]https://www.eustat.eus/estadisticas/tema_268/opt_1/tipo_1/ti_Estadistica_municipal_de_habitantes/temas.html#el

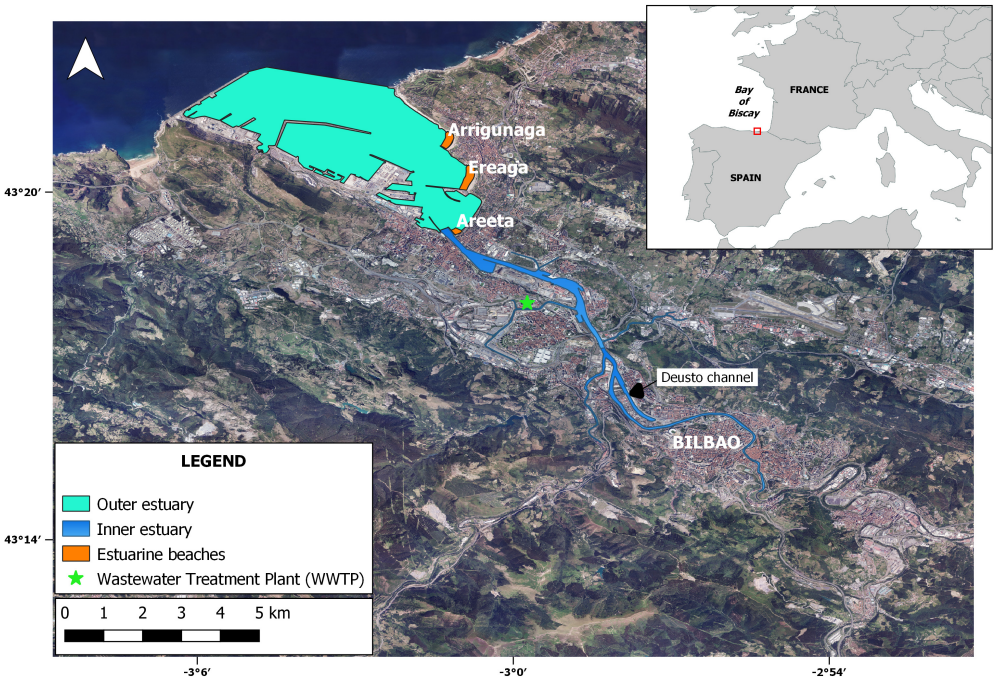

FIGURE 3 | Location of the Nerbioi estuary within the Bay of Biscay and location of the three estuarine beaches, the Wastewater Treatment Plant (WWTP) and the city of Bilbao.

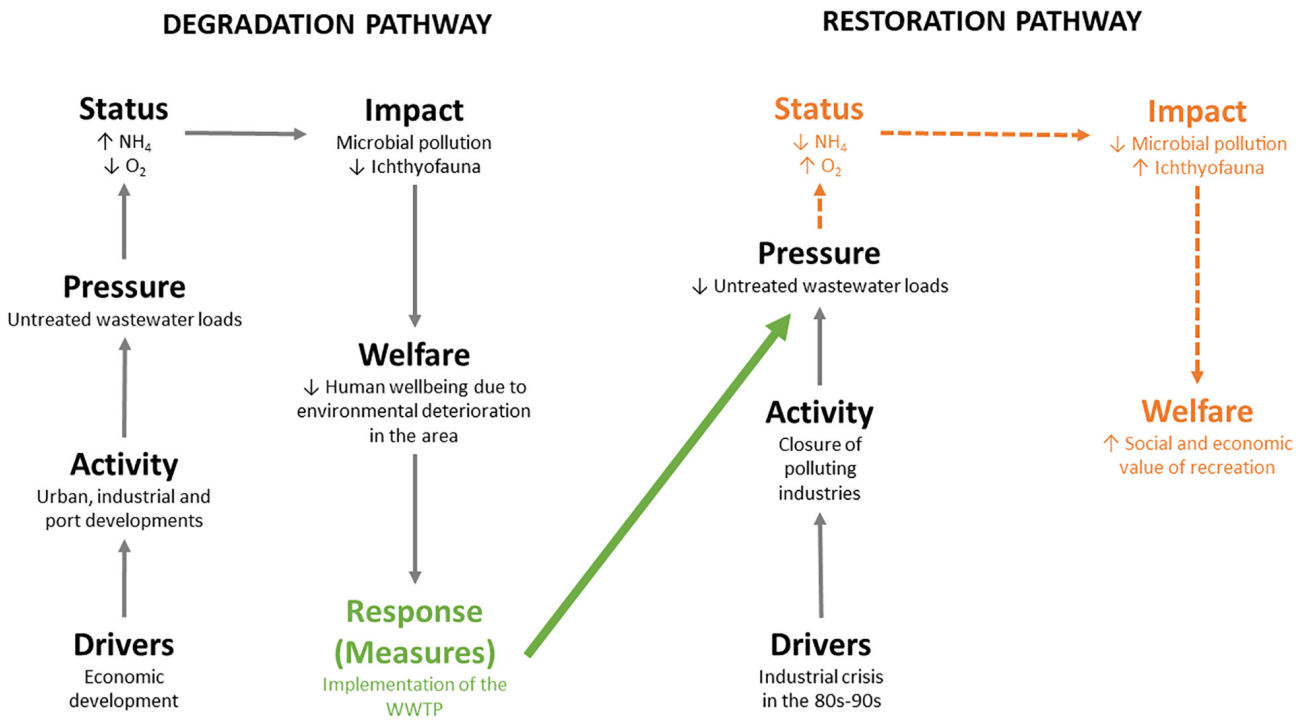

FIGURE 4 | Degradation and restoration pathways in the Nerbioi estuary, under the DAPSI(W)R(M) framework. Green: measures adopted and link/effect arrow. Black: information obtained from the literature; Orange: the part confirmed in recent publications by the authors (Pouso et al., 2018c,a,b, 2019b).

waters in beaches and recreational fishing. These activities were selected due to their direct dependency on or contact with water.

Changes in Recreational Ecosystem Services After Restoration Measures

To understand the flow (or lack of it) between biophysical and human components shaping the supply and demand sides of ecosystem services, the model introduced in **Figure 2** was applied to the Nerbioi estuary case study. Thus, the changes in the two recreational activities were analyzed, attending to the supply and demand sides that shape the benefit (**Figure 5**).

To evaluate the changes in the environmental base (**Figure 5**), we analyzed temporal trends on environmental conditions, using data collected through monitoring programs. The environmental parameters selected were, for recreational fishing, transparency through Secchi disk depth, oxygen saturation, ammonia concentration, fish richness and abundance; and for beach recreation, transparency through Secchi disk depth and concentration of fecal bacteria [for details, see Pouso et al. (2018b; 2018c)] These parameters were chosen due to their critical role for allowing the two recreational activities. For recreational fishing, we focus on two chemical parameters (oxygen saturation, ammonia concentration) linked to the recovery of the fauna in the estuary (Borja et al., 2006). For beach recreation, we focus on the concentration of fecal bacteria, the parameter used in European legislation to determine the quality of bathing waters; and on water transparency, which is a characteristic considered by beach users to judge water quality (Peng and Oleson, 2017).

There has been a significant improvement in water conditions along the estuary, where oxygen saturation increased, and ammonium concentration decreased throughout time (**Table 1**), while changes in water transparency were not statistically significant. Fish richness significantly improved in the inner estuary (minimum 2 taxa in 1990, 1994 and 1997, and maximum 13 taxa in 2015) and in the outer estuary (minimum 4 taxa in 1995 and 1998 and maximum 14 taxa in 2011). Regarding fish abundance, the increase has also been important and statistically significant in both the inner and outer estuary. When comparing inner and outer results from **Table 1**, it is important to note that since 2010 in the outer estuary the number of sampling stations are reduced from two to one, and in the inner estuary, there are three and have been monitored since 1990. Also, that the inner estuary has recovered from a more degraded overall state than the outer estuary.

In the three estuarine beaches, transparency has significantly increased in all of them. The microbial concentration, for which monitoring is mandatory for bathing waters according to EU and national legislation (European Commission, 2006; Spanish Government, 2007), show decreasing trends (**Table 2**). The number and proportion of water samples that exceeded the safety threshold decreased following the implementation of more restrictive legislation in 2008 (**Table 2**).

For analyzing changes in supporting elements (i.e., general or specific recreational facilities), we compared orthophotos from 1983, 1995, 2001, 2013, and 2018 retrieved from GeoEuskadi[2]. Visual comparison of orthophotos was done at first, to detect the locations where the most significant changes have occurred. Focusing on those selected locations, the changes in the available area have been calculated using QGIS (QGIS Development Team, 2009). In the outer Nerbioi, the most important change has been the extension of the industrial port facilities in the left bank of the estuary, which (i) reduced the shoreline accessible to the people (e.g., recreational fishers), as most of the shoreline is now under the domain of the Port Authority and (ii) land reclamation that reduced the extension of the estuary. From the comparison of the orthophotos, we conclude that there has been a loss of circa 3.4 km^2 (i.e., >16%) of the water extension between 1983 and 2018, due to the construction of industrial port facilities (**Figure 6A**). Also, there are certain aquatic areas under the management of the Port Authority where only port activities are allowed. This increase in port facilities in the left bank caused a reduction of the accessible shoreline of ~3 km between the villages of Zierbena and Santurtzi (**Figure 6A**). In the right bank of the estuary, the most important change has been the construction of a recreational port (1998) and its recent enlargement with cruise mooring facilities (first mooring facility started operating in 2006 and the second in 2015) (**Figure 6B**). The three estuarine beaches, which are located in the right bank of the outer estuary, have not suffered intense morphological changes. While the road link has not been significantly altered, public transport connection has improved. The old train line was renewed to a metro line in 1995, which increased the train frequency and added new stations. The locations of the metro stations closer to the three beaches did not change significantly.

In the inner estuary, the main change has been the recent opening of the Deusto channel, a morphological change in the estuary that happened in 2018-2019. The environmental effects of this action have not been yet assessed.

For analyzing the demand side, available data on the current and past number of beach recreationalists and recreational fishers were collected [for details, see Pouso et al. (2018a, 2019b)]. Data on the number of beach visitors were collected in summer period (from June to September) by the regional Government of Bizkaia since 2013. Due to their good accessibility and location, close to Bilbao, the three beaches in Nerbioi receive a high number of recreationalists in summer. Indeed, from 2013 to 2019, Ereaga has ranked at the TOP 3 of most visited beaches of the region every year[3].

There were no records on the number of recreational fishers who have been fishing inside the estuary in the last three decades [for details, see Pouso et al. (2018b)]. Therefore, the number of recreational fishing licenses issued in the nine municipalities located along the estuary was used as proxy.

Since 1999, when licenses became compulsory for practicing recreational fishing, the number of terrestrial fishing and spearfishing licenses first followed an increasing trend in the region of Bizkaia (from 19,038 licenses in 1999 to 41,517 in 2011), and then a decreasing trend (with 33,606 in 2015) (Basque Country Government, personal communication). The proportion of licenses belonging to inhabitants of the nine

[2]http://www.geo.euskadi.eus

[3]https://www.bizkaia.eus/Ingurugiroa_Lurraldea/Hondartzak/listadoplayas.asp

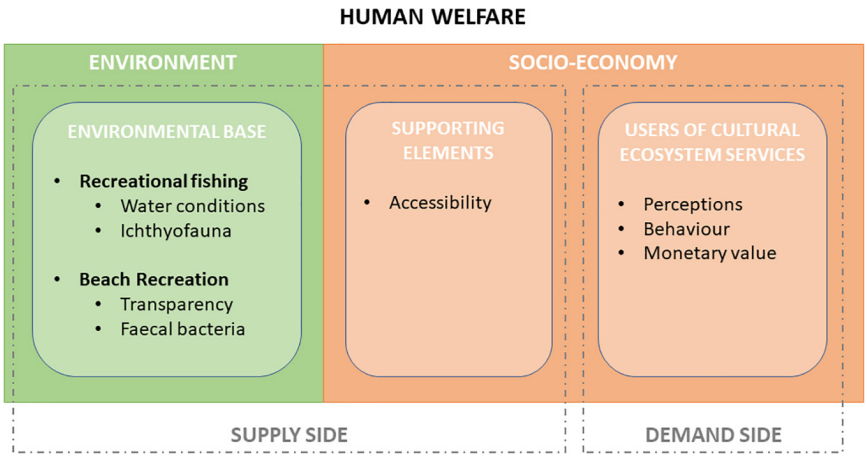

FIGURE 5 | Framework to analyze the human welfare change in the Nerbioi estuary after ecological restoration. **Figure 2** has been adapted here to reflect the elements considered in the analysis of the changes in recreational ecosystem services of the Nerbioi estuary.

estuarine villages has remained stable at around 56–60% of the total licenses issued in Bizkaia. The high contribution of Nerbioi villages to the total amount of licenses in the region goes in line with population data, as the nine Nerbioi villages account for ~60% of the total population in the region (Eustat, 2017).

The current use of the two recreational activities was assessed through two dedicated questionnaires, designed and distributed in 2016. Two anonymous questionnaires were used to analyze the changes in social behavior and perceptions, as well as to collect the necessary information to perform monetary valuations of the activities (Pouso et al., 2018a,b,c, 2019b). The interviewer explained the voluntary nature of the participation and the need for participants' consent before responding to the questionnaire. Data management was done according to the Spanish Law 15/1999 on Protection of Personal Data[4]. Some of the most remarkable results of the questionnaires, mainly related to recreationalists profile, changes in behavior and perceptions on water quality, are summarized in **Tables 3**, **4**. Further details can be found in Pouso et al. (2018b; 2018c).

Relaxation was one of the main reasons most frequently mentioned by users to recreate in the Nerbioi estuary, while spending time with friends and relatives was also important for recreational fishers (**Tables 3**, **4**). This reason was not mentioned among beach goers so often (reasons such as sunbathing and bathing ranked higher) but most of them (>72%) visited the beach with friends or relatives.

Surveys also revealed that users' behavior is influenced by environmental conditions. Thus, percentage of those getting into the water is higher in beaches with better water conditions (higher transparency and lower microbial concentration) (**Table 4**) and fishing is more common in areas that have maintain better conditions (outer estuary over inner estuary) (**Table 3**).

Behavior changed as a consequence of ecological restoration. Among recreational fishers, results suggested that fishers progressively extended their effort to the inner estuary, responding to the improvements in water quality, fish richness and fish abundance [**Table 3** and Pouso et al. (2018b)]. A decrease in the activity in certain areas of the outer estuary was detected by the questionnaire, which was linked to the extension of the industrial port facilities in the left bank (Pouso et al., 2018b). Beach recreationalists were asked to rate the probability that they would return to beaches if water quality was to worsen (Pouso et al., 2018c). Results revealed that most of them would not come back if water quality worsens; and together with the importance placed to aquatic activities as a motivational factor to visit beaches, it was concluded that water quality improvement has been important to the development of the beach recreation. Although most beach visitors bathe in Nerbioi beaches; among the ones that do not, the perceived poor quality of the water was the most frequently mentioned reason (Pouso et al., 2018c).

The study of perceptions revealed that users are able to perceive water improvements. Among experienced beach visitors' users (>5 years visiting the beach), most of them perceived that water conditions have improved (**Table 4**) and most of them believe that the main reason is the implementation of the wastewater treatment (Pouso et al., 2018c). Recreational fishers also perceived an improvement in water conditions (**Table 3**) linked to the wastewater treatment, and most of them believe that the WWTP had positive consequences for the recreational activity (Pouso et al., 2018b).

The travel cost analysis performed to estimate the value of the two activities, estimated a current aggregated-use value of 4.65 M€ year^{-1} (**Tables 3**, **4**). This amount covers all the maintenance and service costs associated to beach recreation (e.g., sampling and analysis of bathing waters, rescue services) and an important amount of the sewage system running costs [more information available in Pouso et al. (2018a, 2019b)].

Following an interdisciplinary approach, it has been shown that the restoration investment resulted in a recovery of the ecosystem components (environmental domain), which provided benefits for human well-being (social domain), in terms of

[4]Law 15/1999 on Protection of Personal Data (https://www.boe.es/eli/es/lo/1999/12/13/15).

TABLE 1 | Trends over time in the general physicochemical and biological conditions of the Nerbioi estuarine waters, expressed as linear regression (Coefficient, Standard Error, and R^2) and minimum and maximum data.

	Outer estuary				Inner estuary			
	Coef. sign	**R^2 (p-value)**	**Min (year)**	**Max (year)**	**Coef. sign**	**R^2 (p-value)**	**Min (year)**	**Max (year)**
Secchi disk depth (m) (1994–2015)	+	0.118 (*n.s.*)	1.66 (2005)	4.33 (2015)	+	0.046 (*n.s.*)	0.60 (2004)	1.48 (2002)
Bottom oxygen saturation (%) (1994–2015)	+	0.221 (0.032)	84.6 (1997)	101.1 (2003)	+	0.755 (<0.001)	30.5 (1994)	87.4 (2014)
Surface Ammonia (μmol l^{-1}) (1994–2015)	-	0.530 (<0.001)	3.6 (2015)	93.6 (1997)	-	0.387 (0.002)	9.0 (2015)	495.0 (1994)
Fish richness (1990–2015)	+	0.624 (<0.001)	4 (1995, 1998)	14 (2011)	+	0.745 (<0.001)	2 (1990, 1994, 1997)	13 (2015)
Fish abundance (ind Ha^{-1}) (1990–2015)	+	0.191 (0.025)	21 (2011)	2147 (2013)	+	0.210 (0.015)	6 (1990)	2579 (2013)

Values are calculated as yearly means in inner and outer sampling stations using data collected by URA (Basque Water Agency) for Secchi disk depth, Oxygen Saturation and Ammonia concentration; and data collected by CABB (Consorcio de Aguas de Bilbao Bizkaia) for fish richness and fish abundance. The yearly means were calculated using data from 3 sampling points for the inner estuary, and 2 sampling points for the outer estuary (reduced to a single sampling point after 2010). Key: m = meters; Coef. sign = sign of the coefficient in the regression equation; Min = minimum yearly mean value; Max = Maximum yearly mean value.

enhancing the provision of cultural ecosystem services, which leads to covering the costs of most of the investments and maintenance of the services (economy domain). This work provides a holistic view to explain how the efforts done in reverting a degraded situation resulted in human benefits in the form of cultural ecosystem services.

DISCUSSION

In this paper, an interdisciplinary approach has been applied to analyze changes in marine cultural ecosystem services after ecosystem restoration, in an integrative way, including environmental, social and economic domains. The approach relies on the DAPSI(W)R(M) framework, a common framework for communicating policy-relevant information on marine management (Atkins et al., 2011), and on integrated methodologies for valuation of recreational ecosystem services (Kulczyk et al., 2018). The interdisciplinary approach has been tested in the Nerbioi estuary, with a focus on recreational services, but it could be adopted to analyze changes in other cultural ecosystem services (e.g., education and training, scientific knowledge, experiences, esthetic value). For the last three decades, the ecological restoration of the Nerbioi estuary has been studied only from an environmental perspective. Five articles published in the last two years analyzed partial aspects of the recovery of recreational ecosystem services in the estuary, including environmental, social and economic domains. In this article, all those partial results from the three domains have been integrated with new information, in order to provide an holistic view of the change occurred in the recreational ecosystem services, and which can serve as guide in other restored coastal areas.

First, it is important to perform an extensive analysis of the environmental base, considering the specific biophysical characteristics that determine the capacity of the ecosystem to provide certain cultural services. Those characteristics might have changed after restoration, either directly (i.e., the change was an objective of the restoration project) or indirectly (as a consequence of the change in another biophysical characteristic). The biophysical characteristics to be analyzed should be chosen considering the particular characteristics of the system, and the ecosystem services under study. Ideally, the biophysical data will cover pre- and post-restoration periods. Despite the successful long-term monitoring networks in marine ecosystems worldwide (Borja et al., 2016), there are many ecosystems still lacking appropriate monitoring (Patrício et al., 2016b). There is a need to improve monitoring of marine areas, especially of those considered to be "ecosystem services hotspots." Also, it is important to put into value the information provided by existing monitoring networks, and the indispensable information they provide for the study of trends and for early detection of changes. Establishing and/or maintaining long-term monitoring networks in restored ecosystems is necessary to be able to link environmental changes to subsequent changes in ecosystem services demand. In the Nerbioi estuary, long-term information on biophysical parameters was available, as the estuary has been

TABLE 2 | Trends in the condition of bathing waters over time and across three beaches (from innermost to outermost beach: Areeta, Ereaga, and Arrigunaga; see **Figure 3**), expressed as linear regression (Coefficient, Standard Error, and R^2) and minimum and maximum data.

	Areeta						Ereaga						Arrigunaga					
	n	>limit	Coeff. Sign	R^2 (*p*-value)	Min (year)	Max (year)	n	>limit	Coeff. sign	R^2 (*p*-value)	Min (year)	Max (year)	n	>limit	Coeff. sign	R^2 (*p*-value)	Min (year)	Max (year)
Faecal coliforms (1985–2007)[A] (MPN)	*No data*	*No data*	*No data*	*No data*	*No data*	*No data*	322	63	–	0.3856 (n.s.)	100 (2006)	1548.1 (2000)	160	33	–	0.4932 (n.s.)	100 (2006)	2133.29 (2001)
Escherichia coli (2008–2016) (MPN)	164	22	–	0.1234 (n.s.)	82.35 (2016)	804.67 (2008)	322	11	–	0.2353 (n.s.)	22.37 (2012)	710.47 (2008)	157	9	–	0.1416 (n.s.)	36.43 (2009)	730.33 (2008)
Secchi disk depth (1999–2016)			+	0.78 (<0.001)	0.77	1.87			+	0.66 (<0.001)	1.25	2.8			+	0.26 (0.03)	1.94	3.05

Regressions are calculated with yearly mean values, using fecal coliforms and Escherichia coli data collected by the Basque Government during bathing season (May-September); Secchi disk depth data collected by CABB (Consorcio de Aguas de Bilbao Bizkaia). Key: n = number of samples; >limit = number of samples above threshold (>2000 MPN 100 ml^{-1} for fecal coliforms (Directive 76/160/CEE[5] European Commission (1976). Council Directive 76/160/EEC of 8 December 1975 concerning the quality of bathing water) and >500 MPN 100 ml^{-1} for Escherichia coli (Law 2006/7/EC[6] European Commission (2006). Directive 2006/7/EC of 15 February 2006 concerning the management of bathing water quality and repealing Directive 76/160/EEC); MPN = Most Probable Number; m = meters; Coef. sign = sign of the coefficient in the regression equation; Min = minimum yearly mean value; Max = Maximum yearly mean value. Fecal coliform sampling in Arrigunaga started in 1992.

monitored since 1989 by two monitoring networks, Bilbao-Bizkaia Water Consortium (CABB) and the Basque Water Agency (URA). The availability of information facilitated the retrieval of the specific parameters we needed to perform the cultural ecosystem services evaluation.

Supporting elements, together with the environmental base, constitute the supply-side of recreational ecosystem services (Kulczyk et al., 2018). In restored ecosystems, the analysis of supporting elements is a crucial step, in order to elucidate if changes in human well-being can be linked to: (i) improvements in the environmental conditions, (ii) changes in supporting elements or (iii) a combination of changes in both. In our case study, the analysis of supporting elements focused in accessibility, known as a crucial element for making recreational ecosystem services reachable (Paracchini et al., 2014). The analysis demonstrated that supporting elements can have an influence on current use patterns; e.g., recreational fishers in Nerbioi estuary do not fish as much as expected in the area with the best environmental conditions due to accessibility limitations (Pouso et al., 2018b).

Once the changes that restoration generated in the supply-side have been analyzed, it is time to check if this translates into a change in the demand-side, i.e., changes in use. This part of the analysis could be challenging, as usually social data are scarcer than data on environmental and supporting elements. In the Nerbioi estuary, the abundant information on environmental parameters was not reflected in socioeconomic aspects. There was little information on recreational fishing activity and beach use that covered the entire restoration process period. Visitors to the beaches were only counted systematically since 2013. For recreational fishing, the only proxy available was the number of licenses. However, living in a nearby village and having the fishing license does not mean that they practice the activity inside the estuary. Similarly, people from other villages outside the estuary can fish there. The available tourism-related information (e.g., number of visitors to nearby villages, number of arrivals through cruises), was not considered appropriate for the objective of the study, as it did not have a straightforward relation with the two recreational activities under analysis. However, these sources might be very useful depending on the aim of the study, e.g., if the focus is to analyze general changes on recreational ecosystem services.

To overcome this problem, socioeconomic information was collected using questionnaires. Face-to-face questionnaires are frequently used in ecosystem services research, usually to collect information on current use and social perceptions (Martín-López et al., 2007, 2012). In Nerbioi estuary, questionnaires were also used to compile information about past use and behavior, in order to check if demand has changed after restoration. The methodology is opened to include any stakeholder considered crucial (e.g., inhabitants in the nearby villages, policymakers, recreation and tourism industries), which will be dependent on the case study. In the Nerbioi estuary, the demand-side analysis was performed by distributing questionnaires exclusively to current recreational users of the estuary. This decision was adopted to increase the efficiency on the questionnaire distribution. However, it also represents a limitation as we could

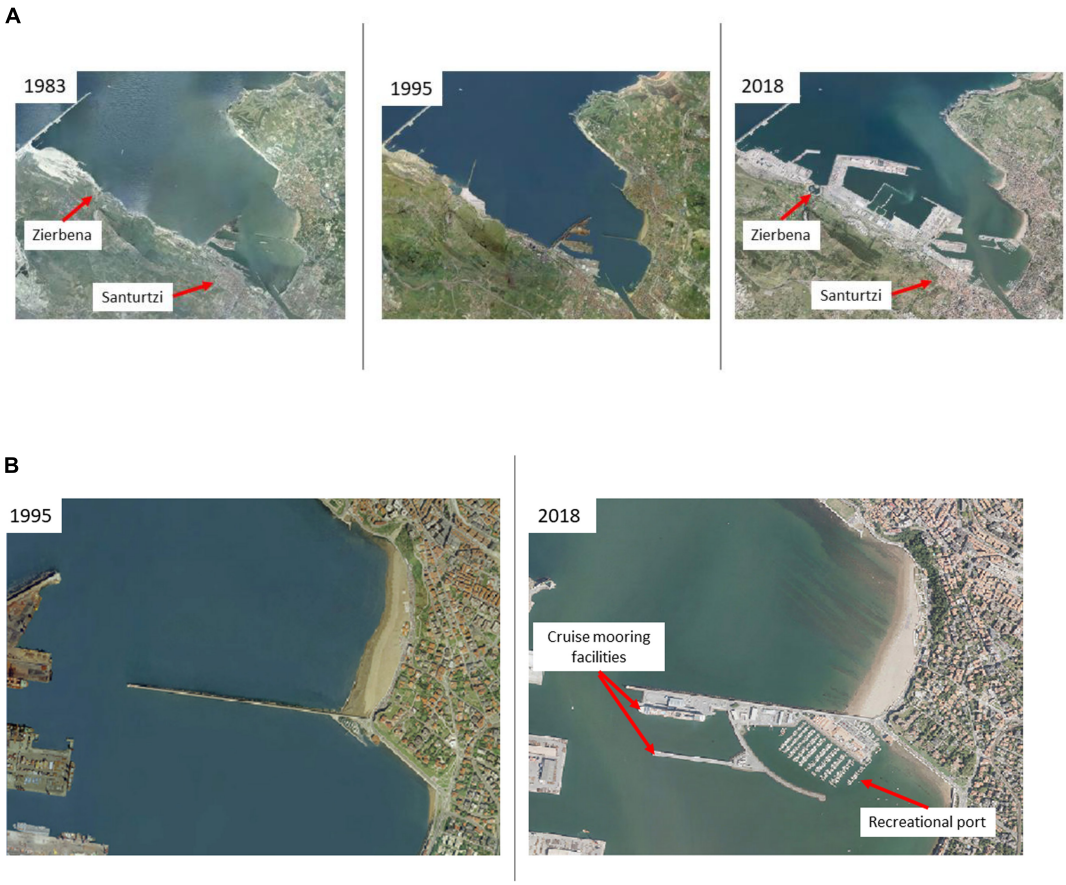

FIGURE 6 | Main morphological changes in the outer estuary. **(A)** 1983 (left), 1995 (middle), and 2018 (right) orthophotos showing the expansion of the industrial port facilities in the left bank. **(B)** 1995 (left) and 2018 (right) orthophotos showing the changes caused by the construction of the recreational port and cruise mooring facilities in the right bank. Source: GeoEuskadi Orthophoto Comparator https://www.geo.euskadi.eus/comparador-de-ortofotos/s69-geocont/es/.

not collect the perceptions of potential users that despite having a good access, do not recreate in the area (e.g., inhabitants of the nearby villages who move farther to recreate, past users that for some unknown reason have stopped recreating in the area, etc.).

Responses to the questionnaire supported our hypothesis that restoration efforts in the Nerbioi estuary led to higher provision of cultural ecosystem services (Pouso et al., 2018c,b). Generally, questionnaire results revealed that recreational users perceive the improvements in the water conditions. Users perceive environmental trends and adapt their behavior accordingly (fishers moving to inner estuary to fish, beaches visitors revealing that the water improvement has been key for them to decide to visit estuarine beaches). Certain concerns exist among recreationalists, e.g., beach visitors that do not bathe due to the perception of poor water quality. Considering the improvements on environmental conditions, the continuation of negative perceptions could be linked to the memory of past conditions (Pouso et al., 2018c). Also, there might be potential users that do not recreate here due to the negative perception they still have on the past water conditions. This will be the case of fishers that despite living nearby, they still prefer fishing in other areas far away; also, the case of beach goers who indicated that bathing is one of the main reasons to go to beaches, but they do not bathe in estuarine beaches due to the negative perception they have on the water conditions. This indicates how difficult is to change negative perceptions associated to past situations.

The interdisciplinary approach used in this research allows us to study changes in the multiple values (i.e., intrinsic, instrumental and relational values) that cultural ecosystem services have (Chan et al., 2012b, 2018). Traditionally, studies on ecosystem services have focused on assessing the instrumental values [or "things that are means to some external end" (Himes and Muraca, 2018)], and this has been done through diverse monetary valuation techniques (Turner and Schaafsma, 2015). In Nerbioi, the instrumental values of the two recreational activities were assessed (Pouso et al., 2018a, 2019b) using the Travel Cost Method (Parsons, 2003), which has been extensively used to value recreational services. The information that econometric tools provide can be valuable; still, ecosystem services should not be valued exclusively with monetary techniques as their result is insufficient to represent the many ways in which people benefit from nature (Chan et al., 2012b). In the Nerbioi estuary, the monetary valuations revealed that recreational activities cover an important percentage of costs for maintaining the environmental

TABLE 3 | Summary of the main characteristics and results of the questionnaires distributed among recreational fishers in the Nerbioi estuary.

Recreational fishing	
Distribution Details	
n	146
Distribution	January–September 2016
Socioeconomic characteristics	
Age	
Mean ± SD	51 ± 14
Gender	
Women	6.8%
Men	93.2%
Main motivations to practice the recreational activity *(3 main motives)*	
Relaxation	75.3%
Be with friends or relatives	41.1%
To practice outdoor activities	31.5%
Why did you choose this recreational spot today? *(3 main reasons)*	
Proximity to home	35.6%
Habit	33.1%
To capture specific species	28.8%
Beginning of the activity in Nerbioi *Median (IQR)*	
Outer estuary	1995 (IQR 1986-2006)
Inner estuary	2001 (IQR 1990-2009)
Travel cost	
M€ year^{-1}	1.12
In which parts of the estuary do you fish?	
Outer estuary	87.0%
Inner estuary	53.4%
Perceptions of changes in water quality	
Better	80.1%
Equal	7.5%
Worse	4.1%
NA	8.2%

More details can be found in Pouso et al. (2018b).

TABLE 4 | Summary of the main characteristics and results of the questionnaires distributed among beach goers in the Nerbioi estuary.

Beach recreation	
Distribution Details	
n	425
Distribution	July–August 2016
Socioeconomic characteristics	
Age	
Mean ± SD	42 ± 16
Gender	
Women	74.4%
Men	25.6%
Main motivations to practice the recreational activity (3 main motives)	
Sunbathing	86.2%
Relaxing and resting	72.8%
Bathing and cooling down	63.8%
Importance of the possibility of practicing aquatic activities to choose the beach	
Essential	25.6%
Important	50.4%
Low	17.2%
None	4.7%
NA	2.1%
Why did you choose this recreational spot today? *(3 main reasons)*	
Proximity to home	81.9%
Accessibility	34.3%
Tranquility	31.0%
Did you come alone?	
Yes	27.0%
No	72.1%
NA	0.9%
Visitors who practice aquatic activities in this beach	
Areeta	44.0%
Ereaga	65.0%
Arrigunaga	75.8%
Beginning of the activity in Nerbioi	
<1 year	10.1%
1–5 years	22.3%
>5 years	66.7%
NR	*0.9%*
Travel cost	
M€ year^{-1}	3.53
Perceptions of changes in water quality (only visitors with > 5 years coming to Nerbioi beaches)	
Better	82.7%
Equal	8.5%
Worse	6.0%
NA	2.8%

More details can be found in Pouso et al. (2018c).

quality (Pouso et al., 2018a, 2019b). However, the high percentage of locals among users, who do not have to invest great time or money to reach the recreational places, resulted in a relatively low monetary value per visit, compared to similar case studies in the literature (Ariza et al., 2012; Alves et al., 2017). The low monetary value per single visit was partially compensated by the many visits along the year. Also, the high representation of locals among users revealed the importance that marine spaces such as the Nerbioi estuary, located in highly urbanized areas, can have for many people. Restored blue spaces in urban areas, such as marine ecosystems, might have a lower environmental value than better conserved areas (e.g., protected coastal areas); still, they play a fundamental role by providing recreational opportunities and cultural ecosystem services to people living nearby (Jacobs et al., 2015; Bowen et al., 2019; Vert et al., 2019).

Beyond the monetary valuation, the questionnaires can be used to explore the social values that people attribute to cultural ecosystem services. In the Nerbioi estuary, the analysis of social values revealed that recreational activities matter to people for many reasons (e.g., "expending time with family and friend" "relaxation," etc.), which are difficult to value in monetary terms. People value the relation with nature and with other people that the recreational activity facilitates; and this is linked to the relational values of ecosystem services (Chan et al., 2016). Also, spending time and practicing outdoor recreational activities in marine spaces, such as the Nerbioi

estuary, can have positive outcomes for human health (Borja et al., 2020). The analysis of social perceptions and behavior provide information on relational values that are so important for understanding cultural ecosystem services. In cultural ecosystem services research, presenting the instrumental values (monetary value) simultaneously with relational values helps to better understand how nature matters to people.

Once the whole process of restoration, including changes in human well-being, is understood, it is possible to link the social and environmental aspects influencing the ecosystem services and human benefits, through cause-effect relationships. These relationships can be used to build social-ecological models, e.g., using system dynamics model tools (Pouso et al., 2019a), which are able to simulate consequences for the human benefits (e.g., recreational activities) under future conditions. Furthermore, these models help to measure the resilience of the system to future pressures and/or impacts, which can be related to the status of regulating services of the restored ecosystem.

The consideration of the three value domains for analyzing the supply and demand sides of the ecosystem services allows us to build a more complete picture of the biophysical and social changes that shaped the present conditions in a restored ecosystem. In the case of the Nerbioi estuary, it has been shown how analyzing all these aspects allowed a deeper understanding of the system's dynamics. For example, analyzing exclusively the biophysical conditions would have led to the conclusion that conditions for recreational fishing were much better in the outer estuary, and that the activity will be concentrated there. However, analyzing the changes in accessibility with orthophotos and users' perceptions with face-to-face questionnaires, we were able to detect a problem for recreational fishers to access certain parts of the outer estuary. The decrease in accessibility to the left bank in the outer estuary could be a reason, together with the general improvement in biophysical conditions (more visible in the inner part), for the extension of the activity to the inner estuary. Our results suggest that the extension of the recreational fishing activity is a consequence of changes in users' perception on water quality and the availability of new areas (e.g., recreational port in the right side of the outer estuary), in the absence of any conscious measure adopted by authorities to mitigate the loss of recreational fishing opportunities after the extension of the industrial port facilities on the left bank. Another example of the added value of performing an integrated valuation to analyze changes in ecosystem services is related with cognitive processes. For recreational fishing, while fishers reported a decrease in fish abundance, environmental data suggested the opposite, with an increasing trend for the last 25 years (Pouso et al., 2018b). For beach recreation, although microbial pollution has decreased and most of beach goers perceived the water quality improvement, an important percentage of users still do not bathe due to the water quality, probably linked to the memory if past water pollution (Pouso et al., 2018c). The dual study of biophysical characteristics and users' perceptions and behaviors allowed us to find mismatches, which can be useful information for local managers.

The understanding of ecosystems as social-ecological systems, and the growing interest in approaches that consider ecosystem services, makes inevitable the need to adapt the ways in which we evaluate restoration projects. This means changing the traditional evaluation processes, which have focused on changes in environmental conditions (Elliott et al., 2007), to integrated valuation processes that analyze the interdisciplinary outcomes of restoration actions. Furthermore, the declaration of the Decade on Ecosystem Restoration (2021–2030) by the United Nations, can be very important for coastal systems (Waltham et al., 2020), as a way to promote their restoration and gain, through new practical examples, their importance for recovery of both environmental conditions and ecosystem services.

In this context, the approach followed here can help to standardize the integrative analysis of ecosystem services in restored ecosystems, i.e., accounting for environmental, social and economic factors that shape the recreational activities and consequent human well-being, building one upon the other. Also, to comprehend the importance that each element has to the delivery of ecosystem services and the consequent human benefits.

CONCLUSION

In this article we present a framework for a standardized-integrative analysis of ecosystem services and consequent human well-being in restored marine ecosystems. Its theoretical background, based on marine management tools [DAPSI(W)R(M)], social-ecological system approach and following an integrative assessment of ecosystem services, provides a sound basis for the study of changes in cultural ecosystem services and human well-being in restored systems. Furthermore, it can be a useful approach when valuing the consequences of marine restoration projects, as it provides a systematic framework for the analysis of environmental, social and economic consequences of the restoration actions. Hence, these three domains transcend each other to give a new holistic view, which is different from what one would expect from the addition of the three domains, providing better and complete view of the restoration efforts.

DATA AVAILABILITY STATEMENT

All the information and data are available in the article of the authors cited in the text.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants, in accordance with the local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

SP, ÁB, and MU developed the idea of the manuscript. SP wrote the first draft. Each author contributed equally to the discussion

and in writing the final manuscript. All authors contributed to the article and approved the submitted version.

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frontiers in Marine Science

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Variation in Seagrass Carbon Stocks Between Tropical Estuarine and Marine Mangrove-Fringed Creeks

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Seagrass and associated blue carbon ecosystems are important carbon sinks, and hence understanding their spatial and temporal variability is vital in appreciating their potential roles in climate change mitigation and adaptation. The Indo-Pacific region has the highest seagrass biodiversity, yet little focus has been made to compare seagrass habitat extent and carbon dynamics with their temperate counterparts. The present study assessed habitat characteristics and seagrass species distribution, diversity, and carbon storage in Eastern (marine) and Western (estuarine) mangrove-fringed creeks of Gazi Bay, Kenya. Data on species composition, canopy cover, biomass, and sediment organic carbon were collected in 80 plots of 0.25 × 0.25 m laid along transects established perpendicular to the waterline. Five species formation, *viz.*, *Thalassia hemprichii*, *Cymodocea rotundata*, *Cymodocea serrulata*, *Enhalus acoroides*, and *Thalassidendron ciliatum*, were encountered as either single or mixed stands. There was a significant difference in total seagrass biomass between creeks ($p < 0.01$), with the Eastern creek recording a mean of 10.2 ± 0.6 Mg C ha^{-1} while the Western creek recording 4.3 ± 0.3 Mg C ha^{-1}. In addition, sediment carbon to 1-m depth varied significantly ($p < 0.01$) between species in the two creeks and ranged from 98 to 302 Mg C ha^{-1}, with the Eastern and Western creeks recording means of 258 ± 90 and 107 ± 21 Mg C ha^{-1}, respectively. The total carbon stock from 50 ha of seagrasses in the Eastern creek was 13,420 Mg C, whereas in the 70 ha of the Western creek it was 7,769 Mg C. The study shows that seagrass community attributes such as species composition and productivity can vary dramatically over a small spatial extent due to differences in biophysical conditions and caution estimations of site-specific carbon stocks using generalized global values.

Keywords: seagrass, carbon stocks, above- and belowground biomass, sediment carbon, Gazi Bay, Kenya

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INTRODUCTION

Conservation of the blue carbon sink such as mangroves, tidal salt marshes, and seagrasses is important because of their contribution to climate change mitigation and adaptations. Despite their role in capturing and storing huge carbon stocks (Fourqurean et al., 2012; Rogelj et al., 2016), less information is available from blue carbon ecosystems when compared to their terrestrial

counterparts (Huxham et al., 2018). The natural and human pressures on these habitats expose them to loss and degradation, leading to the release of CO_2 back into the atmosphere and thereby hindering their role in carbon storage (Duarte et al., 2005; Howard et al., 2018).

Seagrass meadows are keystone ecosystems along the coasts providing a range of benefits to humans and other organisms, among them regulatory, support, provisioning, and cultural services (Hejnowicz et al., 2015; Nordlund et al., 2018). They contribute to nutrient cycling (Costanza et al., 1997) and sediment stabilization and provide nursery to over one fifth of the world's 25 largest fisheries (Unsworth et al., 2019). They are efficient in carbon capture and storage (Duarte and Prairie, 2005; Gedan et al., 2009), hence necessitating their inclusion in carbon offsetting schemes (Howard et al., 2017; Herr et al., 2017). Despite their value, seagrasses across the world are threatened by a combination of both human and natural factors (Cabaço et al., 2008; Mazarrasa et al., 2017; Githaiga et al., 2019), contributing to the global estimated loss of 1.5% per year (Waycott et al., 2009; Pendleton et al., 2012).

Seagrass species thrive in varying habitats ranging from estuaries, mud flats, sheltered bays, and lagoons across wide latitudinal distributions ranging from temperate to tropical latitudes with varying geomorphological, hydrological, and ecological conditions (Lyimo et al., 2018; Bulmer et al., 2020). These affect the distribution and abundance of the seagrass species in their physiological and survival processes (Lyimo, 2016; Gullström et al., 2017; Mazarrasa et al., 2018). The integrity of these marine habitats is also likely to be affected by biophysical factors such as water currents, day length, epiphytes, wave action, temperature, light availability, salinity, and substrate type and depth (Hemminga and Duarte, 2000; Green and Short, 2003). Additionally, anthropogenic stressors upstream or along the coastline, such as effluent discharge and agricultural activities, facilitate sediment and nutrient loading, thereby affecting seagrass health status. Direct effects are on structural traits such as cover, density, and biomass accumulation that subsequently influence seagrass sediment organic carbon (C_{org}) sequestration and deposition in the soil through three major processes: biomass accumulation and productivity, allochthonous C_{org} load in the water column, and the burial rates in sediment (Serrano et al., 2016a,b; Mazarrasa et al., 2018). Largest of the carbon pools is the sediment organic carbon comprising autochthonous and allochthonous carbon which may be deposited for millennia in sediment, though in some conditions get remineralized, leading to further CO_2 emissions (Kennedy et al., 2010). Seagrass meadows have a larger global spatial extent when compared to other blue carbon sinks (Mcleod et al., 2011). They occupy a global coverage of 3,000 km^2 with more than 70 species (Small and Nicholls, 2003; Short et al., 2011). Species vary in abundance and distribution across latitudes, with the tropical bioregions having the highest diversity at 24 out of the known 60 species globally (Short et al., 2007). Compared to other blue carbon sinks, there is less research focusing on seagrass carbon dynamics, leading to uncertainties in the seagrass habitat extent and contribution to the blue carbon budget. In the African coastline for example, there is still a huge paucity of information regarding seagrass habitat extent, quantitative carbon estimates, and habitat influence despite the extensive meadows (Githaiga et al., 2016, 2017).

This study assessed habitat characteristics and the carbon stocks of two seagrass meadows in Gazi Bay, Kenya, that lies within the East African coastline. We hypothesized that the seagrass distribution, abundance, and carbon stocks differ significantly between the estuarine and marine seagrass meadows. The bay is known to host a high seagrass diversity, with up to 12 species described in the Western Indian Ocean (WIO) region occurring here (Ochieng and Erftemeijer, 2003). Our study on habitat variations and influence on seagrass carbon stocks is of significance as it provides a better understanding of tropical seagrass ecosystems for comparison with their temperate and subtropical counterparts. Additionally, as the first study assessing habitat influence on carbon storage in seagrass within the African tropics, it provides insights for the enhanced management of these critical ecosystems.

MATERIALS AND METHODS

The Study Site

The study was carried out in the two creeks of Gazi Bay – Eastern creek (04.41610°S, 039.52610°E) and Western creek (04.41661°S, 039.51253°E) – in Kenya between May and September 2018. The Eastern creek lies on the eastern part of the bay bordering Mikoko Pamoja, a community-managed managed mangrove carbon offsetting project area in Gazi. It is characterized by shallow subtidal areas and channels that intersect the intertidal flats (Hemminga et al., 1994). Some areas have rocky substrate and macroalgae lying in close association with the seagrass species. The area of the eastern creek is estimated at 50 ha and lacks direct influence of freshwater (**Figure 1**). Key mangrove species fringing the eastern creeks are the *Sonneratia alba* and *Rhizophora mucronate* (**Supplementary Figure S1**).

The Western creek, on the other hand, lies on the northwestern part of the bay outside the Mikoko Pamoja project area. This creek covers about 70 ha and is open to the seasonal river channel, River Kidogoweni, allowing inflow of freshwater during the rainy season. The creek is shallow with exposed sand banks during low tides (**Figure 1**). Due to proximity to human settlement in Gazi, the seagrasses in the western creek are highly influenced by fishing and tourism activities in the area (**Supplementary Figure S2**).

Sampling Design

The sampling approach adopted the protocol recommended by the Coastal Blue Carbon manual and the Intergovernmental Panel for Climate Change (IPCC, 2014). In each creek, eight transects at intervals of 100 m were initially laid perpendicular to the creek from the upper zone, adjacent to the mangrove ecosystem, all the way to the seagrass meadows near the open waters of the bay. Five quadrats measuring 0.5 × 0.5 m were laid along the transects at intervals of 25 m to determine the distribution and abundance of seagrass species in each creek. In assessing the spatial variability in sediment organic carbon

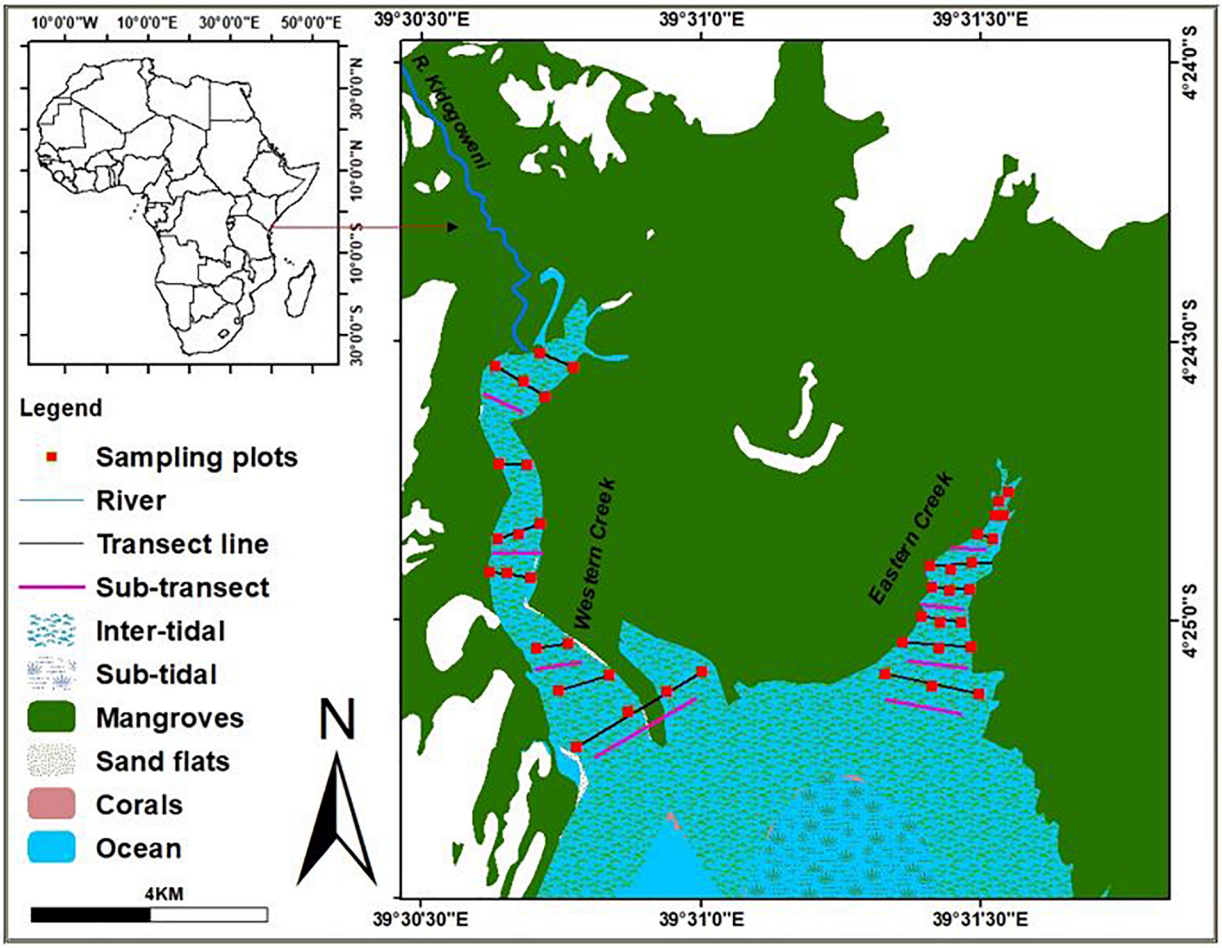

FIGURE 1 | MAP of Gazi Bay indicating the creeks and seagrass-covered areas.

and biomass between creeks, two sub-transects were laid within *Thalassia hemprichii*, *Cymodocea rotundata*, *Cymodocea serrulata* and mixed species stands in Western creek; and within *Enhalus acoroides*, *Thalassodendron ciliatum*, *C. rotundata* and mixed stands in the Eastern creek based on dominance. Five quadrates measuring 0.5 × 0.5 m were then laid along each sub-transect at intervals of 25 m. A total of 40 quadrats were established in each creek and 480 samples obtained for laboratory processing. Data collection was done during low spring tides, when the seagrass beds are easily accessible by foot.

Measurement of Physiochemical Parameters

Measurements for the analysis of the physiochemical parameters were done *in situ*, within the plots. Total dissolved solids (in milligrams per liter), conductivity (in microseconds per centimeter), water temperature (in degree Celsius), and pH were measured using the HANNA Combo PH and EC multimeter Hi-98129. The probe was immersed to 5 cm in water for every reading. Salinity (in parts per thousand) was measured in the creeks using a refractometer, while depth was measured using a tape.

Determination of the Species Type, Cover, Canopy Height, and the Shoot Density

Seagrass species were identified *in situ* using field manuals appropriate for the region included (Richmond, 2002). The percentage canopy cover was determined by visual estimate. Canopy height estimation involved measuring the total blade length of 10% of individual shoots randomly selected from the total number within the quadrat and calculating their mean heights. Shoot density was determined by counting the entire shoots within the quadrats and expressed in square meters (Howard et al., 2014).

Estimation of Above- and Belowground Biomass

Aboveground seagrass materials were harvested within the 0.25-m^2 quadrats and cleaned using freshwater. Sorting was done

followed by scraping using a razor blade to remove the epiphytes. The fronds were then washed in 10% HCl, rinsed to remove the calcareous materials, and then dried in an oven at 60°C for 72 h.

Estimation of the belowground biomass was done by taking four cores from each of the 0.25 m^2 quadrats using a Russian peat sampler. The cores were washed through a 500 μm sieve. Cleaned material was sorted into necromass, rhizomes, and roots and then dried in an oven for 72 h at 60°C. Total biomass was determined by multiplying the biomass with the carbon conversion factor of 0.34 and extrapolation done per hectare (IPCC, 2014).

Determination of Sediment C_{org}

Two sediment cores, each having an extension of 50 cm, were obtained using a peat sampler within the quadrats. Since the relative content of the sedimentary carbon may be influenced by the sediment compaction, the difference in length from the upper part of the core to the surface of the sediment, outside and inside the corer, was assessed when passing it down into the sediment (IPCC, 2014). Since we intended to analyze for sediment C_{org}, plant material, infauna, and larger shells were removed from the sediment samples. The samples were sliced into subsections of 5 cm and oven-dried at 60°C for 72 h in the laboratory to attain a constant weight. The top 50 cm estimates of the sediment were extrapolated to 1 m in estimating the carbon stocks (Howard et al., 2014).

Measurement of Percentage Organic Matter

The organic matter content was determined using the loss of ignition (LOI) technique at 450°C for 6 h. The percentage organic matter (OM) was calculated using the formula

$$\%\ \mathrm{LOI} = \left(\frac{\text{Initial dry weight} - \text{Weight remaining after ignition}}{\text{Initial Dry Weight}} \right) \times 100 \quad (1)$$

where % LOI is the percentage loss of ignition.

Depending on the organic matter in each of the sample, the sediment C_{org} values were calculated using the following relations (Howard et al., 2014):

$$\%\mathrm{LOI} < 0.20, \%\ C_{org} = -0.21 + 0.40\ (\%\ \mathrm{LOI}) \quad (2)$$

$$\%\mathrm{LOI} > 0.20, \%\ C_{org} = -0.33 + 0.43\ (\%\ \mathrm{LOI}) \quad (3)$$

where % LOI is the percentage loss of ignition and % C_{org} is the percentage sediment organic carbon.

Calculation of the Total Carbon Stocks

In order to determine the total carbon stocks in the two creeks, the soil dry bulk density (DBD) (sediment dry weight per unit volume) for each of the subsections per core was calculated using the formula:

$$\mathrm{DBD}\ (\mathrm{g/cm^3}) = \text{Dry weight/Original volume of sediment} \quad (4)$$

where DBD is the dry bulk density.

The soil carbon density was then calculated as follows:

$$\text{Soil carbon density}\ (\mathrm{g/cm^3}) = \text{dry bulk density}\ (\mathrm{g/cm^3}) \times (\%\ C_{org}/100) \quad (5)$$

The amount of carbon in each core section was then calculated by multiplying the soil carbon density (in grams per cubic centimeter) by 5 cm (the thickness interval). The amount of carbon per core was then obtained by the addition of the carbon amount in all the sections of one core and the value extrapolated to 1 m (Howard et al., 2014; Githaiga et al., 2017). An average amount of carbon was then obtained for the two cores in each quadrat for sediment C_{org}.

$$\text{Total core carbon (Mg C/hectare} - \text{cm)} = \text{Summed corecarbon}(\mathrm{g/cm^3}) \times (1\ \mathrm{Mg}/1,000,000\ \mathrm{g}) \times (100,000,000\ \mathrm{cm^2}/1\ \text{hectare}) \quad (6)$$

To determine the total amount of carbon in the two meadows, the average carbon stocks from each pool was summed up for each creek and the sum multiplied by the area of the creek.

The variabilities and errors associated with the measurements were determined by calculating the standard deviation for each pool in each creek and multiplying by the area of the corresponding creek.

Data Analysis

Species richness, diversity, and abundance were determined by the Shannon–Wiener diversity index (*H*) and index of evenness.

To analyze for statistically significant variations between creeks and among species, data were tested for normality and homogeneity of variance and log-transformed, where assumptions of normality were not found. One-way ANOVA was used to test for variations in the aboveground, belowground, and sediment carbon among species. Where significant variations were detected, Tukey's *post hoc* test was used to compare the means. Two-sample *t*-test was used to test for significant variations between the creeks. In all the statistical tests, the significant level was set at $\alpha = 0.05$. A generalized linear model (GLM) with Gaussian error distribution was fitted to establish the relationship between sediment carbon and the environmental variables in the Eastern and Western creeks.

RESULTS

Assessment of Physical–Chemical Parameters in Eastern and Western Creeks

Most of the physical–chemical parameters measured were found to vary significantly between the creeks. Depth ranged between 0.20 and 0.80 m in the Western creek (mean = 0.53 ± 0.31 m), while the values for the Eastern creek ranged between

TABLE 1 | Physical–chemical parameters in the Eastern and Western creeks.

Parameter	Western creek	Eastern creek
Depth (m)	0.53 ± 0.31	0.93 ± 0.20
pH (range)	7.4–8.3	7.8–8.0
Water temperature (°C)	31.9 ± 0.83	29.7 ± 0.40
Salinity	30.0 ± 0.60	34.7 ± 0.65
Turbidity (mg/L)	0.52 ± 0.07	0.32 ± 0.06

0.50 and 1.50 m (mean = 0.93 ± 0.20 m) during the low tide when the samples were taken (**Table 1**). Salinity varied between the two creeks, with the Eastern creek recording higher values (mean = 34.7 PSU, range = 33–35 PSU). The Western creek had a mean of 30.0 PSU (range = 29–31 PSU). The two-sample *t* test revealed a significant variation between the creeks (t = 40.82, df = 70, $p < 0.05$) at the 95% confidence level.

Turbidity values were higher in the Western creek (mean = 0.52 ± 0.07 mg/L, range = 0.35–0.68 mg/L) than in the Eastern creek (mean = 0.32 ± 0.06 mg/L, range = 0.2–0.41 mg/L). The means recorded for the two creeks revealed a significant difference ($t = -13.6$, df = 76, $p < 0.05$) at the 95% confidence level. The pH for the Western creek ranged between 7.4 and 8.3, while the pH values for the Eastern creek ranged between 7.8 and 8.0 (**Table 1**). There was significant variation in the water temperature ($t = -15.66$, df = 51, $p < 0.05$) at the 95% confidence level, with the Western creek having higher values (mean = 31.9 ± 0.83°C, range = 30.3–33.2°C) while the Eastern creek had a mean of 29.7 ± 0.40°C, range = 29.0–30.2°C.

Seagrass Species Diversity and Distribution Between the Creeks

Nine seagrass species out of the 12 species recorded in the entire bay were encountered in the creeks (**Table 2**). Six species – *C. rotundata*, *Halodule uninervis*, *T. hemprichii*, *C. serrulata*, *Syringodium isoetifolium*, and *E. acoroides* – were observed in both creeks. However, *Halophila stipulacea* and *Halophila ovalis* were only observed in the Western creek, while *T. ciliatum* was observed in the Eastern creek. The most common species in the Eastern creek was *T. ciliatum*, while *C. rotundata* was the most common in the Western creek (**Table 2**).

TABLE 2 | Seagrass species distribution and frequency in the Eastern and Western creeks.

Species name	Western creek		Eastern creek	
	Frequency	%	Frequency	%
Cymodocea rotundata	20	50	3	7.5
Halodule uninervis	9	22.5	4	10
Thalassia hemprichii	6	15	6	15
Cymodocea serrulate	6	15	7	17.5
Syringodium isoetifolium	1	2.5	2	5
Halophila stipulacea	6	15	0	0
Halophila ovalis	1	2.5	0	0
Enhalus acoroides	1	2.5	6	15
Thalassodendron ciliatum	0	0	18	45
Number of species observed	8		7	

The diversity of seagrass species (expressed as the Shannon–Wiener index, H) was higher in the Eastern creek (H = 1.71) than in the Western creek (H = 1.67). Similarly, the Eastern creek had a higher evenness value (E = 0.88) than the Western creek (E = 0.80). However, there was no significant difference in seagrass species diversity between the two creeks (t = 0.11, df = 13, p = 0.46).

Variation in Aboveground and Belowground Biomass Between Creeks and Among Species

The mean values in aboveground biomass between the two creeks were significantly different (t = -3.422, df = 79, $p < 0.001$) at the 95% confidence level, with the Eastern creek having higher biomass (1.01 ± 0.15 Mg C ha^{-1}, range = 0.24–3.79 Mg C ha^{-1}) than the Western creek (0.49 ± 0.03 Mg C ha^{-1}, range = 0.21–1.03 Mg C ha^{-1}). In the two creeks, the biomass values varied significantly between species [$F_{(7, 79)}$ = 38.35, $p < 0.001$], with the highest being recorded in *T. ciliatum* species (2.38 ± 0.28 Mg C ha^{-1}, range = 1.22–3.79 Mg C ha^{-1}) and the lowest in *C. rotundata* of the Western creek (0.35 ± 0.04 Mg C ha^{-1}, range = 0.21–0.56 Mg C ha^{-1}).

Belowground biomass indicated a significant difference ($t = -7.25$, df = 79, $p < 0.001$) at the 95% confidence interval, with the Eastern creek recording the highest at 9.17 ± 0.67 Mg C ha^{-1} (range = 0.76–16.72 Mg C ha^{-1}) while the Western creek had 3.84 ± 0.29 Mg C ha^{-1} (range = 0.67–8.92 Mg C ha^{-1}) (**Figure 2**). Belowground biomass was also significantly different among species [$F_{(7, 79)}$ = 12.98, $p < 0.001$], with *E. acoroides* recording the highest at 12.35 ± 1.02 Mg C ha^{-1} (range = 8.19–16.72 Mg C ha^{-1}) while the lowest was in *C. rotundata* of the Western creek at 3.07 ± 0.40 Mg C ha^{-1} (range = 1.14–4.42 Mg C ha^{-1}).

Comparison of Sediment Organic Carbon Among the Species and in the Creeks

Soil properties (dry bulk density and percentage organic carbon) significantly varied between the creeks ($p < 0.001$). These differences strikingly persisted to 50 cm depth (**Figure 3**). The Western creek recorded a higher mean dry bulk density at 1.49 ± 0.38 g cm^{-3}, while the Eastern creek recorded 0.87 ± 0.32 g cm^{-3}. On the other hand, the Eastern creek recorded a higher organic carbon concentration at 3.56%, while the Western creek recorded an average of 0.76%.

Sediment organic carbon differed among the species, with the highest values recorded in the mixed stands of the Eastern creek at 302.45 ± 43.23 Mg C ha^{-1} while *C. rotundata* of the Western creek had the lowest at 97.57 ± 7.74 Mg C ha^{-1} (mean ± 95% CI). One-way ANOVA revealed a significant

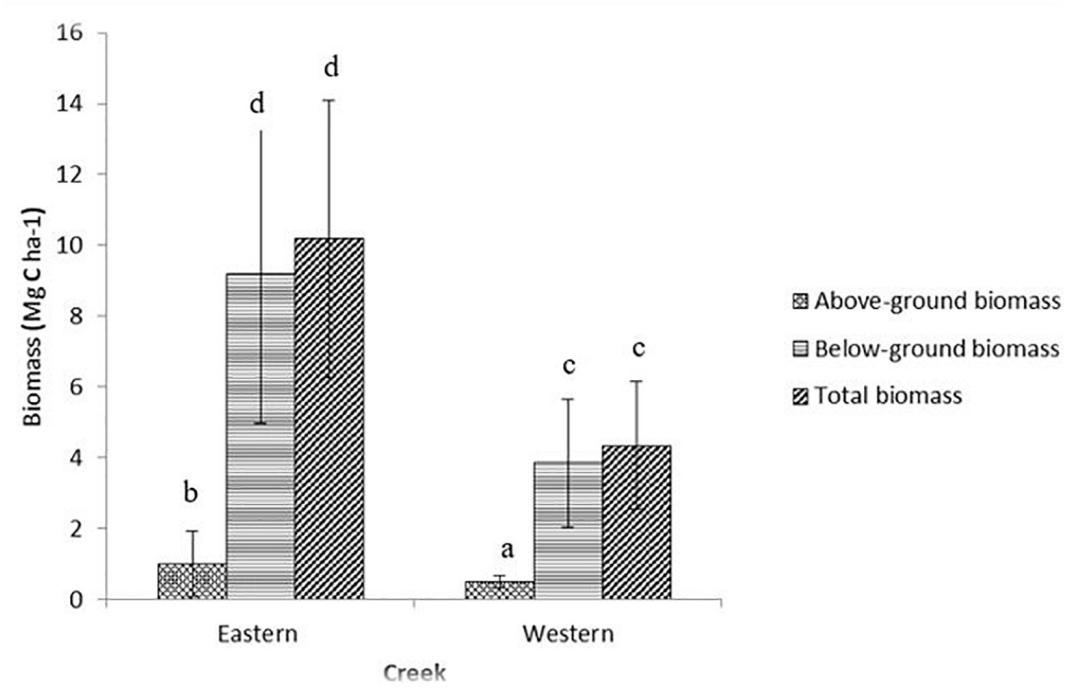

FIGURE 2 | Variations in biomass between the Eastern and Western creeks (mean ± 95% CI). Letters indicate significant differences in biomass ($p < 0.01$).

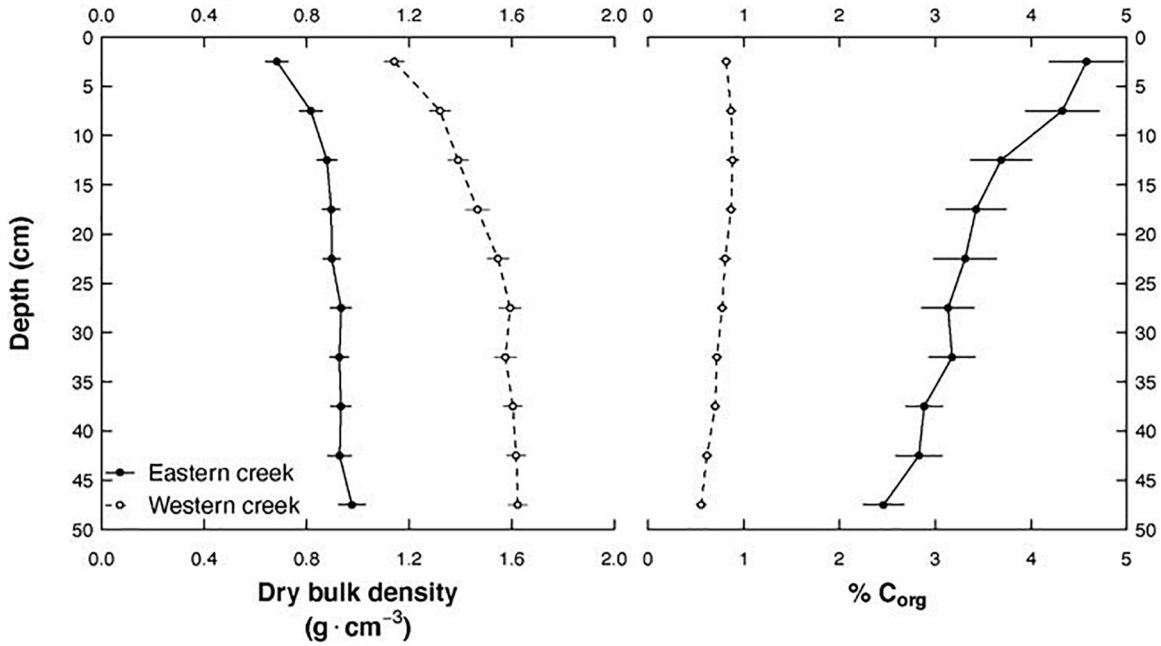

FIGURE 3 | Changes in soil dry bulk density and percentage organic carbon along depth to 50 cm and between the Eastern and Western creeks.

difference among the species C_{org} [$F_{(7,\ 79)} = 20.28$, $p < 0.001$]. Sediment C_{org} also varied between the creeks, with the Eastern creek recording higher values at 258.21 ± 90.12 Mg C ha^{-1} (range = 117.85–544.65 Mg C ha^{-1}) while the Western creek recorded 106.66 ± 21.36 Mg C ha^{-1} (range = 67.25–160.48 Mg C ha^{-1}) (**Figure 4**). The two-sample t tests revealed a significant difference in the sediment C_{org} of the two creeks ($t = -10.86$, $df = 44$, $p < 0.001$).

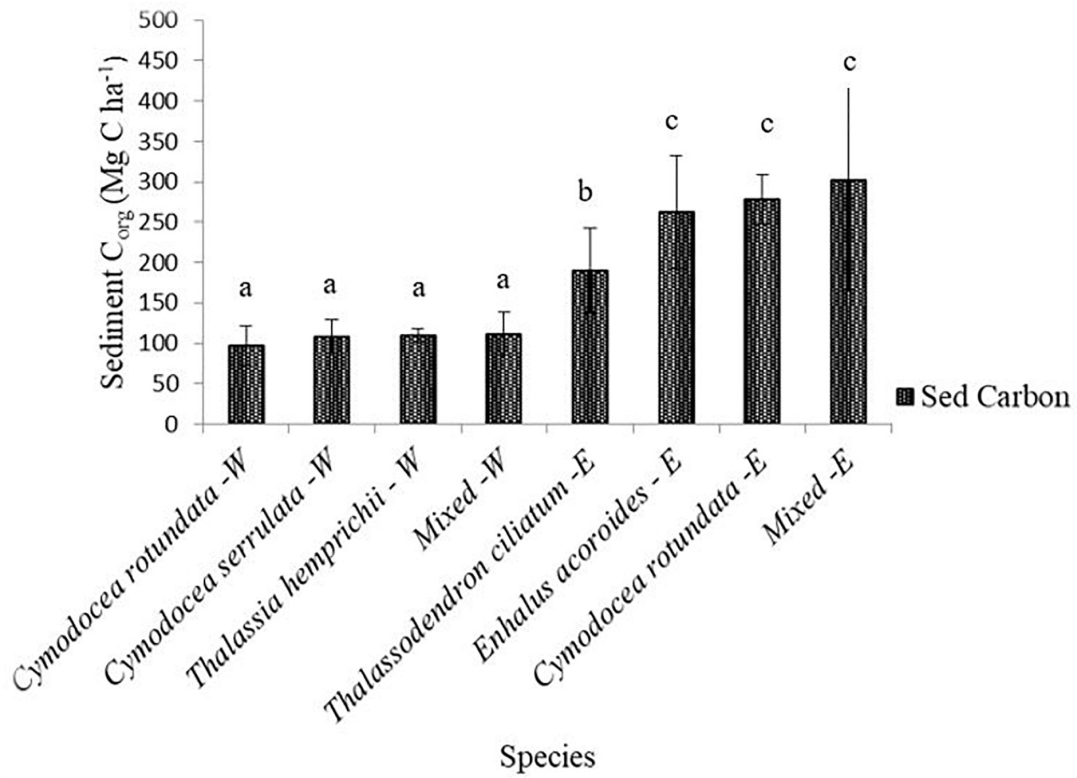

FIGURE 4 | Variations in sediment C_{org} to 1 m depth among species in the Eastern and Western creeks (mean ± 95% CI). *Sed Carbon*, sediment organic carbon; *E*, Eastern; *W*, Western. Letters a, b and c indicate significant difference in sediment carbon among species ($p < 0.001$).

Environmental Factors Explaining C_{org} in Eastern and Western Creeks

A GLM, with Gaussian error distribution, was fitted separately for each creek with sediment carbon as the continuous response variable. In the Eastern creek, GLM was constructed for seagrass species, belowground biomass, aboveground biomass, temperature, salinity, depth, shoot density, and seagrass shoot height as the explanatory variable. Turbidity was found to correlate above 0.7 with depth while temperature correlated to pH. Using the Akaike's information criterion (AIC), species (*T. ciliatum*, $p < 0.01$) and temperature ($p < 0.03$) had a significant influence on sediment carbon. The residuals of the best model (AIC = 22) are presented in **Supplementary Figure S3**.

In the Western creek, a correlation above 0.7 was found between depth and turbidity. A GLM was fitted for aboveground biomass, belowground biomass, species, shoot density, shoot height, pH, salinity, temperature, and turbidity. Aboveground biomass ($p < 0.03$), turbidity ($p < 0.05$), total shoot density (0.008), and species (*C. serrulate*: $p = 0.03$; mixed species: 0.05; and *T. hemprichii*: $p < 0.06$) were found to significantly influence sediment carbon stocks in the Western creek. The residuals of the model with the lowest AIC of 336 are shown in **Supplementary Figure S4**.

DISCUSSION

Sediment C_{org} Stock Variations Between the Creeks

The current study compared seagrass habitats in the Eastern and Western creeks of Gazi Bay, Kenya, in terms of their species composition, distribution and the carbon stocks in the above- and belowground components. The Eastern creek was dominated by *T. ciliatum* and *E. acoroides* that are characterized by long leaves and have higher shoot density, signifying more sediment trapping. Higher values for rhizomes, roots, and necromass were recorded in this creek. On the other hand, Western creek was dominated by small-leaved and short-lived species such as *C. rotundata*, which could be attributed to human perturbations and sediment erosion. It was also characterized by lower diversity, abundance, and shoot density of the seagrass communities. Such meadows are known to have lower dissolved organic carbon (DOC) supply, which is likely to affect the percentage of organic carbon through the reduced decomposition of the refractory organic compounds. This difference in species composition and shoot density between the creeks may therefore partly explain the differences in the concentrations of organic matter between them (Serrano et al., 2018; Enríquez et al., 2019), resulting in variations in sediment carbon between the creeks.

The study found that the Eastern creek had higher seagrass biomass and sediment C_{org} values for the top 1 m when compared to the Western creek and the values obtained by Githaiga et al. (2017) in the open waters of the bay (236 ± 24 Mg C ha^{-1}). Similarly, the average C_{org} values obtained for the two creeks are above the mean derived from the global seagrass data set at 166 Mg C ha^{-1}, although they are within the global range of 115.5–829.2 Mg C ha^{-1} (Fourqurean et al., 2012). Recent studies have indicated variations in organic carbon stock estimates and other seagrass community attributes such as species over such smaller spatial scales (Lavery et al., 2013; Röhr et al., 2016).

In the two creeks, sediment C_{org} stocks varied with species. This was the same case in biomass and other structural attributes such as shoot density and canopy heights, which could explain the variations in the carbon storage capacities. Large-leaved species are efficient in sequestering carbon as well as in trapping allochthonous carbon (Agawin and Duarte, 2002; Mellors et al., 2002). They also tend to establish more permanent and stable beds than the ephemeral and small species due to their higher resistance to hydrodynamic energy, hence the high carbon stocking (Ondiviela et al., 2014; Huxham et al., 2018). Additionally, rhizomes, roots, necromass, and DOC differ among species and contribute substantially to the primary production, resulting in more C_{org} in complex meadows with high shoot density and belowground biomass than in sparse meadows (Kaldy et al., 2006; Armitage and Fourqurean, 2016). The burial rates of both autochthonous and allochthonous organic carbon are estimated at 50% originating from other ecosystems (Kennedy et al., 2010; Duarte and Krause-Jensen, 2017). Past studies have shown that C_{org} from the adjacent mangrove ecosystems were transported to the seagrass meadows in both creeks (Bouillon et al., 2007; Huxham et al., 2018).

Nine seagrass species out of the 12 recorded in Gazi Bay were encountered in the two creeks during the study (Ochieng and Erftemeijer, 2003), with the Eastern creek having higher seagrass species diversity and abundance. Turbidity and depth were found to influence the species distribution and biomass between the creeks. The dominance of *T. ciliatum* in the Eastern creek can be attributed to the stable state of this creek. It is usually intolerant of any freshwater input and occupies hard and rocky substrates (Waycott et al., 2004). On the other hand, the pioneer and short-lived species *H. ovalis* and *H. stipulacea* were recorded only in the Western creek. The availability of an inflow channel (River Kidogoweni) in the Western creek and the shifting sand banks make this area highly disturbed, which could explain the existence of *H. ovalis* and *H. stipulacea* and the higher abundance of *C. rotundata*, which are usually pioneer species and occupy disturbed areas (Noel et al., 2012). Additionally, destructive fishing practices such as boat dredging were observed in this area and could contribute to the disturbance. The higher turbidity recorded in the Western creek may also account for the low seagrass diversity in this creek. Reduction of irradiance as a result of turbidity hinders the photosynthetic process, thereby affecting seagrass morphology and growth (Lee et al., 2007; Lavery et al., 2013).

Aboveground and Belowground Biomass

The total biomass estimates for the current study were within range when compared to other published data. The biomass values compare well with the 5.9 ± 0.9 Mg C ha^{-1} recorded by Githaiga et al. (2017) in the open water of the bay, although higher than the global mean of 2.51 ± 0.49 Mg C ha^{-1} (Fourqurean et al., 2012). The biomass values significantly varied between the creeks and were highly correlated to species and plant shoot density. Seagrass meadows with larger species have higher aboveground and belowground biomass compared to smaller species (Duarte and Chiscano, 1999). The variations in biomass among species and between creeks enhance the meadows' efficiency to sequester autochthonous C_{org}. The estuarine environment of the Western creek is likely to subject this seagrass habitat to periodic freshwater inundation, leading to low light levels and burial by suspended sediments, runoff turbidity, and nutrient loading (McDonald et al., 2016). This may lower the plant growth rate and shoot density in this creek, hence lowering biomass (Peralta et al., 2008). Additionally, the proximity of this creek to human settlement increases the prevalence of anthropogenic impacts on seagrass through boat dredging and seine net fishing, hence affecting seagrass survival and the expansion of meadows. This was observed during the study and may explain the lower biomass values recorded in the Western creek. The Eastern creek had species with numerous stems that have the ability to withstand wave action when compared to the other species. *Enhalus*, which also dominated this area, has big rhizomes, extensive root system, and large fronds, accumulating greater biomass in the belowground components during growth and development (Waycott et al., 2004). In general, the variation is attributed to differences in the biophysical parameters leading to different physiological, phenotypic, and morphological growth patterns of seagrass.

Total Carbon Stocks

The current study focused on seagrass carbon stocks within the mangrove-fringed creeks of Gazi Bay. It compared the carbon stocks between the Eastern and Western creeks that have varying biophysical features. In the Eastern creek (50 ha), the total carbon stocks in the three carbon pools is 13,419.5 ± 4,547 Mg. On the other hand, the Western creek (70 ha) has a total stock of 7,769.3 ± 1,518 Mg of carbon. Although the sediment carbon values were extrapolated to 1-m depth following IPCC (2014) and Githaiga et al. (2017), this may be a limitation since sediment C_{org} decreases with depth. Additionally, future studies may focus on carbon sources and the sediment accumulation rates. Based on the IPCC's tier 1 emission factor of 7.9 tons of C per hectare, protecting seagrass in these two creeks will prevent emissions of 948 Mg CO_2 eq. year-^{1} (IPCC, 2014). (Tier 1 emission factor uses a gain–loss concept to estimate carbon dioxide emissions, based on general conversion factors, obtained from globally combined databases; Howard et al., 2014). The sediment C_{org} data contributes information on the seagrass carbon budget of the greater Gazi Bay region and adds to our understanding of the total C_{org} of seagrass along the Kenyan coast and the African coastline.

This study shows that the community attributes (species) and carbon stocks (biomass and soil) of seagrass meadows can differ dramatically over small spatial scales and complements prior studies. Intertidal areas that are under the influence of riverine inputs (and greater human disturbance) can have lower species diversity and reduced carbon stocks when compared to those areas that do not experience these impacts. This type of spatial variability should be considered when designing blue carbon projects.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

GJ performed conceptualization of the draft, data curation, worked on the methodology, research administration, research investigation, the formal data analysis, writing the original draft, and performed editing and review. AM carried out conceptualization of the research, methodology development, supervision, validation of methods, visualization, writing, review and final editing. GM performed conceptualization, helped in developing methodology, supervision, project administration, validation of methods, and writing of the manuscript (review and editing). JK is a Pew Fellow (2019). He carried out research conceptualization, aligning methodology, field supervision, visualization, and manuscript writing (review and editing). All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00696/full#supplementary-material

FIGURE S1 | A section of seagrass meadows in Mangrove fringed Eastern creek.

FIGURE S2 | A section of seagrass meadows in the Western creek.

FIGURE S3 | Residuals of best fitted model (AIC = 22) for the Eastern Creek.

FIGURE S4 | Residuals of best fitted model (AIC = 336) for variables the Western creek.

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frontiers in Marine Science

ORIGINAL RESEARCH
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Assessing the Toxicity of Leachates From Weathered Plastics on Photosynthetic Marine Bacteria *Prochlorococcus*

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Marine plastic pollution is a well-recognized, global problem. Research addressing plastic pollution has largely focused on investigating impacts on macroorganisms, with few studies investigating effects on marine microbes. We previously showed that marine *Prochlorococcus*, which are important contributors to oceanic primary production, suffer declines in growth and photosynthetic activity following exposure to leachates from new plastic bags (HDPE) and plastic matting (PVC). However, as such plastics reside in the environment they will be subject to weathering processes, so it is also important to consider how these may alter the composition and amounts of substances available to leach. Here we report on how plastic leachate toxicity is affected by environmental weathering (17- and 112-days in estuarine water) of these common plastic materials. We found that while toxicity was reduced by weathering, materials weathered for up to 112-days continued to leach substances that negatively affected *Prochlorococcus* growth, photophysiology and membrane integrity. Weathered plastics were found to continue to leach zinc, even after up to 112-days in the environment. The two *Prochlorococcus* strains tested, NATL2A and MIT9312, showed differences in the sensitivity and timing of their responses, indicating that exposure to leachate from weathered plastics may affect even closely related strains to different degrees. As many marine regions inhabited by *Prochlorococcus* are likely to be subject to continued accumulation of plastic pollution, our findings highlight the potential for ongoing impacts on these important primary producers.

Keywords: weathering, plastic leachate, marine cyanobacteria, stress response, effective quantum yield of PSII, zinc

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INTRODUCTION

Plastics now play an important role in human society (Andrady and Neal, 2009) due to their relatively low cost and strong, durable, lightweight nature (Thompson et al., 2009b). Consequently, annual plastic consumption is increasing rapidly, with ∼350 million tones plastic produced globally in 2017, with 35% more plastic produced from 2007 to 2017 than ever before (Plastics Europe, 2018). Physical hazards to biota associated with marine plastic ingestion and entanglement have been reported across marine and estuarine environments worldwide (Derraik, 2002; Gregory, 2009; Wright et al., 2013; Gall and Thompson, 2015). Marine plastic debris has also been shown

to leach a "cocktail of chemicals" (Rochman, 2015). However, the impact of leached chemicals and trace elements from plastics on biota has been less rigorously studied compared to physical hazards (Hermabessiere et al., 2017). Plastic leachates can include substances added during manufacturing (Browne et al., 2007; Thompson et al., 2009a) and other compounds accumulated from the surrounding marine environments (Mato et al., 2001; Teuten et al., 2009). Additives used in plastic manufacture include polymerization solvents, plasticizers, metals, dyes, flame-retardants, UV stabilizers and antioxidants (Hahladakis et al., 2018). Some of these additives are thought to have the potential to enter the marine food web and adversely affect marine ecosystems (Avio et al., 2017).

Potential impacts of plastic leachate and additive compounds, singularly and as mixtures, have now been investigated for a variety of multicellular eukaryotic organisms. The chemical mixture leached from a range of different plastic items has been shown to have adverse effects on copepods *Daphnia magna* (Lithner et al., 2012b) and *Nitocra spinipes* (Bejgarn et al., 2015), barnacle *Amphibalanus amphitrite* larvae (Li et al., 2016), mussel *Perna perna* embryos (Gandara et al., 2016), sea urchin *Paracentrotus lividus* embryos (Oliviero et al., 2019), and microalgae *Chlorella vulgaris* (Luo et al., 2019). While less is known regarding leachate toxicity in prokaryotes, recent work has shown that a key photosynthetic marine bacteria, *Prochlorococcus*, is also adversely affected by exposure to leachates from new PVC and HDPE plastic items (Tetu et al., 2019). These studies together show many types of plastics have the potential to act as chemical toxicants but this area of research has mainly relied on leachate from new plastics and further work is required to ascertain how environmental weathering affects toxicity.

Plastics may take hundreds to thousands of years to degrade in the environment (Barnes et al., 2009), and degradation is thought to encourage leaching of toxic substances (Lithner et al., 2009) and transport of organic contaminants (León et al., 2018). Plastic debris released into the environment also has the potential to accumulate additional toxicants, with metals such as cadmium being found to adsorb to plastics in marine waters (Boucher et al., 2016). Organic pollutants, such as DDT, PCBs, and PAHs, have been observed on plastics collected from marine environments as well, implying adsorption of these compounds onto plastics (Rios et al., 2007). However, the conditions under which plastic additives or adsorbed toxicants may leach from plastics, and how this varies for different polymer types and weathering environments has only recently begun to be investigated. Laboratory experiments using artificial sunlight (UV irradiation) to look at how simulated weathering affects leachate toxicity found that effects varied for different plastic types, with some plastic products becoming more toxic, others less toxic, and some not changing significantly in their toxicity following UV irradiation (Bejgarn et al., 2015). A recent report from another laboratory experiment also showed temperature and mechanical stress can affect the toxicological impact of tire leachates to minnow embryos, with affects varying between different tire brands (Kolomijeca et al., 2020). Plastic aging experiments performed in marine waters showed that weathering processes involves both adsorption and desorption of different organic and inorganic substances and also found that different changes occur with different plastic items and polymer types (Kedzierski et al., 2018). These findings indicate that multiple issues would benefit from further exploration, including how specific physical conditions during weathering affect leachate toxicity through to how different plastic types are affected by weathering in terms of leachate toxicity, the latter being a focus of this work.

The marine photosynthetic microorganism, *Prochlorococcus*, is highly abundant in the world's oceans (Partensky et al., 1999a) and significantly contributes to global primary production, estimated to be 4 Gt C y^{-1} in some oligotrophic ocean regions (Flombaum et al., 2013). *Prochlorococcus* populations, composed of multiple, coexisting phylotypes, many of which are known to have distinct ecophysiological underpinnings, can be characterized as falling into two broad groupings distinguished by their photophysiology: high-light (HL) and low-light (LL) adapted ecotypes (Biller et al., 2015). Their ecological importance and population diversity make them an important organism to investigate regarding the impact of environmental stressors. Past work has shown *Prochlorococcus* to be negatively impacted by different organic pollutants (Fernández-Pinos et al., 2017), UV radiation (Llabrés and Agustí, 2006), exposure to high concentrations of copper (Mann et al., 2002), and exposure to leachate from unweathered HDPE and PVC plastic items (Tetu et al., 2019). Here we have investigated the response of two representative isolates of *Prochlorococcus*, LLI strain NATL2A and HLII strain MIT9312, to leachates from HDPE and PVC plastic that was weathered for 17- and 112-days in estuarine waters, as a first step in determining how environmental weathering affects leachate toxicity.

MATERIALS AND METHODS

Cell Culturing and Growth Monitoring

The two *Prochlorococcus* strains used in this experiment represent different ecotypes; NATL2A is a LL clade I (LLI) strain generally found in deeper euphotic zone layers of the ocean water column, while MIT9312 is a ubiquitous strain tolerant to higher light levels (Biller et al., 2015) falling within the HL clade I. *Prochlorococcus* NATL2A and MIT9312 cell cultures were grown in AMP1 media (Moore et al., 2007) with LED cool white irradiance of 20 and 40 μmol photons m^{-2} s^{-1}, respectively. All cultures were maintained at 22°C and 100 rpm shaking and experimental glassware was acid-washed as previously described (Tetu et al., 2019). Prior to each experiment all cultures were acclimated under experimental light and temperature conditions for at least three transfers to ensure balanced growth.

Plastic Weathering and Leachate Preparation

The plastic materials used in this study were gray plastic grocery bags (HDPE) and textured black matting (PVC), as used previously in Tetu et al. (2019). Both plastics were weathered during the Austral autumn-winter in tidal estuarine water of the Lane Cove river (GPS coordinates: 33° 49′37.2″S, 151°

09′14.4″E). In preparation for weathering, plastics were cut into ∼30 × 40 cm pieces (∼40–50 individual pieces for HDPE bags and ∼8–10 pieces for the PVC matting), then all pieces of each type of plastic were tied together at one corner using a nylon line. Material was placed into the environment on 8 April 2018 during low tide, with both plastic types secured to a single weight with sufficient line for both buoyant plastics to float ∼20 cm above their anchor point but at a depth sufficient for all plastic material to remain submerged at low tide. On 25 April roughly half of each type of plastic was cut from the anchor line and taken back to the laboratory (referred to as 17-days weathered plastic), while the remaining plastic was left, until 29 July, 2018 when all remaining material was collected (referred to as 112-days weathered plastic).

During the 17-days weathering period temperature and salinity (measured as conductivity) of the estuarine water were 23.4–25.1°C and 50,000–50,400 μS cm^{-1}, respectively (Beachwatch report for Tambourine Bay, Office of Environment and Heritage, NSW)[1], and the UV index ranged from 4.1 to 6.7[2]. The 112-days weathered plastics experienced these same conditions for first 17 days, then experienced an additional weathering period that had a lower and wider range of temperature and UV index (13.6–21°C and 0.9–5.1, respectively) and a more variable range of salinity, 49,600–53,300 μS cm^{-1}. No major storm or wind events were reported by the Australian Bureau of Meteorology during either period (BOM.gov.au).

At each collection time, material was transported immediately to the laboratory where each piece was washed thoroughly with sterile MQ water to remove any mud or debris until there was no visible fouling. The cleaned, weathered material was then used to generate leachates following the methodology applied in Tetu et al. (2019). Briefly, multiple large pieces of weathered, washed plastic were cut with ethanol-sterilized scissors into ∼1 cm^2 pieces, weighed, placed into sterile artificial seawater base for AMP1 (5 g per100 mL), then left for 5 days at 22°C and 100 rpm to allow leaching to occur. Following this leaching period, the contents of each flask were filtered through a 0.2 micron filter in order to obtain a sterile, particle-free leachate stock. Leachates were also prepared from unweathered HDPE and PVC materials using the same methodology. To each volume of filtered leachate stock, the standard AMP1 macronutrients, trace metals and HEPES buffer were aseptically added prior to use in culturing. Leachate stocks were diluted with vol/vol dilutions in AMP1 to make the experimental media. For weathered HDPE, leachate dilutions of 6.25 to 50% were tested, representing 3.125–25 mg mL^{-1} (or equivalent to ∼0.18–1.45 pieces per mL of media). For weathered PVC leachate dilutions of 1 to 50% in AMP1 were used, representing 0.5–25 mg mL^{-1} (or ∼0.002–0.1 pieces per mL of media).

Experimental Setup

Four independent cultures of each strain were set up from acclimated culture stocks and allowed to grow to mid-exponential phase before use as inocula for the replicates in each plastic experiment. Each experiment comprised of replicate control cultures in AMP1 (no leachate) and experimental treatments containing leachate from weathered and unweathered plastics at a range of dilutions. For weathered HDPE dilutions of 6.25, 12.5, 25, and 50% were tested, while unweathered HDPE dilutions of 12.5 and 25% were tested. For weathered PVC, dilutions of 1, 2, 10, and 50% were tested as well as 1 and 2% unweathered PVC. At initiation of the experiment (0 hr) the four independent parent cultures were measured to determine the number of chlorophyll fluorescent cells per mL, cell integrity, and photophysiology parameters (see below) then used to inoculate each of the control and leachate dilution treatments. All control and treatment cultures were then subsampled at 3, 24, and 48 h for all parameters as described below.

Flow Cytometry

The concentration and relative chlorophyll fluorescence of *Prochlorococcus* experimental cultures was quantified using a CytoFLEX S flow cytometer and data analyzed with CytExpert software (Beckman Coulter) as previously described (Tetu et al., 2019). *Prochlorococcus* cells were identified by chlorophyll fluorescence using blue laser (488 nm) excitation and violet side angle light scattering properties using violet laser (405 nm) excitation. Samples were gated so that only cells with chlorophyll fluorescence intensities indicative of healthy cells were counted. At each time point, subsamples were collected from each flask and analyzed immediately with the Cytoflex flow cytometer for all AMP1 control and weathered leachate treatments, while samples from unweathered leachate treatments were collected, fixed with paraformaldehyde (final concentration of 1%), stored at −80°C and run as a batch after conclusion of the experiment.

SYTOX Assay of Membrane Integrity

The membrane integrity of *Prochlorococcus* cells was measured on fresh samples within 1 h of collection using "live/dead" SYTOX Green stain (Invitrogen # S7020) and flow cytometry, based on the method of Mikula et al. (2012) with slight modifications optimized for our cells. Briefly, SYTOX stain was applied at a final concentration of 0.2 μM and cells were incubated for 15 min in the dark before measurement on a CytoFLEX S flow cytometer. Healthy *Prochlorococcus* cultures grown in AMP1 media were treated with 1% paraformaldehyde and stained with SYTOX as above as a dead control, used to determine the green fluorescence level (emission at 525/40 nm) of SYTOX positive stained cells. SYTOX-positive cells, i.e., those with damaged or compromised membranes, were identified by high green fluorescence and the proportion of SYTOX stained cells within the total chlorophyll fluorescence population was calculated for each treatment.

Functional Chlorophyll *a* Fluorescence Measurement

The effective quantum yield of photosystem II was measured using a Phyto Pulse Amplitude Modified (PAM) Fluorometer (Walz Heinz GmbH, Effeltrich, Germany) and the saturation pulse technique as described previously (Tetu et al., 2019). Briefly, light adapted fluorescence yield (F) was determined under growth

[1] www.environment.nsw.gov.au

[2] www.arpansa.gov.au

light conditions for each strain and a saturation pulse was applied to determine maximum light adapted fluorescence yield (F_m') to calculate the effective quantum yield of photosystem II, Φ_{PSII} ($\Phi_{PSII} = [F_m' - F]/F_m'$). Three technical replicates were run for each individual biological replicate, and an average of these for each biological replicate was used to calculate the average and standard deviation presented for each time point.

Elemental Analysis of Leachates

Experimental leachate and AMP1 media were subsampled into acid washed glass vials at the start of each experiment, acidified with 3.5% nitric acid and sent for Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma-Optical Emission Spectrometry ICP-OES analysis at the Mark Wainwright Analytical Centre, University of New South Wales, Sydney, NSW, Australia. ICP-MS and OES analyses were conducted on NexION 300D and Optima 7300DV instruments (Perkin Elmer, United States) with three technical replicates run for each sample. For ICP-MS internal standards, Rh, Ir, and Te (Choice Analytical, Australia) were used and analyses performed with a plasma gas flow rate of 15–17 L min^{-1}, auxiliary gas flow rate of 1–2 L min^{-1}, nebulizer gas flow rate of 0.85–1.2 L min^{-1}, and radio frequency power of 1500 W. The data were analyzed using Syngistix for ICP-MS software (Perkin Elmer, United States). For ICP-OES analyses, the internal standard Y, 371.029, was used and analyses performed with the plasma gas flow of 10–15 L min^{-1}, auxiliary gas flow rate of 0.30 L min^{-1}, nebulizer gas flow of 0.70 L min^{-1}, forward power of 1200–1400 W and reflected power of 20 W. The data were analyzed using Winlab32 software.

Statistical Analysis

The growth, photophysiology and SYTOX data were analyzed using one-way ANOVA followed by Tukey's multiple comparison test with 95% confidence interval. Inter-strain comparisons of SYTOX staining were performed using two-way ANOVA with a Sidak's multiple comparisons test for the length of weathering and for the % leachate addition for each plastic. For all the data treatments were compared to the control at the matching timepoint and considered significant where $p < 0.01$. The change in population over time (day^{-1}) was calculated as growth rates are calculated, by fitting linear regression models to the flow cytometric population density measurements from 3 to 48 h. All statistical tests were performed using GraphPad Prism 8 for Windows (GraphPad Software, La Jolla, CA, United States).

RESULTS

Changes in Population Growth

To investigate how environmental weathering of plastics affected leachate toxicity, PVC and HDPE plastics were weathered in estuarine waters for 17- and 112-days, then placed in artificial seawater to generate sterile-filtered, particle-free leachate stocks which were added to *Prochlorococcus* MIT9312 and NATL2A cultures at a range of dilutions. Unweathered HDPE and PVC materials were tested in parallel, allowing direct comparison of toxic effects from leachates derived from weathered and unweathered products. Weathered HDPE and PVC leachates reduced growth of *Prochlorococcus* at some concentrations but resulted in less severe declines in growth rates than for the equivalent unweathered leachate dilutions tested here (**Figures 1A–D**). For both plastic types, exposure to the 112-days weathered leachates resulted in more modest reductions in growth rate than for the 17-days weathered leachates when comparing equivalent dilutions, indicating that duration of weathering affected leachate toxicity (**Figure 1**).

The two *Prochlorococcus* strains showed differences in their growth rate responses to each of the weathered leachates, as seen for unweathered leachates. In MIT9312 exposure to weathered HDPE resulted in a significantly reduced ($p < 0.01$) growth rate compared to zero leachate controls for the two highest concentrations of 17-days weathered HDPE and the highest concentration of 112-days weathered HDPE. For NATL2A, growth rates were reduced to a lesser degree with only 50% weathered HDPE leachate from the 17-days treatment resulting in negative growth rates and showing a significant ($p < 0.01$) reduction relative to the control (**Figures 1A,B**).

For weathered PVC, MIT9312 also showed a strong response, with 10 and 50% treatments of 17-days weathered PVC resulting in statistically significant ($p < 0.01$) growth rate reductions relative to the control (**Figure 1C**). For this strain 112-days weathered PVC exposure also strongly reduced growth rates at the two highest concentrations (10 and 50%) (**Figure 1C**). NATL2A showed reductions in growth rate following exposure to the higher weathered PVC concentrations from both 17- and 112-days weathering (**Figure 1D**), but these were less severe than seen for MIT9312, reflecting what was observed for the unweathered PVC leachate.

Photophysiology

To determine if weathering altered the capacity for plastic leachates to affect photochemical efficiency of photosystem II (PSII) in *Prochlorococcus*, PSII quantum yield (Φ_{PSII}) was also measured following MIT9312 and NATL2A exposure to the weathered and unweathered PVC and HDPE leachates. Weathered leachate exposure affected Φ_{PSII} in a dose dependent manner but was less pronounced than for equivalent treatments with unweathered plastic leachates (HDPE shown in **Figure 2**, PVC in **Figure 3**).

The two strains showed differences in their photophysiological responses with respect to leachate dose sensitivity and timing. In strain MIT9312 photophysiology was not noticeably impacted at the 3 h time point by 17-days weathered HDPE leachate at any of the tested concentrations (**Figure 2A**). Significant ($p < 0.01$) declines in MIT9312 Φ_{PSII} were not observed until 24 h of exposure for 25 and 50% dilutions, and 48 h for 12.5%. In contrast NATL2A showed significant ($p < 0.01$) reductions in Φ_{PSII} starting at 3 h of exposure to all tested dilutions of 17-days weathered HDPE leachates. However, while the 17-days weathered HDPE elicited an earlier photophysiological response in NATL2A, this strain still retained measurable Φ_{PSII} after 48 h exposure to the 50% dilution, whereas MIT9312 was completely inhibited by this (**Figures 2A,B**).

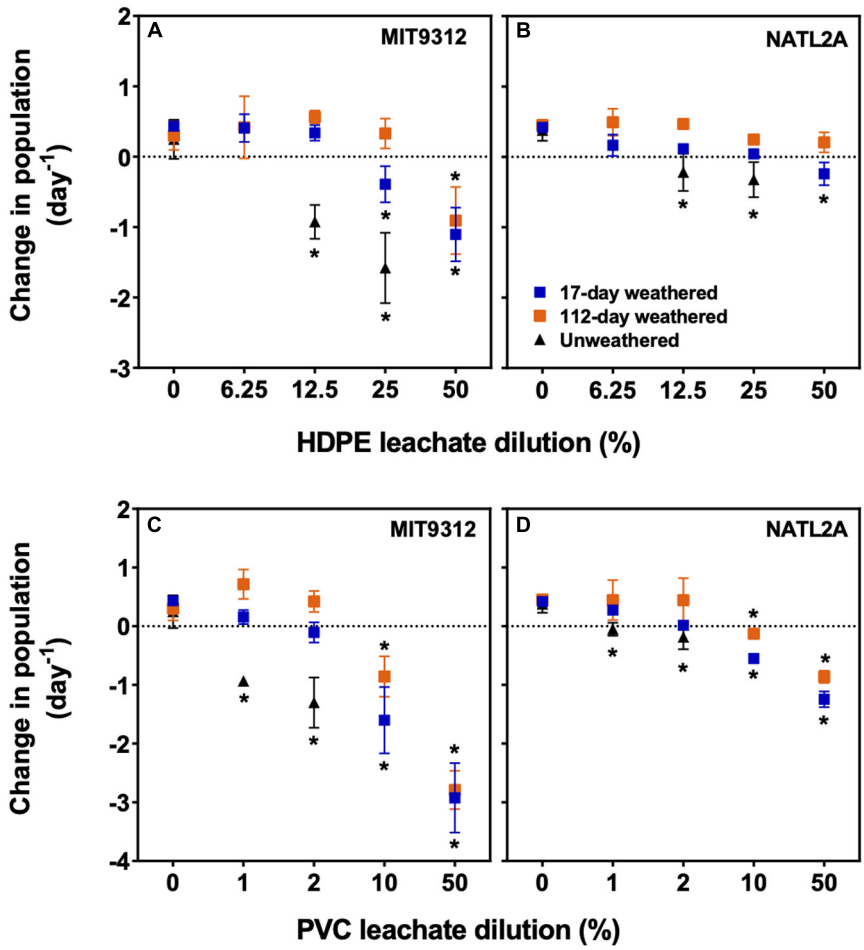

FIGURE 1 | Rate of population change **(A–D)** of *Prochlorococcus* MIT9312 and NATL2A in AMP1 media in the presence of different dilutions of leachates from HDPE and PVC materials subjected to two weathering treatments (17- and 112-days in estuarine sea water). Experiments were conducted over 48 h using biological replicates (n = 4; except unweathered treatment, n = 3) for each condition shown as mean values of all replicate cultures with error bars representing the standard deviation. Asterisks (*) indicate that the rate was significantly (p < 0.01) different for a specific leachate concentration relative to the no leachate control (0% leachate dilution). Symbols shown in panel **(B)** indicate the weathering treatment for all panels.

The longer weathering period of 112-days resulted in HDPE leachates which affected *Prochlorococcus* photophysiology to a lesser degree than leachates from 17-days of weathering, consistent with what was observed for growth rates. For both strains exposure to 112-days weathered HDPE only exhibited strongly impaired Φ_{PSII} when the 50% dilution was applied. In NATL2A short term Φ_{PSII} impairment was observed following exposure to 112-days weathered HDPE of 12.5% at 3 h and 25% at 24 h, but by 72 h these treatments had recovered and were similar to the control (**Figure 2D**). Measurement of Φ_{PSII} in MIT9312 remained unchanged for 112-days weathered HDPE concentrations below 50% over the 48 h monitoring period (**Figure 2C**).

Weathered PVC leachate exposure also resulted in differences in the timing and degree of response between the two strains, particularly for exposure to leachates from the 17-days weathered material (**Figure 3**). Similar to what was observed for weathered HDPE, 3 h of exposure to 17-days weathered PVC did not affect Φ_{PSII} in MIT9312 for most concentrations, with only the 50% leachate sample significantly affected at this early time point (**Figure 3A**). In NATL2A 3 h exposure to 17-days weathered PVC leachate resulted in significant reductions in Φ_{PSII} across all tested concentrations (**Figure 3B**). Again, as for HDPE, while NATL2A Φ_{PSII} responded more quickly to leachate exposure at all dilution levels, MIT9312 Φ_{PSII} exhibited stronger declines by 24 h to the higher levels of weathered PVC leachate (10 and 50%) compared to NATL2A, where Φ_{PSII} was still measurable for these treatments (**Figures 3A,B**).

After the longer weathering of 112-days, PVC leachates were still inhibitory to photosystem II in both strains when higher leachate percentages were applied (**Figures 3C,D**). Exposure to this longer weathered PVC leachate resulted in significant (p < 0.01) reductions in Φ_{PSII} in MIT9312 when applied at 10% and higher from 24 h onward (**Figure 3C**). In NATL2A the 112-days weathered PVC leachate at 50% concentration also strongly reduced Φ_{PSII}, at 24 h and after, while the 10% concentration

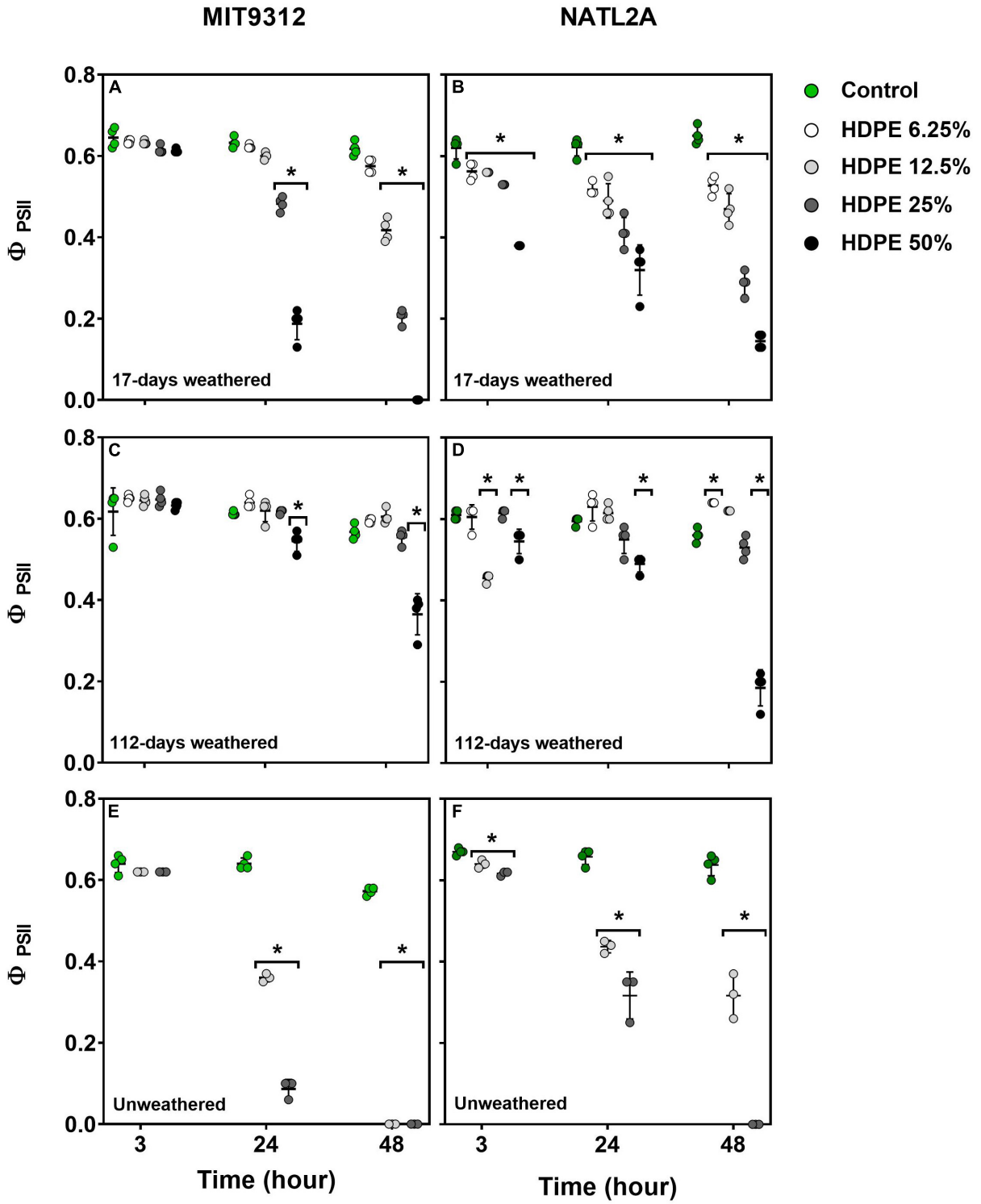

FIGURE 2 | Effective quantum yield of photosystem II (Φ_{PSII}) for *Prochlorococcus* MIT9312 and NATL2A exposed to different dilutions of HDPE leachates (**A,B**, weathered for 17-days; **C,D**, weathered for 112-days; **E,F**, unweathered) following different exposure times in hours. Experiments were conducted over 48 h using biological replicates (n = 4 for all weathered control and leachate treatments; n = 3 for all unweathered control and leachate treatments). Symbols represent the value for each replicate culture, the bar represents the mean ± standard deviations for the treatment at each time point. Asterisks (*) signify treatments for which measurements were significantly ($p < 0.01$) different compared to the control at the same time-point.

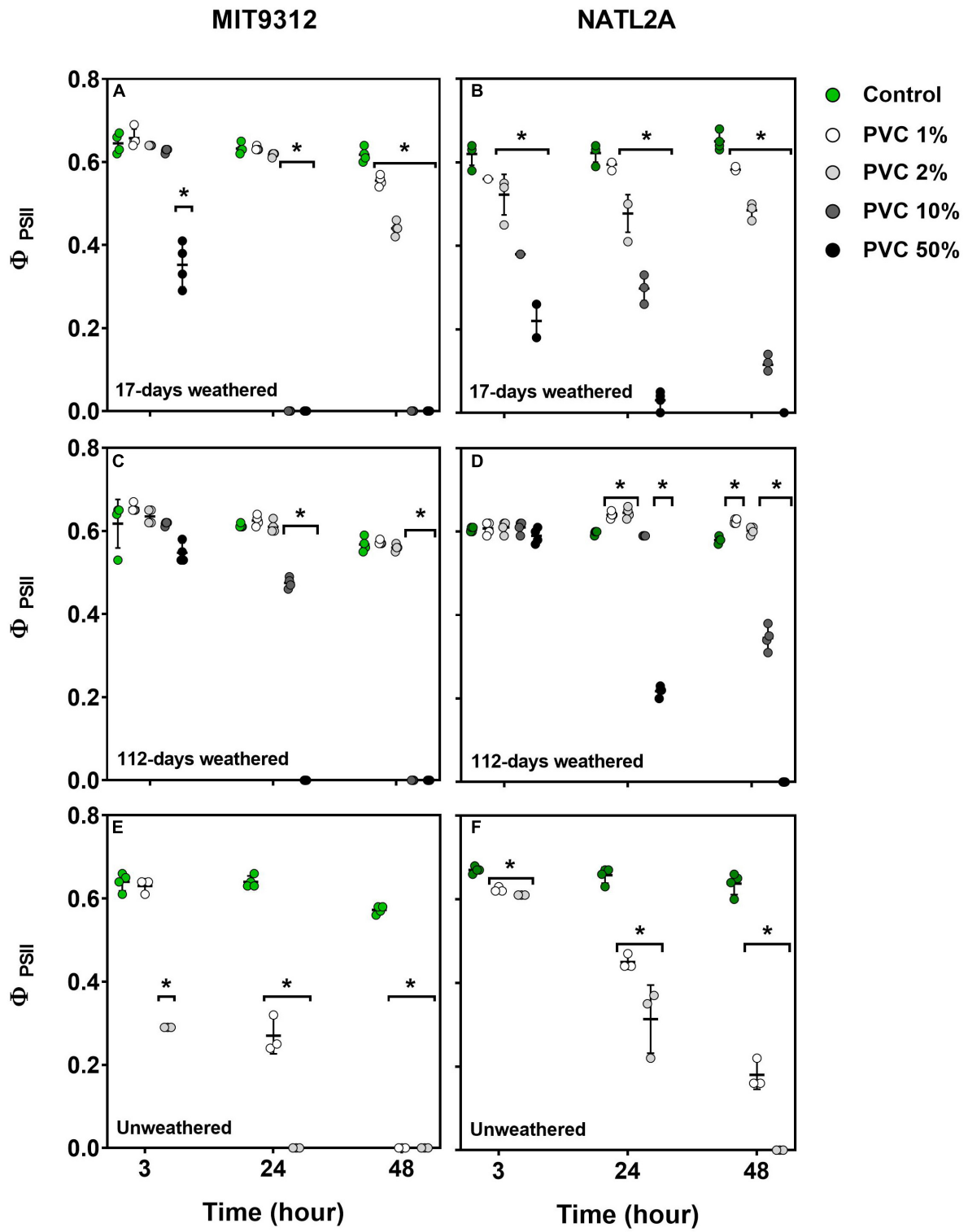

FIGURE 3 | Effective quantum yield of photosystem II (Φ_{PSII}) for *Prochlorococcus* MIT9312 and NATL2A exposed to different dilutions of PVC leachates (**A,B**, weathered for 17-days; **C,D**, weathered for 112-days; **E,F**, unweathered) following different exposure times. Experiments were conducted over 48 h using biological replicates (n = 4 for all weathered control and leachate treatments; n = 3 for all unweathered control and leachate treatments). Symbols represent the value for each replication, the bar represents the mean ± standard deviations for the treatment at each time point. Asterisks (*) signify treatments for which measurements were significantly ($p < 0.01$) different comparing to the control at the examined time-point.

resulted in strong reductions only at 48 h (**Figure 3D**). Exposure to lower concentrations of 112-days weathered PVC did not strongly affect Φ_{PSII}, with values remaining similar or slightly higher than controls (**Figures 3C,D**).

Cell Membrane Integrity

For both *Prochlorococcus* strains, cell populations were examined using the "live/dead" SYTOX Green stain at 3, 24, and 48 h to determine whether leachate exposure resulted in membrane damage. The strains of *Prochlorococcus* showed differences in the proportion of the population showing membrane damage and in the timing at which this damage occurred following weathered leachate exposure. In strain MIT9312 noticeably higher proportions of the population showed cell membrane damage than for NATL2A when comparing most weathered and unweathered HDPE and PVC leachate treatments by 48 h (**Figure 4** and **Supplementary Table S1**).

Exposure to leachate from weathered HDPE plastic items resulted in a significant ($p < 0.01$) increase in the proportion of MIT9312 cells showing membrane damage compared to the no leachate control, with 17-days weathering effects observed as early as 3 h for 12.5% HDPE and higher. Additionally, the proportion of cells showing damage continued to increase over time (**Figures 4A–C**). By 48 h up to 70% of the MIT9312 population was membrane compromised for the 17-days weathered 50% HDPE treatment. The longer weathered (112-days) HDPE leachate also resulted in a significant increase in membrane compromised cells in MIT9312 for the 50% treatment at 24 h as well as both 25 and 50% at 48 h. Unweathered HDPE leachate had a similar or higher impact on membrane damage to the 17-days weathered leachates in MIT9312 (**Figures 4A–C**).

In NATL2A no significant changes in membrane integrity were observed at the early time point (3H) for any of the weathered HDPE leachate treatments (**Figure 4D**). For this strain small but significant ($p < 0.01$) changes were reported for 17-days weathered leachate at 24 h for 25% HDPE and higher, and for all % HDPE treatments at the 48 h point, while 112-days weathered HDPE only impacted membrane integrity at 50% after 24 h exposure or longer (**Figures 4E,F**). Unweathered leachate treatments affected NATL2A membrane integrity sooner and to a higher degree than weathered leachates, but the proportion of population affected remained below 40% (**Figures 4D–F**).

Plastic PVC matting leachates from both weathering periods resulted in significantly ($p < 0.01$) increased proportions of membrane compromised cells after 48 h exposure for concentrations of 10% or higher for both tested strains (**Figure 4**). For MIT9312 17-days weathered PVC leachate significantly ($p < 0.01$) increased the population of SYTOX stained cells after as little as 3 h for dilutions as low as 1% PVC (**Figures 4G–I**). Longer weathering (112-days) resulted in leachates that damaged cell membranes more slowly. However, by 24 h MIT9312 exposure to 2% PVC and above had significantly increased the % SYTOX stained populations, indicating that plastics were still leaching substances damaging to cells after close to 4 months of weathering. In NATL2A after 3 h, only exposure to 50% of 17-days weathered PVC leachate exhibited significantly ($p < 0.01$) compromised membranes, and not until 48 h of exposure did all tested 17-days weathered leachate treatments show significant membrane damage (**Figures 4J–L**). For both strains unweathered PVC showed a similar or higher impact on membrane integrity than equivalent dilutions of leachate from weathered material (**Figure 4**).

Elemental Analysis

Leachate elemental composition analyses conducted using Inductively Coupled Plasma-Optical Emission Spectrometry and Mass Spectrometry (ICP-OES and ICP-MS) identified elements enriched in leachates relative to AMP1 control medium with no plastic leachate added. The concentration of zinc (Zn) was elevated in all analyzed leachates, with the highest degree of enrichment in leachates from unweathered material, followed by 17-days weathered, then 112-days weathered material (**Tables 1A, B**). PVC consistently leached significantly ($p < 0.01$) higher amounts of Zn than HDPE with leachates from unweathered HDPE and PVC plastics containing ∼30X and ∼458X higher Zn than the AMP1 control, respectively, similar to what was observed previously (Tetu et al., 2019). After 17-days of weathering, average Zn levels dropped in both HDPE and PVC leachates such that they were ∼13X and ∼70X higher, respectively, compared to what was measured for the AMP1 control, however, these differences were not statistically significant. After the longer 112-days period of environmental weathering, HDPE leachate contained slightly elevated Zn (∼3X) while levels were still ∼30X enriched in the PVC leachates relative to AMP1 control media (both differences not statistically significant). Both HDPE and PVC weathered leachates also showed somewhat higher levels of strontium (Sr) than the AMP1 control media, however, this was only significant ($p < 0.01$) for 112-days weathered HDPE (**Tables 1A, B**). The concentrations of chromium (Cr), copper (Cu), manganese (Mn), and nickel (Ni) were below the method detection limit (MDL) in the AMP1 control media but within the measurable range in some leachates suggesting these may have also been slightly enriched in some leachates. Of the other elements measured, most were below the MDL in both media and leachate (Si, As, Cd, Mo, Pb, Sn, V) or were observed at similar levels in leachates and the AMP1 base media (Ca, Na, S, Al, B, Ba) (**Tables 1A, B**).

DISCUSSION

While there is now some recognition that plastic pollution may impact marine organisms via leaching of harmful chemicals (Hermabessiere et al., 2017), the effect of weathering on leachate toxicity is still poorly understood. To our knowledge only a few studies have investigated how weathering of plastics affects the toxicity of substances which leach from this material and these have focused on toxicity to eukaryotes rather than to bacteria (Bejgarn et al., 2015; Kedzierski et al., 2018; Gardon et al., 2020; Kolomijeca et al., 2020). In this study, we report that common HDPE and PVC plastic items continue to leach substances following environmental weathering for up to 112-days which can adversely impact *Prochlorococcus* growth, photosynthesis

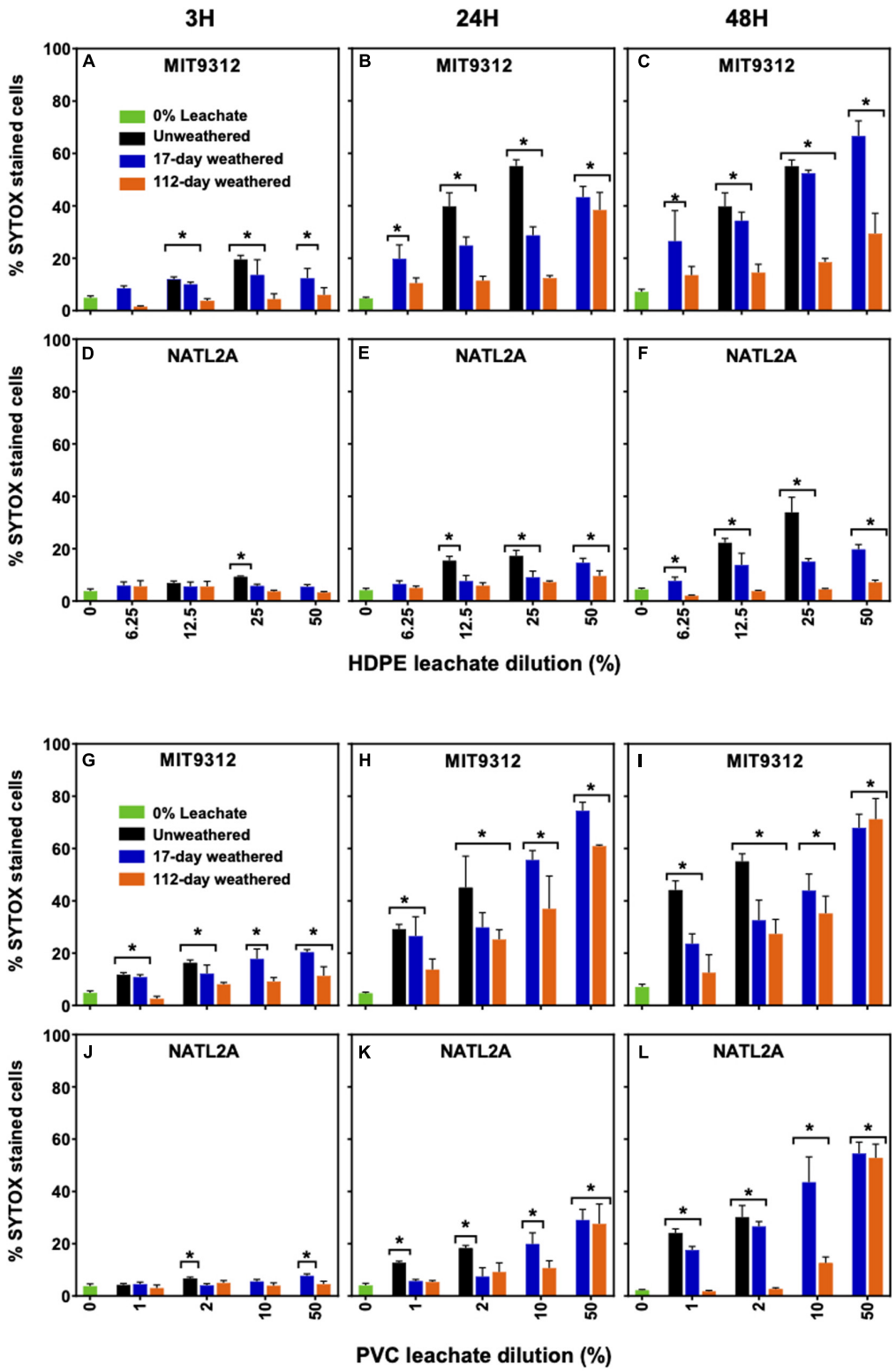

FIGURE 4 | SYTOX Green stained (i.e., membrane compromised) populations after exposure to different dilutions of weathered HDPE leachates in *Prochlorococcus* **(A–C)** MIT9312, **(D–F)** NATL2A and PVC leachates in *Prochlorococcus* **(G–I)** MIT9312, **(J–L)** NATL2A. Leachate from HDPE and PVC weathered for 17-days in blue bars, weathered for 112-days in orange bars, unweathered in black bars. Zero leachate control are represented by green bars. Column height corresponds to mean ± standard deviation values of the biological replicates (n = 4 for all except unweathered where n = 3). Asterisks (*) are used to signify data points where measurements were significantly ($p < 0.01$) different compared to the 0% leachate control at each time point to eliminate the small changes in % SYTOX stained cells for the control.

TABLE 1A | Concentrations of selected elements in unweathered and weathered (17- and 112-days) HDPE leachates AMP1 and control media detected by ICP-OES and ICP-MS, and their factor of increase in leachates relative to control.

Method	Element	MDL	Unit	Control (AMP1)	HDPE leachate			HDPE leachate factor of increase relative to control		
					Unweathered	17-days	112-days	Unweathered	17-days	112-days
ICP-OES	Ca	10	mg/L	378 ± 35	379 ± 67	363 ± 19	321 ± 21	1.00	0.96	0.85
	Na	20	mg/L	11375 ± 534	11030 ± 1225	10385 ± 788	9338 ± 204	0.97	0.91	0.82
	S	10	mg/L	985 ± 95	932 ± 148	899 ± 62	799 ± 57	0.95	0.91	0.81
ICP-MS	Al	5	μg/L	70 ± 61	91 ± 3.5	96 ± 70	83 ± 44	1.30	1.38	1.19
	B	5	μg/L	47 ± 12	44 ± 12	82 ± 20	56 ± 12	0.93	1.74	1.19
	Ba	5	μg/L	28 ± 11	27 ± 6	47 ± 14	38 ± 9.5	0.96	1.64	1.35
	Cr	5	μg/L	0.43 ± 0.14	0.60 ± 0.09	11 ± 0.68	6.3 ± 0.20	NA	NA	NA
	Cu	5	μg/L	1.9 ± 1.6	4.5 ± 3.07	9.5 ± 10	4.4 ± 0.25	NA	NA	NA
	Mn	5	μg/L	2.6 ± 0.40	5.7 ± 1.1	1.4 ± 0.53	1.3 ± 0.18	NA	NA	NA
	Ni	5	μg/L	4.8 ± 0.37	5.4 ± 1.6	5.6 ± 1.7	2.5 ± 0.38	NA	NA	NA
	Sr	5	μg/L	49 ± 13	57 ± 25	70 ± 19	105 ± 9.1	1.17	1.43	2.16
	Zn	5	μg/L	11 ± 11	340 ± 132	152 ± 22	30 ± 11	30.22	13.53	2.63

Values reported here are means ± standard errors; where mean concentrations were lower than the method detection limit, results are shown in gray font. Factors of increase were not calculated where measurements were below the accurate detection limit for control media. Si, As Cd, Mo, Pb, Sn, V concentrations were under the detection limit for both leachate and control (so values not shown).

TABLE 1B | Concentrations of selected elements in unweathered and weathered (17 and 112-days) PVC leachates and AMP1 control media detected by ICP-OES and ICP-MS, and their factor of increase in leachates relative to control.

Method	Element	MDL	Unit	Control (AMP1)	PVC leachate			PVC leachate factor of increase relative to control		
					Unweathered	17-days	112-days	Unweathered	17-days	112-days
ICP-OES	Ca	10	mg/L	378 ± 35	357 ± 78	397 ± 15	408 ± 21	0.94	1.05	1.08
	Na	20	mg/L	11375 ± 534	10635 ± 898	10774 ± 462	9987 ± 283	0.93	0.95	0.88
	S	10	mg/L	985 ± 95	942 ± 143	943 ± 57	837 ± 49	0.96	0.96	0.85
ICP-MS	Al	5	μg/L	70 ± 61	38 ± 3.5	78 ± 49	86 ± 57	0.54	1.12	1.24
	B	5	μg/L	47 ± 12	52 ± 1.6	120 ± 25	92 ± 4.1	1.10	2.56	1.97
	Ba	5	μg/L	28 ± 11	38 ± 2.3	33 ± 10	29 ± 12	1.33	1.15	1.03
	Cr	5	μg/L	0.43 ± 0.14	0.87 ± 0.36	0.45 ± 0.14	0.48 ± 0.13	NA	NA	NA
	Cu	5	μg/L	1.9 ± 1.6	6.9 ± 1.3	5.3 ± 2.1	7.2 ± 0.83	NA	NA	NA
	Mn	5	μg/L	2.6 ± 0.40	5.1 ± 1.6	8.6 ± 1.8	10 ± 0.84	NA	NA	NA
	Ni	5	μg/L	4.8 ± 0.37	4.6 ± 0.03	4.9 ± 0.15	3.8 ± 0.27	NA	NA	NA
	Sr	5	μg/L	49 ± 13	438 ± 268	199 ± 62	183 ± 11	8.98	4.07	3.75
	Zn	5	μg/L	11 ± 11	5157 ± 1544	791 ± 29	337 ± 32	458.25	70.24	29.92

Values reported here are means ± standard errors; where mean concentrations were lower than the method detection limit, results are shown in gray font. Factors of increase were not calculated where measurements were below the accurate detection limit for control media. Si, As Cd, Mo, Pb, Sn, V concentrations were under the detection limit for both leachate and control (so values not shown).

and membrane integrity. However, the weathering process did substantially reduce toxicity.

The environmental weathering applied here to HDPE bags and PVC matting resulted in leachates that were considerably less toxic than leachates from unweathered material, and there was a continued reduction in toxicity between the 17- and 112-days leaching period, based on growth rate, photophysiology and membrane integrity measurements. This indicates that over time, weathering in estuarine waters can change the composition or concentration of leachable compounds that are capable of adversely affecting marine *Prochlorococcus* growth. This is similar to what was recently reported in work on pearl oysters comparing leachate toxicity from new and aged plastic pearl-farming gear (a mix of polyethylene and polypropylene), which reported reduced toxicity for leachates from aged material (Gardon et al., 2020).

Leachates derived from weathered PVC showed higher toxicity than was observed with the equivalent HDPE weathered leachate, as seen with unweathered leachates from these materials. Toxicity of PVC was also maintained over a longer period of weathering with 112-days weathered PVC leachate still able to significantly impair growth and photophysiology at concentrations as low as 10%. The elemental analysis performed in this study showed PVC continued to leach zinc at amounts higher than the basal media at the longer 112-days weathering period. The HDPE product, which leached lower levels of zinc to begin with, showed zinc levels only slightly higher than

the base media in 112-days weathered material. PVC products have been shown to leach higher levels of zinc than other polymer types, in our previous study (Tetu et al., 2019) and by others (Oliviero et al., 2019). Our results here indicate that PVC litter may also be particularly problematic as it has the potential to continue to leach zinc over a considerable period of environmental weathering. Additionally, it is likely that leachate components not measured in this study, including organic substances, were also different across the two tested weathered materials and the composition and concentrations of these other substances could also have contributed to the observed differences in toxicity. Both organic and inorganic additives are likely to be substantially higher in weathered PVC leachate than from other plastics types, as production of PVC uses much higher amounts of additives than any other polymer type, with an estimated 73% of world production of additives directed to PVC plastics (Rochman, 2015). Copper, a known toxicant of *Prochlorococcus* at concentrations as low as 2.3 pM (Mann et al., 2002), and manganese, known to reduce chlorophyll *a* biosynthesis and photosynthesis in *Synechocystis* sp. PCC 6803 at 150 μM (Brandenburg et al., 2017; Eisenhut, 2020), also continued to leach from weathered PVC at amounts above those measured in the AMP1 control media and may have also contributed to the toxicity of weathered PVC.

Environmental weathering processes have the potential to alter plastic leachate composition in a variety of ways. A wide range of plastic additives, including metals and organic compounds used during manufacturing, can leach out from plastic debris immersed in water (Hermabessiere et al., 2017; Hahladakis et al., 2018). Work by Kedzierski et al. (2018) examining PVC plastic weathered in seawater showed that additives released from this material had increasing estrogenic activity on *Saccharomyces cerevisiae* from 14 to 63 days, following which it declined for the remainder of the 502-days study period. They suggest this may be due to immersion resulting in an initial loosening of the PVC polymer matrix, facilitating the desorption of entrapped compounds into the seawater (Kedzierski et al., 2018). However, desorption of substances from weathered plastics likely varies for different starting materials, as seen in this study and in previous work with marine copepods which showed simulated weathering (UV) of a variety of plastics resulted in leachates with increased toxicity for some items but unaltered or decreased toxicity for other materials (Bejgarn et al., 2015). Recent lab-based experiments which have begun to explore how certain characteristics of the weathering environment, such as temperature and mechanical stress, can affect leachate toxicity have also indicated that the nature of such changes is complex and product dependent (Kolomijeca et al., 2020).

The other main potential source of toxicants from weathered plastic are substances from the environment that adsorb to plastic debris whilst immersed in marine waters (Rochman, 2015), which may, under some set of conditions, later desorb. While the dynamics of adsorption and desorption relating to plastics are variable and generally not well understood (Ashton et al., 2010; Holmes et al., 2012, 2014), it is thought that this process may be a potential source of metals in some marine ecosystems (Munier and Bendell, 2018; Prunier et al., 2019). Our elemental analysis showed that higher levels of Cr and Sr were leached from weathered HDPE than from unweathered material, while leached Mn was elevated in weathered PVC, with levels increasing as the weathering period extended, indicating these metals may have been adsorbed from the surrounding estuarine waters or sediments. However, it is also possible they represent additives which have only begun to be released after some period of weathering. In either case it is clear there is potential for complex alterations in the makeup of leached substances and for continued toxicity as plastic weathering proceeds.

While this work sheds light on the potential for environmental weathering to affect the composition and toxicity of plastic leachates, it is important to point out that these experiments were conducted using methodology based on previous leachate ecotoxicology testing (Lithner et al., 2012a) rather than seeking to mimic environmental exposure scenarios. Indeed, it is difficult to determine what marine bacteria in the oceans may currently experience in terms of leachate exposure, as there are very few measurements of the substances that leach from plastic debris, or their concentrations, in the marine environment. The patterns and timeframes associated with movement of plastics from coastal source locations to open ocean regions are also complex and variable, influenced by temporal and spatial factors (e.g., season and currents), water properties (e.g., sea surface height and current velocities), and plastic particle properties (e.g., size, type and extent of biofouling) (Kako et al., 2010; Maximenko et al., 2012; Liubartseva et al., 2018; Jalón-Rojas et al., 2019). In one study based on models of drifters, Maximenko et al. (2012) estimated that the minimum time for microplastic debris to reach the Great Pacific Garbage Patch from the West Coast of the United States was less than 100 days. While there are still many unknowns, studies to date do suggest the HDPE bags and PVC matting used in this work represent the types of plastic that are likely to maintain buoyancy, even when degraded into smaller particles, remaining for some time in the photic zone down to at least 50 m (Erni-Cassola et al., 2019; Lebreton and Andrady, 2019) where the *Prochlorococcus* strains used in this study reside (Partensky et al., 1999b; Malmstrom et al., 2010). Although the marine cyanobacterium *Prochlorococcus* used in this study is the dominant open ocean photosynthetic genus, it is also found in mesotrophic and coastal seas, including the Adriatic Sea (Santic et al., 2011) and East China Seas (Jiao et al., 2005) which receive significant amounts of plastic waste that are estimated to have a floating half-life before beaching of 7–80 days (Kako et al., 2014; Liubartseva et al., 2018).

The two *Prochlorococcus* strains used in this study showed noticeable differences in the timing and extent of certain aspects of their response to each of the tested weathered leachates, similar to what was observed in our previous study (Tetu et al., 2019). Growth rate measurements indicated that MIT9312, a high light ecotype, was more susceptible to strong growth rate reduction than NATL2A, a low light ecotype, when exposed to HDPE and PVC weathered leachates. Photophysiological measurements showed MIT9312 exhibited stronger reductions in Φ_{PSII} at a wider range of weathered leachate concentrations at 24 and 48 h, but responses tended to be observed at earlier timepoints in NATL2A than for MIT9312. Transcriptomics results from

our earlier study showed that each of these strains co-opts a different regulatory network in response to unweathered leachate exposure, which likely accounts for the different growth and photophysiological responses and sensitivities also observed here for weathered leachate exposure. Interestingly, previous work on copper toxicity in *Prochlorococcus,* using different strains to those tested here, showed high-light adapted *Prochlorococcus* to be more copper resistant than low-light adapted ecotypes (Mann et al., 2002), contrasting with what we observed here for plastic leachate toxicity. Although there are no known studies on metal toxicity for the strains of *Prochlorococcus* used in our study, it is possible that the differences in plastic leachate toxicity between these two strains may be related to ecotypic differences in responses to the high amounts of zinc released by these weathered plastic items. Investigating plastic leachate sensitivities and transcriptional responses across a wider range of *Prochlorococcus* strains and ecotypes would assist with determining if the leachate sensitivity differences seen here are specific to particular strains, or generally consistent among different representatives of high light and low light ecotypes.

We also observed clear differences between our tested strains in regard to membrane damage following leachate exposure, with membrane integrity compromised in MIT9312 sooner (as early as the 3 h timepoint) and across a wider range of weathered leachate concentrations than seen in NATL2A. We measured changes in membrane integrity in this work as transcriptomic results from our previous study (Tetu et al., 2019) implied that MIT9312 might be more sensitive to membrane damage following plastic leachate exposure. In the previous work MIT9312 showed significantly reduced transcription of a number of cell wall and membrane biogenesis-associated genes in response to unweathered leachate exposure, while few genes in these categories showed significantly different transcription in NATL2A, which is consistent with the greater membrane sensitivity observed here for MIT9312. While it is not possible to identify whether specific leachate components are responsible for membrane damage, one possibility is that zinc in the leachates may have contributed, as previous investigations into the response of freshwater cyanobacteria to high levels of zinc showed cell membrane impairment (Newby et al., 2017). Future studies focused on toxicity of specific plastic leachate components, including organic substances, would help determine which component, or mix of components, contributes to membrane damage and would allow the investigation of mechanisms by which specific toxicants affect cell membranes and other processes in these organisms.

CONCLUSION

Both HDPE and PVC plastic products investigated here showed reduced toxicity after environmental weathering, whilst retaining some capacity to negatively affect *Prochlorococcus* cell membrane integrity and photophysiology. Weathering was observed to alter the elemental composition of plastic leachates, with the substances leached into artificial seawater following weathering, potentially representing both additives and substances adsorbed from the estuarine environment. Zinc, a widely used plastic additive and a known toxicant, was particularly noticeable in PVC products and leached at relatively high levels, suggesting PVC materials may retain the capacity to adversely impact some photosynthetic marine bacteria for at least 112 days after introduction to the environment, as observed in this work. Further studies into adsorption/desorption dynamics of different plastics under environmental weathering conditions looking at both organic and inorganic leached substances are needed to better understand how plastic litter may affect key marine organisms, particularly microorganisms. In this work we have also shown that two strains of *Prochlorococcus* differed in the timing and severity of their response to the weathered leachate, in ways reminiscent of their responses to unweathered plastic leachate. Extending such investigations across a wider variety of *Prochlorococcus* strains, other marine photosynthetic microorganisms and natural communities will help determine the range of organisms which respond negatively to plastic leachates and potentially identify different stress response mechanisms employed to respond to toxicants. Such information could help with predicting whether release of toxicants from marine plastic debris during weathering has the potential to alter the composition or functionality of marine microbial communities.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

ST conceptualized the research with input from IS. IS performed the experiments and carried out the data analysis with help from LM and ST. All authors contributed to writing the manuscript.

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Me and My Behavior: An Experiment on Individual Characteristics and Compliance Behavior in Recreational Fishing

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Non-compliance with regulations is a complex problem in recreational fisheries management, having the potential to evoke uncertainty for conservation and socio-ecological outcomes and to undermine management efforts. While we know that in fisheries people make trade-offs between following or breaking rules, it is of interest to determine how people respond to different management incentives to curtail non-compliance. The overall aim of this study is to examine what individual psycho-social characteristics are associated with responses to instrumental and normative management incentives in a recreational fisheries context through the use of an economic experiment. We examined five psycho-social characteristics, three of which (expectation of behavior of others, social norms, and risk preferences) have separately been explored within the fisheries compliance literature, while two factors (ecological values and personality types) have yet to be explored. While information about these two latter characteristics is limited within the fisheries compliance literature, our results suggest that they are relevant predictors for certain compliance groups across compliance incentives. The findings underline that there is significant heterogeneity in the associations between psycho-social make-up and compliance behaviors. Knowledge of this behavioral relationship can progress fisheries management toward increased innovation by encouraging the management of the individual fisher rather than the average fisher.

Keywords: economic experiment, social norms, fisheries management, psycho-social characteristics, marine social science

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INTRODUCTION

Marine recreational fisheries are ecologically, culturally, and economically important. Recreational fisheries are generally managed as a regulated open access resource, but the common pool nature of recreational fisheries makes them vulnerable to overexploitation. The success of fisheries management depends on factors such as strong leadership, social capital, and incentives (Gutiérrez et al., 2011) as well as having congruent objectives (Hilborn, 2007), and good governance (Potts et al., 2020). Recreational fisheries are traditionally managed via a mixture of regulations and rules

(Morison, 2004). However, achieving an acceptable rate of compliance in recreational fisheries is inherently difficult because there is often no formal mechanism to monitor and record the actions of recreational fishers (Green and McKinlay, 2009). Additionally, due to the high numbers and wide distribution of fishers enforcement of rules and regulations for recreational fishing is costly and typically low (Raakjær Nielsen and Mathiesen, 2003; King and Sutinen, 2010). Non-compliance is a tenacious problem in recreational fisheries management, posing a risk to marine conservation and socio-ecological systems (Blank and Gavin, 2009; Smallwood and Beckley, 2012; Arias and Sutton, 2013). In fisheries management, deterrence-based approaches have traditionally been used to tackle non-compliance. However, sufficient monitoring and enforcement are often limited and prohibitively costly in recreational fisheries (Cooke et al., 2013).

Understanding compliance behavior of recreational fishers is thus of great policy and management relevance. In response to this, behavior change initiatives that are not based solely on deterrence methods are beginning to be proposed and implemented to improve compliance (Battista et al., 2018; Mackay et al., 2018). Compliance is typically framed as a binary issue, wherein fishers are either compliant or not, with substantial research directed at measuring and identifying compliance (Honneland, 1999; Sutinen and Kuperan, 1999; Thomas et al., 2016; Bergseth et al., 2017). Increasingly, attention has focussed toward understanding the drivers and motivations of compliant and non-compliant behaviors (Boonstra et al., 2017) with several theories being proposed to explain why individuals engage in compliant behaviors (Bottoms, 2002).

For example, instrumental theories suggest that the decision of whether to comply or not is based on self-interested calculations about the expected costs and benefits of compliance, and that non-compliance occurs because the cost outweigh the benefits (Becker, 1968). Rules and regulations for recreational fishing are traditionally designed and implemented based on the assumption that fishers are instrumental actors (Sutinen and Kuperan, 1999) with reported instances of improved compliance with more enforcement (Gigliotti and Taylor, 2004). Normative theories, on the other hand, argue intrinsic values, such as an individual's perceptions of the legitimacy and fairness of rules, are crucial to fishers' decisions about compliance (Nielsen, 2003; Nielsen and Mathiesen, 2003; Grimes, 2006; Viteri and Chávez, 2007). In accordance to this theory, there are cases of high compliance where there is weak enforcement and low penalties due to established normative behavioral drivers (Sutinen and Kuperan, 1999; Gezelius, 2002, 2003).

In addition to instrumental and normative drivers, the literature suggests that psycho-social characteristics of individuals, such as attitudes, personality traits, and specific values toward the good in question, are important factors determining the patterns in individual compliance behavior (Nielsen, 2003). Key psycho-social characteristics that have been attributed to compliance behavior are social norms, such as morality and social reputation (Milner-Gulland and Rowcliffe, 2007; Challender and MacMillan, 2014; Arias, 2015). There are several examples drawn from fisheries as well as wider literature that build a strong case for the application of social norms in fisheries compliance management (Kuperan and Sutinen, 1998; Sutinen and Kuperan, 1999; Thomas et al., 2016). For example, empirical studies of norm conformity show that focusing people on an existing norm is an important step toward compliance (Cialdini et al., 1990; Reno et al., 1993). Another psycho-social characteristic influencing compliance behavior is expectation of others' compliance behavior as it reflects social perceptions (Bergseth and Roscher, 2018). Expectations about others' choices have been found to significantly predict one's own choice (Bicchieri and Xiao, 2009; Bova et al., 2017). Often expectation of others' compliance behavior will reflect an individual's own behavior. The expectation of others' behavior is regularly over-estimated, for example fishers who poach may also overestimate the prevalence of poaching (Berkowitz, 2005; Rimal and Real, 2005; Bergseth and Roscher, 2018).

Other psycho-social characteristics are ecological values and personality types. Environmental ethics literature suggests that having strong ecological values should render high compliance rates where non-compliance would result in some form of environmental degradation (Brennan and Lo, 2002; Nuyen, 2011). Broadly, ecological values and attitudes are key drivers of environmental behavior which relevant for non-compliance issues related to fisheries (Dunlap and Van Liere, 1978; Stern and Dietz, 1994; Ones et al., 2015). The relationships between personality types and compliance behaviors is not prevelant in fisheries compliance literature. However, personalty types, such as openness, extraversion and neuroticism, have been linked with rates of policy violations (McBride et al., 2012) within other compliance literatures. Compliance and co-operation, on the other hand, has been linked to agreeableness (Digman and Takemoto-Chogk, 1981; Graziano and Eisenberg, 1997; Graziano et al., 1997). Finally, individuals' risk preferences have been found to be correlated with compliance with fisheries regulations (Brick et al., 2012; Girardin et al., 2017).

The overall aim of this study is to examine what psycho-social characteristics of individuals are associated with responses to instrumental and normative management incentives in a recreational fisheries context. While there is literature reviewing and testing some of the characteristics mentioned relating to compliance behaviors in fishing and non-fishing contexts, there is a gap in the literature exploring these characteristics concurrently within a controlled experimental setting. To achieve this aim, we conducted a laboratory-based common pool resource economic experiment in which participants faced four hypothetical fishery scenarios where compliance is measured in terms of whether participants exceed a catch limit. The fishing scenarios use a combination of normative and instrumental incentives to encourage compliance behavior with a catch limit. Building on the results of Mackay et al. (2019) which presents the results for each of the four scenarios comparing the normative and instrumental incentives, here we examine both consistency and variation in behavior across the four scenarios. In doing so we can isolate the effects of an instrumental and normative incentive in both a low deterrence and a high deterrence context. The implication of such a study will contribute to the gap in identifying if there are any patterns in psycho-social characteristics for those who are consistently compliant, those

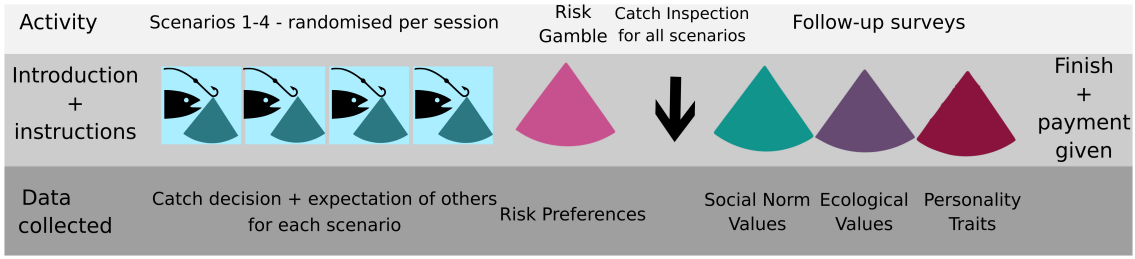

FIGURE 1 | Sequence of data collection within experiment in order. Segments colors represent each of the data collected; teal represents the catch/compliance data, pink represents risk preferences, green represents social norm values, purple represents ecological values and dark red represents personality types.

TABLE 1 | Specifications of the fishery scenarios [adapted from Mackay et al. (2019)].

Fishery scenario	Level of deterrence (instrumental incentive)	Normative message included (normative incentive)	Regulation reminder statement
Scenario 1	5%	No	There is a catch limit of TWO (2) fish. There is a 5% chance that you will come across an inspector on your fishing trip who will be checking if you are within the catch limit.
Scenario 2	5%	Yes	There is a catch limit of TWO (2) fish, but according to last year's data the average fisher chose to catch only ONE (1) fish. There is a 5% chance that you will come across an inspector on your fishing trip who will be checking if you are within the catch limit.
Scenario 3	20%	No	There is a catch limit of TWO (2) fish. There is a 20% chance that you will come across an inspector on your fishing trip who will be checking if you are within the catch limit.
Scenario 4	20%	Yes	There is a catch limit of TWO (2) fish, but according to last year's data the average fisher chose to catch only ONE (1) fish. There is a 20% chance that you will come across an inspector on your fishing trip who will be checking if you are within the catch limit.

who free-ride, and those who are influenced as intended by improving compliant behavior for different incentives.

MATERIALS AND METHODS

Compliance Decision Data Collection

We collected compliance decision data by running an economic experiment in which student participants faced four hypothetical scenarios in a recreational fishery context (**Figure 1**). The experiment was run for 20 sessions with 120 student participants (i.e., 6 students × 20 sessions) at the University of Tasmania, Australia from 12 May to 2 June 2017. At the start of each session, participants were provided an information sheet and consent form, in accordance with ethics approval from the Tasmania Social Sciences Human Research Ethical Committee (Ethics Ref: H0016420). The experiment was designed to reflect the common pool resource context of recreational fishing with groups of six anonymous participants fishing individualistically from the same resource. This design is a standard static common pool resource game used in economic experiments (Cardenas, 2011; Castillo et al., 2011). For more detail on the experimental process and design please see Mackay et al. (2019).

For each session, a group of six participants earned money by 'catching fish', which reflects the enjoyment fishers receive from going fishing. The amount they earned was based on how many fish they decided to catch and the group total catch. Specifically, as each person caught more fish they earned more money, however, as the group's total catch increased *ceteris paribus*, the individual's reward for catching additional fish decreased. The payoff function is detailed in **Supplementary Appendix A**. To measure compliance, we set an individual catch limit of two fish, but each fisher had the option to catch up to five fish in each fishing scenario. Catch equal to or below the catch limit was categorized as compliant and catch higher than the limit was non-compliant.

We encouraged compliance with the catch limit using a combination of two management incentives, specifically an instrumental (i.e., level of deterrence) and a normative incentive (i.e., social norm message), resulting in four scenarios (**Table 1**). These were delivered through regulation reminders prior to catch decisions for each scenario. The instrumental management incentive was applied by setting the probability of having the catch inspected at either 5 or 20% to create low and high levels of deterrence. If inspected and found to have caught more fish than the limit, the participant received a payoff of zero. The normative management incentive was framed around a descriptive social norm. The norm depicted the catch of a typical fisher in a hypothetical fishery and was given alongside the reminder of the catch limit and level of deterrence (**Table 1**). The exact wording of the normative message was; "according to last year's data the average fisher chose to catch only ONE (1) fish." The experiment

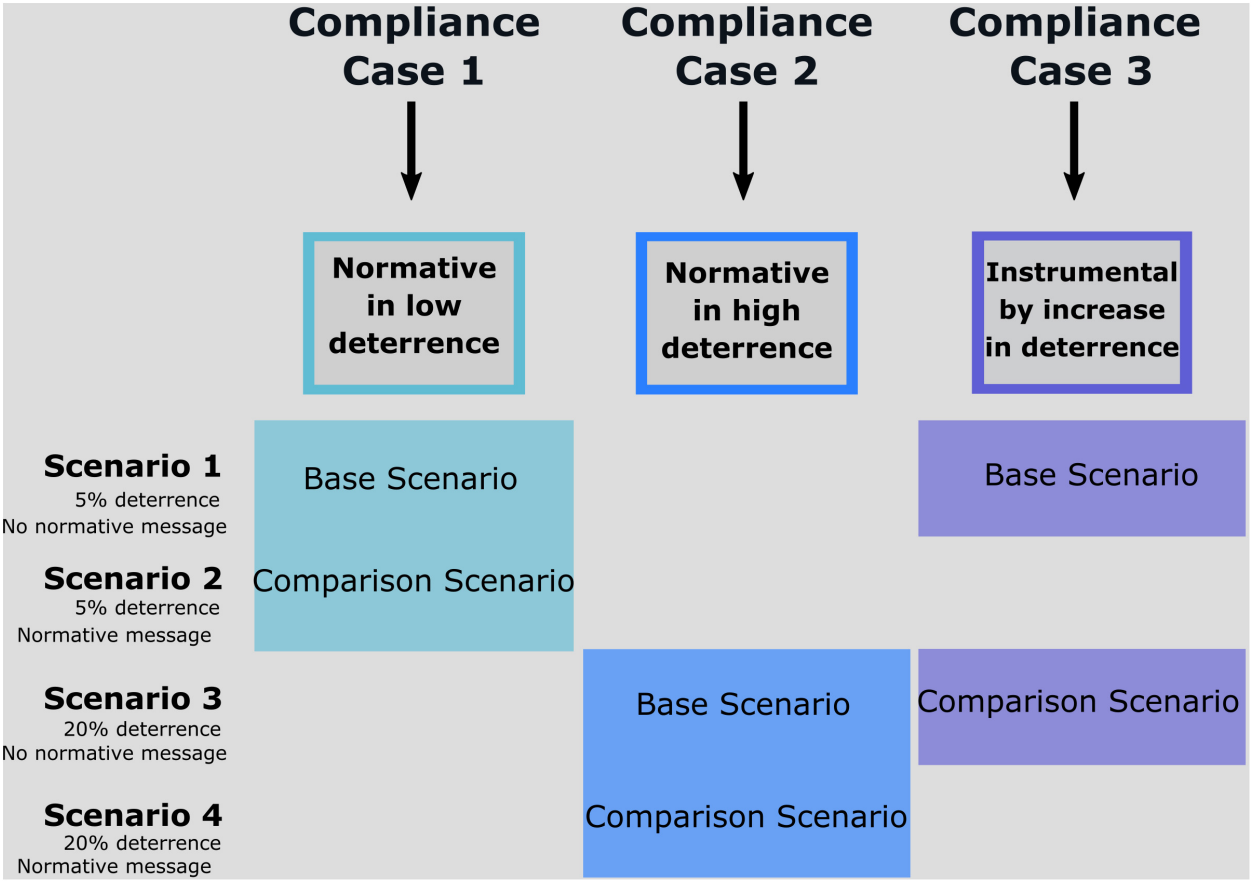

FIGURE 2 | Fishery compliance cases. Using the four experimental fishery scenarios three compliance cases are defined by comparing compliance decisions in a base scenario and a comparison scenario. The three compliance cases are: (1) normative incentive in a low deterrence context, (2) normative incentive in a high deterrence context, and, (3) an instrumental incentive via an increase in deterrence.

is a within-subject design in which each participant took part in all four fishery scenarios. To mitigate the potential ordering effect, the order of the scenarios was randomized for each session.

In this study, our interest is in understanding the association between individual's psycho-social characteristics and their response to management incentives aimed at improving compliance outcomes. Specifically, we draw on the fishery scenarios to define three compliance cases, each comprising a base scenario and a comparison scenario in which either a normative or instrumental incentive is applied (**Figure 2**). For compliance case 1, we compare behaviors with and without a normative incentive in a low deterrence context (Scenario 1 and Scenario 2 in **Table 1**). For compliance case 2, we compare behaviors with and without the normative incentive in a high deterrence context (Scenario 3 and Scenario 4 in **Table 1**). The third compliance case observes the influence of an increase in deterrence without the normative incentive (Scenario 1 and Scenario 3 in **Table 1**).

Compliance Response Groups

We constructed the categorical compliance response variable based on participants compliance decisions within the base scenario and comparison scenario (**Figure 3A**) resulting in four nominal categories, namely; (i) the *compliers*, (ii) the *free-riders*, (iii) the *incentivized*, and (iv) the *non-compliers*. First, the compliers are those who were consistently compliant for both base and comparison scenarios. The free-riders are those who were compliant in the base scenario and non-compliant in the comparison scenario. The participants who behaved this way are named the free-riders as they have responded to the incentive in an unintended way, possibly in an attempt to maximize payoff on the assumption that others will comply in response to the management incentive resulting in their own increased catch yielding a higher return. Third, the incentivized, who were non-compliant in the base scenario and compliant in the comparison scenario, are named as such as they have responded as intended to the management incentive. The final group, the non-compliers, were consistently non-compliant across both scenarios. Each of the four compliance response groups are potentially characterized by different psycho social-factors which is shown conceptually in **Figure 3B**) and is the hypothesis empirically tested in this study to answer the overall research question.

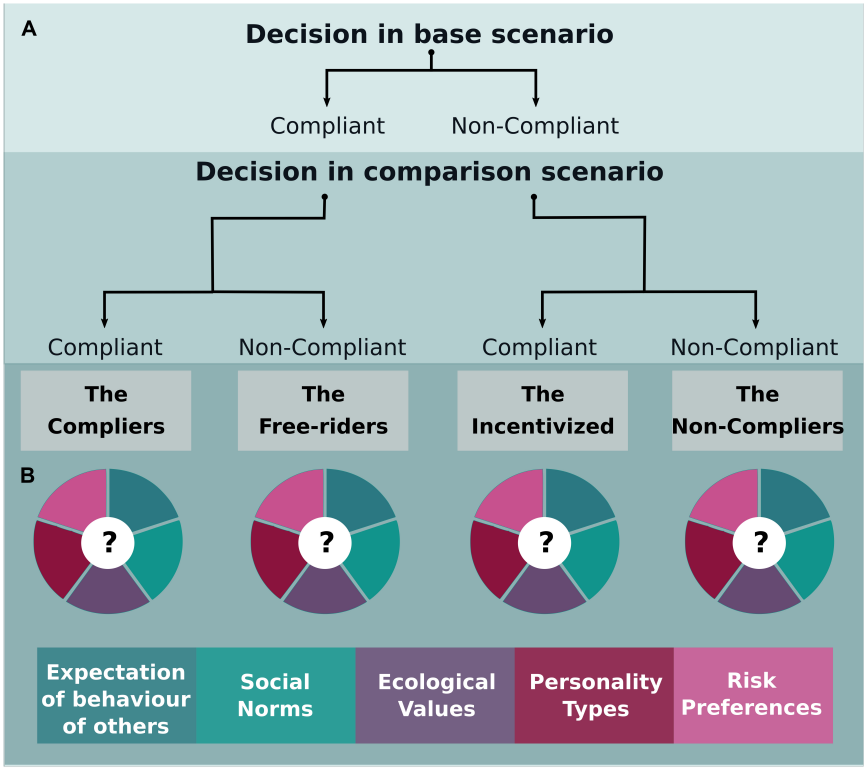

FIGURE 3 | Conceptual model of the research procedure. **(A)** Compliance decisions made in the base and comparison scenarios define the four compliance response groups (the compliers, the free-riders, the incentivized, and the non-compliers. **(B)** The research aims to identify a pattern in the five psycho-social characteristics of individuals in the four compliance response groups.

TABLE 2 | Distribution of the number of participants within the four compliance groups for each of the compliance cases.

Compliance response group	Compliance response		Compliance case		
	Base scenario	Comparison scenario	(1) Normative in low deterrence	(2) Normative in high deterrence	(3) Instrumental by increase in deterrence
The compliers	Comply	Comply	30	63	33
The free-riders	Comply	Non-comply	7	11	4
The incentivized	Non-comply	Comply	19	15	41
The non-compliers	Non-comply	Non-comply	64	31	42

The number of members in each compliance response group varies for the three compliance cases (**Table 2**). When the normative incentive is applied in a low deterrence context, the non-compliers formed the largest group (64). When the same normative incentive was applied in a high deterrence context, the largest group (63) were the compliers. The free-riders are the smallest group (<10%) across all three compliance cases. Individuals may respond either consistently or differently to different management incentives. For the compliers, 28 out of the 120 participants were consistently compliant across all compliance cases, whereas 27 of the 120 were consistently non-compliant. The incentivized and the free-riders were less consistent across the three compliance cases, only 2 out of the 120 people were consistent free-riders for all three compliance incentives, and none were consistently incentivized.

There is a chance that the order in which the scenarios were played will influence the responses and consequently the compliance response groupings. For example, the comparison scenario could come before the base scenario for each of the cases due to the randomized order participants played the game. Therefore, to account for any ordering effect within these groupings we checked the representativeness of the full data set with two sub-samples. We did this by examining whether there is a statically significant difference in the proportion of each compliance response group for the full sample and the sub-samples. The first sub-sample comprised of data from the first two scenarios played and only the responses that were in the order of base scenario then comparison scenario were included (i.e., scenario 1 followed by scenario 2 would be included as data for case 1, scenario 3 followed by

TABLE 3 | Summary of psycho-social characteristics.

Variable		Definition	Description	
			Low scores	**High Scores**
Expectation of behavior of others	Base scenario Comparison scenario	An in-time expectation of others' behaviors as a measure of social perceptions	Expect few others to exceed catch limit (other are mostly compliant)	Expect many others to exceed catch limit (others are mostly non-compliant)
Social norms		Measure of the extent in which people believe in and value social norms	Low belief in and value of social norms	High belief in and value of social norms
Ecological values	Rejection of human exemptionalism Environment-alism	Rejection that humans are exempt from the constraints of nature Concerns for environmental protection and improvement of the health of the environment	Regards the world in terms of human values and experiences Low concern for the environment	Regards the world in terms nature-centered system of values High concern for the environment
Personality type	Agreeableness Conscientious-ness Extraversion Neuroticism Openness	Taxonomy of personality traits	Analytical/detached Easy-going/careless Solitary/reserved Secure/confident Consistent/cautious	Friendly/compassionate Efficient/organized Outgoing/energetic Sensitive/nervous Inventive/curious
Risk preferences		The attitude people hold toward risk	Risk averse	Risk seeking

The possible range for expectation of behavior of others is 0–5, social norms is 14–70, each personality type is 0–10 and risk preferences is 1–5. The two variables of ecological values are the PCA scores.

scenario 4 would be included as data for case 2, scenario 1 followed by scenario 3 would be included as data for case 3). The second sub-sample comprised data from all four scenarios but only responses that were in the correct order were included (i.e., if a comparison scenario came before a base scenario it would not be included). These comparisons show that there is no statistical difference between either of the sub-samples and the full data set, suggesting that the randomized order of scenarios did not have an effect on responses and therefore compliance response groupings. The proportions for each of the sub-samples and the results of the proportional comparison statistical tests are found in **Supplementary Appendix B**.

Psycho-Social Data

In addition to the compliance decisions that participants made in the economic experiment, we collected information for each participant's psycho-social makeup that might be associated to their compliance decisions based on a review of the literature. The timing of data collection is shown in **Figure 1**. The psycho-social characteristics considered in this study were (1) expectation of behavior of others, (2) social norms, (3) ecological values, (4) personality types, and (5) risk preferences. A description of the variables relating to each of the five psycho-social characteristics is provided in **Table 3**.

Expectations of Behavior of Others

In the experiment, and for each scenario, participants were asked about their expectation of the number of others they thought would not comply. They were asked this question at the same time as they determined the number of fish they were going to catch. Specifically, we asked "How many of the others in the group do you think will exceed the catch limit?" We used this data to create two variables that capture in time expectations of others' behaviors in both the base scenario and comparison scenario for each fishery compliance case.

Social Norms

Participants were asked 14 questions on a 5-point Likert scale that make up the Social Norms Espousal Scale (SNES) proposed by Bizer et al. (2014). This survey is used to assess individual differences in the extent to which people believe in and value social norms. Within this survey participants are asked to rate the extent to which the statements were characteristic of them. The statements are framed generally around the importance and influence of social norms (e.g., statement 1: I go out of my way to follow social norms). Individual question scores are summed and the total is ranked on a scale representing participants' values on a low to high value of social norms scale.

Ecological Values

The New Ecological Paradigm (NEP) is a 5-point Likert scale survey to measure the environmental concern of people. We used the revised version proposed by Anderson (2012), which was originally developed by Dunlap and Van Liere to assess ''primitive beliefs' about the nature of the earth and humanity's relationship with it" (1978, p. 427). The NEP scale is made up of 15 statements, within which three questions represent each of the five hypothesized facets of an ecological worldview, namely (i) reality of limits to growth, (ii) anti-anthropocentrism, (iii) the fragility of nature's balance, (iv) rejection of human, and (v) possibility of an ecocrisis (Dunlap et al., 2000). The intention of the survey is to develop a scale of ecological

values from low ecological paradigm/high social paradigm to high ecological paradigm/low social paradigm. However, this scale is only recommended for use when the result of one question is consistent with the results of the remaining questions (i.e., have a high corrected item total correlation). The responses were varied and therefore we did not use the summed scores from the survey. Instead, we processed the scores for each of the five hypothesized facets of an ecological worldview using a Principal Component Analysis (PCA) to reduce the number of ecological values variables from five (one per facet) to two. The first component (which explained 45.2% of the data) was defined by one of the five facets; "rejection of human exemptionalism." Human exemptionalism represents the belief that humans are different to all other animal and exempt from the constraints of nature, and the world is interpreted more in terms of human values and experiences (Wallhagen and Magnusson, 2017). The second component (which explained 20.7% of the data) was defined by the other four hypothetical facets. We summarized the four facets to represent environmentalism. Individual loadings on these components were used as two variables representing ecological values in our model.

Personality Types

A widely recognized and accepted taxonomy of personality traits is the "Big Five" (John et al., 1991). These five broad traits are; agreeableness (*analytical/detached* vs. *friendly/compassionate*), conscientiousness (*easy-going/careless* vs. *efficient/organized*), extraversion (*solitary/reserved* vs. *outgoing/energetic*), neuroticism (*secure/confident* vs. *sensitive/nervous*), and openness (*consistent/cautious* vs. *inventive/curious*). The Big-Five-Inventory was first presented by John et al. (1991) as a self-reported assessment to measure the five traits. In this study, we used a 10-item version of the Big-Five-Inventory (Rammstedt and John, 2007). Unlike the measures for social norm and ecological values the scores for personality type are not additive, and so we formed five variables based on their scores for each of the five personality traits.

Risk Preferences

In addition to the common pool resource game, participants were asked to undertake a paid experimental exercise in which they chose from a range of gambles to elicit their risk preferences. We used the Eckel-Grossman Risk Task (Eckel and Grossman, 2002) which is an established way of elucidating risk preferences. Participants were asked to undertake the paid gamble in which they chose one of six possible gambles which all have the same 50/50 chance of winning as an assessment of risk attitudes. The gambles range from a safe bet with guaranteed but lower payoff, to a higher risk gamble with a larger payoff. Gambles range from risk averse to risk neutral to risk seeking.

Compliance Decision and Psycho-Social Data Analysis

To understand which of the psycho-social characteristics are related to the four compliance response groups, we used a multinomial (MNL) regression. We estimated a separate model for each of the three compliance cases (**Figure 2**) to capture the change in participants' decisions in response to either normative or instrumental incentives. Each of the three models includes all of the psycho-social variables as independent variables. Specifically, for each compliance case k (k = 1,2,3), we model the probability that individual j belongs to compliance response group m (m = 1,2,3,4) conditional on the psycho-social characteristics of the individual, that is:

$$p_{jkm} = Prob(y_{jk} = m) = F_{km}(x_j^{'}\beta) \quad (1)$$

where y_{jk} is an indicator variable that takes value one if individual j belongs to compliance response group m and zero otherwise. F_{km} is the cumulative distribution function which lies between zero and one and adds up to one over m; i.e., $\sum_m p_{jkm} = 1$ (i.e., each individual must belong to one of the response groups). In equation (1), the psycho-social characteristics of individual j is denoted by x_i and β is a vector of the corresponding parameters. We used the multinominal logistic model to estimate the parameters in (1), thereby the cumulative distribution function is given as:

$$F_{km}(x_j^{'}\beta) = \frac{1}{1 + \sum_{m=2}^{4} exp(x_j^{'}\beta_{km})}, m = 1 \quad (2)$$

$$F_{km}(x_j^{'}\beta) = \frac{exp(x_j^{'}\beta_{km})}{1 + \sum_{m=2}^{4} exp(x_j^{'}\beta_{km})}, m = 2, 3, 4 \quad (3)$$

We set the compliers as the baseline group (m = 1) as the compliers represent the behavior that we want to emulate (i.e., it reflects the desired compliance behavior of recreational fishers under all management incentives). Given the baseline compliance response group, the log-odds for all other groups relative to the baseline group can be calculated as a linear combination of the psycho-social factors, such that:

$$ln\left(\frac{Prob\left(y_{jk} = m^{-}\right)}{Prob\left(y_{jk} = 1\right)}\right) = x_j^{'}\beta_{km^{-}}, m^{-} = 2, 3, 4 \quad (4)$$

Therefore, the signs and statistical significance of each parameter $\beta_{km^{-}}$ indicate whether a change in the psycho-social factor makes an individual's membership to the compliance response group m^{-} more or less likely relative to the baseline group (i.e., compliers). For example, a positive and significant coefficient for a characteristic for one of the compliance response groups would suggest a higher probability of an individual being part of that group. Given the number of independent variables included in the model (**Table 3**), the multicollinearity between each psycho-social factor is of potential concern in the regression analysis. We calculated the correlation coefficients and confirmed that the correlation between social norms, ecological values and risk preferences is relatively low (< 0.25). Where a correlation coefficient was higher than 0.25 for expectation of behaviors of others and personality type, the

model results were checked to ensure the multicollinearity did not confound results.

RESULTS

Expectation of Behavior of Others

Among all the psycho-social factors, expectation of behavior of others in the base scenario was the most frequent significant variable in explaining individuals' membership in the compliance response group for both the instrumental and normative incentives (**Table 4**). For the non-compliers, the coefficient was positive and significant for compliance cases 1 and 3, indicating that those who have less faith in others to comply with the catch limit in the base scenario are more likely to be non-compliers. Expectation of behavior of others in the base scenario was consistently significant and positive for the incentivized group for all the three compliance cases. Conversely, for free-riders, expectation of others in the base scenario was significant for compliance case 2, indicating that those who have less faith in others to comply with the catch limit in the base scenario are less likely to be free-riders.

Expectation of others' behavior in the comparison scenario was only significant for compliance case 2 (**Table 4**). This result was found for the non-compliers and the free-riders. For the non-compliers group, the coefficient was positive and significant, suggesting those who have less faith in others to comply in the comparison scenario are more likely to be in the non-compliers group, reflecting their own behavior as they are non-compliant in this scenario. For free-riders -who were compliant in the base scenario, and non-compliant with the incentive- the result was positive and significant, indicating that those who have less faith in others to comply with catch limit with the management incentive applied are more likely to be in this group. Expectation of others in the comparison scenario was not significant for any management incentive for the incentivized group. This suggests that in the case of a management incentive having the desired effect, the expectation of others is no longer correlated with an individual's own behavior within the comparison scenario.

Social Norms

The estimated coefficient of social norms was not significant for the non-compliers or the free-riders for any compliance case (**Table 4**). The estimated coefficient of social norms was positive and only significant for the incentivized for compliance case 3, suggesting that those who have a high value of social norms are likely to be non-compliant when deterrence is low but compliant with high deterrence. The coefficient of social norms was not significant for the incentivized for the normative message incentives in either a high or low deterrence context which means there is no association between the value of social norms and the influence of a normative message on compliance behaviors.

Ecological Values

For the cases where human exemptionalism and environmentalism is a significant predictor variable, the direction of the effect is negative, indicating that those with high ecological values are less likely to be part of the response groups they were significant for (**Table 4**). For compliance case 3, the coefficient of rejection of human exemptionalism was significant for all response groups and environmentalism was significant for two response groups, respectively. These results suggest that those with high ecological values are less likely to be part of the groups responding in a way other than complying with an increase in deterrence, which infers compliers have high ecological values. By contrast, rejection of human exemptionalism was not significant for any group for compliance case 1 and for only one group for compliance case 2. This suggests that the link between human exemptionalism and responses to a normative management incentive is weak. Likewise, environmentalism was significant for non-compliers for case 1 and not significant for any groups for case 2, suggesting that the link between environmentalism and a response to a normative management incentive is also weak.

Personality Type

The "Big Five" personality traits that are significant in this analysis all have a negative coefficient (**Figure 4**). This means that those who have these personality traits are more likely to be the compliers (i.e., baseline group). The personality traits that are significant, however, vary across both compliance cases and the compliance response group. For example, those with agreeableness, conscientiousness or extraversion as personality traits are less likely to be non-compliers in response to either a normative or an instrumental incentive (**Figure 4**). In response to the normative incentive (in compliance cases 1 and 2) extraversion and openness were significant for the incentivized and the free-riders, respectively, indicating that those with these personality traits are less likely to be part of these groups and more likely to be the compliers. Finally, in response to the instrumental incentive, the coefficient of conscientiousness was significant and negative again indicating those with this personality trait are more likely to be compliers than the incentivized.

Risk Preferences

Risk preference was significant in explaining respondents' compliance response to both the normative and instrumental incentives (**Table 4**). For non-compliers, risk preference was significant and positive for all compliance cases, suggesting that those who are risk seeking are more likely to be non-compliers regardless of the management incentive applied. Risk preference was also significant and positive for the incentivized for compliance case 2, suggesting that those who are risk seeking are more likely to be in this group, which may explain why they were non-compliant in the base scenario. Risk preference is significant for the free-riders for compliance case 3. There are fewer significant results for compliance case 1 (normative in low deterrence) compared to the other compliance cases, which may reflect that the risk of being caught in this context is the lowest and therefore not a strong predictor for the incentivized or the free-riders.

TABLE 4 | Multinomial model results on responses to normative and instrumental incentives.

Psycho-social characteristic		Compliance Case 1 Normative in low deterrence			Compliance Case 2 Normative in high deterrence			Compliance Case 3 Instrumental		
		Non-compliers	**Free-riders**	**Incentivized**	**Non-compliers**	**Free-riders**	**Incentivized**	**Non-compliers**	**Free-riders**	**Incentivized**
Expectation of behavior of others	Base scenario	**0.941*** **	−0.173	**0.895*** **	0.311	**−0.785***	**0.441***	**1.108*** **	0.219	**0.965*** **
		(0.001)	(0.676)	(0.004)	(0.118)	(0.071)	(0.066)	(0.000)	(0.637)	(0.000)
	Comparison scenario	0.221	0.542	−0.42	**0.461***	**1.244*** **	0.239	0.23	0.542	−0.246
		(0.387)	(0.215)	(0.131)	(0.059)	(0.006)	(0.438)	(0.322)	(0.184)	(0.325)
Social norms		0.068	−0.011	0.052	0.022	0.08	0.04	0.072	0.024	**0.081***
		(0.120)	(0.865)	(0.318)	(0.516)	(0.139)	(0.427)	(0.123)	(0.851)	(0.067)
Ecological values	Rejection of human exemptionalism	−0.257	0.003	−0.369	−0.043	−0.096	**−0.438***	**−0.479***	**−1.267** **	**−0.498** **
		(0.244)	(0.993)	(0.149)	(0.812)	(0.746)	(0.084)	(0.064)	(0.036)	(0.037)
	Environmentalism	**−0.629** **	−0.305	−0.407	−0.05	0.229	−0.075	**−0.725** **	−0.106	**−0.607***
		(0.047)	(0.545)	(0.227)	(0.848)	(0.572)	(0.830)	(0.038)	(0.888)	(0.064)
Personality type	Agreeableness	**−0.496** **	−0.16	0.002	−0.091	−0.288	0.104	−0.189	0.04	−0.342
		(0.029)	(0.606)	(0.992)	(0.607)	(0.260)	(0.641)	(0.428)	(0.940)	(0.119)
	Conscientiousness	**−0.525** **	0.108	−0.305	−0.109	0.321	0.068	**−0.578** **	−0.406	**−0.504** **
		(0.014)	(0.757)	(0.187)	(0.496)	(0.238)	(0.749)	(0.017)	(0.413)	(0.024)
	Extraversion	−0.009	0.118	**−0.433** **	−0.2	0.187	−0.175	**−0.427** **	−0.36	−0.26
		(0.958)	(0.666)	(0.039)	(0.155)	(0.384)	(0.345)	(0.035)	(0.365)	(0.165)
	Neuroticism	0.111	0.122	0.156	−0.17	−0.071	0.326	0.044	0.422	0.103
		(0.520)	(0.651)	(0.423)	(0.246)	(0.729)	(0.126)	(0.812)	(0.398)	(0.534)
	Openness	−0.142	0.219	0.067	0.003	**−0.487***	0.33	0.083	0.696	−0.058
		(0.444)	(0.475)	(0.758)	(0.983)	(0.056)	(0.123)	(0.689)	(0.132)	(0.763)
Risk preferences		**0.467** **	−0.215	−0.149	**0.438*** **	0.146	**0.611** **	**0.650*** **	**1.401** **	0.335
		(0.020)	(0.508)	(0.518)	(0.008)	(0.545)	(0.014)	(0.004)	(0.044)	(0.103)
Constant		0.366	−3.732	−0.528	−0.938	−4.388	−11.432***	−1.515	−14.034	0.803
		(0.905)	(0.444)	(0.884)	(0.741)	(0.331)	(0.008)	(0.662)	(0.154)	(0.799)
McFadden's pseudo-R2			0.331			0.214			0.308	
Log-likelihood			−91.47			−110.00			−99.86	
AIC			254.947			292.002			271.729	
Likelihood ratio test (*p*-value)			**2.943e-07*** **			**0.002725** **			**4.975e-07*** **	
Number of observations		64	7	19	31	11	15	42	4	41

*This table reports the estimates of the coefficients and p-values in parentheses for the three compliance cases. The baseline compliance response group is the compliers. Significant coefficients are bolded, and significance level are: *p < 0.1; **p < 0.05; ***p < 0.01.*

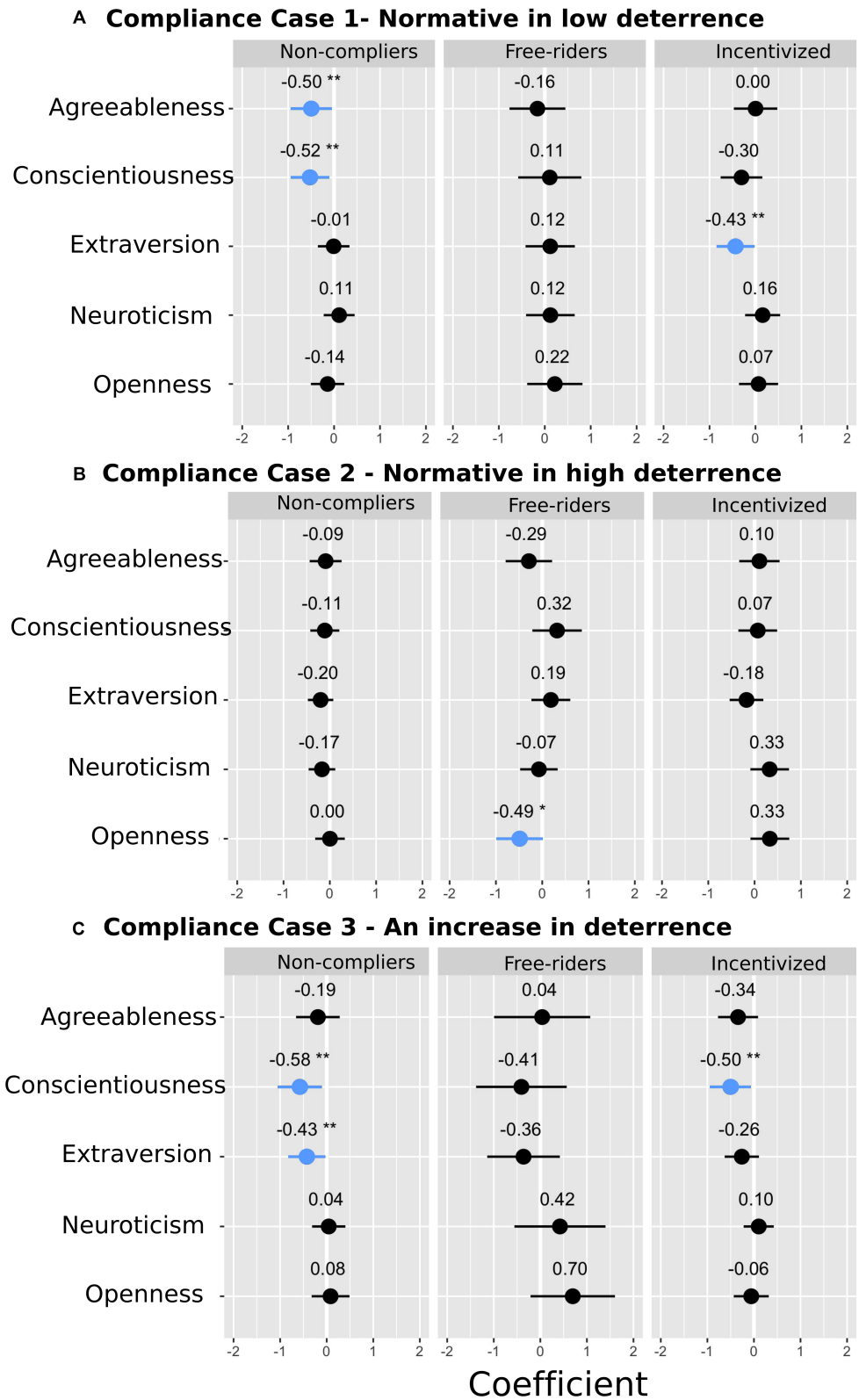

FIGURE 4 | Multinomial logit model results for personality types for non-compliers, free-riders, and the incentivized for **(A)** compliance case 1: normative message in low deterrence, **(B)** compliance case 2: normative message in high deterrence, and **(C)** compliance case 3: an increase in deterrence. Coefficients are included, and error bars indicate standard error. Significant coefficients are highlighted in blue, and significance level are: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$. Full regression results are reported in **Table 4**.

DISCUSSION

While we know that in fisheries people make trade-off decisions between following or breaking rules, it is of interest to determine how people respond to different management incentives. Accurately understanding the different responses to instrumental and normative incentives and highlighting the psycho-social patterns within these responses is highly relevant for fisheries policy. In our laboratory-based economic experiment, in which participants faced four hypothetical fishery scenarios to provide the controlled setting to measure behavioral responses and to remove any potential confounding influences, we were able to shed light on this issue. While this study is framed around a recreational fisheries context, the compliance problems faced for other natural resources (Keane et al., 2008) are similar and potentially similar policy opportunities (as discussed below) may apply. In this paper, we first identified patterns in compliance behavior. The pattern reveals a group of people who are consistently compliant, a group who are consistently non-compliant, a group who respond counterintuitively, and a group who are incentivized to become compliant (as intended by the management incentive). In this paper, we further explored how the pattern in compliance behavior is associated with five psycho-social factors, three of which (perceptions of behavior of others, social norms, and risk preferences) have separately been explored within the fisheries compliance literature, while two factors (ecological values and personality types) had yet to be explored. While information about these two latter factors is limited within the fisheries compliance literature, our results suggest that they are relevant predictors for individuals' compliance response to different management incentives.

To summarize the findings, we combine results for individual factors into umbrella factors to conceptually present the results in **Figure 5**. For example, the umbrella factor *expectation of others' behavior* combines the results of base scenario and comparison scenario, *ecological values* represents both rejection of human exemptionalism and environmentalism and *personality types* includes all five personality factors. The shading of the segments indicates that at least one of the included factors for the umbrella factor is significant (but not necessarily all of them). The aim of this study was to compare the role of psycho-social characteristics of individual fishers in explaining responses to an instrumental and normative management incentives. Each of the umbrella factors is statistically significant in explaining compliance behavior in at least one compliance case and for at least one of the three compliance response groups (**Figure 5**). For example, one consistent result across both the normative and instrumental incentive was the relationship between risk preferences and non-compliance. The *expectation of others' behavior* was also the most frequently statistically significant factor (in 7 of the 9 cases[1] – dark green shaded segment in **Figure 5**).

[1]There are a total of nine cases, three response groups (compared to the "compliers") and three compliance cases.

Broadly we see that more psycho-social factors were statistically significant in explaining the behavior of non-compliers and the incentivized compared to the free-riders. Individual's membership in the free-riders is the hardest to predict based on the five psycho-social factors. This may be due to the low number of observations for this group and therefore the results for this group must be interpreted with care. Moreover, we can see that more psycho-social factors explain behavioral responses to an instrumental incentive than a normative incentive (**Figure 5**). Ecological values, for example, was consistently a significant predictor for responses to an instrumental incentive but not for either of the normative incentives. The results suggest that there is a relationship between having high environmental values and acting consistently compliant because the relationship between ecological values and all other response groups (non-compliers, free-riders, and the incentivized) was negative and significant. That is to say, the compliers have higher environmental values than any other group in response to an instrumental incentive, suggesting that compliance behavior could be encouraged by increasing environmental values and concern. These results are consistent with the behavioral literature suggesting a link between high environmental values and pro-environmental behavior (Nuyen, 2011; Ones et al., 2015).

Social norms was only significant for the incentivized for the instrumental incentive. Social norms was expected to be a significant predictor, especially for the incentivized in response to the normative incentives. However, we find that social perceptions of others' behaviors are more effective at representing the implicit expectations of an individual. The results for expectation of others' behavior suggests that when participants are non-compliant they think others are also exceeding the catch limit. This behavior, also known as false consensus or pluralistic ignorance, can lead to misperceived norms and reinforce non-compliant behavior (Berkowitz, 2005; Rimal and Real, 2005). Targeting these misconceptions results in a more accurate normative feedback with expected improved compliance (Bergseth and Roscher, 2018). This can be achieved through highlighting pro-compliance perceptions and norms of fishers as well as reporting consequences of non-compliant behavior (Bova et al., 2017; Bergseth and Roscher, 2018). This could resemble social punishment through shame and moral unacceptance of non-compliance as well as traditional deterrence such as fines (Thomas et al., 2016; Mackay et al., 2018). The SNES survey is intended to assess individual differences in the extent to which people believe in and value social norms, however, from our results it was related to the response to the instrumental incentive. Although instrumental incentives are expected to crowd out social or moral norms (Kroneberg et al., 2010; Barile et al., 2015), we find that high social norms value complements the effectiveness of the instrumental compliance incentive.

There were differences in behavioral responses to an instrumental incentive and a normative incentive for different personality traits. For the instrumental incentive introversion was inferred for non-compliers for the case of an increase

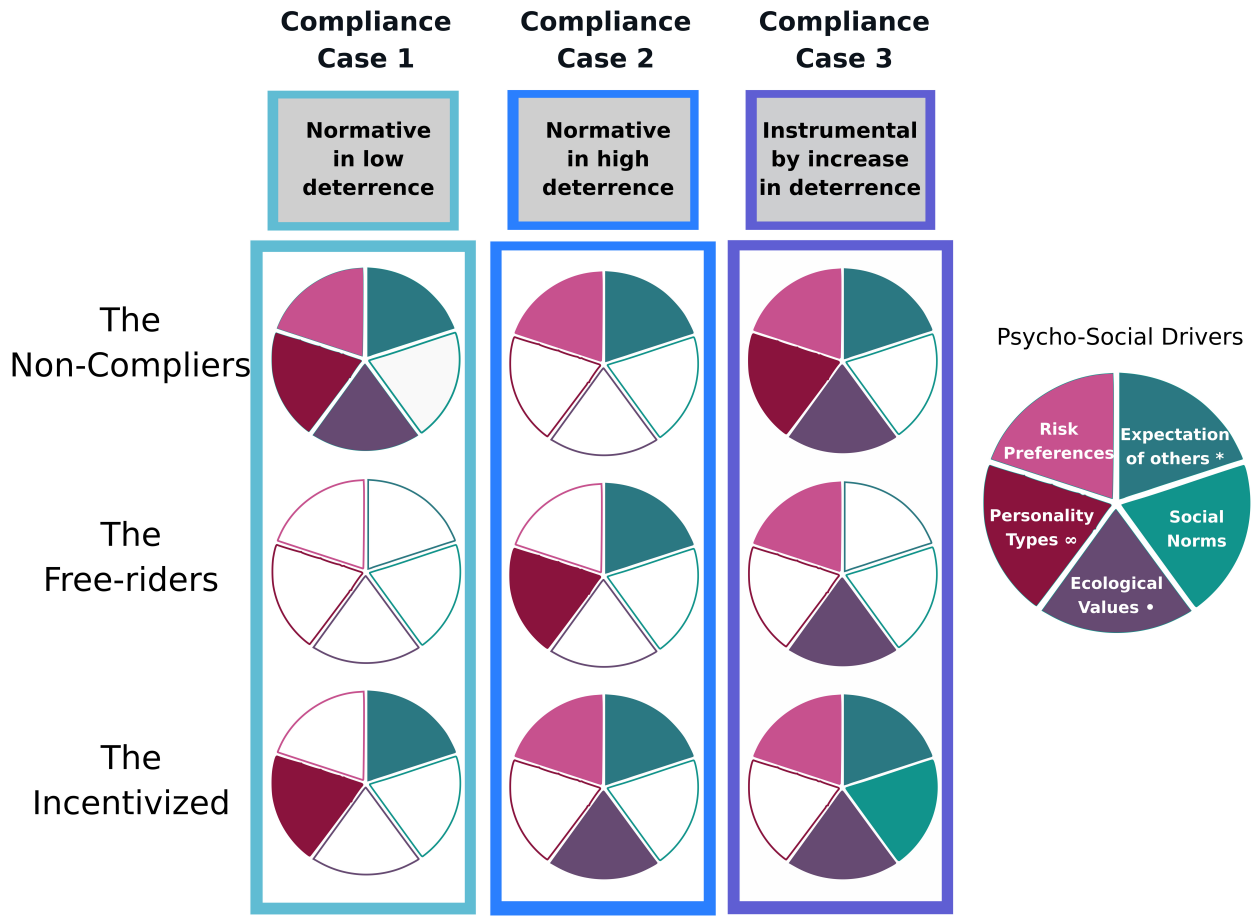

FIGURE 5 | Conceptual summary of the results. Shaded segments indicate if one of the factors included in the umbrella factors was significant and left unshaded if not significant. **Expectation of others* combines the results of base scenario and comparison scenario, *Ecological values* represents both rejection of human exemptionalism and environmentalism, and ∞*Personality types* includes all five personality traits.

in deterrence. Non-compliant behavior has been found to be associated with introversion but only when combined with high neuroticism (Gudjonsson et al., 2004), however, neuroticism was not a significant personal trait in our results. The results also indicated a low likelihood of being non-compliant or the incentivized in response to an increase in deterrence for those with high conscientiousness. Low conscientiousness is associated with impulsivity (Sharma et al., 2014). This suggests that impulsivity may be related to non-compliance when there is a low chance of being caught but it is over shadowed when there is a higher chance of being caught.

Low conscientiousness is also linked to deviousness (Salgado, 2004), which may explain why the trait is found to be associated with those who are non-compliant in response to the normative incentive in a low deterrence context. However, we did not find this result for the normative incentive in a high deterrence context, suggesting that the risk of being caught may overshadow the tendency to be devious. The only personality type that was significant for normative incentive in high deterrence was openness. Specifically, our result suggests that those who are open are unlikely to be free-riders for the normative incentive in a high deterrence context. This may infer that free-riders have low openness as part of their personalities. A low score for openness represents a consistent and cautious personality which would be unexpected for the free-riders as they become non-compliant and at risk of a penalty. This result is somewhat counterintuitive, but may be associated with the low number of observations for this group.

For normative incentive in a low deterrence context, personality types were more frequently statistically significant. The results for non-compliers for this management incentive infer low agreeableness and low conscientiousness. People with low agreeableness tend to be less cooperative and more competitive in groups (Graziano and Eisenberg, 1997), which may explain the non-compliant behavior as participants may be acting competitively to make more money in the experiment. The results may reflect that the compliers are more agreeable which has been linked to prosocial and altruistic behaviors (Graziano et al., 1997). Introversion is expected to correlate with compliance behavior since a typical introvert is depicted

as a responsible person who is expected to be compliant (Gudjonsson et al., 2004). Consistent with the expectation, the results suggest introversion is associated with the incentivized for the case of normative incentives in low deterrence. This suggests that introversion is correlated with compliant behavior for a normative incentive and non-compliers for an instrumental incentive.

Future Research

In this study, we explore what psycho-social characteristics of individuals are associated with responses to instrumental and normative management incentives in a recreational fisheries context, yet there are some caveats to consider when interpreting the results.

First, we use a controlled environment via an economic experiment with student participants, which is useful for minimizing potential confounders. However, WEIRD (western, educated, industrialized, rich, and democratic) participants made up the study sample and are sometimes criticized as not being representative of the general population (Levitt and List, 2007; Loomis, 2014). No difference in behavioral patterns or overestimations of social preferences were found between student and non-student samples in other studies (Janssen et al., 2011; Exadaktylos et al., 2013; Falk et al., 2013). Therefore, the policy implications that can be drawn from these findings can contribute toward improving compliance management since a better understanding of recreational fishers' behavior can reduce unintended outcomes of management interventions (Pine et al., 2009) and better predict and assist how recreational fisheries adapt to changing environments and evolve to maintain resilience and sustainability on a global scale (Arlinghaus et al., 2013). In fact, the heterogeneity of fishers is thought to be a key ingredient of the complex dynamics of recreational fisheries and key for better management (Johnston et al., 2010; Post, 2013). We do recognize that different demographics in a fishery or alternate natural resource context may result in different conclusions. For example, an area for further research not within the scope of this study would be to examine the influence of socioeconomic characteristics and their interaction with psycho-social characteristics. For example, dependency on fishery/resource (Karper and Lopes, 2014), scale of corruption (Akpalu and Mohammed, 2013), and socioeconomic inequalities and mortality risk (Pepper and Nettle, 2017) -that leads to making more present-orientated behaviors rather than future-orientated behaviors- are key domains worth exploring in terms of compliance responses that is applicable across resource and location context.

Second, while we find that the normative message in the experiment changed behavior, a normative expectation can be strengthened on the belief that others think they should or have an obligation to conform to the norm (Bicchieri and Xiao, 2009). We envisage that future work can explore the use of normative messages that are not only based on what the wider group is doing but where the message suggests there is a consciousness of what is accepted by others to strengthen the normative expectations (Reno et al., 1993). We also acknowledge that there are a number of alternative psycho-social drivers to explore in relation to compliance responses. For example, while we found links between personality traits that are linked to impulsivity, it may be worth exploring the link between behavior and impulsivity directly (Maccallum et al., 2007). Additionally, the role of self-control has been explored in the trade-off between short term temptation to be selfish and long term pro-social behavior (Martinsson et al., 2010), which would be highly applicable to natural resource use and actions impacting the global climate.

Finally, there are several findings from this study and while we have highlighted the findings that we determined to be the most novel within the fisheries compliance literature, we acknowledge that there are many dimensions to the results and a number of interesting results were not developed in the discussion. For example, while some results were as expected such as the link between high environmental values and pro environmental behavior there is an opportunity for more research in to the less expected and more specific associations such as between expectation of others and specific personality types and risk preferences. There scope for more research investigating interacting psycho-social characteristics which will add richness to the discussion of compliance behavior.

CONCLUSION

People respond differently to management incentives and often they respond in a way that is contradictory to expectation. While there are different instrumental and normative incentives that can be used to influence compliance behavior, the aim of this study was to explore the association between individual psycho-social characteristics and compliance responses. We explored five psycho-social factors: expectations of others' behavior, social norms, ecological values, personality types, and risk preferences. Our results highlight there are different psycho-social factors associated with certain compliance response behaviors. For example, risk seeking is associated with people who can be categorized as non-compliers. There are certain behaviors that are harder to predict, for example for people who behave contrary to the compliance incentive, who we labeled free-riders. We acknowledge findings outside the laboratory experimental context and fishery example may vary from these conclusions, but we offer a number of policy suggestions based on the results of our findings, such as emphasizing the risk of non-compliance and using compliance campaigns that target encouraging environmental concerns. The findings underline that there is significant heterogeneity in the associations between psycho-social make-up and compliance behaviors. Knowledge of this behavioral relationship can progress fisheries management toward increased innovation by encouraging the management of the individual fisher rather than the average fisher. In the context of managing people the whole may not be greater than the sum of the parts,

as modifying behavior requires nuance and specifics rather that generalities and ambiguity.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Tasmania Social Sciences Human Research Ethical Committee (Ethics Ref: H0016420). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MM conceived, developed and designed the study, led data collection activities, led data analysis and wrote the manuscript. EP contributed to the design and data analysis and contributed input into the writing of the manuscript. SJ contributed to the development of the study and provided input into the writing of the manuscript. SY contributed to the design and development of the study and provided comment on draft versions of the manuscript. HS contributed to the development of the study and provided comment on draft versions of the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.579213/full#supplementary-material

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Subsurface Ocean Warming Hotspots and Potential Impacts on Marine Species: The Southwest South Atlantic Ocean Case Study

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In the southwest South Atlantic Ocean (SWAO) strong ocean surface warming hotspots have been observed mainly along the path of the Brazil Current (BC), Brazil-Malvinas Confluence (BMC), and in the Río de la Plata (RdlP). However, there is no knowledge about the signature of ocean hotspots below the surface and the potential effects of ocean warming on marine biota. In this work, we provide initial evidence of how deep the hotspots of the SWAO extend in the water column, in particular at mid-water and bottom layers where two marine species - the green turtle (*Chelonia mydas*) and the Patagonian scallop (*Zygochlamys patagonica*) - inhabit. We compare 15 years (2003–2017) of Copernicus Marine Environment Monitoring Service (CMEMS) ARMOR3D high−resolution (1/4°) 3-D temperatures reprocessed from combined satellite and *in situ* observations with high−resolution (1/12°) Mercator ocean reanalysis. We also use location data of *C. mydas* and *Z. patagonica* to discuss the potential impacts of warming on these species in terms of geographic distribution, phenological shifts and thermal tolerance. The potential distribution of *C. mydas* changes in relation to the sea surface temperature (SST) and the bathymetry. The warming of the whole water column in the RdlP (>0.4°C/decade) and the southward movement of the mean surface isotherms, which likely drove turtle displacements, could enable the opening up of novel optimal thermal habitats and/or a longer seasonal residency for the species. At the BMC, warming is driven by the southward displacement of the BC during the past decades. Ocean model temperature indicates cooling/warming in deep waters along the outer shelf and shelf break regions, which vary according the displacements of the BMC. The expected warming of the waters over the Patagonian scallop largest bed could exceed the thermal tolerance of this species and its survival. Given the lack of long-term monitoring programs to address the impacts of climate change on marine biota in the SWAO, our results provide the first effort to call the attention of stakeholders and decision makers on marine conservation and fishery management to work toward better management strategies in the context of climate change.

Keywords: southwest South Atlantic Ocean, climate change, ocean warming, green sea turtle, Patagonian scallop, ocean governance

INTRODUCTION

During the past decades, a consistent poleward shift of the major subtropical ocean gyres driven by climate change has been reported, and a stronger surface ocean warming trend has occurred over the western boundary currents of the oceans (Wu et al., 2012; Yang et al., 2016, 2020). In the South Atlantic Ocean, a poleward displacement of the subtropical gyre at a rate of 0.11°/decade has been observed (Yang et al., 2020), and the western boundary current - the Brazil Current (BC) - has been reported as one of the most extensive and intense surface warming hotspots in the global ocean (Hobday and Pecl, 2014). Although changes in the distribution and productivity of marine species have been recorded over faster ocean warming regions worldwide (Burrows et al., 2014; Sunday et al., 2015; Pecl et al., 2017), potential changes remain largely unexplored in the southwest South Atlantic Ocean (SWAO, see Franco et al., 2020).

The SWAO extends from ∼22°S (Brazil) to the tip of Tierra del Fuego (55°S, Argentina) (**Figure 1**). The dynamics in the SWAO is dominated by the Brazil-Malvinas Confluence (BMC), which is the region of convergence of two distinct western boundary currents: the Brazil and Malvinas currents (MCs) (**Figure 1**). The MC transports cold and nutrient-rich waters northward along the continental slope and shelf-break of Argentina, while the BC transports warm and salty waters southward along the continental slope and outer shelf of Brazil and Uruguay. Changes in sea surface temperature (SST), sea surface height (SSH) and numerical simulations indicate that the BC is shifting southwards 0.81–0.39°/decade driven by the poleward displacement of the subtropical gyre (Goni et al., 2011; Lumpkin and Garzoli, 2011; Combes and Matano, 2014; Yang et al., 2020). Intense surface ocean warming hotspots in the SWAO have been observed mainly along the BC path and at the BMC (Yang et al., 2016, 2020; Oliver et al., 2018). While surface ocean warming hotspots and marine heatwaves are relatively well studied based on the availability of satellite data, subsurface temperature changes remain poorly described, despite their possible impact on neritic, pelagic and benthic ecosystems.

In the SWAO, the northern shelf is occupied by waters of subtropical origin and the southern shelf by waters of subantarctic origin (Piola et al., 2000). Subantarctic shelf waters are exported offshore mainly near the BMC region (Franco et al., 2018). In the northern SWAO shelf, tropical waters are observed in upper layers (Campos et al., 1995). The Río de la Plata (RdlP, 35°–36°S) discharge is the major freshwater inflow, with annual averages of ∼23,300 m^3 s^{-1} (Möller et al., 2008). The RdlP discharge modulates the input and distribution of freshwater and nutrients, impacting the marine food web and the feeding of the most abundant pelagic fishes and several marine species over the shelf (Acha et al., 2012). Although a relatively weak surface warming has been observed in the RdlP (Oliver et al., 2018), a long-term shift from cold-water to warm-water species in industrial fisheries of Uruguay suggests the impact of climate change (Gianelli et al., 2019). Whether ocean warming affects other components of the ecosystem is unknown. In this study, we provide the first evidence of the vertical extension of the warming hotspots of the SWAO and discuss the potential impacts of ocean warming on two marine species: an ectothermic vertebrate species of conservation concern and a benthic cold-water invertebrate species of great economic importance.

Sea turtles are a useful case study for understanding the impacts of ocean warming on wild populations of conservation concern (Hawkes et al., 2009; Fuentes et al., 2013; Hamann et al., 2013). As ectotherms, sea turtles are likely to have range distributions largely defined by temperature, which is the most important environmental factor affecting sea turtles from eggs to adults (Spotila et al., 1997). However, more is known about the effects of changing temperatures on the reproductive phase — e.g., loss of nests due to sea level rise, shifts in the timing of nesting season, altered hatchling sex ratio and survival of incubating eggs — than to other stages of sea turtle life cycle (Hawkes et al., 2007; Fuentes et al., 2009; Mazaris et al., 2015). The effects of ocean warming on sea turtle ecology in foraging grounds are less understood (Hawkes et al., 2009; Fuentes et al., 2013; Hamann et al., 2013).

The RdlP is a seasonal, highly used foraging ground for at least three sea turtle species within their southern boundary range (Frazier, 1984; González Carman et al., 2011, 2012, 2016a; Vélez-Rubio et al., 2013). The green turtle (*Chelonia mydas*) distribution is mainly associated with tropical and sub-tropical warm waters, which sustain the bulk of the species nesting colonies and foraging grounds (Pritchard, 1997; Campos and Cardona, 2019). However, *C. mydas* has also been recorded south of the RdlP, in the El Rincón (ER) estuary (39°–41°S, see **Figure 1**) and sporadically over the northern Patagonian shelf to ∼42°S (González Carman et al., 2011, 2012). Whether these southernmost records are related to ocean warming that has occurred during the past decades is difficult to assess since no sea turtle systematic records exist in this region before 2003 (González Carman et al., 2011). Nonetheless, if current *C. mydas* satellite tracking is coupled with distribution modeling, the species austral distribution - and its potential changes due to ocean warming - could be explored in the region.

A second example is the Patagonian scallop (*Zygochlamys patagonica*), a useful case study for understanding the impacts of ocean warming on wild populations of economic interest. The species is an important economic resource in Argentina, whose fishery is certified by the Marine Stewardship Council[1] (Ciocco et al., 2006; Soria et al., 2016). This cold-water affinity bivalve feeds by filtering phytoplankton and organic matter (Schejter et al., 2002; Bogazzi et al., 2005; Mauna et al., 2011; Cragg, 2016). Since the survival of the Patagonian scallop beds along the Argentine shelf-break ground is highly dependent on the productivity of the Patagonian Shelf Break Front (SBF) and benthic-pelagic coupling processes (Franco et al., 2017), the southward displacement of the warm, nutrient-poor BC along the outer shelf and shelf break could have negative impacts on the productivity of the SBF, and hence reduce the sustainability of *Z. patagonica* fishery.

[1]www.msc.org

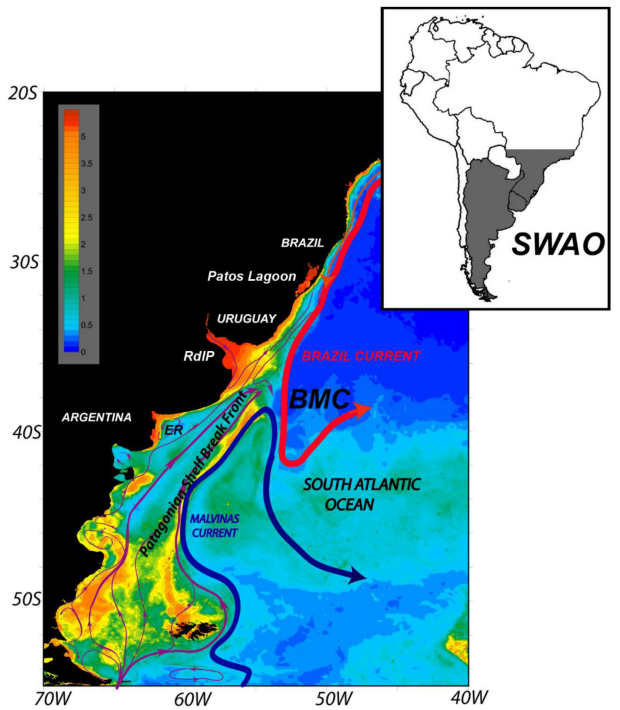

FIGURE 1 | Schematic circulation in the southwest South Atlantic Ocean (SWAO). Concentration of surface chlorophyll-a (mg m^{-3}) from the SeaWIFs radiometer (austral summer average) is shown in the background colors. The magenta lines indicate the schematic shelf circulation. The Brazil-Malvinas confluence (BMC) region is shown. El Rincón estuary is shown as ER. From Franco et al. (2017), with permission.

MATERIALS AND METHODS

GLORYS12 Data

The physical ocean model used here is the 1/12° global Mercator Ocean reanalysis (hereafter, GLORYS12). GLORYS12 provides monthly mean sea temperature for the period 1993–2017 on 50 verticals levels. The model also provides monthly mean mixed-layer depth (MLD) outputs. However, the model presents an unrealistic water mass structure and a cold bias prior to 2003. The introduction of more temperature and salinity profiles from Argo floats in the model assimilation after 2003 led to more realistic water mass vertical structure. Our conclusion is based on the comparison of model data with historical *in situ* data (more than 20,000 *in situ* observations available from World Ocean Database[2]) for the study region. Therefore, in this study we have restricted the analyses of model outputs to the 2003–2017 period. GLORYS12, available from Copernicus Marine Environment Monitoring Service[3] (CMEMS), is based on the current real−time global high−resolution forecasting CMEMS system PSY4V3 (Lellouche et al., 2018). The model assimilates observations with a 7−day assimilation cycle (Lellouche et al., 2013), including along−track satellite altimetry data from CMEMS (Pujol et al., 2016), satellite SST from NOAA, sea−ice concentration, and *in situ* temperature and salinity vertical profiles from the latest CORA *in situ* databases (Szekeley et al., 2016). GLORYS12 provides a realistic representation of the general circulation of the SWAO and the location of the BMC (Artana et al., 2018, 2019).

[2]https://www.nodc.noaa.gov/

[3]http://marine.copernicus.eu

ARMOR3D Data

The physical ocean model will be compared to the ARMOR3D dataset which is based on observations. The ARMOR3D dataset provide the 3-D temperature, salinity, and velocity fields derived from satellite (sea level anomalies, geostrophic surface currents, and SST) and *in situ* (temperature and salinity profiles) observations (Guinehut et al., 2012). ARMOR3D data is provided on a 1/4° resolution grid and is available from CMEMS (see text footnote 3). The monthly mean temperature for the period 2003–2017 will be used in the following analyses.

Green Turtle Data and Distribution Modeling

To explore potential changes in *C. mydas* austral distribution likely driven by the warming of inner shelf waters, we used satellite tracking of nine juveniles during the period (2008–2011) (González Carman et al., 2012). The species mostly occurs from late austral spring (October) to the fall (May). By the end of the fall, *C. mydas* start migrating to the southern Brazil shelf to winter in warmer waters. Some juveniles performed a round-trip migration using offshore waters to return to different parts of the RdlP in consecutive years (González Carman et al., 2012). Thus, we divided the year in four periods resembling *C. mydas* behavior in the SWAO: 1) arriving (October to December), 2) remaining (January to March), 3) leaving (April to June), and 4) absent (July to September).

Green turtle tracking data were collected using the Argos satellite system and downloaded with the Satellite Tracking and Analysis Tool (STAT; Coyne and Godley, 2005). Argos locations are classified as 3, 2, 1, 0, A, B and Z, according to accuracy. Location classes 3, 2, 1, 0 are categorized to lie within 150 m, 150–350 m, 350–1,000 m or >1,000 m of the tag's true position, respectively. Locations classes A and B have no location error estimate. Routes were reconstructed using locations 3, 2, 1, 0, A, and B. Duplicated locations, locations class Z, locations on land and those implying high rate of travel >5 km/h were removed from analysis. We also removed locations from the first 48 h of transmission after deployment to avoid abnormal turtle behavior after release.

After filtering the data, we developed maximum entropy (MaxEnt) species distribution modeling (Phillips et al., 2006) to identify the potential distribution of *C. mydas* in relation to two predictor variables: SST and bathymetry. SST is derived from GLORYS12 data for the period 2008–2011, and bathymetry is obtained from the GEBCO Digital Atlas and ETOPO2 Global 2′ Elevations datasets (British Oceanographic Data Centre and NOAA's National Geophysical Data Center). Bathymetry is a good predictor variable in marine species distribution modeling,

and it is important for green turtles given their coastal habits and benthic foraging behavior (Meylan et al., 2011).

Compared to other distribution modeling approaches MaxEnt is much less sensitive to sample size (Hernandez et al., 2006; Wisz et al., 2008); which make it suitable for small sample sizes (in terms of number of individuals and years) like ours. To reduce the effect of spatial autocorrelation of consecutive locations on short time intervals, we selected the best position (according to Argos accuracy) for each turtle every 48 h, as done in other studies (e.g., Edrén et al., 2010; Pikesley et al., 2013, 2015) using R (R 3.5.0; R Development Core Team, 2018) (see **Supplementary Table S1**). MaxEnt modeling was implemented in MaxEnt version 3.4.1. We obtained a mean response model after running 15 models for each month. Each time, a random sample of 25% of the dataset was saved to test the model. To ensure convergence of the model, the number of iterations was set to 5,000 (Young et al., 2011; see **Supplementary Table S2** for further modeling details). We then generated 12 maps of habitat suitability (HS) scaled from lowest (blue) to highest (red) suitability (Phillips et al., 2006; Elith et al., 2011). The area under the curve (AUC) was used to provide a measure of model performance. An AUC value of 0.5 indicates that the performance of the model is not better than random, while values closer to 1.0 indicate better model performance (Phillips et al., 2006; **Supplementary Table S3**). To identify the mean SST that is likely to drive the austral distribution of *C. mydas* we also used MaxEnt response curves – showing the SST at which HS for *C. mydas* is ≥0.5 (**Supplementary Figure S1**). We then overlapped those identified monthly mean SST isotherms with turtle HS. Relative contribution of SST and bathymetry to the models were obtained from MaxEnt outputs (**Supplementary Figure S2**).

After identifying the surface isotherms likely to drive *C. mydas* distribution through the year, we chose the middle month of the periods "arriving," "remaining," and "leaving" to explore changes in the thermally accessible range of *C. mydas* (i.e., changes in the location of the identified isotherms) during three 5-years periods: 2003–2007, 2008–2012, and 2013–2017. Given our limited sample size and tracking years, our main assumption is that green turtle behavior observed during 2008–2011 is representative of the GLORYS12 period analyzed (2003–2017).

RESULTS

Regional Oceanography

The MLD represents the lower limit of the surface layer at which variables are nearly constant with depth due to turbulent mixing processes. Therefore, there is no important changes in temperature throughout the water column until the depth of the MLD. The MLD along the Brazilian shelf, the RdlP, and the northern shelf of Argentina is shallower than 10–15 m depth. There is a sharp increase of MLD along the path of the BC between ∼32° and 36°S, and a slight deepening along the southern shelf of Argentina (**Figure 2A**). GLORYS12 results show a sharp shoaling trend of the MLD (>5 m/decade) along the middle shelf and shelf break of Argentina. The highest shoaling trend of the MLD occurs along the BC path between ∼34° and 38°S, where values reach up to >15 m/decade, extending toward the open ocean (**Figure 2B**).

Surface and Subsurface Ocean Warming

To characterize how deep the main hotspots of the SWAO extend in the water column we compare the temperature trends from both GLORYS12 and ARMOR3D at the surface and selected subsurface levels. At the surface, the larger positive temperature trends (°C/decade) from GLORYS12 are located over the path of BC up to ∼36°S with the highest values along the southernmost extension of BC (south of ∼38°S). Negative temperature trends are observed along the BC path, between ∼36°–38°S with the highest negative values located over the slope. Over the shelf warming stronger than 0.4°C/decade occurs along the southern mid shelf of Brazil, Uruguay, RdlP, and inner-mid shelf of Argentina (**Figure 3A**). ARMOR3D reports similar warming trends along the BC path and BMC regions. In the RdlP, both datasets exhibit trends higher than 0.4°C/decade (**Figures 3A,B**).

Temperature trends from both GLORYS12 and ARMOR3D reported at 20 m depth are quite similar to the surface trends (**Figures 4A,B**). Most intense positive temperature trends from GLORYS12 are located over the path of BC up to ∼36°S with maxima along the southernmost extension of BC (south of ∼38°S), while negative trends are observed along the BC path between ∼36° and 38°S. Over the shelf, trends higher than 0.4°C/decade are reported from GLORYS12 over the northern coast of Brazil, in the RdlP, and along the inner-mid shelf of Argentina. A similar warming pattern along the BC path is observed from the surface down to 50 and 100 m depth in GLORYS12 (**Figures 4C,E**). Unlike the GLORYS12 subsurface trends, the ARMOR3D trends along the BC path present maxima along the southernmost extension of BC and over distinct areas in the open ocean (**Figures 4D,F**). Over the Argentina (∼36°S) outer shelf, negative temperature trends are reported by GLORYS12 while positive trends are reported by ARMOR3D at 50 and 100 m depth.

Green Turtle Distribution

A total of 1.456 locations of *C. mydas* occurrence was used to run the models. Monthly distribution models returned AUC values higher than 0.86, indicating a good model performance for all months (**Supplementary Table S3**).

Our modeling exercise shows that the potential distribution of the species in the SWAO is driven by SST and bathymetry, though the contribution of SST changes during different seasons (**Figure 5**, **Supplementary Figure S2**). During the "arriving" period, highest (red) suitable areas occur in shelf waters of southern Brazil (south of 25°S) and offshore waters (∼36°S) (**Figure 5A**), and then shift southward, reaching the ER estuary at ∼39°S (**Figures 1**, **5C**). The mean SST isotherms likely drive the species distribution (i.e., HS ≥ 0.5) also increase during this period: from 16 to 20°C as austral spring progresses (**Figures 5A–C**). During the "remaining" period, highest suitable areas are restricted to shelf waters mainly off Uruguay and Argentina, and SST isotherms range from 20 to 22°C (**Figures 5D–F**). During both periods, bathymetry has the

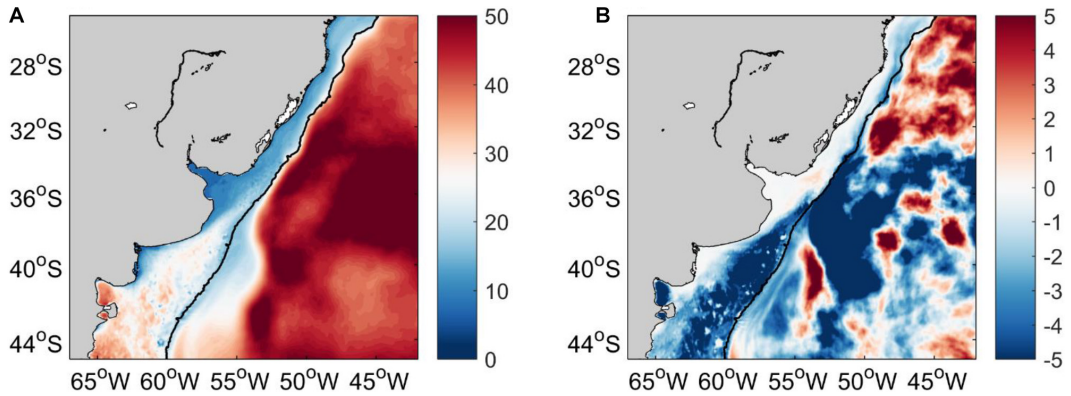

FIGURE 2 | (A) Mean mixed layer depth (MLD) in meters. **(B)** Trend of MLD in m/decade during 2003–2017. The 200 m isobath is shown in black.

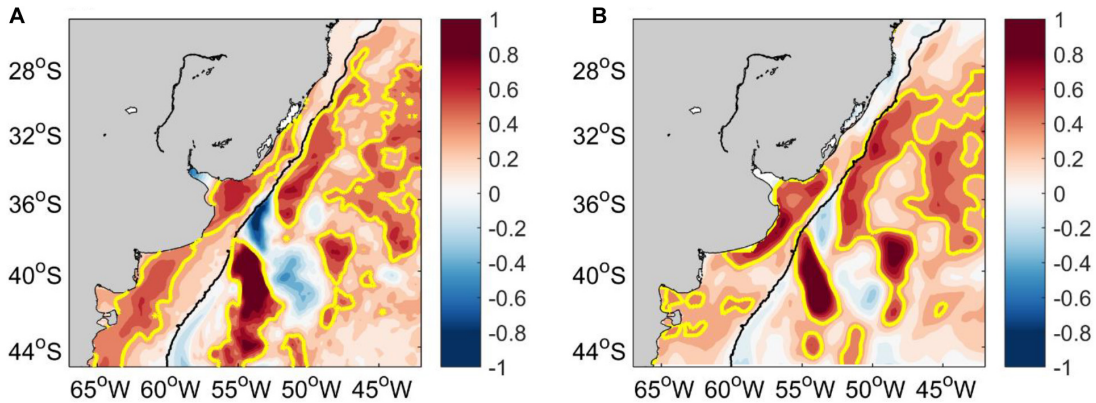

FIGURE 3 | (A) GLORYS12 and **(B)** ARMOR3D surface temperature trend (°C/decade) during 2003–2017. The yellow contour corresponds to the 0.4°C/decade isoline. The 200 m isobath is shown in black.

higher relative contribution to the model (from 77.8 to 88.3%) compared to SST (**Supplementary Figure S2**).

During the "leaving" period, however, highest suitable areas begin to shift northwards reaching the southern Brazilian shelf, accompanied by a decrease in the mean SST isotherms (from 17–18° to 12–13°C; **Figures 5G–J**, **Supplementary Figure S1**). During the "absent" period, high suitable areas are restricted to shelf waters off northern Uruguay and southern Brazil. Offshore high suitable areas shift northward reaching similar latitudes in October (∼36°S, **Figures 5J–L**). In contrast to the previous two periods, SST increases and equals its relative contribution compared to bathymetry (from 37.8 to 50.0%) during both "leaving" and "absent" periods (**Supplementary Figure S2**).

The thermally accessible range of *C. mydas* changes throughout the years (**Figure 6**). When the species arrives (November) and leaves (May), its thermal range seems to be associated with the 18 and 15°C isotherms, respectively. In February, the species thermal range is associated with the 22°C isotherm. The mean monthly location of these isotherms shifted southwards along the three 5-year periods (2003–2007, 2008–2012, and 2013–2017) at rates of −0.08, −0.12, and −0.14 degree of latitudes per year, respectively (**Figure 6**).

Patagonian Scallop Thermal Tolerance

GLORYS12 displays a large variability of the southern position of the BC over the slope between 2005 and 2014 at the surface (**Figures 7A,B**). The mean surface temperature during 2014 shows warmer BC waters (T > 20°C) reaching latitudes further south than observed during 2005. The BC reaches the Argentina-Uruguay Common Fishing Zone (AUCFZ) during 2014 (until ∼40°S; **Figure 7B**). A similarly large variability of the southern position of the BC over the slope is also observed at 92 m depth (**Figures 7C,D**).

The **Figure 7** is useful to show how upper ocean cooling/warming trends are modulated by BMC displacements. Since cold waters are transported by MC and warmer waters by BC cooling/warming trends may be induced by displacements of the BMC (**Figure 8**). The dynamical connection (coupling) between the high surface phytoplankton concentration along the SBF (overlying water) and the largest bed of the Patagonian scallop (bottom) is promoted by benthic-pelagic coupling processes which are particularly strong in austral spring (Franco et al., 2017). Therefore, we focus on the temperature trend in spring (October–November–December).

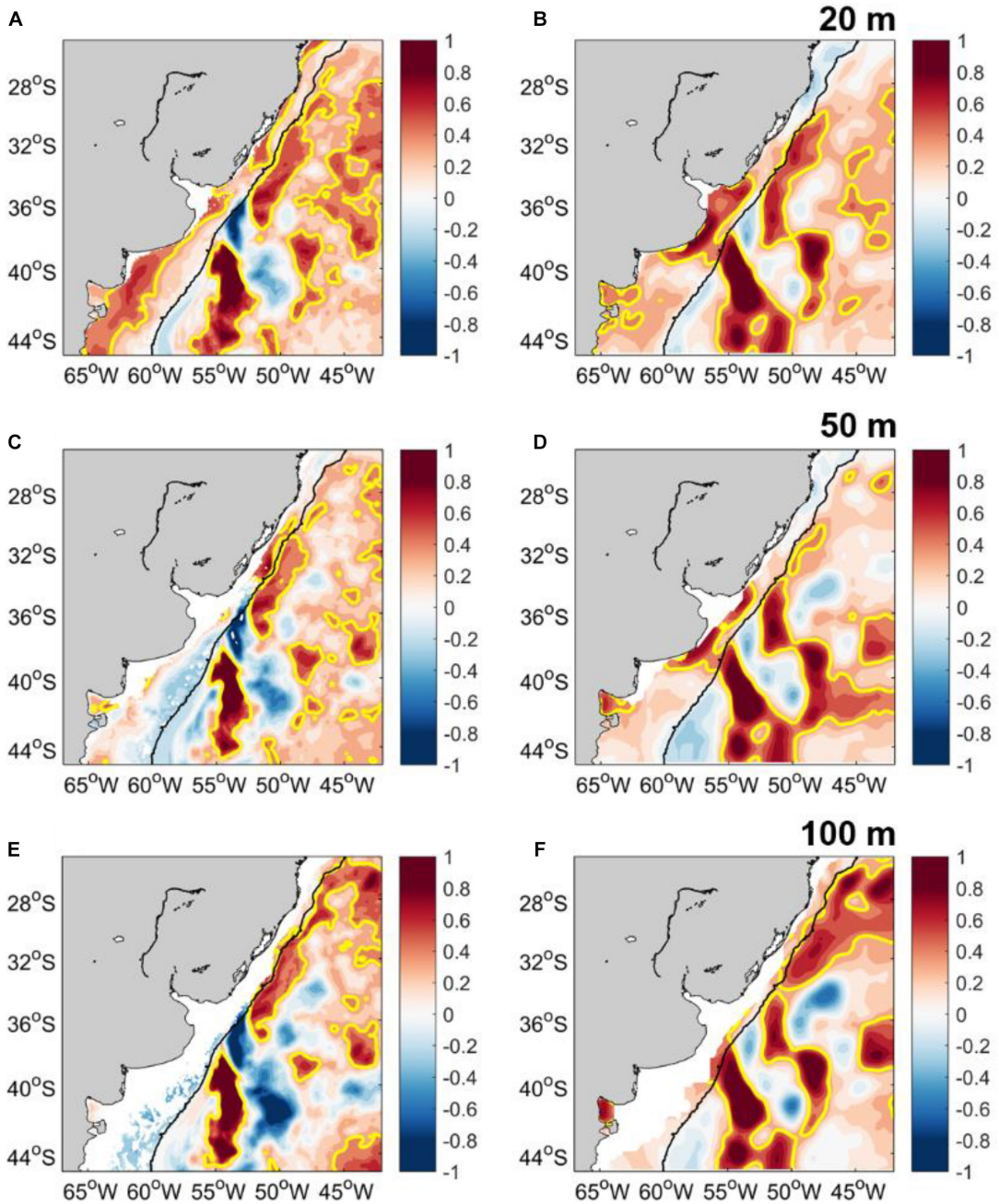

FIGURE 4 | GLORYS12 temperature trend (°C/decade) during 2003–2017 at **(A)** 18 m, **(C)** 47 m, and **(E)** 92 m. ARMOR3D trend (°C/decade) at **(B)** 20 m, **(D)** 50 m, and **(F)** 100 m. The yellow contour corresponds to the 0.4°C/decade isoline. The 200 m isobath is shown in black.

The model shows a clear warming trend along the path of the BC north of 37°S over the past 15 years with positive trends over the outer shelf, shelf break, slope and oceanic regions north of 37°S at 92 m depth in spring (**Figure 8**). As Patagonian scallop is a cold-water affinity species this warming trend and its projected southward displacement implies a trend toward unfavorable thermal conditions for the species. While this study focuses on the kinematics of the region, the dynamics of the driving mechanisms of those trends will be addressed in a separate study.

DISCUSSION

It is widely recognized that climate change must be incorporated into species conservation and management (Hannah et al., 2002; Grémillet and Boulinier, 2009; Evans et al., 2010; Hamann et al., 2010; O'Brien et al., 2013). Satellite derived surface chlorophyll-a distributions indicate that the SWAO, and the Argentine shelf in particular, present abundant phytoplankton concentrations (Gregg et al., 2005). Nonetheless, there are limited *in situ*

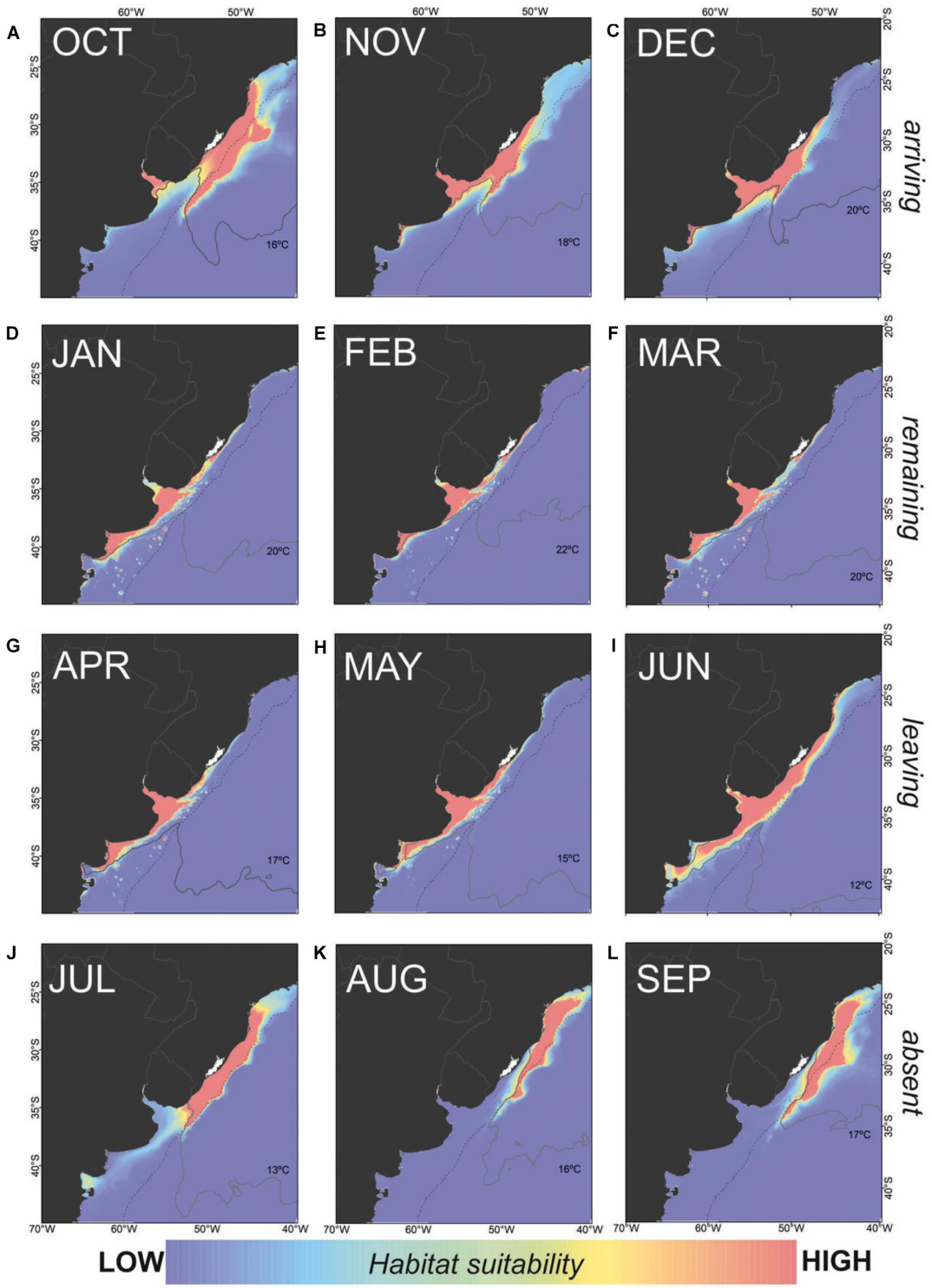

FIGURE 5 | Green sea turtle (*Chelonia mydas*) monthly habitat suitability throughout the year in its boundary range of the SWAO. *C. mydas* behavior is divided in periods as: **(A–C)** arriving, **(D–F)** remaining, **(G–I)** leaving, and **(J–L)** absent. Dashed black line indicates 200 m isobath.

observations of plankton composition and primary productivity observations (e.g., Lutz et al., 2018) and therefore the detection of ocean warming-driven impacts is constrained. Our results indicate negative trends of MLD over the Argentine mid-shelf and shelf break, which could alleviate light limitation and result in an increase in primary productivity (**Figures 2A,B**).

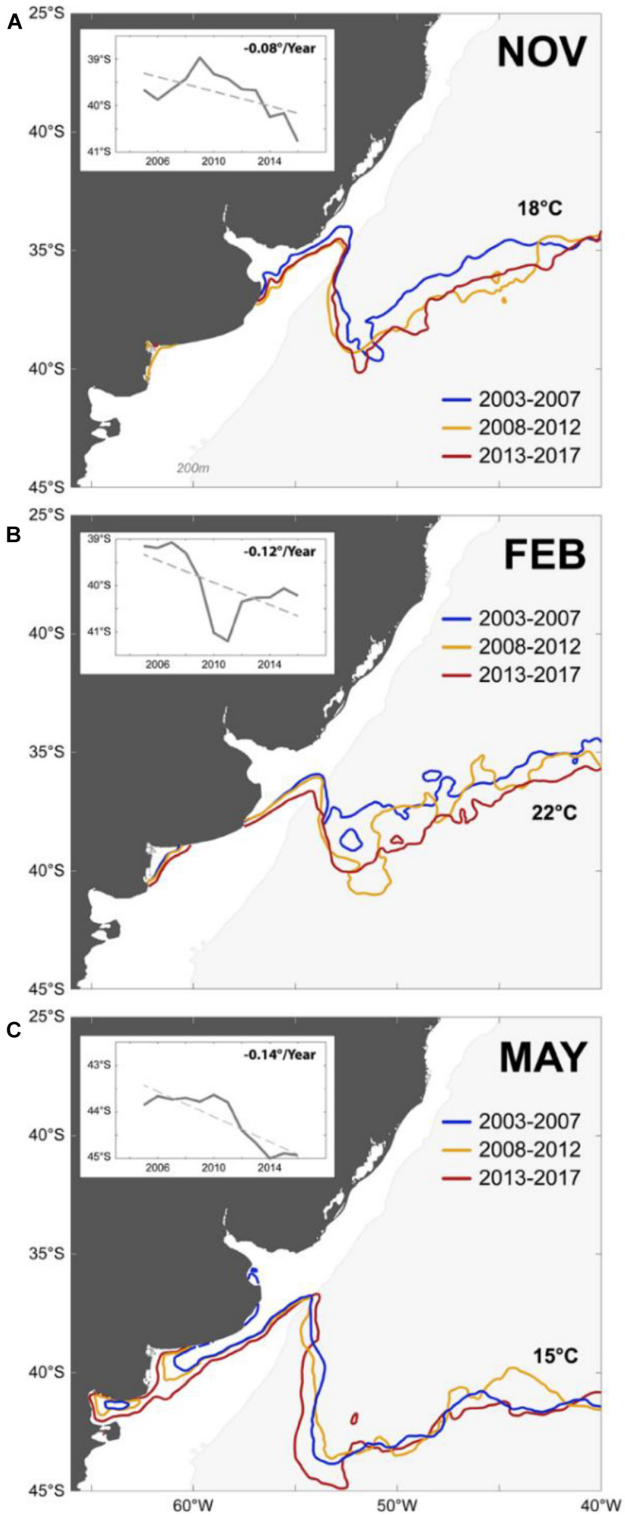

FIGURE 6 | Changes in the thermally accessible habitat range of the green sea turtle (*Chelonia mydas*) from 2003 to 2017 in the SWAO. The southward displacement of the surface isotherms likely drove the species distribution is shown for the representative months of the **(A)** "arriving," **(B)** "remaining," and **(C)** "leaving" periods. The inset shows the southward movement (latitude/year) of the mean isotherms for each period.

This is in accordance with the 2% increase in annual surface chlorophyll-a concentration observed in the mid- and outer shelf regions of the SWAO (Marrari et al., 2017) during 1998–2017. These changes in surface chlorophyll-a concentration are likely associated with changes in the cold, nutrient-rich water supplied by MC onto the adjacent, seasonally stratified waters of the outer shelf (Valla and Piola, 2015).

In the SWAO, surface warming induced by climate change is reported from GLORYS12 along the BC path, the BMC, the RdlP, and over the Patagonian inner and mid-shelf (**Figure 3A**). Higher positive temperature trends reported from GLORYS12 throughout the whole water column (surface to 100 m depth) along the path of the BC and BMC regions are consistent with the southward shift of the BC (**Figures 3A**, **4A,C,E**). Subsurface warming over the continental shelf is reported from the southern of Brazil, RdlP, and over the Patagonian inner and mid-shelf (**Figures 4A,C**). Our study provides initial evidence on the vertical extent of the main hotspots of the SWAO.

We also explored the potential impacts of ocean warming on two thermally constrained species. Water temperature plays a key role in the seasonal occurrence of sea turtles in high-latitude foraging grounds in the SWAO (González Carman et al., 2012, 2016a; Vélez-Rubio et al., 2018). The potential distribution of *C. mydas* in the region is explained by both, SST and bathymetry. SST increases its relative contribution to the model during the "leaving" and "absent" periods of turtle behavior, when individuals are most likely to be spatially constrained by temperature (**Figure 5**, **Supplementary Figure S2**). The warming implied by the displacement of mean surface isotherms likely drove the southward displacement of the species in the region during the period 2003–2017 (**Figure 6**). This is in agreement with the observed and projected poleward displacement of the thermal habitat of loggerhead turtles (*Caretta caretta*) reported by Witt et al. (2010).

Potential impacts of ocean warming on *C. mydas* in the SWAO are diverse. First, an increase in SST could imply an expansion of the optimal thermal habitat available for the species. For example, if the mean 18°C isotherm – critical for *C. mydas* when arriving to and remaining at Argentine shelf waters – continues displacing southward (**Figure 6**), the potential distribution of the species could also extend poleward. This seems a plausible hypothesis given that similar poleward displacements have been suggested for other sea turtle species such as loggerheads and leatherbacks (*Dermochelys coriacea*) in the North Atlantic (McMahon and Hays, 2006; Hawkes et al., 2007). In addition, subsurface ocean warming observed at 20 m depth in areas highly used by *C. mydas* (**Figure 4**), suggest a vertical expansion of the optimal thermal habitat.

However, the sea turtle distribution is likely driven by factors other than temperature. Sea turtles – especially *C. mydas*– show high fidelity to foraging areas (see Hart and Fujisaki, 2010 for a review), which may constrain exploration and settlement in alternative foraging grounds. Nevertheless, at least some juveniles of *C. mydas* in the SWAO show more behavioral plasticity compared to individuals of populations at lower latitudes. They are neither strictly herbivore nor neritic, as the canonical knowledge on the species claims. In summer and

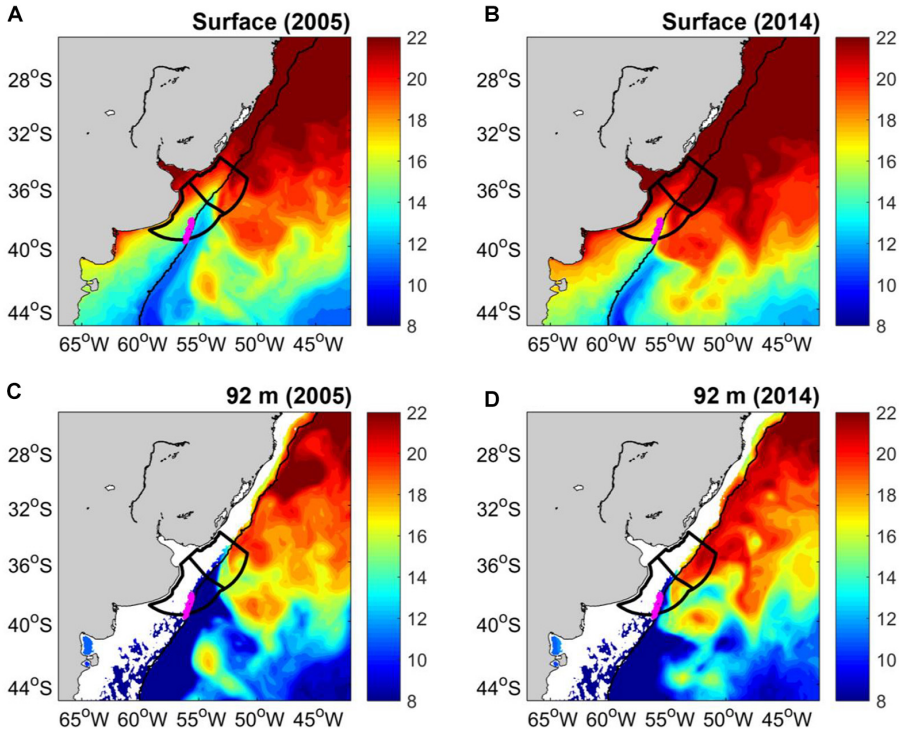

FIGURE 7 | GLORYS12 mean temperature at surface during **(A)** 2005 and **(B)** 2014. GLORYS12 mean temperature at 92 m depth during **(C)** 2005 and **(D)** 2014. The Argentina-Uruguay Common Fishing Zone (AUCFZ) is shown by two polygons with black heavy lines. The northernmost and largest Patagonian scallop bed is shown by a magenta polygon. The 200 m isobath is shown.

fall, juveniles forage most of the time in estuarine areas where no submerged macrophytes are found. In winter and spring, they either migrate northward to warm coastal areas where macroalgae and seagrass are available or inhabit deep-water areas (>200 m) compatible with a pelagic feeding behavior on gelatinous plankton (González Carman et al., 2012, 2014). Therefore, this behavioral plasticity exhibited by *C. mydas* could favor the exploration of new foraging areas.

Another factor driving sea turtle distribution is food availability (Witt et al., 2010). Brazilian seagrass communities are being affected by eutrophication, increased storm frequency, and sediment shifts associated with climate change (Short et al., 2006). Increased temperatures negatively affect growth and calcification of subtropical macroalgae, posing a great threat to macroalgal populations (Koch et al., 2013; Graba-Landry et al., 2018). But compelling evidence suggests that jellyfish abundances fluctuate with climatic cycles (Condon et al., 2013), with the majority of the temperate species studied increasing their abundance in warm temperatures due to increased asexual reproduction (Purcell, 2005; Purcell et al., 2007). Ocean warming may increase many populations of gelatinous species and trigger changes in its distribution and timing (Purcell, 2005; Purcell et al., 2007). This can be beneficial for *C. mydas* feeding on jellyfish in the SWAO, although trends in jellyfish abundance are ambiguous (Brotz et al., 2012; Condon et al., 2012).

An additional potential impact of ocean warming on *C. mydas* in the SWAO is a shift in the timing of seasonal movements (i.e., arriving earlier and leaving later). The southward displacement of the 15°C isotherm, critical for *C. mydas* when leaving Argentine shelf waters in May (**Figure 5H**), could potentially trigger a longer seasonal residency in these relatively high latitudes, along with increased foraging times if food availability is unchanged.

Besides the species considered in this study, the SWAO - especially the Argentine and Uruguayan shelves up to 20–50 m of depth - is a key ecological area for several megafaunal species of conservation value such as the loggerhead and leatherback turtles, the Brown-eyed albatross (*Thalassarche melanophris*), two sea lions (*Otaria flavescens* and *Arctocephalus australis*), among others (González Carman et al., 2016b). The potential impacts of ocean warming on some of these species might not be directly related to availability of optimal thermal habitats/periods or thermal tolerance, but to changes in the populations of their main prey species.

A key question emerging from our study is how climate change will impact the distribution and thermal tolerance of marine species in the SWAO. To answer this question and to overcome the high uncertainty levels associated with global predictive climate models (Franco et al., 2020), outputs from future regional models with higher horizontal resolution than Coupled Model Intercomparison Project (CMIP5)-class models (1° × 1°) will be necessary to better resolve changes in the circulation over the SWAO shelf and then the changes in marine species distribution.

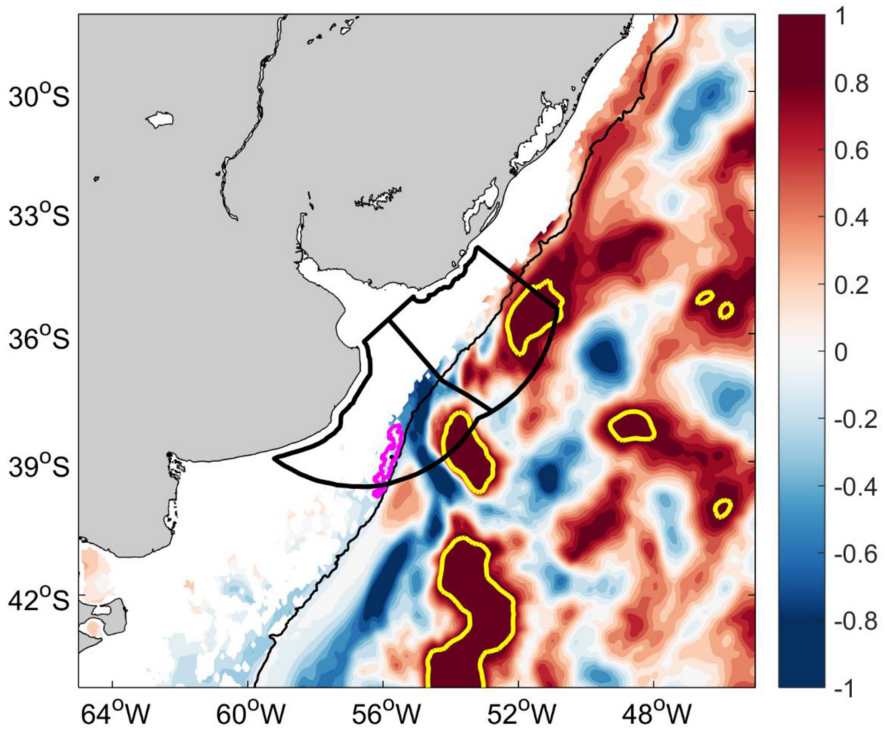

FIGURE 8 | GLORYS12 temperature trend (°C/decade) during spring of 2003–2017 at 92 m. The Argentina-Uruguay Common Fishing Zone (AUCFZ) is shown by two heavy-black polygons. The northernmost and largest Patagonian scallop bed is shown by a magenta polygon. Trends higher than 1°C/decade are depicted by a heavy yellow line. The 200 m isobath is shown in black.

The poleward displacement of warm tropical and subtropical waters of the BC (**Figure 7**) may have a strong impact on the productivity of SBF and the sustainability of the northernmost scallop beds. These benthic cold-water affinity communities that inhabit the outer shelf and shelf break region along the MC benefit from shelf-break upwelling and benthic-pelagic processes induced by MC. The southward shift of the BC could trigger significant changes on productivity of northern extent of the SBF. The resilience capacity of the benthic communities dependent on SBF productivity is also a key issue which requires further investigation. Stronger warming trends in subsurface waters reported by our study (**Figure 8**) are consistent with observations from Artana et al. (2019), who report a long-term trend of BC intensification and warming at 36°S in the upper 1,000 m (see their **Figures 13A,C**). The southward displacement of the tropical BC waters and the induced changes in the advection of BC deeper waters are suggested to induce such changes in the warming trend of deeper waters (their **Figures 2**, **13**). In a climate change scenario, warming of the BC and BMC is expected to continue during the 21st century, driven by the southward shift of the BC and the weakening of the MC transport (Yang et al., 2016, 2020; de Souza et al., 2019). This southward shift of water masses may induce a gradual warming over outer shelf and shelf break regions. The shelf break region currently under the influence of the northernmost extent of the MC (south of ∼38°S), where the largest Patagonian scallop bed is located, may be particularly vulnerable to such poleward displacement of warm waters.

A poleward shift of the subtropical gyres of the oceans and a fast warming of western boundary currents like the BC have been reported during the past decades (Yang et al., 2016, 2020). In addition, large changes in the strength and position of the western boundary currents have already been observed (Van Gennip et al., 2017). Therefore, we suggest that future impacts of climate change could affect import commercial fisheries and the conservation of several marine species in other regions located near poleward extension of western boundary currents.

Planning of analytical techniques in response to the increasing vulnerability of targeted fish stocks and affected communities to climate driven effects is required to support decision making (Ogier et al., 2020). Level of feasibility, risk of negative effects, and expected benefit in responding to a specific climate challenge should be evaluated based on a selected sub-set of options. Regional network between scientists, fisheries managers, and government stakeholder groups are required to plan the first steps to identify and evaluate the implications of temporal and distributional effects of implementing adaptation options (Ogier et al., 2020).

CONCLUSION

Surface and subsurface warming in the SWAO has been occurring at least during the past four decades, particularly in highly productive areas such as the RdlP, the BMC and the SBF.

Given the high uncertainty levels associated with predictions of global climate models (Franco et al., 2020), outputs from future regional models with higher horizontal resolution will be necessary to better resolve the potential changes in the circulation over the SWAO shelf and their potential impact on species distributions.

Ocean warming in the SWAO has potential impacts on the ecology of two thermally restricted species - *C. mydas* and *Z. patagonica*. Selection of case studies - as done here - to assess species exposure and sensitivity to ocean warming, and modeling of species response to climate changes are necessary to advance our understanding of the biological impact of climate change. These actions will be useful on the implementation of conservation programs (such as the National Plans of Action) and stock assessments of commercially important species.

Given the lack of long-term monitoring programs to address the impacts of climate change on marine biota in the SWAO, our results provide evidence to call the attention of stakeholders and decision makers on marine conservation and fishery management. These results are a useful basis toward better management strategies in the context of climate change.

In rapidly warming regions urgent efforts are needed to establish inter-disciplinary networks to set management and adaptation pathways, promote global learning, and implement adaptation options to cope with future changes in climate, the oceans, the marine species they host, their ecosystem services and the socioecological systems they conform.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: Copernicus Marine Environment Monitoring Service (CMEMS) (https://marine.copernicus.eu/).

AUTHOR CONTRIBUTIONS

BF conceived and developed the idea and design of the original manuscript, led sections 1, 3.1, 3.2, 3.4, 4, and 5, prepared the original manuscript, critically revised all versions of manuscript, and adapted **Figure 1** and prepared **Figures 2**, **3**, **4**, **7**, and **8**. VGC led sections 2.1, 2.2, contributed with the temperature trends calculation, made substantial contributions and revised critically all versions of manuscript. VC led sections 2.3 and 3.3, refined the content and scope of the original manuscript, made substantial contributions, critically revised all versions of the manuscript, prepared **Figures 5** and **6**, **Supplementary Tables S1–S3**, and **Supplementary Figures S1, S2**. All authors contributed according to their expertise to section 4 and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.563394/full#supplementary-material

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Bridging the Spatiotemporal Gap in Diazotroph Activity and Diversity With High-Resolution Measurements

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The biological fixation of dinitrogen (N_2) by marine microbes called "diazotrophs" sustains ∼50% new production in the ocean, boosting CO_2 absorption by photoautotrophs and thus contributing to the mitigation of climate change. New environmental conditions sustaining N_2 fixation have been revealed in recent years, enabling more accurate forecasting of future nitrogen inputs and localized hot spots. However, at present the paucity and biased geographical coverage of N_2 fixation and diazotroph diversity measurements impede attempts to reconcile global nitrogen budgets with observed rates. Most studies have been conducted at disparate spatiotemporal scales, including: (i) discrete and short duration measurements in small seawater volumes isolated from the environment, and (ii) spatial extrapolations and global models of diazotrophy projected over decades to centuries. We argue that this knowledge gap lies at the fine scales: dynamic seawater structures < 200 km wide and < 2 months lifetime. However, the spatiotemporal resolution of conventional oceanographic cruises, with stations separated by tens to hundreds of kilometers, is too poor to resolve fine scale processes. Bridging this gap requires leveraging high spatiotemporal resolution measurements. Here we present and discuss the advantages and disadvantages of contemporary methods and equipment able to provide high-resolution measurements at sea. We also provide insights into high-resolution sampling approaches to be developed in the near future. Increasing the spatiotemporal resolution of diazotroph activity and diversity will provide more realistic quantifications of nitrogen fluxes in the dynamic ocean.

Keywords: diazotrophs, fine scale dynamics, physical-biological coupling, cyanobacteria, N_2 fixation

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THE GAP IN OCEANIC N_2 FIXATION

Nitrogen is considered the predominant nutrient limiting primary production in the ocean (Tyrrell, 1999). Most of the ocean surface is too remote to benefit from land and atmospheric inputs but can receive from dinitrogen (N_2) fixation: the reduction of N_2 to ammonia carried out by specialized types of microbes called "diazotrophs." Diazotrophs play a crucial role in ocean biogeochemistry: they sustain ∼50% of marine new production (Mahaffey et al., 2005) and can contribute > 70% to carbon sequestration in the vast oligotrophic regions of the ocean (Karl et al., 2012; Caffin et al., 2018).

Our current knowledge of diazotroph diversity and activity (diazotrophy) is derived from disparate spatiotemporal scales (**Figure 1**). At smaller spatiotemporal scales, diazotrophs are studied by manipulating communities in incubation bottles with restricted volumes (typically < 5 L). Such incubations require a physical isolation from their environment, which can lead to exposure to well known "bottle effects" that introduce bias in our results (Zobell and Anderson, 1936). These small scale discrete incubations as well as local nutrient climatologies can be used to extrapolate rates of N_2 fixation regionally (e.g., Hansell et al., 2004; Luo et al., 2012). On larger scales, the isotopic composition of dissolved and particulate nitrogen are used to infer regional N_2 fixation rates (e.g., Bates and Hansell, 2004; Knapp et al., 2016). Mathematical models allow the extrapolation of diazotroph and N_2 fixation rate distribution patterns up to the global scale (Ward et al., 2013; Dutkiewicz et al., 2014; Gruber, 2016). Current estimates of fixed nitrogen inputs to the ocean via small or large scale approaches vary by dozens of Tg N y^{-1} (Luo et al., 2012; Landolfi et al., 2018). These discrepancies are perhaps not surprising given the spatiotemporal variation between these approaches.

Flow instabilities such as mesoscale (10–200 km, weeks) and submesoscale (1–10 km, days) structures—here collectively referred to as "fine scales"—control major processes fundamental to microbial physiology, including nutrient advection and export (Falkowski et al., 1991; Johnson et al., 2010; Guidi et al., 2012). Despite their importance, there is currently a spatiotemporal gap between small- and large-scale approaches in typical oceanographic research, limiting our understanding of microbial dynamics at fine scales (**Figure 1**). The inherent dynamic and sporadic character of fine scale structures makes them difficult to observe on individual oceanographic cruises (Mahadevan, 2016; McGillicuddy, 2016). Satellite ocean color data enables the observation of how fine scale dynamics accumulate or disperse chlorophyll, and even specific groups of phytoplankton (reviewed in Lehahn et al., 2017a). These approaches have formed a solid foundational understanding of physical-biological interactions in the ocean. However, *in situ* sampling remains imperative to measure changes in distributions at depth and microbial processes, which cannot be captured by satellite oceanography. Typical oceanographic cruises transect geographic locations separated by hundreds to a few thousand kilometers. With a regular navigation speed of ∼18 km h^{-1} (or 10 kn) and sampling operations that last several hours, such approaches result in poor spatiotemporal resolution sampling, incapable of resolving fine scale dynamics for most chemical and biological processes (Lévy et al., 2012).

As the physical features that create biogeochemical conditions dictating microbial activity, fine scale structures should be a focus, but they require a sampling scale that matches the structure of interest (Lévy et al., 2012). Recent technological advances have significantly improved this resolution. In this perspective, we provide an overview of the role of fine scale processes in structuring diazotrophic communities, the available tools to measure diazotrophic activity, abundance and diversity at high spatiotemporal resolution, and provide recommendations for future developments in the field.

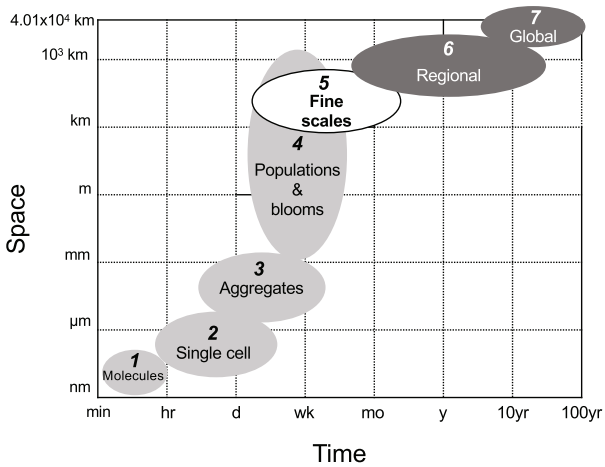

FIGURE 1 | The spatiotemporal scales of diazotrophy studies in the ocean ranging from minutes to 100 years in time and from nm to 4.01 × 10^4 km (the circumference of the Earth) in space. Light and dark gray ellipsoids depict the spatiotemporal scales of diazotrophy studied to date, i.e., lower and larger scales in light and dark gray, respectively. The white ellipsoid depicts the current gap in knowledge: the fine scales. This gap can only be filled by developing novel methods capable of measuring diazotroph community composition, abundance and activity at high spatiotemporal resolution. (1) We refer as "molecules" to molecular processes covered in transcriptomic studies. Gene transcription typically takes place in a time range of minutes. (2) The interaction between molecules and cells is approached by nano- to microscale techniques exploring chemical microenvironments with microsensors (e.g., Eichner et al., 2017, 2019), substrate uptake using nanoscale secondary ion mass spectrometry (e.g., Finzi-Hart et al., 2009; Thompson et al., 2012; Bonnet et al., 2016), or molecular marking targeting proteins (e.g., Lin et al., 1998; Foster et al., 2006; Hynes et al., 2009) at the single-cell level. This spatiotemporal scale ranges in space from the size of intracellular compartments visible with those techniques to the maximum size of a single diazotroph cell. In time, this spatiotemporal scale reaches the maximum incubation time used in such studies, i.e., usually up to 72 h. (3) The localization of substrates or sub-cellular structures of interest in colonies and or aggregates can be approached with the techniques included in (2). The size, shape and horizontal/vertical distribution of aggregates in the ocean is usually resolved with microscopy (e.g., White et al., 2018), bench flow cytometry (Bombar et al., 2013; McInnes et al., 2014), field semiautomated flow cytometry (Dugenne et al., 2020), or automated underway devices such as the video plankton recorder (Davis and McGillicuddy, 2006). The size of this spatiotemporal scale ranges from tens of microns to several mm. The time range is considered to range between several hours and a few weeks, although the fate of aggregates in the ocean or how long they remain intact or alive is uncertain. (4) The composition and distribution of diazotroph populations is usually approached by discrete sampling along oceanographic cruise transects spanning hundreds to a few thousands of km. Such studies cover a time range from a few days to several weeks and depict communities using microscopy and/or molecular analyses such as quantitative PCR (e.g., Moisander et al., 2010; Bonnet et al., 2015; Benavides et al., 2016; Shiozaki et al., 2017). *Trichodesmium* blooms can cover extensions of hundreds to thousands of square km and are studied with customized algorithms applied to satellite products such as SeaWiFS or MODIS (Hood et al., 2002; Subramaniam et al., 2002; Rousset et al., 2018). (5) Submesoscale (1–10 km, days) structures such as filaments, and mesoscale (10–200 km, several weeks) structures including fronts and eddies (here collectively referred to as "fine scales," see section "How Fine Scale Processes May Affect Diazotrophs" of the main text). Studies seeking to link fine scales to diazotrophy have conducted discrete sampling along the central edge of mesoscale eddies at stations situated tens of km apart at best (e.g., Fong et al., 2008; Zhang et al., 2011; Löscher et al., 2016; Liu et al., 2020). In these studies, the distribution

(Continued)

FIGURE 1 | Continued
and activity of diazotrophs has been approached with traditional methods for the characterization of the diazotroph community (i.e., microscopy, quantitative PCR, $^{15}N_2$ stable isotope incubations). Underway N_2 fixation rate measurements hold great promise in providing submesoscale resolved data (e.g., Moore et al., 2018; Tang et al., 2019), but to date such approaches have not been investigated in depth with parallel physical oceanography parameters. (6) Regional studies often stem from direct N_2 fixation rates or diazotroph abundance measurements obtained from a single oceanographic cruise or a combination of several datasets extrapolated over a given region (Luo et al., 2012; Tang et al., 2019). Indirect methods to obtain N_2 fixation estimates such as the N* parameter or $\delta^{15}N$ distributions (e.g., Hansell et al., 2004; Deutsch et al., 2007) as well as modeling approaches integrating nutrient climatologies, repeated transect datasets and ocean circulation (Landolfi et al., 2008; Torres-Valdés et al., 2009) have also been used to infer regional diazotrophy estimates. The temporal span of this scale is thus large, ranging from several weeks to tens of years. Finally, (7) global marine diazotrophy studies have been addressed with models integrating biogeochemistry, ecological and circulation models (e.g., Monteiro et al., 2011; Dutkiewicz et al., 2014; Wang et al., 2019). At present, our poor mechanistic knowledge of the diversity, physiology, trophic interactions and environmental constrains of different diazotrophs, combined with computational power constraints makes it difficult to run models considering more than two or three diazotroph ecotypes. The numbering of the different spatiotemporal scales considered in this figure is illustrative and does not intend to exclude possible subdivisions, overlaps or clustering between scales in marine diazotrophy yet to be described by new techniques and sampling approaches.

HOW FINE SCALE PROCESSES MAY AFFECT DIAZOTROPHS

Although there are a limited number of diazotroph taxa, their ecologies are very distinct (referred to here as "ecotypes"; Thompson and Zehr, 2013), with different morphologies, activities and physiological constraints which dictate their biogeographical and seasonal distribution globally (Zehr and Capone, 2020). Due to the high variability of physical and chemical factors at the fine scale, the extent to which physical features affect diazotrophs will depend on how the resulting physicochemical changes affect each ecotype's physiology and metabolism (Lévy et al., 2012). Due to the range of factors contributing to the relative success of each ecotype, rates alone cannot provide enough information to model diazotrophy. It is necessary to collect rates while quantifying the organism(s) responsible to better characterize the bottom-up controls on distributions and activities of each ecotype.

Fine scales comprise a wide range of structures including filaments, fronts and eddies, with different physical dynamics that influence their biogeochemical properties. For example, vertical transport in submesoscale fronts causes rapid injections of deep nutrient rich waters, enhancing phytoplankton growth locally (Mahadevan, 2016). It is uncertain to which extent diazotrophs may benefit from such rapid inputs given their slow growth rates. Horizontal stirring strains fine scale features into thinner filaments, distributing phytoplankton niches (d'Ovidio et al., 2010) and regulating the access to limiting nutrients and mortality due to grazing and viral infection (Lehahn et al., 2017b). The success of a given species will depend on the balance between physical and biological time scales, e.g., when nutrient delivery promotes sufficient growth to overcome grazing and viral pressure (Lehahn et al., 2017b).

Eddy trapping can isolate planktonic assemblages in Lagrangian coherent structures where lateral exchange with surrounding waters is limited (Lehahn et al., 2011). Such structures may act as a shield impeding dilution of nutrients permitting phytoplankton growth, or as a trap if a given species gets "trapped with the enemy" (i.e., predator; Bracco et al., 2000; Lehahn et al., 2014). Mills and Arrigo (2010) argued that non-Redfield usage of nutrients by non-diazotrophic phytoplankton lowers N:P ratios, creating diazotroph niches. Following this logic, we hypothesize that non-diazotrophic phytoplankton thrive in coherent eddies until the nitrogen trapped within them is depleted. While non-diazotrophic phytoplankton thrive, diazotrophs would be outcompeted (likely with the exception of UCYN-A, as discussed below). Once nitrogen is depleted diazotrophs may succeed, benefiting from a decrease in competition for phosphorus and trace metals with non-diazotrophic phytoplankton. This balance is likely further set by grazing and viral infection on diazotrophs. Indeed, Dugenne et al. (2020) observed higher growth rates and lowered grazing pressure on *Crocosphaera* inside a lower-biomass anticyclonic eddy as compared to a cyclonic eddy.

Eddy pumping is postulated to explain differences in diazotroph abundance and/or N_2 fixation rates, i.e., anticyclonic eddies deepen isopycnals, lowering nutrient availability and promoting diazotroph development, while the reverse occurs in cyclonic eddies. For example, *Trichodesmium* is sensitive to dissolved inorganic nitrogen (Knapp et al., 2012) and accumulates in anticyclonic eddies (Davis and McGillicuddy, 2006; Fong et al., 2008). However, anticyclones do not only hamper the upwelling of nitrate, but also of dissolved inorganic and organic phosphorus which exert an important control in the growth and diazotrophic activity of *Trichodesmium* (e.g., Dyhrman et al., 2006; Hynes et al., 2009).

Trichodesmium harbors gas vesicles that provide them with buoyancy control (Villareal and Carpenter, 2003). *Trichodesmium* may be thus treated as buoyant particles accumulating at frontal structures (Taylor, 2018). Forced accumulation at surface frontal structures may increase nutrient limitation in *Trichodesmium* colonies while increasing sunlight exposure, potentially inducing cell mortality via autocatalytic death pathways and thereby vertical export (Berman-Frank et al., 2004). The unicellular diazotroph *Crocosphaera watsonii* can be found as small (2–3.5 μm) and large (4–5 μm) cell types (Bench et al., 2016). While the oligotrophic conditions that promote *Trichodesmium* in anticyclonic eddies similarly contribute to the proliferation of *C. watsonii* (Fong et al., 2008; Liu et al., 2020), physical accumulation at high density frontal areas is less likely for non-floating unicellular diazotrophs. The large cell type may be more prone to accumulation aided by the excretion of extracellular polymeric substances and formation of aggregates, a characteristic not described for the small cell type (Webb et al., 2009; Sohm et al., 2011) and implied previously to explain their distinct vertical distributions at the edge of an anticyclone (Bench et al., 2016). Wilson et al. (2017) quantified an 11% contribution to net community production attributed

to N_2 fixation by abundant *Crocosphaera* near an anticyclonic eddy, and an increased contribution of N_2 fixation to particulate nitrogen export flux.

The uncultivated unicellular diazotroph UCYN-A is a small (<1 μm) cyanobacterium in obligate symbiosis with a prymnesiophyte host to whom they provide fixed nitrogen in exchange for fixed carbon (Thompson et al., 2012). While widely distributed in warm low latitude seas (Moisander et al., 2010), UCYN-A also thrives in nutrient-rich and cold waters such as coastal upwelling ecosystems and polar seas (Agawin et al., 2014; Harding et al., 2018; Moreira-Coello et al., 2019). Both UCYN-A and its host are dependent on N_2 fixation for their nitrogen needs even in the presence of abundant inorganic nitrogen, which has been found to stimulate N_2 fixation (Mills et al., 2020). Such tolerance makes UCYN-A a good candidate to benefit from the biogeochemical conditions provided by eddy pumping in cyclonic eddies. However, abundant UCYN-A have been reported in anticyclones but not cyclones (Fong et al., 2008; Robidart et al., 2014; Liu et al., 2020). Perhaps driven by Ekman pumping of deep nutrient-rich waters in anticyclonic eddies (Anderson et al., 2011), as proposed to explain higher abundances of *Trichodesmium* in cyclonic eddies in the North Atlantic (Olson et al., 2015). Counter to expectations, episodic nutrient advection at the periphery of an anticyclonic eddy has previously been found to contribute to lower *nifH* transcription from both UCYN-A and *Crocosphaera* (Robidart et al., 2019).

Non-cyanobacterial diazotrophs (bacteria and archaea) cannot photosynthesize, which renders them dependent on organic matter to fulfill their energy and carbon needs (Bombar et al., 2016) although other metabolisms such as chemolithoautotrophy are plausible (Riemann et al., 2010). Their prevalence in anticyclonic eddies has been attributed to the accumulation of organic matter within the core (Löscher et al., 2016), while a separate study finding higher abundances in cyclonic eddies predicted that is was due to the alleviation of phosphorus stress (Zhang et al., 2011). Finally, diatom-diazotroph associations (DDAs) dominate in low salinity and high silicate waters of river mouths such as the Mekong and the Amazon river plumes (Foster et al., 2007; Bombar et al., 2011). As the plume dilutes, the diazotrophic community shifts toward unicellular diazotroph ecotypes, indicating that the dispersion of the plume ultimately determines their geographical distribution (Grosse et al., 2010). In the oligotrophic North Pacific, Harke et al. (2019) measured coordinated gene expression between the *Richelia-Rhizosolenia* DDA over the same anticyclonic transect as *Crocosphaera* and *Trichodesmium* high-resolution metatranscriptomes mentioned previously (Wilson et al., 2017; Frischkorn et al., 2018, respectively). Comparative analysis of these metatranscriptomes within the dynamic physical environmental context may reveal conserved mechanisms of response associated with N_2 fixation.

As discussed above, fine scale structures may affect diazotroph ecotypes in different ways according to their autoecology and physiology as well as trophic interactions within the planktonic community. The biogeochemical characteristics and trophic interactions taking place within these structures change between formation and dissipation. We thus predict that the impacts on diazotrophs evolve over the lifetime of these structures.

TOOLS FOR HIGH-RESOLUTION DIAZOTROPH SAMPLING

Fine scale structures are dynamic and ephemeral, making instrumentation for high-resolution measurements indispensable for their study. This instrumentation must be capable of providing activity, abundance and diversity data at spatiotemporal resolutions equal to or smaller than that of the physical and biological processes under study (Lévy et al., 2012). Below we present currently available technology to address the dynamics of diazotroph assemblages embedded in dynamic fine scale structures.

The studies that have sought to understand the role of fine scales on structuring diazotrophic communities or modulating N_2 fixation rates have used traditional sampling approaches consisting of CTD-rosette casts at discrete stations. These approaches may suffice when applying a Lagrangian sampling strategy, i.e., following a given water mass at the pace it moves. However, ephemeral submesoscale structures associated with eddies are not easily quantified or characterized with traditional sampling (Johnson et al., 2010). In the past decade, technological developments have allowed the quantification of diazotroph ecotypes at a higher frequency than that provided by conventional sampling. The first study to do so used a towed video plankton recorder to continuously visualize *Trichodesmium* colonies across the North Atlantic, finding clear associations with anticyclones (Davis and McGillicuddy, 2006). Using an ecogenomic sensor, Robidart et al. (2014) found that diazotroph abundances changed over three orders of magnitude in less than 2 days and 30 km in the North Pacific. Most recently, a microbiological autosampler collected 1 sample/h over a transect in the North Atlantic, showing record abundances of UCYN-A in cold coastal regions and less abundant *Trichodesmium* in warmer waters offshore (Tang et al., 2020). In the same region, another study with a spatial resolution of 1 sample each ∼5 km found peak abundances of *Trichodesmium* coinciding with steep gradients of current velocity at the edge of the Gulf Stream (Palter et al., 2020).

Geochemical approaches to measure N_2 fixation include the N^* parameter, which measures the concentration of nitrate in excess (or deficit) of that expected from the remineralization of phosphate at Redfield stoichiometries (Gruber and Sarmiento, 1997). This method has been used to study diazotrophy within mesoscale eddies in the eastern tropical South Pacific (Löscher et al., 2016). The $\delta^{15}N$ approach measures the relative $^{14}N/^{15}N$ isotope signature and relates low values ($\delta^{15}N \sim 0.6‰$) to diazotrophic activity (Karl et al., 2002). Geochemical methods have the disadvantage that N_2 fixation signatures ($N^* > 2.5$ μmol kg^{-1} or low $\delta^{15}N$ values) can be caused by processes other than N_2 fixation (Hastings et al., 2003; Zamora et al., 2010), but have the advantage that they can be used in large oceanic regions and are incubation-independent.

The most common biological method to measure N_2 fixation rates is using stable isotope tracers in 24 h incubations

(Montoya et al., 1996; White et al., 2020). *In situ* stable isotope incubations have been previously adapted to surface drifters (the Submersible Incubation Device, or SID), with 4 × 24 hour incubations per deployment (Bombar et al., 2015). Indirect methods such as hydrogen production measurements or the acetylene reduction assay allow working with smaller volumes and shorter incubation times, thus providing a faster measurement alternative for high spatiotemporal resolution studies. Hydrogen production measurements are based on the principle that N_2 reduction produces hydrogen (H_2) in an equimolar reaction, so that every mole of H_2 produced can be equated to a mole of N_2 fixed (Wilson et al., 2010b). However, uptake hydrogenase enzymes are also present in diazotrophs to re-assimilate H_2 and recover energy, altering the ratio of N_2 reduced to H_2 released, which in practice varies between 0.2 and 13 (Wilson et al., 2010b; Wilson et al., submitted). This method yields rates every ∼20 min, and can be used in diel cycle studies (Wilson et al., 2010a,b) or on high-frequency measurements over oceanographic cruise transects (Moore et al., 2014, 2018).

The acetylene reduction assay is based on the ability of the nitrogenase enzyme to reduce other triple-bonded molecules such as acetylene, which is reduced to ethylene and converted to N_2 fixation rates using a ratio of 3:1 or 4:1 depending on if hydrogen re-assimilation is considered or not (Stal, 1988; Capone, 1993), but just as with hydrogen measurements, empirically determined ratios vary widely (Mulholland et al., 2004, 2006). Recently, this assay has been adapted to measure continuous N_2 fixation in underway seawater systems (Cassar et al., 2018; Tang et al., 2020). Indirect methods measure gross N_2 fixation rates, i.e., how much N_2 has been reduced by the nitrogenase enzyme, independent of whether it is channeled to diazotroph biomass or released extracellularly as dissolved nitrogen compounds. Because diazotrophs are known to release significant amounts of fixed N_2 extracellularly (Mulholland et al., 2004; Benavides et al., 2013; Berthelot et al., 2015; Bonnet et al., 2016), gross N_2 fixation measurements may provide better estimates of fixed N_2 inputs to the ocean.

FUTURE PERSPECTIVES

In situ DNA sensors, samplers and rate measurements have provided abundance or activity data at an unprecedented spatiotemporal resolution. Understanding how fine scales shape diazotroph communities requires the combination of diazotroph identification, enumeration and N_2 fixation measurements at high, 4-dimensional spatiotemporal resolution.

Directed sampling within fine scale structures can be challenging, requiring the inspection of hydrographic variables and Lagrangian structures prior to the cruise (Nencioli et al., 2011; Doglioli et al., 2013). Following Lagrangian coherent structures requires the deployment of floats or vehicles capable of geolocalizing a moving water parcel. Fronts and mesoscale eddies are easier to characterize than ephemeral structures such as submesoscale filaments. Importantly, synoptic measurements of physical and chemical variables including horizontal and vertical current speed, vorticity, vertical turbulent microstructure and inorganic and organic nutrient diffusion are needed to comprehensively understand how fine scale processes affect diazotrophs.

Recent advances in vehicles and sensors will contribute to our understanding of physical-chemical-biological interactions *in situ*. Measurements of turbulence are becoming more frequent on seagliders (e.g., Fernández-Castro et al., 2020). Deployed nutrient sensors with nanomolar limits of detection (Beaton et al., 2012) can facilitate the observation of episodic or small-scale events in oligotrophic mixed layers. Autonomous vehicles capable of Lagrangian drift can follow specific water masses, sampling the microbial community in its environmental context (Birch et al., 2019) and autonomous orientation using chlorophyll concentrations allows targeted sampling of structures within the water column (Zhang et al., 2019). Deployments of combined sensors will enable a more thorough understanding of diazotroph – environmental interactions on fine scales, to be integrated across water masses for larger scale understanding. Measurements of flux, although currently providing data at higher resolution (Bombar et al., 2015; Tang et al., 2019; Wilson et al., submitted) currently require ship-based manipulations and/or analysis and are not yet capable of *in situ* deployment. Integrated, cross-disciplinary field-based efforts are crucial to resolve effects of short spatiotemporal scale dynamic processes fundamental to microbial activity.

RECOMMENDATIONS

Providing detailed sampling procedures to study the effects of fine scale structures on diazotrophs is challenging since dedicated high-resolution sampling devices are not widely available nor standardized for the oceanographic community. Nevertheless, dedicated study of fine scale processes is required in order to connect biological processes to underpinning physical and biogeochemical drivers. Below we provide a list of recommendations hoping to inspire microbial oceanographers to embrace such studies in their research programs.

(1) Fine scales are dynamic and ephemeral, requiring Lagrangian sampling approaches. Prior geolocalization of structures with satellite products is required for targeted sampling. Post-cruise satellite-derived data such as altimetry and ocean color aid description of underlying physical processes. In addition, *in situ* measurements of current speed and vertical mixing are highly recommended to better constrain fine scale structures.
(2) High-resolution measurements within large eddies can deliver the same diazotroph dynamics observed via long-term Eulerian measurements in time-series station data (McGillicuddy et al., 1999; Robidart et al., 2014). Since comprehensive time-series stations cannot be implemented across the global oceans, strategic observations targeting fine scale features should be implemented in representative oceanic provinces to capture biogeochemical variability over short field programs.

(3) Diazotroph abundance and diversity measurements should be measured synoptically with N_2 fixation measurements. Fine scales comprise a wide array of structures which may affect different diazotroph phylotypes in disparate ways. Coupling activity and abundance/diversity measurements will provide insights into passive (accumulation) versus active (N_2 fixation activity stimulation) effects on diazotrophs.
(4) Growth and mortality measurements should be implemented (e.g., Dugenne et al., 2020). While few studies have attempted to measure *in situ* growth of diazotroph phylotypes, redistribution of assemblages by fine scale structures may alter the balance between growth, mortality and predator pressure.

DATA AVAILABILITY STATEMENT

All datasets presented in this study are included in the article/supplementary material.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Microplastic Pollution in Deep-Sea Sediments From the Great Australian Bight

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Interest in understanding the extent of plastic and specifically microplastic pollution has increased on a global scale. However, we still know relatively little about how much plastic pollution has found its way into the deeper areas of the world's oceans. The extent of microplastic pollution in deep-sea sediments remains poorly quantified, but this knowledge is imperative for predicting the distribution and potential impacts of global plastic pollution. To address this knowledge gap, we quantified microplastics in deep-sea sediments from the Great Australian Bight using an adapted density separation and dye fluorescence technique. We analyzed sediment cores from six locations (1–6 cores each, n = 16 total samples) ranging in depth from 1,655 to 3,062 m and offshore distances ranging from 288 to 356 km from the Australian coastline. Microplastic counts ranged from 0 to 13.6 fragments per g dry sediment (mean 1.26 ± 0.68; n = 51). We found substantially higher microplastic counts than recorded in other analyses of deep-sea sediments. Overall, the number of microplastic fragments in the sediment increased as surface plastic counts increased, and as the seafloor slope angle increased. However, microplastic counts were highly variable, with heterogeneity between sediment cores from the same location greater than the variation across sampling sites. Based on our empirical data, we conservatively estimate 14 million tonnes of microplastic reside on the ocean floor.

Keywords: deep-sea, fiber, fragment, microplastics, pollution, sediment

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INTRODUCTION

Plastic pollution of the world's oceans is an internationally recognized environmental issue (UNEP, 2018). The extent of this pollution, and increasing understanding of its potential impacts, make it a matter of increasing public concern (Bonanno and Orlando-Bonaca, 2018). Millions of tonnes of plastic enter the marine environment annually, and quantities are expected to increase in coming years (Jambeck et al., 2015; Geyer et al., 2017; Lebreton and Andrady, 2019). Over time, plastic items in the marine environment can degrade or break down into smaller pieces predominantly through weathering and mechanical forces such as wave action and abrasion with

sand (Thompson et al., 2004; Corcoran et al., 2009). Once a plastic item is between 5 mm and 1 μm, it is defined as microplastic (MP) (GESAMP, 2015). Due to their size, MPs are easily ingested by an extensive range of marine species from high to low trophic species (Wright et al., 2013) and can cause negative effects on organisms (Teuten et al., 2009; Galloway, 2015; Auta et al., 2017; Hermabessiere et al., 2017).

Research has shown that plastic pollution (including MPs) accumulate in seafloor sediments either directly by sinking through the water column or indirectly via currents and sediments transported down continental slopes (Clark et al., 2016). However, the extent of MP accumulation in deep-sea sediments is poorly understood due to numerous logistical factors. Namely, the ocean is deep and vast, and there are significant costs and operational challenges associated with obtaining samples from deep-sea environments. Regardless of these limitations, it is important to investigate MPs in the benthic environment as the deep seabed may be harboring a large amount of plastic pollution that is unaccounted for Woodall et al. (2014). To date, MPs have been found in deep-sea sediments in surveyed areas of all major oceans (e.g., Van Cauwenberghe et al., 2013; Bergmann et al., 2017; Zhang et al., 2020). Although all major oceans have been explored, the survey areas are small and scarce, and to date, there have been no studies of deep-sea sediments in Australian waters.

To fill this knowledge gap, we sampled deep-sea sediment from the Great Australian Bight (GAB), a large ocean area to the south of Australia that is home to a range of iconic marine species (CSIRO, 2018). The risk of plastic pollution on the seabed here via local land-based sources is extremely low due to the low population density in adjacent coastal areas (Hardesty et al., 2017). However, when considering the estimated movements of ocean surface particles on a global scale (UNEP, 2016), the GAB is not immune to land-based sourced of plastic pollution and may be receiving plastic pollution from as far away as Africa and Asia (Lebreton et al., 2012; van Sebille et al., 2015). Furthermore, ocean-based anthropogenic activity due to the GAB supporting Australia's largest fishing industry (CSIRO, 2018) and mining exploration (O'Neil, 2003), sea-based sources of pollution are not unlikely. Despite the region's ecological and economic importance, the GAB has only been previously surveyed in one marine plastics study, which focused on the ocean surface and found low levels of floating plastic pollution (Reisser et al., 2013).

In addition to investigating the quantity and distribution of seabed MPs in the region, we used oceanographic models to assess the potential origin sources of MP we observed. Finally, we extrapolated from our empirical data to provide a conservative global and mass of MPs on the seabed floor.

MATERIALS AND METHODS

Sample Collection

Deep-sea sediments were collected from six locations in the GAB in March and April 2017 (**Figure 1**). Sample locations ranged from 288 to 356 km off the Australian coastline with ocean depths ranging from 1,655 to 3,062 m (**Table 1**). A remotely operated vehicle deployed from the REM Etive (Voyage RE2017_C01) was used to press polycarbonate sediment cores (500 mm long, 100 mm internal diameter) into the seafloor, with between one and six cores collected at each of the six survey sites (**Table 1**). Onboard the vessel, each core was subsampled using two to three polypropylene mini-cores (91 mm long, 29 mm wide), and one bulk sample was taken from the surface of each main core. In total, 35 mini-core subsamples and 16 bulk subsamples were collected, totaling 51 subsamples for analysis (**Table 1**). All subsamples were wrapped in aluminum foil and immediately frozen for storage. Sampling personnel wore cotton fiber overalls to minimize sampling contamination through air-borne plastic fibers from clothing.

Laboratory Analysis

The laboratory analysis method was adapted from an MP fluorescence technique developed by Maes et al. (2017). Sediment subsamples were defrosted and homogenized with filtered deionized water. Each subsample was homogenized via gentile agitation. Approximately 15 g (about a third of each mini-core) of each homogenized subsample was added to 30 mL of zinc chloride ($ZnCl_2$) solution (density of 1.37 g mL^{-1}) and 400 μL of Nile Red dye solution (Nile Red 1 mg: n-propanol 1 mL) to give a final concentration of approximately 10 μg mL^{-1} Nile Red. Each subsample was treated individually in this way. These subsamples were agitated on an orbital shaker for 30 min and centrifuged at 1,800 × *g* for 5 min. Following centrifuging, the supernatant was vacuum filtered through a 0.22 μm mixed cellulose ester filter membrane. The sediment was rinsed with another 30 mL of $ZnCl_2$ solution and centrifuged again at 1,800 × *g* for 5 min. The rinsing and centrifuging step was repeated a second time; hence, a total of three supernatant volumes were collected per sediment subsample. The supernatant from each subsample was then filtered through a single filter paper for microscopy analyses. The specific density of the $ZnCl_2$ solution, combined with the centrifuging step, reduced the possibility of organic matter in the collected supernatant per subsample. This was an important step because organic matter is also known to take up Nile Red dye (Shim et al., 2016) and can potentially lead to false-positive results. A ratio of wet to dry sediment mass (air-dried while covered with pre-rinsed aluminum foil, with mass measured to four decimal places) was determined for each subsample and used to convert the number of MPs per wet sediment to a dry sediment result (per gram of dry sediment).

Quantification Analysis Using Fluorescence Microscopy

The MPs present on each subsample filter were counted using a Leica MZ16FA microscope viewed at 25 times magnification with a fluorescent light source and a GFP2 filter. Microscope camera settings: exposure 240.9 mS, gain 4.9×, saturation 0.25, and gamma 0.73. MPs were categorized as being fragments or fibers. We counted all MPs that were ≥50 μm in size (see section "Methodological Considerations" for more information about the size limitation applied). A qualitative verification analysis was

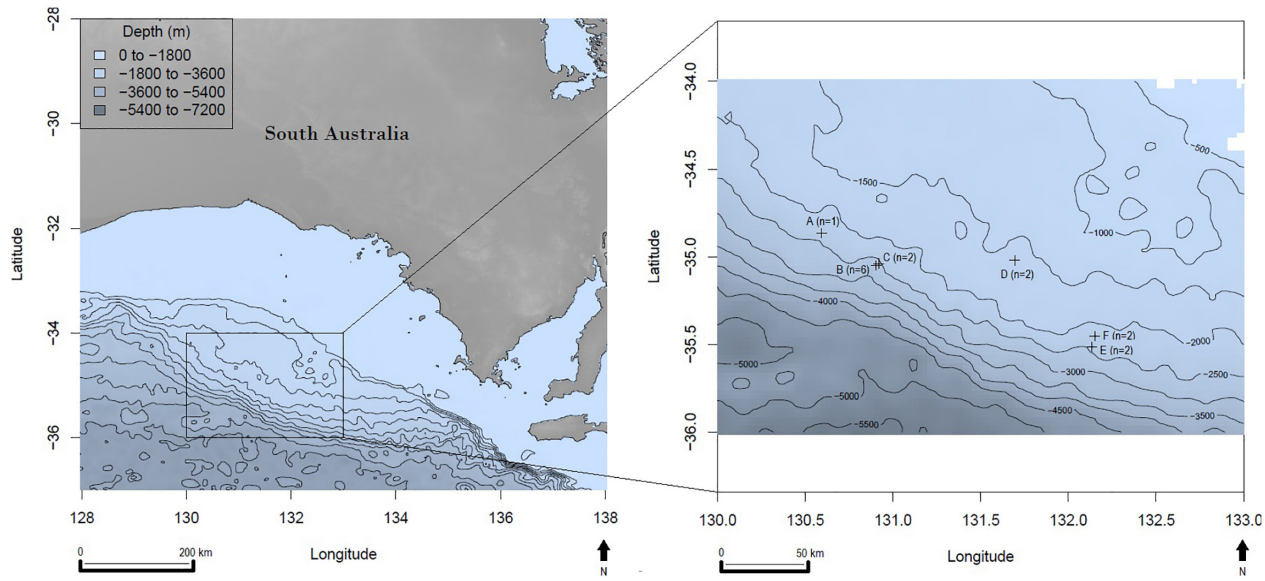

FIGURE 1 | Great Australian Bight sampling site locations with bathymetry; *n* = the number of sediment cores collected per site, latitude, and longitude are in decimal degrees.

TABLE 1 | Sediment core and subsample information, including ocean depth at the sample location and the distance from the nearest Australian coastline.

Site name	Core number	Number of mini-core subsamples	Number of bulk-surface subsamples	Ocean depth (meters)	Approximate distance from coast (km)
A	1	2	1	2,073	349
B	1	3	0	3,016	356
	2	2	1	3,016	356
	3	2	1	3,051	356
	4	2	1	3,052	356
	5	2	1	3,055	356
	6	2	1	3,062	356
C	1	2	1	2,783	355
	2	2	1	2,821	355
D	1	2	1	1,655	312
	2	2	1	1,659	312
E	1	3	1	2,502	291
	2	3	1	2,502	291
	3	3	1	2,502	291
F	1	2	1	2,253	288
	2	2	1	2,253	288

performed to confirm if the fluorescing fragments were, in fact, plastic (see section Verification of Microplastics).

Prevention of Microplastic Contamination During Laboratory Analysis

Contamination is a major issue in MP laboratory-based work. Therefore, we took several measures to prevent environmental contamination from impacting our results. First, during sampling onboard the vessel, a cotton over suit was worn by all personnel involved, and the mini-core sampling tubes and wrapping foil were pre-rinsed in deionized water. In the laboratory, we pre-rinsed all equipment three times with deionized water prior to use, and glass equipment was used where possible. All solutions were filtered through 0.22 μm mixed cellulose ester membranes. The laboratory analyst wore dark-colored merino wool clothing with their hair tied back, and the laboratory floor, benchtops, and fume cabinet were cleaned daily prior to analysis using a natural fiber (bamboo) paper towel and water. Where possible, laboratory processes were carried out within a fume cabinet to minimize air-borne contamination. Finally, only essential people were in the laboratory during the sediment analysis to minimize the introduction of any clothing or air-borne fibers into the sediment

samples. During method trials, wet-mount filter membranes were placed in the fume cabinet for the duration of the analysis. We observed zero MPs on the wet-mount filter membranes following adjustment for the MP counts from negative control samples. This meant that environmental MP contamination was unlikely to be influential on the sample results.

Method Verification

Laboratory Method Verification

The following steps were taken to enable the detection of any potential contamination in the laboratory analysis;

- The 51 sediment subsamples were randomly assigned a laboratory analysis order.
- Approximately every five subsamples (n = 10), a duplicate was taken from the same sediment subsample and analyzed the same as all other subsamples.
- Experimental replicates were included in the analyses as the subsamples from each main sediment core.
- Negative controls were processed approximately every eight samples (n = 6) using the same method as the subsamples (minus the sediment). Meaning the zinc chloride and Nile Red dye solution was added to an empty tube, centrifuged and filtered repeatably, then analyzed under microscopy as per the subsamples. The mean MP count observed in the negative controls was subtracted from each subsample MP count to account for environmental contamination.
- Positive controls were analyzed approximately every eight subsamples (n = 6) using known common polymers (PP, PVC, LDPE, HDPE, and PS). These polymers were cut into 2 mm × 2 mm squares and added to each positive control at a concentration of 20 pieces per 15 g sediment. The near-perfect square shape of the known plastic pieces meant they were unlikely to be mistaken for MPs already in the sediment. The mean MP count from the positive controls was used to calculate a recovery percentage, which was factored into the MP count for each sediment subsample.
- The laboratory analyst was not aware of the sample or control order when counting MPs.

Due to the negative control and recovery adjustments, the final MP count for each subsample was not always a positive number. In this instance, the MP count was reported as 0 (for example, if, after adjustments, an MP count was −1, it was reported as 0).

Verification of Microplastics

Following microscopy, the fluorescing MP fragments were analyzed with Optical photothermal infrared (O-PTIR) spectroscopy to verify them as being a polymer. O-PTIR spectroscopy is a novel method for qualitative analysis of MPs with a previous study indicating it may be a better technique for detecting environmental plastics (nano) than other IR techniques (Merzel et al., 2020). The O-PTIR was used with an mIRage IR microscope (Photothermal Spectroscopy Corp., Santa Barbara, CA, United States) equipped with a Quantum Cascade Laser (QCL) with a tunable range from 790 to 1890 cm^{-1}, an Optical Parametric Oscillators (OPO) laser with a tunable range from 2700 to 3600 cm^{-1} and a continuous-wave probe laser at 532 nm with adjustable output powers.

Spectra and images were collected through a 40×, 0.78 NA, 8 mm-working-distance, all-reflective Cassegrain objective. The MP fragments samples were placed on a standard 75 mm × 25 mm microscope slide. O-PTIR was operated at 80% (QCL) or 16% (OPO) IR power, 5% probe power, and the system was purged with dry nitrogen to maintain a constant humidity at 0%. O-PTIR spectra were collected on MP surfaces with an effective spectral resolution of 2 cm^{-1} and co-averaged for 10–20 spectral scans. O-PTIR data were processed using PTIR studio software (Photothermal Spectroscopy Corp., Santa Barbara, CA, United States). Spectra were "deglitched" to remove laser intensity jumps arising around the transition wavelength between QCL laser stages. Savitzky-Golay smoothing (polynomial order 3, side points 6) was applied to the point spectra. The spectra obtained from each MP fragment analyzed were matched to the closest known spectra using SpectraBase (Jung et al., 2018; Bio-Rad Laboratories Inc, 2020). A minimum of five matching absorption bands were required for acceptable identification.

As our study was focused on the quantity of MPs rather than the plastic material of which they were comprised, only a portion of MPs underwent O-PTIR. Eight sediment subsamples were prepared for O-PTIR verification (at least one from each major sampled site location) with 24 fragments identified as MPs through the staining technique. A random subset of 8 (30%) of these fragments were analyzed (discussed in section "Verification of Microplastics").

Statistical Analyses

We restricted statistical analyses to fragment counts as these were the data of highest quantity. We acknowledge that fiber counts were few in number and could have resulted from contamination (see section "Laboratory Method Considerations"). Hence, they were excluded from analyses. To investigate sampling and experimental bias, we looked for a correlation between results (MP fragment counts) and sediment sampling order, and laboratory analysis order using the respective coefficients of determination. Method verification was investigated by comparing results from the replicate samples (subsamples from the same sediment core) and the larger cores from the same sample site location using the statistics software R (R Core Team, 2017). We performed a Generalized Additive Model (GAM) between MP fragment counts of the replicate samples, and applying a Tweedie distribution, to look for a statistically significant relationship. Tweedie was selected as the best-suited distribution family because the experiment results (MPs) were in the form of count data where the mean and variance were not considered to be equal. The MP count variance was also investigated using a GAM where a fixed effect was used to test for significant differences in subsample types (mini-cores versus bulk subsamples), core identification, and site location.

We investigated the potential causes of MPs observed in the sediment by identifying natural site attributes and potential anthropogenic associations of relevance. The following factors were considered to have a potential causal effect on MP fragment

counts in GAB sediments: ocean depth, the distance from the nearest coastal town with regard to town population [distance in km × (town population/total population of South Australia)], fishing effort (the number of fishing vessels adjacent to the sampling site in a given year), location (latitude and longitude), proximity to the nearest oil exploration site (anthropogenic activity investigating site suitability for an oil and gas well), shipping activity (the number of transit ships passing through the ocean area adjacent to the sampling site), surface plastic plume (the estimated amount of plastic floating on the ocean surface above the sediment sample sites), and seafloor slope (derived from detailed seafloor bathymetry information obtained during the sampling voyage). Although the list of explanatory variables included seems extensive, we wanted to explore which factors could potentially influence MP counts: local anthropogenic variables or greater environmental variables.

To investigate which combination of variables had the strongest effect on the MP fragment counts, we implemented a dredge function in the R statistical language (2017). This was done using the Akaike's Information Criterion (AIC) to determine the variable effect compared to the null hypothesis (no variables having any effect on MP counts). To control for correlation among the explanatory variables, we removed from the model any two variables with a correlation >0.7 within the same model. This combination of variables was then analyzed against MP fragment counts using a GAM in R (2017), again with a Tweedie distribution. The best GAM provided the likelihood of the selected explanatory variables effect on MP counts in the sediments (**Table 2**). We then compared the effect size of the variables within the selected model by multiplying the regression coefficient for a variable by the median value of that variable in our data.

RESULTS

Method Verification

For analysis and verification of the robustness of the method we employed, we ran positive and negative controls (as outlined in the methods). The mean MP count in the negative control samples was 0.175 ± 0.046 fragments per gram of dry sediment. The mean MP recovery of positive controls was 71%. Sediment sampling order, laboratory sample processing order, and subsample type (mini-core or bulk) were found to have no influence on MP results. The duplicate samples had a mean count difference of 0.26 ± 0.052 fragments g^{-1} of dry sediment. A significant relationship was found between MP counts from the sample replicates (subsamples of each sediment core) (p-value < 0.05). All of the MP fragments that underwent O-PTIR analysis were confirmed as being MPs. Specifically, we observed *cis*-polyisoprene (n = 4), polyurethane (n = 2), polyester (n = 1), and polypropylene (n = 1) (**Supplementary Material, Table S1** and **Figures S1–S6**).

Microplastic Counts

Based on the Nile Red staining, the MP counts from the 51 deep-sea samples analyzed ranged from 0 to 13.6 fragments (mean of 1.26 ± 0.68 fragments) g^{-1} dry sediment. The average MP counts for the six sediment locations were 0.97, 0.12, 0.17, 0.62, 2.90, and 0.10 fragment g^{-1} dry sediment (sites A to F, respectively, **Figure 1**). By comparison, fibers made up only 10% of all MPs detected in the sediments, thus fibers were excluded from the statistical analysis.

Sample Variability

The range of MP counts amongst cores was highly variable with the overall mean fragment variance being 13.1 MPs g^{-1} dry sediment. The standard error for MP fragment counts ranged from ±0 to ±4.5 g^{-1} dry sediment, with an overall mean standard error of ±0.68 fragments. Core B6 had the greatest variability of MPs ranging from 0 to 13.6 g^{-1} dry sediment among subsamples (**Figure 2**). The overall variance in MP counts at a site location level was not significantly different. However, a significant variance (p-value 0.002) was detected in results at a core level (cores from the same location).

Spatial and Causal Association

Potential explanatory variables were added to a statistical model (GAM) in differing combinations and compared for best fit

TABLE 2 | The best fit GAM (based on the lowest AIC value) for investigating potential explanatory variable effects on MP counts.

Covariates used in model	AIC
Ocean depth + Seafloor slope + Surface plastic plume	170.77
Seafloor slope + Surface plastic plume	170.84
Surface plastic plume	171.06
Fishing effort + Longitude + Seafloor slope	172.15
Distance from the nearest coastal town + Fishing effort + Seafloor slope	172.18
Fishing effort + Latitude + Seafloor slope	172.50
Fishing effort + Seafloor slope + Surface plastic plume	172.54
All covariates in the model (Distance from the nearest coastal town + Fishing effort + Latitude + Longitude + Ocean depth + Proximity to oil exploration site + Seafloor slope + Shipping activity + Surface plastic plume)	173.93
Null model	177.11

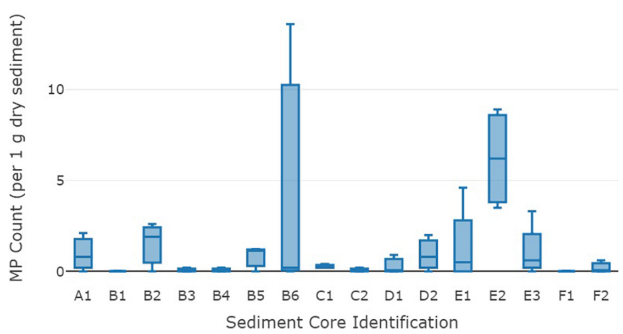

FIGURE 2 | Mean microplastic fragment counts (g^{-1} dry sediment) from the 16 sediment cores from the deep-sea Great Australian Bight. The middle line on each box is the median, the lower and upper lines are the first and third quartiles, and the whiskers represent the minimum and maximum MP counts.

through the model AIC value. The explanatory variables present in the model with the lowest AIC and those within two units of the lowest AIC (**Table 2**) were the distance from the nearest coastal town, fishing effort, latitude, longitude, ocean depth, seafloor slope, and the surface plastic plume at the sediment sample locations.

The best fit model included ocean depth, seafloor slope, and surface plastic plume. These three variables in the model explained 23.3% of the deviance in MP fragment counts. When considering best fit model, a significant relationship was evident between MP counts and the variables surface plastic plume ($p = 0.031$) and seafloor slope ($p = 0.002$) (**Table 3**). MP counts increased as surface plastic plume increased, and as the angle of the seafloor slope increased. The median × coefficient was used to compare the effect of the explanatory variables on MP counts in the sediments. The surface plastic plume showed the greatest effect on MP counts in sediments.

DISCUSSION

Microplastic Fragments in Deep-Sea Sediments

The global ocean is expansive, covering more than 70% of the earth's surface. Given its vastness, and the cost associated with sampling in remote areas, sampling of the seafloor is variable and typically limited to small areas. From our work, the average number of MPs from the GAB was 1.26 MPs g^{-1} dry sediment. While there are no other deep-sea sediment studies in Australia, two studies have investigated MP counts in coastal ocean sediment in southern Australia. In the Derwent Estuary in Tasmania, MP counts were 2–3 times higher than those we observed (2.43 and 4.2 fragments g^{-1} sediment; Willis et al., 2017). In another study, authors reported an average MP count of 3.4 mL^{-1} of sediment from 42 sites across south-eastern Australia (Ling et al., 2017). However, these sediments were from coastal environments, and the majority of their findings were filaments (Ling et al., 2017). Given the lack of contamination prevention procedures, their higher counts may be in part due to contamination issues. However, since both these studies are from coastal areas with higher local population densities, it is not surprising they reported substantially higher numbers of MPs.

While low compared to coastal sediment studies in Australia, the MP counts from our study are high compared to other deep-sea sediment analyses globally (**Table 4**). Four other studies of MPs in deep-sea sediment reported MP counts similar to ours including samples from the Arctic (Bergmann et al., 2017), the Mediterranean (Woodall et al., 2014; Kane et al., 2020), the North Atlantic (Woodall et al., 2014), and the Western Pacific (Zhang et al., 2020; **Table 4**). Even in these instances, however, the MP counts we observed were more than double those reported in other studies, in spite of our careful measures to exclude contamination and not including fibers.

Scaling up our empirical data to the global approximation, we estimate that there could be as much as 14.4 million tonnes of MP in the top 9 cm of sediment throughout the world's ocean (9 cm being the depth of our sediment cores and subsequent results used for this estimation). Based on the MP count of global deep-sea sediment studies (0.72 MP g^{-1} dry sediment; **Table 4**) we estimate a mass of 8.4 million tonnes of MPs [determined by first calculating the average MP count per wet sediment volume, then multiplying by the average density of MP (1.099 g per cm^3; Kooi and Koelmans, 2019), per 100 μm (the average MP size we observed), and finally scaling up to a global level based on the ocean size estimate of 361,132,000 km^2 (Pidwirny, 2006)]. Overall, given the much higher density of MPs reported in sediment in coastal areas, both global estimates are extremely conservative. The estimated global mass we calculated suggests that the bottom of the ocean has between 34 and 57 times the standing stock of plastic at the surface (based on the surface estimate of 250,000 tonnes; Eriksen et al., 2014). However the estimated mass is only a fraction of the annual input from coastal pollution (between 1 and 1.7 times) based on 8.5 million tonnes per year (Jambeck et al., 2015).

Variability in Microplastics

Interestingly, the variability in MPs was much higher within cores at the same site (merely meters away) than we observed from sediment sampled hundreds of kilometers away. It is likely that this difference would be highlighted further if a greater number of samples were collected and analyzed. The high variance at a core level points to the high heterogeneity of MP deposition on the seabed and the likely influence of oceanographic conditions at a very fine scale. The small size and variable density of MPs suggest these small particles are easily transported via ocean currents (Lusher, 2015; Kane et al., 2020), climate and weather changes (Welden and Lusher, 2017), fish and animal behavior (Davidson, 2012; Cózar et al., 2014), biofouling (Ye and Andrady, 1991; Fazey and Ryan, 2016), and buoyant rise velocity (Reisser et al., 2013).

Additional implications of this variability suggest that the MP counts in one sediment location are unlikely to be a reliable predictor of MP counts nearby. We suggest that MP sediment studies without replication at all levels (sample, site, and

TABLE 3 | A summary of the best fit model (GAM) outputs for the explanatory variable effect on MP counts.

Variable	Estimate	Standard error	*p*-value	Median	Median × coefficient
Intercept	−2.742	1.661	0.10530	–	–
Surface plastic plume	1.018×10^{2}	3.151×10^{1}	0.00226	0.034	| 3.461|
Seafloor slope	9.847×10^{-3}	4.432×10^{-3}	0.03114	214.5	| 2.112|
Ocean depth	-1.130×10^{-3}	6.987×10^{-4}	0.11269	2,503	| 2.828|

TABLE 4 | Counts from all known studies of MP in deep-sea sediment studies.

Author	Study contamination control	Survey location	Ocean depth (m)	*n*	MPs counts g^{-1} dry sediment
Our study		Great Australian Bight	1,670–3,060	16	0–13.6
Bergmann et al., 2017	More	Arctic Sea	2,340–5,570	9	0.04–6.6
Cordova and Wahyudi, 2016	None	Indian Ocean	67–2,182	10	0–0.24
Courtene-Jones et al., 2020	Equivalent	North Atlantic Ocean	2,200	3	Maximum of 0.2
*Fischer et al., 2015	None	NW Pacific Ocean	4,870–5,770	12	<0.1[e]
Kane et al., 2020	Equivalent	Mediterranean Sea	~150 to ~1,400	16	0.18–3.8
Kanhai et al., 2019	Less	Arctic Sea	885–4,353	11	0–0.2
Martin et al., 2017	Equivalent	North Atlantic Ocean	Not specified	11	0.04–0.22
Peng et al., 2020	Equivalent	Pacific Ocean	4,800–10,980	6	Maximum of 0.7
Sanchez-Vidal et al., 2018	More	Southern European seas	42–3,500	29	0.39–0.41[e]
*Van Cauwenberghe et al., 2013	Less	Southern Ocean	2,750–4,880	3	0.07[e]
		North Atlantic Ocean	4,840–4,840	3	0.21[e]
		Gulf of Guinea	4,790	3	0.0
		Mediterranean Sea	1,180	2	0.07[e]
Woodall et al., 2014	Equivalent	North Atlantic Ocean	1,400–2,200	5	0.21–1.40[e]
		Mediterranean Sea	300–3,500	4	0.35–1.22[e]
		SW Indian Ocean	900–1,000	3	0.05–0.14[e]
Zhang et al., 2020	Equivalent	Western Pacific Ocean	4,601–5,732	15	0–1.04

**MPs defined as <1 mm (other studies, including ours, use the size definition of <5 mm). n is the number of sediment sample locations per study. Study contamination control: None = no controls specified, Less = less rigorous control than this study, Equivalent = equivalent control to this study, More = more rigorous control than this study.*
[e]Extrapolated values based on an average marine sediment density of 1.70 g/cm^3 (Tenzer and Gladkikh, 2014) and a wet to dry sediment mass ratio of 2.97:1 based on the average from our study.

region) should be treated with great caution. This is particularly important when estimating global hotspots for MP deposition.

Explanatory Factors Associated With Microplastic Deposition

While the high variance made the detection of spatial and causal associations challenging, we found surface plastic plume and seafloor slope angle were both significantly associated with MP density. As plastic floating on the surface near the sampling site increased, so too did the MP counts in the seabed sediments. We also found that where the seafloor slope angle increased, there was a corresponding increase in the number of MPs in the sediment. Due to logistical difficulties, no samples were collected from the bottom of a steep slope, where it might be expected that MP fragments would accumulate even more.

Other studies have predicted the movement of surface particles (including plastic pollution) to water south of Australia from as far as Asia and Africa from a western direction (Lebreton et al., 2012; van Sebille et al., 2015; UNEP, 2016). To investigate a potential relationship between ocean currents and MP counts in our study, the explanatory factor of site location longitude was used because the main currents in the GAB (both local and global) move in a longitudinal manner (Middleton and Bye, 2007). If plastic pollution driven by current had a significant impact on MP counts in deep-sea sediments from the GAB, then a statistical relationship would have been observed between MP counts and longitude. However, no association was detected, suggesting there was no significant relationship between current driven plastic pollution and sediment MP density. The GAB is a tumultuous body of water where current directions and circulation patterns vary seasonably (Middleton and Bye, 2007; Middleton et al., 2017). These oceanographic events are likely to contribute to the highly variable MP counts in GAB sediments.

Methodological Considerations

Laboratory Method Considerations

Upon analysis of the 51 sediment subsamples, it was clear that fibers were many fewer in number compared to fragments. No correlation was detected between MP fiber and fragment counts (r^2 = 0.0002) within the sediment subsamples, and the variation between fibers (in total) was only a tenth of the variation among fragments. Thus we took the conservative perspective that MP fibers resulted from contamination (sensu Wesch et al., 2017; Willis et al., 2017), and we did not include them in further analysis.

We verified our method based on the presence of an association between MP results in sediment subsamples, the low difference in the number of fragments between duplicates, as well as the absence of an effect of MP counts and sampling order and laboratory processing order. In addition, no statistically significant difference was detected in MP counts between subsample types (mini-core and bulk). However, there were still two methodological issues to consider.

Firstly, the mean result of 71% of plastic fragments and fibers recovered in the positive experimental controls was much lower than expected given that laboratory equipment was triple rinsed with deionized water where possible throughout the method, thus creating ample opportunity for MPs to be washed onto the membrane filter for microscopic observation. One reason for the low recovery may have been due to the low-density nature of

many MPs (Chubarenko et al., 2016), including those used in the positive control. The low density of MPs means they were likely subject to water surface tension tendencies, causing them to remain fixed to the surface of laboratory equipment rather than being carried onto membrane filters for microscopic analysis. To increase the recovery of MPs from sediment in future analyses, a drop of detergent could be added to laboratory solutions and equipment rinsing water to reduce the presence of water surface tension bonds (sensu Mani et al., 2015).

The second consideration is that of size reporting. In our study, we only reported on MPs $\geq$50 μm (and $\leq$5 mm). Implementing a size limitation in MP studies is not unusual (e.g., Kanhai et al., 2019), and in our case was applied due to the presence of fragments of approximately 5–10 μm in size, which could not be reliably counted. Furthermore, these fragments were also too small to undergo qualitative analysis for confirmation of material type. Given our focus on data quality, we opted for a conservative, consistent size range where we could have high confidence. We also thought it possible that the smaller fragments were organic false-positive fragments because they increased substantially when the laboratory analyst wore white cotton overalls. To explore the potential false-positive fragments further, atmospheric particulate matter (0.3–10 μm) was monitored. The monitoring revealed that the laboratory space showed high levels of atmospheric particulates (e.g., maximum of 47.7×10^3 per m^3 particles of 5 μm in size) ($3.3–5.9 \times 10^6$ per m^3) compared to a laboratory space that is under strict cleanliness and quarantine regulations (e.g., an accredited ISO Class 4 laboratory space has 0 particles of 5 μm in size) (International Organization for Standardization [ISO], 2015). Although many of these atmospheric particulates were not likely MPs, air monitoring suggested that efforts could be made to increase the cleanliness of the laboratory environment, for example, using a laminar flow workspace (Wesch et al., 2017). Anecdotally, we observed that changing the laboratory analyst's attire to dark-colored merino wool fiber clothing reduced the number of suspected false-positive fragments. Setting a fragment size limit well above the size of the suspected false-positive fragments and as per other studies (e.g., Frias et al., 2018) meant that smaller and suspected false-positive fragments were not counted and had no impact on the overall results and subsequent interpretation of our findings.

Verification of Microplastics

We used O-PTIR analysis to verify the Nile Red staining technique with eight samples. Because the instrument was located at a laboratory in another state, and given that fluorescence fades with time, only a third of the samples intended for verification were still fluorescing at the time of O-PTIR analysis. An obvious remedy is to undertake all analyses at the same facility, if possible.

Even with the small proportion of fragments analyzed, the O-PTIR verification step gave confidence that the fragments identified as MPs through the Nile Red staining technique were indeed MPs: 100% of the O-PTIR analyzed fragments were confirmed as plastic. The four different plastic polymers identified [*cis*-polyisoprene (rubber/latex), polyurethane, polyester, and polypropylene] are all used in and may originate from anthropogenic activities. However, *cis*-polyisoprene also naturally occurs in a variety of ocean plants (Broadgate et al., 2004). At this time, we cannot definitively identify the *cis*-polyisoprene source. However, it's unlikely that the *cis*-polyisoprene came from natural sources given the depth of the sediment studied and the absence of plant material in any of the sediment cores. In the future, further research to investigate the polymer types of each of the MPs found in the sediment would be greatly beneficial to provide a clearer picture of potential plastic origins.

CONCLUSION

The presence of MPs in sediment from each of the deep-sea locations in the GAB has highlighted both the ubiquity and the heterogeneity of MPs in the marine environment. We found that the distribution of MPs at a deep-sea level correlated with surface plastic plume and seafloor slope (at least in the absence of deeper sinks such as submarine canyons which are known to have higher MP densities (Mordecai et al., 2011; Pham et al., 2014). This suggests that plastic fragments floating in the ocean surface layers may, in fact, settle to the bottom, making the benthic sediments a sink for this material. However, our estimated 14.4 million tonnes of MPs in deep-sea sediment does not account for the estimated 8 million tonnes of plastic lost from the world's coast annually (Jambeck et al., 2015). In spite of claims that the seabed floor is a major "sink" (Woodall et al., 2014; Koelmans et al., 2017; Chiba et al., 2018) our results suggest that while MPs were numerous (14 million tonnes), sediments account for but a minuscule proportion of the ocean's "missing plastic" (Thompson et al., 2004).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

JB conducted the laboratory analysis, the statistical analyses, and wrote the manuscript. BH, CW, and ZC co-supervised the project and assisted with various methodological, statistical, and writing aspects of the project and associated manuscript. KW assisted with method development, statistical analyses, and editing. MH and JZ conducted the spectral analysis on MP fragments. AW secured funding, carried out ship-based research, collected sediment samples, and contributed to editing. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.576170/full#supplementary-material

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The Intersection Between Illegal Fishing, Crimes at Sea, and Social Well-Being

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Illegal, unregulated, and unreported (IUU) fishing is a major contributor to global overfishing, threatening food security, maritime livelihoods, and fisheries sustainability. An emerging narrative in the literature posits that IUU fishing is associated with additional organized criminal activities, such as drug trafficking, human trafficking, slavery, and arms smuggling. We explored this narrative through a systematic literature review to identify the empirical evidence of the association between illegal fisheries activities and organized crimes. Here we show that there is minimal evidence of organized crimes being linked to IUU fishing. Due to the covert nature of both organized crime and IUU fishing, we supplemented the literature review with analysis of media reports on illegal fishing from 2015 to 2019. We reviewed more than 330 individual media reports from 21 countries. From this database, < 2% reported crimes associated with illegal fishing. The predominantly associated crime mentioned were violations of worker's rights, forced labor and/or modern slavery. We resolve the contradiction between the common narrative that fisheries and other crimes are linked by presenting three distinct business models for maritime criminal activities. These models explain why certain crimes such as forced labor are associated with illegal fishing, while other crimes such as trafficking or smuggling are less likely to be linked to fishing activities. By disentangling these crimes from one another we can better focus on solutions to reduce illegal behavior on the sea, protect those vulnerable to fisheries exploitation, and enhance livelihoods and social well-being.

Keywords: illegal fishing, organized crime, forced labor, fisheries crime, social well-being

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INTRODUCTION

Fisheries are one of the largest and oldest primary industries in the world, providing an estimated 59.6 million people with jobs globally (FAO, 2018). The increasing dependency on fisheries is evident from the increase in per capita fish consumption, from 9 kgs in the 1960s to 20.5 kg in 2018, fuelling an industry with a total export trade worth US$164 billion in 2018 with exports of fish and fish products representing about 11% of the export value of agricultural products (FAO, 2020b). Fisheries contribute to the food security of millions of people and are the predominant protein sources in developing countries. While fisheries management can be successful (Hilborn et al., 2020), overfishing remains persistent, with 33% of stocks currently overfished and 40% fished to their maximum limit (FAO, 2018). The threatened economic and social stability of fisheries is

further weakened by the prevalence of illegal, unregulated, and unreported (IUU) fishing (formal definition see FAO, 2001, Articles 3.1–3.3). IUU fishing is a major contributor to global overfishing, threatening food security, maritime livelihoods, and fisheries sustainability (Pauly et al., 2002; Gallic and Cox, 2006; Sumaila et al., 2006). IUU fishing is widespread, comprising an estimated 20% of global fish catch (Agnew et al., 2009), with annual economic losses estimated between US$26-$50 billion (Sumaila et al., 2020).

IUU fishing can occur at all scales, in domestic and international waters, with catastrophic effects on fisheries and the marine environment. For example, The Southern Ocean was once a hotspot of IUU fishing activity, with a substantial illegal catch of Patagonia Toothfish reported from the mid 1990s until the late 2000s (Österblom et al., 2010). Toothfish stocks came close to commercial collapse, seabirds such as albatross were significantly threatened due to by-catch by illegal fishers, and licensed fishers lost hundreds of millions of dollars (CCAMLR, 2002; COLTO, 2003; Michael et al., 2017). A consolidated and collaborative effort, facilitated through a network of state actors, the fishing industry, and environmental non-governmental organizations reduced the prevalence of IUU fishing in the Southern Ocean (Österblom et al., 2014). Subsequently, the stock status of Patagonia Toothfish began to recover and is now deemed "sustainable" (Patterson, 2018).

The consequences of IUU fishing impact the economies of developing countries most. For example, Indonesia alone has lost an estimated US$4billion in revenue annually to IUU fishing (Palma et al., 2010). This has been linked to foreign-flagged vessels fishing within Indonesia's exclusive economic zone (EEZ) (Sodik, 2009). China, South Korea and Taiwan are ranked as the top three flag states fishing in foreign EEZs (Cabral et al., 2018). The Indonesian government issued a moratorium on foreign-flagged vessels fishing within their EEZ in 2014, as it was thought to be a key driver of illegal fishing. By removing the fishing effort from foreign vessels the subsequent reduction in IUU fishing has the potential to generate a 14% increase in catch and a 12% increase in (legal) profit (Cabral et al., 2018).

Despite some progressive examples of aggressive governance and collaborative approaches, IUU fishing remains pervasive. There is an arms race of progress between combating IUU fishing and new and innovative ways to commit IUU fishing. Illegal transhipment is an example of the latter. Transhipment is the exchange of goods between alternative modes of transport and is not necessarily illegal. It does, however, open up issues around transparency of the supply chain and documentation of difficulties (Satria et al., 2018) facilitating IUU fishing. Technological advancements such as the use of radar and automatic identification systems (AIS) are helping to combat clandestine activities, which may be linked to IUU fishing (Ford et al., 2018).

Recognizing the consequences and prevalence of IUU fishing has led to increased research focus on the fishing industry, including the potential link between IUU fishing and organized crime, and the interplay between illegal fishing and other crimes. This was specifically mentioned by the UN General Assembly, where members noted a possible connection between IUU fishing and organized crime, and called for increased knowledge and understanding of the potential issue (UNGA, 2009). Subsequently, The United Nations Office of Drugs and Crime (UNODC) commissioned a report focusing on transnational organized crime in the fishing industry (UNODC, 2011). The report was predominantly a review of literature, supplemented by expert consultation. The report presented several instances of workers' rights violations, such as forced labor and inhumane treatment. The report also discussed the use of fishing vessels for smuggling migrants and trafficking of drugs, serving as venues for illegal activity, supply ships or as a cover for illicit behavior. Following this, empirical studies have documented crimes occurring within fisheries activities. For example, there has been a concentrated effort in researching the working conditions and treatment of fishers. These reports document 20+ h workdays, unsafe working conditions, physical abuse, or abandonment of fishers without pay (ITF, 2006; IOM, 2016; Yea, 2016). Predominantly, this research is found within the gray literature published by non-governmental organizations, as opposed to the primary literature.

Despite this recent progress in addressing IUU fishing and associated crimes, significant knowledge gaps remain. There is a paucity of empirical evidence on actual links between illegal fishing and organized crimes. However, a narrative is emerging that fisheries violations are linked to other crimes, including labor abuses, drug trafficking, and human trafficking (Liddick, 2014; Telesetsky, 2014). The narrative suggests that the involvement of organized crime is resulting in the mixing of these activities (Chapsos and Hamilton, 2019; Lindley et al., 2019). Here, we explore the veracity of these two claims. Specifically, we (1) used a literature analysis to examine the balance of direct vs. indirect evidence for links among IUU fishing and other crimes, (2) through this analysis, we evaluated the genesis of this narrative, and the level of primary data in the source literature, and (3) conducted a media analysis in a case study region to evaluate the coincidence of fisheries and other crimes from primary sources.

METHODS

Literature Review

The literature review method is based on that used by the Centre for Reviews and Dissemination (CRD, 2001), which employs systematic examination of research databases using keyword searches. We used SCOPUS and Web of Science databases. All document types were searched and the search was not limited by language or publication date. The search for keywords was limited to paper titles, abstracts, and paper keywords only. The keyword search terms used were: illegal AND fishing AND organi* AND crime. Additional searches were conducted using "IUU" but these searches did not provide any additional results. Papers were included if they included both illegal fishing and organized crime. Information was extracted on location, details of associated crimes, and data types [primary data- where the information is collected by researchers first hand, or secondary data- where information is not directly collected but cited from secondary sources (Rabianski, 2003)]. We term the papers identified in the literature review the first generation papers i.e.. *parent papers*.

For papers that used secondary data, key references were identified. The 10 most common key references across all parent papers and -as an additional step of verification- 15 randomly selected key references across all parent papers made up the second generation literature review ("*children papers*"). The data type (primary or secondary) was also noted for these papers. The search was conducted on 19th September 2019.

Media Review

News articles were collected through ProQuest news portfolio which has access to current and cataloged news from over 3,000 of the world's news sources (ProQuest, 2019). The ProQuest search included searching across 45 databases. The source types included newspapers, reports and government and official publications, as well as "Other Sources." Document type "Theses" was excluded. Google Alerts was also set up for News articles. For both, "illegal fish*" was used as search terms. Data collated by Liberty Asia, a non-profit organization working on labor abuses in South East Asia among other locations, was shared with the authors to supplement and cross-reference the articles found. Only articles that were within the Asia-Pacific Fishery Commission (APFIC) region were included.

The Asia-Pacific region was selected as a case study because the region is the world's largest producer of fish and aquaculture (50 and 89%, respectively) (FAO, 2020a). Fisheries sectors within this region are important contributors to the social and economic security as 85% of people employed in fisheries and aquaculture worldwide are located within Asia (FAO, 2020a). This results in a higher number of people who are vulnerable to loss of livelihood through the collapse of stocks or rampant IUU fishing. The APFIC is also considered to be a hotspot for trafficking of persons and contraband within the fishing industry, and therefore potentially vulnerable to such crimes. The adaptive capacity to changes are generally low within this region and predicted to be more vulnerable and less resilience to changes in markets and reduced access to services (Allison et al., 2009; Blasiak et al., 2017; Cinner et al., 2018). The APFIC region spans the Indian to the Pacific Ocean and includes Australia, Bangladesh, Cambodia, China, France, India, Indonesia, Japan, Malaysia, Myanmar, Nepal, New Zealand, Pakistan, Philippines, Republic of Korea, Sri Lanka, Timor-Leste, Thailand, United Kingdom, United States of America, and Vietnam.

The final dataset comprised of media articles published between 01 January 2015 and 15 August 2019, inclusive. Articles were translated into English if published in another language. For each article, we extracted information about the location of the incident, reporting entity, and additional crime(s) mentioned.

RESULTS

Direct vs. Indirect Evidence of Associated Crimes

The systematic review of literature produced 24 first generation papers (hereafter called "*parent papers*"). Of these, 12 were discarded as they either did not refer to both illegal fishing and organized crime or were duplicates. Of these 12 remaining studies, three focussed on Indonesia and one on Thailand, one was in Cameroon and one in South Africa, three focussed on multiple locations or global context, one was geographically unreferenced, one focused on Australia, and one on the Southern Ocean (**Table 1**).

The types of crimes mentioned in addition to IUU fishing included forced labor and human rights violations, which were mentioned in nine of the 12 papers (75%; papers 1–9). Drug smuggling was referred to in five papers (42%; papers 3, 5, 9, 10, 11), all based on secondary sources. Fisheries violations, including illegal exploitation or smuggling of high value species and endangered marine mammals, were mentioned in five papers (42%; papers 1, 2, 3, 10, 11).

Three of the papers included primary data (papers 1, 2, 6), however, for one of those papers the primary data collected was on the availability of liability insurance (paper 6). For this paper, there was no primary or secondary data to support the claim that IUU fishing is related to human rights violations and organized crime. Therefore, only two (17%; papers 1 and 2) included primary data collected on illegal fishing and associated crimes.

The majority of the papers ($n = 7$; 59% of papers) were published in the last 2 years, while the oldest papers were published in 2011 (**Table 1**).

Genesis of Narrative

For papers that used secondary data, key references were identified (the 10 most common key references and 15 randomly selected key references from *parent papers*), hereafter called "*children papers.*"

The types of additional crimes within these publications consisted of mostly forced labor or human rights violations (mentioned in 17 of the papers or 68% of the total), followed by drug trafficking which was mentioned in four or 16% of the papers. Smuggling which was mentioned in three (12% of papers) (list of *children papers* provided in supplementary materials).

Of these 25 papers, six included primary data (24%) with the majority of citations from gray literature ($n = 5$, 20%). Only one paper included primary data from the peer reviewed literature. Of the remaining papers, five (20%) were peer reviewed and based on secondary data. The majority of papers cited by the parent papers were based on secondary data and information gleaned from gray literature consisting of reports from NGOs and media reports (**Figure 1**). When findings are not based on primary data collected, they should ideally be backed up by empirical research as opposed to secondary data. The most cited paper was the report written by the UNODC, which is based on secondary data and was not peer reviewed.

Case Study Review of Media Content

A total of 330 independent events were collected from thousands of news articles scanned. From these 330 events, only six events included incidents of additional crimes (**Table 2**).

Half of these reports mentioned labor abuses such as modern slavery or human trafficking, while documentation offenses were mentioned in two stories and drug smuggling was mentioned in two stories. The number of stories that included any additional crime accounted for just under 2% of the total reports on IUU fishing.

TABLE 1 | Summary of first generation literature review (parent papers).

	Author Year	Journal	Data Type	Methodology	Geography	Additional crimes mentioned
1	Beseng (2019)	Marine Policy	Primary Secondary	Direct observations, informal group discussions, and semi-structured interviews ($n = 28$) Published articles, government reports, speeches, and Navy Facebook.	Cameroon	Corruption (i.e., bribery and extortion), document and identity fraud, illegal exploitation of fish and endangered marine mammals, illegal recruitment, and abuse of workers' rights, smuggling of contraband goods, and illegal migration.
2	Chapsos and Hamilton (2019)	Trends in Organized Crime	Primary	Surveys ($n = 285$) Interviews ($n = 1{,}342$)	Indonesia	Recruitment patterns and target groups; document forgery; forced labor and abuse; and fisheries violations.
3	Lindley et al. (2019)	Australian Journal of International Affairs	Secondary	Literature review	Australia	Drug, human, weapon, and other contraband trafficking and smuggling; irregular maritime arrivals; and maritime piracy.
4	Moreto et al. (2019)	Deviant Behavior	Secondary	Content analysis of reports	Thailand and UK	Labor trafficking.
5	Yuliantiningsih et al. (2018b)	E3S Web of Conferences	Secondary	Literature review	Indonesia	Human trafficking, smuggling, drugs trading, corruption, and piracy.
6	Soyer et al. (2018)	Transnational Environmental Law	Primary NONE	On the availability of liability insurance On relatedness to organized crime	N/A	IUU linked to human rights violations and organized crime.
7	Yuliantiningsih et al. (2018a)	Journal of East Asia and International Law	Secondary	Literature review	Indonesia	Human rights violations, child labor, human trafficking.
8	Ewell et al. (2017)	Marine Policy	Secondary	Review of regional fisheries management organization policies	Multiple	Linking transhipment at sea to facilitating human trafficking, forced labor, and human rights abuses.
9	Telesetsky (2014)	Ecology Law Quarterly	Secondary	Literature Review	Multiple	Human and drug trafficking. Posits that IUU fishing should be considered a transnational organized crime.
10	Liddick (2014)	Trends in Organized Crime	Secondary	Literature Review	Multiple	Organized criminal groups engage in IUU fishing, illegal harvesting and smuggling of high value marine products, money laundering, drug, and human trafficking and racketeering.
11	Raemaekers et al. (2011)	Ocean and Coastal Management	Secondary	Literature Review	South Africa	Trading illegal abalone for drugs.
12	Österblom et al. (2011)	Trends in Ecology and Evolution	Secondary	Literature Review/Commentary	Southern Ocean	Illegal fishing as an organized criminal activity.

Included are a number of each paper, author, year, journal, data type (primary/secondary), the method employed, geographic location of the study if reported, and list of additional crimes included in the publication.

DISCUSSION

There is an emerging narrative suggesting that there are links between organized crime and illegal fishing, despite a dearth of evidence. This narrative suggests that the crimes are associated; for example, that fishers who are involved in illegal fishing will also be involved in smuggling drugs and a range of other crimes via organized criminal networks. We found little evidence to suggest this is true when examining both primary and gray literature (e.g., published reports). Analysis of recent media from South East Asia found that $< 2\%$ of stories on illegal fishing mentioned any additional crimes. Here, we discuss these results in further detail, specifically using the findings to offer distinct business models that operate within the world's oceans to offer clarity on maritime criminal activities.

While there are many illegal activities taking place on the ocean, there are distinctions and differences between them. These activities can be conceptualized through their underlying business models. We propose there are three basic business models operating: harvesting, moving cargo, and provision of a venue (**Table 3**). The three models are distinct based on key components of a business model. There are some consistencies, notably that they are all based on a physical asset. Perhaps this is why these different business models are sometimes

incorrectly conflated. However, they differ in key activities and value proposition. We suggest that integrated criminal activities where multiple business models are operating simultaneously are uncommon.

In our data analysis, harvesting, and cargo endeavors are more often associated such as trafficking drugs via a fishing vessel, compared with venue based crimes. This may be because harvesting and cargo associated activities are more likely to be based on movements between ports, whereas venue based crimes could be stationed offshore. Most likely, cargo based crimes are mimicking harvesting based activities, such as fishing, and therefore are more likely and incorrectly combined as one activity.

There is a logical differentiation between business models from the perspective of the criminal organization. For instance, for a business moving illegal drugs between countries the key value proposition is the movement of the material in a clandestine manner over a short period. The time the cargo spends in transit is an opportunity cost, as the sunk assets of production cannot be recovered until the onward sale occurs. In contrast, illegal harvesting is constrained by the rate of discovery and harvest of the species of interest. For instance, vessels harvesting giant clams must find appropriate habitat, deploy divers, and then recover the clams. In this case, the transit out and back from the fishing grounds is purely a cost, while the operation on the fishing ground is likely less costly in fuel, but generates increasing revenue per time. Given this, vessels using a harvesting model should be expected to maximize their returns by staying at sea as long as possible –constrained by the volume of catch the vessel can hold, and its fuel and food supplies. Thus, the harvesting and cargo business models are in some sense fundamentally at odds in terms of their likely operating model. As such, one might expect vessels engaged in one business, such as harvesting, to occasionally move cargo as a minor activity in the context of their harvesting business, but it is unlikely that vessels would simultaneously engage in a mixed model.

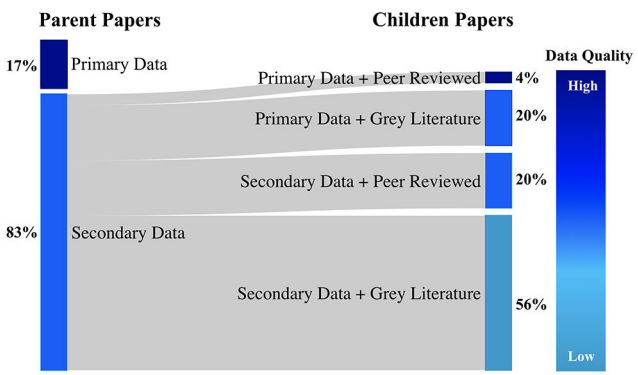

FIGURE 1 | Schematic of the narrative genesis of parent and children papers.

There was a lack of evidence for certain crimes, such as drug and weapon smuggling being related to IUU fishing. The predominant crimes identified both in the literature and media data were forced labor and workers' rights violations. Extensive over-fishing and declines in fish stocks have been linked to driving increases in human slavery and forced labor activities (Brashares et al., 2014). Decker Sparks and Hasche (2019) highlighted how geographic, regulatory, and cultural contexts create a supply of vulnerable peoples who can be exploited, while the current fisheries context provides the demand in the cycle. Specifically, as stocks decrease and catch per unit effort decreases, effort must increase to maintain catches resulting in smaller profit margins. Subsequently, the demand for cheap labor increases and the chance of labor exploitation increases as does the susceptibility of fishers to engage in illicit activity (Okafor-Yarwood, 2020). In geographical contexts where there are high volumes of displaced peoples, undocumented workers, migrants, or geographic isolation, exploitative practices are more likely (International Labour Office (ILO), 2005; Robertson, 2011;

TABLE 2 | Media cases with additional crimes reported, based on 330 independent events, 2015–2019 inclusive.

Additional crime	Type of Vessel	Location	Reporting entity	Year	Headline (Hyperlink)
Modern slavery/Human trafficking	Refrigerated cargo ship	Indonesia	Business Mirror	2015	Indonesia court upholds seizure of fishing vessel
Drug smuggling	Fishing vessel	Indonesia	Straits Times	2018	1 ton of crystal meth seized from boat off Batam
Fake documentation	Fishing vessels	Thailand	Phuket News	2016	Navy seizes suspected IUU fishing boats in Phuket
Modern slavery/Human trafficking	Fishing vessel	Thailand	Phuket News	2018	Phuket whale shark fishing boats probed for human trafficking
Labor abuses/Lack of correct documentation	Fishing vessel	Indonesia	Manila Times	2015	43 pinoy fishermen repatriated from Indonesia
Kidnapping/drug smuggling	Various vessels (non-specific)	Malaysia	Targeted News Service/Interpol	2016	INTERPOL Alerts Issued for Kidnapped Sailors Following Maritime Security Operation

TABLE 3 | Key components of different marine business models.

			
Component	**Harvest**	**Cargo**	**Venue**
Key activities	Producing a product-e.g., seafood	Providing a service e.g., moving cargo	Providing an asset e.g., offering venue with less exposure
Product/Value proposition	Reducing costs e.g., Illegal fishing, harvesting endangered species	Covert transport e.g., Drugs, arms, people smuggling by boat, or vessel	Privacy e.g., Drug production, gambling, prostitution on a boat, or vessel
Target Customer	Mass Market—those who want to purchase seafood/marine species	Multi-sided—supply and demand segments	Niche Market—those in need of discretion
Key Resources	Physical assets—vessels to harvest	Physical assets—vessels to move cargo	Physical assets—vessels as venues
Cost Structure	Cost-driven—minimizing costs	Variable costs—costs that vary proportionally with the volume of goods, discretion required, urgency	Variable costs—costs that vary proportionally with the volume of goods and services
Revenue Models	Asset sale—ownership of physical product e.g., seafood	Usage fee—offering a particular service e.g., moving cargo	Leasing/Renting -temporary exclusive access to particular asset e.g., venue on a vessel
Key Partnerships	Buyer-supplier relationships to assure reliable supplies	Joint ventures to develop new businesses	Joint ventures to develop new businesses

Crane, 2013). More so, if the regulatory context is one which has government complicity, political instability, high levels of corruption, limited regulations, regulatory failures, poor fisheries management, a lack of effective regulatory infrastructure, and much less enforcement (Crane, 2013; Pomeroy et al., 2016). Finally, cultural contexts can also exacerbate the vulnerability of certain groups, for example, if there are deep-rooted social inequalities (Crane, 2013; Decker Sparks and Hasche, 2019). These drivers reduce alternative choices for groups of people, leaving them extremely vulnerable in a context with little agency. There is a clear relationship between the fishing industry, and hence IUU fishing, and forced labor, human rights violations and examples of modern slavery. For example, the empirical data collected from the International Organization for Migration reported more than 1,200 trafficked fishers in 2015 in Indonesia alone (IOM, 2016). Worryingly, within Lake Volta's fishing industry 56% of workers ($n = 444$) are child workers who have been trafficked into forced labor (Adeyemi et al., 2015).

When it comes to the relationship between the fishing industry and cargo based illegal activities such as smuggling, the connection is less clear. Trends in drug, human, arms, and wildlife trafficking vary. Arms trade is unclear due to difficulties in differentiating between legal and illegal sales, drug trafficking is thought to be stabilizing, while human and wildlife trafficking are on the rise (Jacobson and Daurora, 2014). The use of boats for these activities has been documented (Sorensen, 1990; Kassar and Dourgnon, 2014; Atkinson et al., 2017), as illicit cargo vessels can often avoid detection or inspection at sea. In port, they can be disguised as fishing vessels. Organized criminal groups have even gone to the extent of purchasing fish processing factories and registering as a fishing company as a cover for drug trafficking (Aning, 2007). Within the UNODC report, it is explicit that fishing vessels are used for smuggling activities but "it seems clear that, as in the case of migrant smuggling, fishers are not generally perceived to be part of the organized criminal activity" (93: 2011). There are examples, especially within drug smuggling reports, that fishers are "hired" on an *ad hoc* basis for navigation and maritime skills or lookouts, but as a separate endeavor, as opposed to in addition to fishing activities (Liss, 2014).

The use of vessels as venues for illegal activities was not evident within the media or literature we reviewed. The link between IUU fishing and illicit venues is not commonly discussed, however, there have been reports of illicit venues on vessels. "Women on Waves" is a Dutch non-profit group which offers reproductive information, workshops, and abortions offshore of countries with anti-abortion laws (Gomperts, 2002; Aljazeera, 2017). Boats have also hosted drug production laboratories (Boffey, 2019). There are examples of vessels being used as casino cruises for illegal gambling (Kra, 2004; Lo, 2015). Just as trafficking occurs on boats, so too do venue based criminal activities occur on vessels, yet the link between venue-based illicit activities and fishing is not made. However, the distinction between harvesting and venue business models are clear.

Where we see an association between crimes is within the harvesting business model, most notably linked with forced labor or human trafficking. This is likely due to the revenue

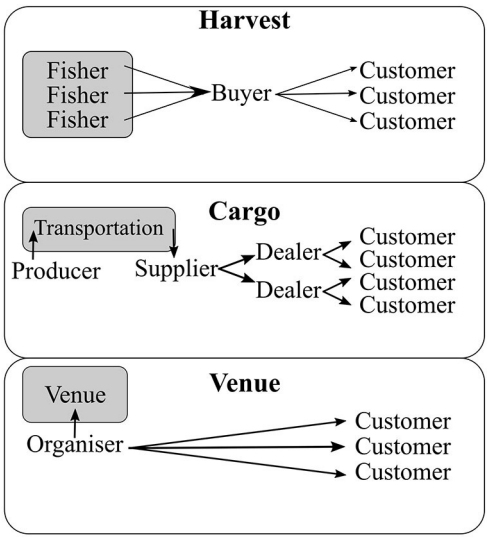

FIGURE 2 | Key partnerships across three distinct marine business models. The shaded box for each business model depicts where the key activity takes place.

models within each business model. The harvesting business model is a price taker compared to the cargo and venue business models which are price setters. As a price taker, the harvesting model is based on accepting the prevailing market prices and is more closely linked to the customer (**Figure 2**). This results in a less stable market. Perhaps this explains the increase in associated crimes, as the crimes are attempts to maximize profit via reducing costs by forcing inhuman working hours or lack of pay. Price setters, for example, drug smuggling, may scale prices not only by quantity but also in risk, as cargo that carries a more severe punishment will come with a larger price (i.e., heroin vs. marijuana). For venue based activities, the cost will scale with infrastructure provisioning. This is inherently a more stable market and is further removed from customer interaction (**Figure 2**).

CONCLUSION

The consequences and severity of illegal fishing, associated fisheries crimes, and organized crime that occurs on the sea are severe (Tickler et al., 2018; Moreto et al., 2019; Teh et al., 2019). While we present the argument that marine business models are discrete, there are numerous examples of leaders and experts conflating these issues (Witbooi et al., 2020). The intention of doing so may be to raise concern and attention to improve the well-being and safety of fishers however it may have the opposite effect. For example, the Indonesian minister of marine affairs and fisheries has stated "illegal fishing is often a vehicle for other crimes, such as people smuggling, drugs smuggling and slavery" (IOM, 2016: 1). Conflating these issues and including slavery or forced labor in the same context as drugs trafficking runs the risk of criminalizing victims of modern slavery or forced labor. For example, recent literature has argued that fisheries are heavily linked to drug trafficking (Belhabib et al., 2020), whereas the link seems to be based on the use of fishing vessels as disguises as opposed to boats and crews that are actively fishing. The difference may seem subtle but we argue that links between organized crime and illegal fishing should be made with caution to protect those at risk.

This paper aimed to explore the empirical and secondary data surrounding a narrative linking illegal fishing and organized crime. While extensive media data was collected within South East Asia—which accounts for 68% of the words' fishing fleet (FAO, 2020b)- there is potential regional bias within this data. Other regions such as West Africa and Latin America may have yielded different proportions of associated crimes and is worth exploring but was beyond the scope of this study. Additionally, within the literature review, additional papers may have emerged using different search terms such as "fisheries crime." Finally, the clandestine nature of illegal activity creates uncertainty surrounding any conclusions as illicit relationships are more often anecdotally shared rather than empirically (Telesetsky, 2014). None-the-less our research is contributing to a significant knowledge gap and evolving the conversation to help identify where more resources can be allocated to improve fisheries operations globally.

While we suggest that there are links between IUU fishing and human rights abuses but less with IUU fishing organized crimes we stress that addressing all human and environmental violations are important. Protecting the people who work within marine industries and ensuring the sustainability of the global marine estate is complex and challenging. As difficult as enforcement is on land, it is exponentially more challenging to identify, enforce and prosecute illegal activities on the high seas. The trafficking of illegal substances, illicit arms trade and the vulnerability of exploited people, not to mention global food security, are transboundary issues of global concern. We present three distinct business models that operate within the world's oceans to offer clarity on maritime criminal activities. This distinction explains why certain crimes such as forced labor are associated with illegal fishing, while other crimes such as trafficking or smuggling are less likely. By disentangling these crimes, we can better focus on solutions to reduce illegal behavior on the sea and protect those vulnerable to fisheries exploitation, to enhance livelihoods, social well-being and the sustainability of global fisheries.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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frontiers in Marine Science

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A New Paradigm for Social License as a Path to Marine Sustainability

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Traditional marine governance can create inferior results. Management decisions customarily reflect fluctuating political priorities and formidable special-interest influence. Governments face distrust and conflicts of interest. Industries face fluctuating or confusing rules. Communities feel disenfranchised to affect change. The marine environment exhibits the impacts. While perceived harm to diverse values and priorities, disputed facts and legal questions create conflict, informed and empowered public engagement prepares governments to forge socially legitimate and environmentally acceptable decisions. Integrity, transparency and inclusiveness matter. This article examines positive contributions engaged communities can make to marine governance and relates it to social license. Social license suffers critique as vague and manufactured. Here its traditional understanding as extra-legal approval that communities give to resource choices is broadened to include a legally sanctioned power to deliberate—social license to engage. The starting hypothesis rests in the legal tradition designating oceans as public assets for which governments hold fiduciary duties of sustainable management benefiting current and future generations. The public trust doctrine houses this legal custom. A procedural due process right for engaged communities should stem from this public-asset classification and afford marine stakeholders standing to ensure management policy accords with doctrinal principles. The (free), prior, informed consent participation standard provides best practice for engaged decision-making. Building on theories from law, social, and political science, we suggest robust public deliberation provides marine use actors methods to earn and sustain their social license to operate, while governmental legitimacy is bolstered by assuring public engagement opportunities are available and protected with outcomes utilized.

Keywords: marine governance, free, prior, and informed consent, public participation, public trust doctrine, social license to engage, stakeholder decision making, stakeholder deliberation, social license to operate

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INTRODUCTION

Unsustainable use of marine resources and environmental degradation behooves governments responsible for their marine waters to devise more effective means of governance. The extra-legal concept of social license is one such means but requires a firmer footing to enhance its credibility and usefulness. Legalized rights of stakeholder engagement in decision-making for marine space

uses, via stakeholders' social license to engage (SLE), can provide a sound way for marine project proponents *and* the governments that oversee them to earn and maintain their social license to operate (SLO). This hypothesis grounds the primary author's Ph.D. thesis work in process – *Legally Sanctioned Engagement in Marine Governance: A New Paradigm for Social License as a Path to Ocean Sustainability*.

We propose that the marine space's distinctive character as a public natural asset generates a public right to engage in making decisions that accord with fiduciary principles of the public trust doctrine applicable to shared environmental assets. Our work contributes to marine governance research by synergistically linking three separate concepts–the legal public trust doctrine, the prior informed consent (PIC) participation model and the social license concept. Utilizing this theoretical linkage, it proposes creation of an implementation framework for best practice marine use decision-making that utilizes a fiduciary model of legal standards customizable to various marine applications and governance regimes.

Challenges to Optimal Marine Governance

Sustainably governing our world's marine space faces significant challenges. Not only does the interconnected marine estate lie in a multitude of international governmental jurisdictions (United Nations Convention on the Law of the Sea, 1982) other exigent factors include those dealing with actors, scale and knowledge (Campbell et al., 2016). Below, we overview four themes challenging effective marine governance and the decision-making behind it.

Fluctuating Political Priorities

Marine policy priorities that vary with political party or controlling regimes can lead to one step forward-two step back governance, lacking consistently high standards of sustainable use and protection (Wood, 2014; Bakaki et al., 2019).

Formidable Industry and Public Interest Influence

Diverse values and priorities held by different stakeholder networks (On Common Ground Consultants Inc., and Robert Boutillier and Associates, 2014) can create tension and conflict in marine governance. Economic development priorities can clash with marine conservation, esthetic, or recreational goals. Interest-aligned stakeholders can exert significant pressure on government actors to sway decision-making outcomes (Campbell et al., 2016).

Conflicting Government Roles and Responsibilities

Faced with external policy pressure and intra-governmental disagreements fed by the scope and often divergent nature of public service roles and responsibilities, government actors can find themselves at odds with making sustainable marine decisions. For example, governments' political responsibility to facilitate a robust and stable yet equitable economy can conflict with its fiduciary responsibility to protect public natural resources, which are often the site or source of economic development activities (Callahan, 2007; Wood, 2014).

Vague Environmental Principles and Bureaucratic Rules

Finally, marine policy principles, enabling statutes, and administrative rules can be vaguely written, leaving final use decisions and law enforcement subject to the variable discretionary interpretation of government administrators. These can also fluctuate based on the bias of political elites and their responsiveness to lobbying by vested economic interests (Wood, 2014; Scotford, 2017). In addition, areas of sovereign marine space usually fall under different bureaucratic regimes. For example, in federally constituted countries such as Australia, Canada, and the United States, the Exclusive Economic Zone customarily falls under national jurisdiction, while inshore areas of territorial seas can be governed under state/provincial legislation (United Nations Convention on the Law of the Sea, 1982).

Benefits and Costs of Public Stakeholder Engagement

To govern effectively when faced with competing priorities and values, legislators and administrators "need mechanisms with which to view and understand the relevant public values at play for a given policy issue or controversy. (and) frameworks that allow them to more effectively and consciously consider which public values to uphold and which tools and methods are most likely to do so" (Nabatchi, 2018, p. 6). "(N)o single institution can be expected to hold all of the expertise and knowledge needed for good decision-making." (Richardson and Razzaque, 2006, p. 170). A framework of best-practice marine project review and management procedures containing robust public engagement should provide those entrusted with governing highly valued natural resources, such as the marine space, with a much-needed mechanism to balance conflicting views that often frustrate a clear direction.

Understandably, it can cost additional time and money to implement the integral participatory processes, including those related to early project planning and development (Richardson and Razzaque, 2006). However, a plethora of benefits support increasing citizen participation in governance, including public education, facilitation of transparency, accountability, and legitimacy, and reduction of unproductive conflict (Callahan, 2007; Reed, 2008). These benefits, along with improved corporate relations, goodwill and governmental trust that can develop from inclusive and transparent decision-making, have flow-on rewards.

In times of widespread mistrust and lack of confidence in government leaders (Wike et al., 2019),[1] the integrity of the process for governing environmental resources especially matters (van Putten et al., 2018). As beneficiaries of public natural resources, marine stakeholders have a reasonable interest being

[1]For example, in Pew Research's Spring 2018 Global Attitudes Survey of 27 countries, 60% of respondents felt that, "No matter who wins an election, things do not change very much" describes their country well and 54% felt that, "Most politicians are corrupt" describes their country well (Wike et al., 2019).

involved in decision-making regarding activities affecting that resource (Callahan, 2007).

In Arnstein's renowned "ladder" representing levels of citizen participation, credible consultative processes involve partnerships that include discussion, deliberation, and negotiated outcomes (Arnstein, 1969; International Association for Public Participation, 2017). It is not one-way reporting to keep others informed of pre-determined plans and outcomes (Ross et al., 2002; Callahan, 2007). Robust, legally sanctioned stakeholder engagement should reduce counter-productive conflict about marine governance, support diverse, socially licensed stakeholder relationships, increase likelihood of environmentally sustainable marine management (Nanz and Steffek, 2006) and legitimatize decisions made. Likewise, transparent decision-making should improve management quality (Richardson and Razzaque, 2006; Callahan, 2007; Nordquist et al., 2018). Effective marine management is ultimately measured against ecological sustainability,[2] which is in civil society's highest and best long-term interest (United States Supreme Court, 1892). In the short-term, however, its importance can be diluted by competing policy considerations such as economic development and political expediencies.

We argue that citizen stakeholders are entitled to fair, consistent and accountable treatment with more than merely a voice in legislative decisions about the marine estate. Marine stakeholders have right to a *say* in those decisions to ensure they utilize local knowledge and conform to standards of care embodied in governments' fiduciary role. This role carries legal obligations of honesty, full disclosure and acting in public beneficiaries' best interest as stewards of the natural asset. We further argue that these rights are embodied in a legal theory of public trust, which courts of law can uphold. Discussion of these propositions follows.

DISCUSSION

An Expanded Paradigm for Social License

We envision social license to encompass a framework of marine management standards and public participatory consent rights. We also advocate its use as the ultimate barometer of governmental decision-making in public natural resource governance.

"Social license to operate" is traditionally understood as the extra-legal "stamp of approval" that a substantial majority of community stakeholders give to proponents and operators of commercial endeavors (Parsons et al., 2014; Moffat et al., 2015). One issue with social license concerns what portion of a stakeholder community can sanction a project's approval (Reed et al., 2009). Without a tallied vote, a quantifiable majority is uncertain. However, attaining acceptance commonly requires factors of legitimacy, credibility and trust being present in relations between the community and a business (On Common Ground Consultants Inc., and Robert Boutillier and Associates, 2014; van Putten et al., 2018). The presence of SLO can be recognized on a continuum from absence of significant conflict over operations to community enrollment in the vision and mission of a company or industry[3].

The SLO concept also has geographically diverse usage and endorsement. Its intangible nature and the practical questions that begets create a lack of universal understanding of its meaning and differences in assumptions relative to its application. This includes critique of corporate use as a method to manage development opposition or downplay conflict (Hall et al., 2015; Moffat et al., 2015). We find shortcomings in the concept for additional reasons relating to lack of protocols and processes for its expression and the limited purpose of its traditional meaning. For example, the best criteria and process for SLO attainment in discrete sectors are not well substantiated in current practice. Further, SLO is often used only in relation to community views of private sector conduct (van Putten et al., 2018).

A Proposed New Social License to Engage

Social license should encompass not only more rigorous criteria for its attainment, but also be applied more broadly.

While the literature on SLO suggests a collection of elements believed to necessitate its attainment and, to a lesser extent, its retention, a dearth of practical guidance exists on a process for acquiring and linking those elements to sustainable marine management. Our research aims to help fill this gap by examination of empirical evidence of marine stakeholder views on marine project approval processes and sustainable marine governance. Utilizing case studies of salmon aquaculture industries in Tasmania, Australia, and Nova Scotia, Canada, in addition to drilling offshore Nova Scotia, we aim to propose a customizable implementation framework for participatory marine management. Results of this research, its implications and applications will appear in future publications and presentations associated with the Ph.D. thesis.

In the interim, we posit that the premise behind SLO is best understood and utilized through study of Greek Sophist philosophy reflecting empowerment of the governed (Keeley, 1995). Viewed through this lens, the concept is reframed to encompass civil society's power to deliberate and negotiate the rules governing them and their domain—what we term a SLE. This imbues social license with a *multifaceted* grant of action. Social license should not only represent an *operational* permit for industry predominantly free of non-productive conflict. Rather,

[2]Ecological sustainability as used herein draws from Richardson and Razzaque (2006, p. 166) *"Sustainability depends largely on the way economic, social and environmental considerations have been integrated in decision-making."*; Goldsmith et al. (1972). (*". . . a society . . . depend[ing] not on expansion but on stability."*); World Commission on Environment and Development (1987, p. 43), in which resource exploitation and investment direction (among others) are *". . . in harmony and enhance both current and future potential to meet human needs and aspirations."*).

[3]Ibid, at *What Is the Social License?*

the essence of social license should also represent a *participation* permit for civil society that is legally sanctioned and protected.

Further, a framework for marine governance is best developed from criteria necessary for creation of value-influenced relationships like social license. This research finds these criteria embodied in the concept of PIC as a best-practice standard for engaged participation (World Commission on Environment and Development, 1987). Traditionally known as free, prior informed consent, PIC is most often recognized with indigenous peoples in relation to their land, community space and natural resources (United Nations, 2007). In our research, the practice provides a benchmark for high-level engagement of public stakeholder networks in decision-making about marine space uses. The intrinsic nature of PIC is as a qualitative process by which a project proponent strives to achieve agreement to proceed from stakeholder groups potentially affected in some material way. The group members and application method of PIC depends on the specific context of its use because it is not a "stand-alone" right. Rather, the freedom to engage in deliberative decision-making derives from rights associated with underlying things that a marine activity might potentially affect (United Nations REDD Programme, 2013). For example, the right to participate in marine decision-making arguably derives from society's substantive right of access to and enjoyment of a healthy, sustainable marine space held by the state as a public trust asset.

Elements generally recognized as essential for establishing PIC are:

1. A voluntary participation process with **Freely-given** project acceptance (Food and Agriculture Organization of the United Nations, 2016);
2. Stakeholder consent given **Prior** to official project approval or grant of legal license and before financing (Hanna and Vanclay, 2013);
3. Stakeholders fully-**Informed** about project details, their rights, implications, risks and worst-case scenarios (Goodland, 2004);
4. **Consent.** Descriptions include:

   4.1 a collective decision made in phases by rights-holders, "reached through their customary decision-making processes" (United Nations REDD Programme, 2013);
   4.2 acceptance of at least 51% of potentially affected parties (Goodland, 2004) (but ordinarily a substantially larger majority);
   4.3 a process with participation and consultation being central (Barelli, 2012);
   4.4 a voluntary agreement designed to make a project acceptable (Goodland, 2004).

While application of PIC in diverse marine stakeholder communities can instigate discontent, an inclusive deliberative process should best assure socially licensed decisions. At any rate, management of marine resources by government agencies with only token involvement of impacted and interested stakeholders is already a common source of marine community conflict.

It is through legal legitimization of a participatory consent protocol, like PIC, that extra-legal, socially licensed, mutually endorsed relationships between a network of diverse marine use stakeholders (interested citizens, project proponents, and government officials) has potential to exist.

The Public Trust Doctrine: A Normative Legal Foundation for Social Licenses to Operate and Engage

If project proponents' SLO and public stakeholders' SLE include a right of stakeholder consent in public natural resource management decisions, a legal basis is needed for ensuring both management practice standards and a right for citizens to participate in deliberation about them.

The legal public trust doctrine fundamentally stands for the premise that certain natural resources are part of an inalienable public trust. As such, government authorities have a fiduciary role to sustainably manage and guard those resources against harm. Further, every citizen is considered a beneficiary of the trust and may invoke its terms to hold government trustees accountable, with potential judicial protection against violation of their related rights (Sand, 2007). The doctrine's historic focus in the United States, the jurisdiction where the doctrine has received greatest legal affirmation, is in regard to navigable waters (Sax, 1970; Thompson, 2006).

We look to the doctrine's ability to serve as the legal basis for required marine standards of care necessary to attain SLO. The SLO can benefit from rigorous linkage to these fiduciary duty elements of the public trust as the criteria under a SLO attainment protocol. We also tap the doctrine as the basis for stakeholder rights to engage in marine decision-making under a model of PIC.

In legal jurisdictions firmly recognizing the doctrine, governments' role is that of a trustee in a fiduciary capacity to citizen beneficiaries[4]. The doctrine is commonly understood to include the duties depicted in **Table 1**, which also may be legislatively enacted or judicially defined (Archer et al., 1994; Wood, 2014). Duties having the nature of overarching policy should be embedded in legislative preambles that direct the laws' purpose and intent. Duties having discreet methods for operationalization should be contained in appropriate sections of the substantive legislation with sufficient detail as to adequately guide administrative rule-making that supports their mandate.

Our research considers the doctrine's normative potential for governance of all environmental resources in the marine estate. Because the public trust duties of care should apply equally whether the waters and resources are under local, national, or international management and control, it follows that the right for public stakeholder decision-making participation should also apply. In four large-scale trials, Weeks concluded the possibility exists for large, public deliberation processes that enable governments to take effective action on difficult issues

[4]To varying degrees, the Doctrine or its core principles exist as a component of environmental law in several countries including Australia, Brazil, Canada, Ecuador, Eritrea, India, Kenya, Nepal, Nigeria, Pakistan, Philippines, South Africa, Sri Lanka, Tanzania, Uganda, and the United States. See Hare and Blossey (2014).

TABLE 1 | Public Trust Governmental Duties of Care.

Trustee's substantive duties	Trustee's procedural duties
Take, keep control of public assets; use moderation in privatization	Undivided loyalty to public beneficiaries versus private interests
Diligently preserve public trust assets; guard future interests	Furnish complete, accurate information to public beneficiaries
Vigorously enforce claims of harm against public assets	Be impartial among citizen beneficiaries
Keep public trust assets beneficial; maximize value	Adequately supervise assets and use cautionary management
Restore assets when damaged	Use good faith and skill in asset management

(Weeks, 2000). Further, an international example of participatory decision making in action is the Commission for Environmental Cooperation (CEC) concerning North American environmental issues. The CEC also enables empowered participation in environmental law compliance via public submissions of enforcement concerns (Commission for Environmental Cooperation, 2020). Finally, direct democracy via ballot issue voting remains the purest form of participatory decision making in appropriate situations.

The Independent World Commission on Oceans has declared *"[a] more informed and active civil society with significantly enlarged opportunities to participate in ocean affairs is a precondition for a more responsive and democratic system of ocean governance. It is in the critically important area of ocean governance that competing issues and divergent interests and opinions must be accommodated and reconciled."* (Independent World Commission on the Oceans, 1998).

We propose civil society's permit for deliberative engagement on marine use affairs, encompassed in a SLE and nested under a standard of PIC, should be legally sanctioned and judicially protected through legislative or common law revitalization of the public trust doctrine. The doctrine can extend legal standing rights to citizens to protect their beneficiary interests in sustainable ocean resource management when government actors abuse or neglect duty of care terms under the public trust (Turnipseed et al., 2009).

CONCLUSION

"Humanity's relationship to the sea is not just a legal property relationship, but a social relationship of participation." (Van Dyke et al., 1993).

The foundational rationale of our research is that diverse stakeholders have a value and/or priority-driven interest in reaching a mutually agreeable position on marine resource uses, especially when their values and priorities diverge. SLO is the carrot that makes a participatory consent process worth pursuing. And a participatory consent process, akin to PIC, presumptively available to civic marine stakeholders under a public trust legal theory of SLE, is a means for possible creation of that social acceptance. While unanimous agreement on decisions is unlikely, our proposals in this article widen the participation sphere for input, thus improving chances of developing a SLO. However, if non-governmental marine stakeholders are not empowered to make *final* decisions, the full community of consultative and beneficial parties should receive a report of official conclusions reached, including their rationale, along with a process by which stakeholders can petition the governmental authority to reconsider its decision on specified grounds.

When separated, PIC and social license miss not only the nature of their relationship, but also their ability to work symbiotically for creation of win^3 outcomes (for project proponents, governments, and concerned stakeholders) in marine space activities. As beneficiaries of public marine assets, civic stakeholders hold power through their SLE in decision-making to shape sustainable management of the public marine trust. These voices, and the decisions made by way of them, represent the real relationship between PIC and social license.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

LU-K conceived of the presented idea and developed the theory. All authors discussed the results and contributed to the final manuscript. All authors contributed to the article and approved the submitted version.

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Five Organizational Features That Enable Successful Interdisciplinary Marine Research

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To generate innovative solutions for marine sustainability challenges, scientists, policymakers, and funders are increasingly calling for interdisciplinary research that transcends disciplinary boundaries. However, challenges associated with doing interdisciplinary research persist and undermine progress toward tackling the complex challenges faced by marine social-ecological systems. One barrier for engaging in effective interdisciplinary research is a lack of understanding about the institutional capacities that support interdisciplinary knowledge production. Based on in-depth qualitative interviews with members of the Centre for Marine Socioecology in Australia, we identify five principles that underpin effective interdisciplinary research organizations. The principles are: (1) support female leadership; (2) forge partnerships outside of academia; (3) develop impact-based performance metrics; (4) focus on long-term funding; and (5) cultivate a visible brand. Going forward, these principles could be used to inform organizational design that transforms institutional barriers into enablers of innovative interdisciplinary research for more sustainable, desirable, and equitable futures.

Keywords: interdisciplinary research, anthropocene, sustainability, interdisciplinary institutions, institutional capacity, Australia

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INTRODUCTION

As we progress into the Anthropocene, societal well-being and environmental sustainability are increasingly uncertain (Nash et al., 2017; Steffen et al., 2018; Lam et al., 2020). While the academic community historically sought to address such challenges within the confines of a single scientific discipline, it is now widely accepted that this approach to knowledge generation is no longer adequate (Brondizio et al., 2016). As Crow and Dabars (2017, p. 482) articulate, "biologists alone cannot solve the loss of biodiversity, nor chemists in isolation negotiate the transition to renewable energy."

Instead, the unique challenges presented by the Anthropocene to marine socio-ecological systems necessitate new approaches of knowledge production that are capable of integrating scientific disciplines to develop solutions for complex challenges that are desirable, equitable, and viable (Castree et al., 2014; Bai et al., 2016; Bennett et al., 2019a,b; Nash et al., 2020). Increasing support for interdisciplinary research is reflected by a growing number of local to global programs that seek to address global sustainability challenges through interdisciplinary research

(Van Noorden, 2015). In 2019, for example, the United Kingdom's Research and Innovation body announced over $260 million in funding for 12 Global Research Hubs over 5 years, including the One Ocean Hub, which involves 56 partner organizations across 11 countries (United Kingdom Research and Innovation, 2019b). Given the potential of integrative forms of research, sustainability scientists have shifted from asking *whether* interdisciplinary research is essential to asking *how* we can best build interdisciplinary research organizations that facilitate joint problem solving (Brown et al., 2015).

Despite increasing rhetorical support for interdisciplinary research, however, significant challenges associated with doing interdisciplinary research remain (Roy et al., 2013; Cundill et al., 2019a). For example, numerous studies have explored the challenges associated with integrating divergent academic disciplines in a meaningful way, such as those associated with different "languages" and research methodologies of individual disciplines (e.g., Blythe et al., 2017; Alexander, 2019). Navigating such roadblocks requires additional resources, which in itself has proven problematic, and in extreme cases, has led to destabilizing tensions within research teams (Frusher et al., 2014). Bammer (2017) argues that the specific personal and relational skills needed to operate effectively as part of an interdisciplinary research process are poorly defined, recognized, and rewarded within existing academic institutions.

In response, an emergent body of literature has sought to identify strategies for overcoming the documented barriers to building capacity for interdisciplinary research (reviewed in section "Enablers of Interdisciplinary Research: Current Knowledge and Critical Gaps" below). A dominant theme throughout this literature has been identifying pathways to build the capacity of interdisciplinary researchers (e.g., Haider et al., 2018; Hein et al., 2018; Kelly et al., 2019). While such studies have helped to understand how best to cultivate individual researchers that are capable of engaging effectively within interdisciplinary research processes, there is very little empirically derived guidance for how to build institutional capacity and structures that support interdisciplinary research, particularly for research organizations focused on developing solutions to marine sustainability challenges (Cvitanovic et al., 2020). The identification of core principles to guide such efforts can be achieved through the evaluation of existing interdisciplinary efforts, which in turn can help generate guidance for other research organizations seeking to enhance their interdisciplinary capabilities (e.g., Cvitanovic et al., 2018a).

Thus, the aim of this study is to begin to identify core principles for building effective interdisciplinary research organizations for tackling complex marine sustainability challenges. We address this aim via an in-depth evaluation of the Centre for Marine Socioecology (from here on CMS) in Tasmania, Australia, which brings together disciplinary expertise in physics, law, economics, biology, sociology and governance to solve the grand challenges facing the world's coastal and marine environments. In focusing on a single case study, we are able to clarify the key perspectives of CMS members across all disciplines and career stages (PhD students, post-doctoral researchers, mid-level and senior academics, and the leadership team) so as to generate a comprehensive initial set of principles underpinning interdisciplinary success (e.g., Cvitanovic et al., 2016b). Undertaking an in-depth evaluation then allows for future efforts to compare the results across multiple cases to evaluate the applicability of the identified principles in other contexts and settings (Reed et al., 2014; Norström et al., 2020).

ENABLERS OF INTERDISCIPLINARY RESEARCH: CURRENT KNOWLEDGE AND CRITICAL GAPS

Given the challenges of undertaking interdisciplinary research, there is a need to better understand how to develop the capacities—from individual to institutional—that support effective interdisciplinary research (Roy et al., 2013; Mitchneck et al., 2016). Here, we provide a brief review of the existing research, to highlight progress to date and situate our study amongst this broader body of literature.

A key theme throughout the emerging literature on supporting interdisciplinary research has been the need to build individual capacity for interdisciplinarity (e.g., Haider et al., 2018; Hein et al., 2018; Kelly et al., 2019; Andrews et al., 2020). Research suggests that interdisciplinary researchers tend to be motivated to contribute to the advancement of a "common good," characterized by attitudes of tolerance and reflexivity and by skills including team management and facilitation, among other attributes (Guimarães et al., 2019). Another important individual capacity is the extent and quality of team members' past collaborative experiences with each other and their experience with collaboration in general (Misra et al., 2011). Research is showing that individual collaborative capacities are not simply intuitive, but rather must be carefully developed through processes of collaborative learning (Freeth and Caniglia, 2020). To this end, Kelly et al. (2019) offer ten tips designed to help students and early career researchers develop interdisciplinary competencies. The first tip, for example, advises students to develop an area of expertise before attempting interdisciplinary research. However, debate remains as to whether specialized disciplinary training is an essential prerequisite for an individual's efforts in cultivating interdisciplinary competencies (Stokols, 2014).

Research has also identified that relational capacities are crucial for interdisciplinary innovation and performance. Relational capacities are defined as the interpersonal dynamics that shape the process and outcomes of collaborative initiatives (Cundill et al., 2019a). Interpersonal trust is considered an essential relational capacity for the success of interdisciplinary initiatives (Pischke et al., 2017). For example, trust allowed members of the Resilience Alliance to engage in high-impact collaborative research over more than a decade (Parker and Hackett, 2012). Power dynamics also shape the performance of interdisciplinary research teams. For example, power asymmetries can prevent some actors from playing an active role in collaborative processes, which undermines one of the core tenants of interdisciplinarity (Cundill et al., 2015). However, even when the individual and relational capacities described here are

present in interdisciplinary teams, emerging research suggests that institutional factors also strongly influence the outcomes of interdisciplinary efforts (Cundill et al., 2019b).

Interdisciplinary knowledge production depends on institutional contexts (Van Noorden, 2015; Mitchneck et al., 2016). For example, in the Oxford Handbook on Interdisciplinarity, Crow and Dabars (2017, p. 476) argue that "despite broad consensus regarding the imperative for inter- and transdisciplinary approaches to inquiry, twenty-first-century academic culture remains defined by the organization and practices established by this set of historically determined institutions." In response to these barriers, researchers have begun to focus on identifying institutional capacities that support interdisciplinarity. Institutional capacities refer to the cultures, practices and structures of research organizations (Mitchneck et al., 2016). There are a number of areas where supportive institutional practices can impact the productivity and effectiveness of interdisciplinary research (Andrews et al., 2020). Examples include division of overhead between departments and provision of administrative support for the increased coordination that is required for conducting multi-departmental or multi-institutional research (Misra et al., 2011). Cundill et al. (2019b) also identify the alignment of institutional cultures as critical for supporting interdisciplinary knowledge production. Yet, empirical studies on the institutional capacities required to support interdisciplinary research remain limited (Crow and Dabars, 2017). Thus, we see institutional capacity as a key, but often underexplored, dimension of enabling high-quality interdisciplinary research and promoting impact on the ground, particularly in relation to marine sustainability challenges.

MATERIALS AND METHODS

Data Collection

To develop principles for building effective interdisciplinary research organizations we employed a qualitative research approach. Qualitative methods are considered advantageous over quantitative methods for achieving this objective as they allowed us to establish an in-depth understanding of the perceptions of each study participant (Bryman, 2012). Further, qualitative research approaches have previously proven effective for identifying the key principles underpinning the success of research processes, which in turn allows for the establishment of design principles that can inform the efforts of other research teams and organizations (e.g., Reed et al., 2014; Marshall et al., 2017; Norström et al., 2020).

We selected the Centre for Marine Socioecology (CMS) as the case for this study as it embodies the key features of interdisciplinary research organizations (Creswell and Poth, 2016). Here, we define interdisciplinary research as inquiry that involves collaboration among scholars from multiple scientific disciplines to advance research approaches and theories to understand and address complex social-ecological challenges (adapted from Roy et al., 2013). In using this definition, interdisciplinary research is distinguished from other commonly used terms such as multidisciplinary science (which is additive opposed to integrative) and transdisciplinary science (which also includes non-academic forms of knowledge). We define research organizations as collectives of people oriented toward solving shared tasks, which include universities, research institutions, and research groups (following Perrow, 1979).

In order to select participants with a deep understanding of interdisciplinary research organizations who could best inform our research question, we followed a criterion sampling protocol (Creswell and Poth, 2016). Members of CMS were invited to participate in the study based on two criteria: (a) they had to have been members for at least 12 months and (b) they had to be "active members." In this regard, active members were those who regularly attended CMS meetings, seminars and events, and contributed to the CMS community. Participants were identified through consultation with key CMS staff (e.g., administrative support role and Director) and through meeting minutes where attendance was recorded. At the time of the study there were 48 CMS members across all career stages, but only 27 who qualified as "active members." Of the active members, 18 were female and 9 were male. Past members were excluded to ensure that all participants were reflecting on the current structure of CMS (e.g., current director, aims, research themes, etc.). Others (e.g., non-active members) were excluded on the basis that whilst they had joined the CMS they had not taken any part in any CMS initiatives, and thus were not well placed to reflect on the aspects of CMS that contribute to its operation, successful or otherwise.

Interviews began with "the most active" CMS members, and continued until theoretical saturation was reached, meaning that the adequate depth of information had been achieved and no new data was generated by additional interviews (Patton, 2002). While there is no universally appropriate sample size for qualitative interviews, best practices suggest that saturation tends to occur after 12 interviews, while meta-themes are often present after six interviews (Guest et al., 2006; Baker and Edwards, 2012). In total, 18 of the 27 "active members" of the CMS were interviewed (thus representing 67% of the active members), composed of PhD students (n = 7), post-doctoral researchers (n = 3), mid-career scientists (n = 4), and members of the leadership team (n = 4). Where possible, interviews were conducted face to face, however, for logistical reasons some interviews were conducted either via Skype or phone.

All interviews were guided by a set of open-ended questions (e.g., an interview guide) that were designed to explore the perceptions of participants against the study objectives (full interview guide at **Supplementary Material**). The interview guide itself was developed following grounded theory guidelines (Charmaz and Belgrave, 2012) and by drawing on previous efforts to characterize principles of success (i.e., Reed et al., 2014; Cvitanovic et al., 2018a; Kelly et al., 2019), but adapted to suit the specific aims of this study. As such, the interview guide focused on four key areas. Specifically, it was designed to assess the perceptions of participants regarding:

1. The establishment, goals, and operation of the CMS;
2. The extent to which they felt the CMS had achieved meaningful interdisciplinary research processes, and the

extent to which that new knowledge had been used to influence policy and practice;
3. The barriers they had experienced working in an interdisciplinary research environment; and
4. The key lessons that they had learnt relating to how to ensure success within interdisciplinary research teams and organizations.

To ensure the utility of the interview guide, it was first pilot tested among three members of the CMS and refined accordingly. Changes were minor, and focused on improving the wording of questions for clarity, opposed to the intent of the actual question. While we acknowledge that in some circumstances it may not be appropriate to pilot the interview guide on individuals who are part of the focal research group (Bryman, 2012), the specific nature of our case study made it important to ensure that the questions were clear and applicable to the specific context (following previous studies such as Cvitanovic et al., 2016b, 2018a).

Data Analysis

All interviews were digitally recorded and professionally transcribed to ensure their accuracy. To allow for principles to emerge from the data, without the limitations that can be imposed by deductive coding approaches, we employed an inductive coding approach based on Grounded Theory Analysis (Glaser and Strauss, 1967; Charmaz and Belgrave, 2012). Interview transcripts were coded using NVIVO 10 qualitative data analysis software.

To improve the accuracy of the coding, both researchers started by independently coding the same four transcripts. Coding results were then discussed and high levels of overlap among the emergent themes were present. Where minor divergence was evident, it was discussed and a course for resolution jointly agreed. Following this, a single author (JB) coded the remaining interviews.

Following Grounded Theory Analysis, all interview transcripts were coded through an "*in vivo*" coding method during the first cycle of coding (Charmaz, 2008). By using the participants' own words to derive and summarize key themes, the "*in vivo*" coding approach allowed participants perspectives to emerge without the constraints imposed by more structured methodologies (Hay, 2010). To ensure the validity and relevance of themes that emerge through this approach, the evolving interpretations were continually verified against the raw data from which they were derived (following Fleming and Vanclay, 2009; Marshall et al., 2011). This coding process resulted in 27 codes.

Following the initial coding of raw data, a second cycle of coding was undertaken. During this step in the analysis, data was re-coded following a thematic coding technique in order to develop a coherent synthesis of key themes (Saldaña, 2015). Thematic coding refers to the identification and interpretation of patterns, or "themes," in qualitative data that are relevant to the research question (King et al., 2018). We selected thematic coding as an appropriate approach for the second round of coding, as we sought to identify common patterns or themes within our participants' perspectives the characteristics of effective interdisciplinary research organizations. This iterative process resulted in 12 sub-themes and five main themes that were directly derived from the data (summarized in **Table 1**). As with the initial phase of coding, to ensure that emerging themes were valid and relevant, the evolving interpretations were continually verified against the raw data from which they were derived. This approach of deriving themes and sub-themes to ensure that results are both rigorous and representative is well established in the literature (for example, see Reed et al., 2014; Cvitanovic et al., 2016a; Kelly et al., 2019; Norström et al., 2020).

RESULTS AND DISCUSSION

Through the coding process we identified five key principles (i.e., the main "themes" derived from the coding process) for building effective interdisciplinary research organizations (**Figure 1**). The principles are: (1) support female leadership, (2) forge partnerships outside of academia, (3) develop impact-based performance metrics, (4) focus on long-term funding, and (5) cultivate a visible brand. We recognize that the principles are not discrete, they interact. Moreover, the order of presentation is not indicative of importance. In this section, we describe each principle by drawing on the 12 sub-themes that emerged during data analysis (sub-themes summarized in **Table 1**). We then situate our findings within the broader literature to identify and discuss the key insights that our study provides for building effective interdisciplinary research organizations. In doing so we also identify specific actions for scientists, policymakers, and funders to help support the achievement of each principle.

Principle 1. Support Female Leadership

The first of our five principles highlights the importance of supporting female leadership across all levels, from centre directors to project and research group leaders. When developing interdisciplinary research organizations, the results of our analysis suggest that it is critical that women are supported to both attain, and to be successful in, leadership positions. Our results suggest that doing so can (i) encourage innovation, (ii) cultivate a more inclusive research environment, and (iii) remove hierarchical power imbalances that have the potential to derail collaboration among researchers from different disciplines. Here, we discuss these findings in the context of research on gender studies from other sectors, as well as emerging evidence from sustainability science.

First, our analysis indicates that in the case of the CMS, female leadership across the organization has driven innovation and creativity, both of which are necessary for identifying novel solutions to contemporary sustainability challenges. For example, one participant in our study reflected:

> *"It is important to have a channel for that continual refresh and to always be trying to think how can we bring in something new or what could we be doing different? Or where could we get some new ideas?. I'm glad to see that [the female director]is definitely driving that view and hopefully, that will continue, and I think that that's really important for other interdisciplinary centres as well.*

TABLE 1 | Five principles for building effective interdisciplinary research organizations identified through the coding process.

Principle Sub-principle	**Coding frequency**	**Example quote from interviews**
1. Support female leadership		
Foster innovation	70	*"[Our director] has an open and inspiring kind of attitude that is forward-looking. . .being open to all disciplines and really encouraging and setting up meetings or processes for people to work with new people is so important. And I do think there was a gender component, which was really important"* (Interview 18)
Nurture a culture of inclusion	42	
Share power horizontally	21	
2. Forge partnerships outside of academia		
Engage in knowledge co-production	15	"*What we need is more of those in between roles, knowledge brokers, people who can be more embedded with the decision-makers and get inside those systems*" (Interview 3)
Involve science-policy boundary-spanners (such as knowledge brokers)	16	
Create trust through partnerships	11	
3. Develop impact-based performance metrics		
Develop interdisciplinary indicators	21	"*[We need to] have some real tangible outputs and promote those like crazy, so people can see. . .something is coming out of this*" (Interview 15)
Demonstrate impact	2	
4. Seek long-term funding		
Identify innovative funding	44	"*Somewhere like Sweden, for example, they can achieve such fantastic centres of research, because they have incredible philanthropic funding that is really quite long-term. Something like that here would be a real game changer*" (Interview 18)
Shift from project funding to long-term funding	49	
5. Cultivate a visible brand		
Identify your unique identity	50	"*You need people to recognise you. You need brand and you need credibility*" (Interview 12)
Promote your brand (e.g., via non-traditional venues such as social media)	15	

These principles and the sub-principles were derived from qualitative data generated from interviews with 18 members of the Centre for Marine Socioecology in Tasmania, Australia, following Grounded Theory Analysis.

FIGURE 1 | Five principles for building effective interdisciplinary research organizations to tackle complex marine social-ecological challenges. The principles were derived from qualitative data generated from interviews with 18 members of the Centre for Marine Socioecology in Tasmania, Australia, following Grounded Theory Analysis. The order and color of presentation is not indicative of importance.

> *It's not just mixing a few disciplines and then that's it. It really is about trying to do everything essentially differently and creating a whole new environment, so that you can achieve true innovation"* (Interview 18)

Indeed, the majority of respondents reflected on the positive influence of CMS' female director on innovation within the center, and attributed that influence directly to her gender. Thus, the experiences of members of the CMS suggests that teams led by women, and that are inclusive of diverse perspectives, may be more likely to generate novel ideas for solving intractable sustainability problems.

The positive relationship between the presence of women in leadership positions and innovation is well documented in

the business and corporate sectors (Apesteguia et al., 2012; Lückerath-Rovers, 2013). In Spain, for example, Díaz-García et al. (2013) observed that gender diversity within Research and Development teams foster radical innovations in technology firms. In Denmark, a study of 1648 companies documented enhanced innovation resulting from gender diversity within leadership roles (Østergaard et al., 2011). While the positive influence of women leaders is well established in other sectors and settings, in academia it remains relatively understudied. There are, however, a few notable exceptions. For example, Nielsen et al. (2018) recently found that gender diversity can drive scientific discovery. They attribute the boost in innovation to the cognitive diversity associated with gender balanced teams. They describe cognitive diversity as the varied ways in which women frame problems, which can drive creative solutions for complex challenges (Nielsen et al., 2018).

Second, our analysis suggests that within the CMS, female leadership was a critical factor in fostering a culture of inclusion, trust, and mutual respect. For example, one participant described how creating an inclusive environment is essential for interdisciplinary teams:

> *"You really have to have leadership that tries to develop a culture that is inclusive and allows people to experiment in working in different ways because they are not working in a set disciplinary way with set rules and expectations. There has got to be an expectation that sometimes you will do things that will fail, sometimes you will do things that won't work but that's okay because that is what this interdisciplinary work is about and that's what the director sort of embraces"* (Interview 16)

As highlighted by Ledford (2015), inclusion, trust and respect are critical for successful interdisciplinary collaboration (Ledford, 2015). This finding aligns with other emerging research that has shown that feelings of inclusion, respect and trust are vital for building effective interdisciplinary research teams and organizations (Cvitanovic et al., 2018b). Similarly, in reflecting on more than a decade of interdisciplinary water research, Brown et al. (2015) attribute successful collaboration to leaders who nurtured empathy and respect between team members.

Third, our analysis found that female leaders across different levels within the CMS context (e.g., director, group leaders, and team leaders) were perceived as highly effective at creating horizontal power structures that dismantle traditional hierarchies. The necessity of shared power was highlighted by one respondent:

> *"...tolerance is needed in all directions, so it's not just tolerance across disciplines, it's tolerance by the older scientists to hear younger scientists with a valid opinion and a different experience to what you've got who are facing different challenges, but equally for the younger scientists to appreciate that they don't always know the whole political landscape that the older scientists are trying to navigate to keep the thing going. So, it just needs tolerance and happiness and willingness on all directions to really make the thing work"* (Interview 17)

The removal of hierarchical power imbalances is particularly important within interdisciplinary research settings because it encourages all participants (irrespective of discipline, career stage, or other factors) to contribute to all stages of the research process (Andrews et al., 2020). When power hierarchies are present, leaders (or other more senior people such as later career scientists) can either consciously or subconsciously steer research processes toward their own biases (e.g., discipline) and thus derail a collaborative research process.

Based on our findings, and the literature discussed here, it is clear that supporting women in leadership positions is a critical component of building successful interdisciplinary research organizations. Doing so, however, will require a number of strategies that challenge outdated academic cultures (e.g., Howe-Walsh and Turnbull, 2016). One approach for supporting female leadership is through mandatory gender bias training. For example, Mitchneck et al. (2016) propose a six-point plan for promoting diversity within academic institutions, which includes gender bias training to better inform the campus community about hurdles to hiring, retaining, and promoting women and changing promotion and tenure timeline to better support early career women. Similarly, Nielsen et al. (2018) outline specific management techniques for building gender diversity across four scales: research teams, disciplines, research organizations, and society. Techniques include cultivating positive beliefs about diversity and developing formal policies that link funding to team diversity (Nielsen et al., 2018).

Another way to support female leadership within interdisciplinary research organizations is through gender quotas. For example, a recent experimental study found that gender quotas increased the equity and efficiency of climate policy interventions (Cook et al., 2019). While gender quotas can be subject to challenges, such as provoking backlash against women (Leibbrandt et al., 2017), they nevertheless represent a tangible strategy for promoting gender balance within academic institutions and warrant further consideration as well as exploration of how they can be most effectively integrated into organizational settings.

Our first principle proposes that female leadership can stimulate innovation and support inclusive research environments where hierarchies are dismantled. Before moving on, we want to point out an important caveat associated with the first principle. A risk associated with advocating for women in leadership positions and gender balance is that "female 'difference' is used as the basis to stereotype capabilities and cast them in a collective negative light" (Díaz-García et al., 2013, p. 157). In other words, unfavorable typecasts about female leadership can be used to characterize all female academics as possessing the same traits. Therefore, we would like to qualify our first principle by stressing that the diversity of female leadership styles and women as academics should always be recognized.

We would also like to emphasize that, in no way, does this principle suggest that good leadership is constrained to a single gender. Nor does it suggest that all leaders must be female. Rather, this principle, which was derived from our data and the specific case of CMS, highlights that female leadership at different levels within the CMS led to several benefits relating to culture and inclusion. This finding supports an existing body of literature, as

highlighted above, about the importance of gender diversity and inclusion more broadly in academia. However, further work is needed to more comprehensively understand the importance and influence of gender (and we suggest diversity and intersectionality more broadly) in terms of their influence on interdisciplinary success, particularly in terms of teamwork and leadership.

Principle 2. Forge Partnerships Outside of Academia

The second principle highlights the importance of forging partnerships outside of universities. Our results suggest that when academics collaborate with actors from outside of academia (for example, with policy makers or industry representatives), both the quality of the scientific outputs, as well as their relevance to decision-makers, increased. For example, one respondent described how diverse viewpoints can drive holistic problem framing:

> *"...that [workshop] was really great because we had people from law, marine ecology, psychology, broader social sciences, and that generated really exciting conversations...it was one of those times where it was super beneficial to be like 'I didn't even think about the international commission on X, but thank goodness our collaborator from law is here to remind us of that"* (Interview 11)

Previous work has argued that it is difficult, if not impossible, for any single individual or disciplinary group to develop a complete picture of solution pathways and the dynamics of potential impacts and unintended consequences they may entail (Castree et al., 2014; Blythe et al., 2017). Thus, achieving holistic interdisciplinary research on multiple, interacting stressors on social-ecological systems necessitates the inclusion of a range of stakeholders, perspectives and knowledge systems (Cornell et al., 2013; Bennett et al., 2016; Cinner et al., 2016), not just academic knowledge systems. Moreover, collaboration between individuals with widely different, even polarized, perspectives has been shown to generate higher quality research than traditional disciplinary approaches alone (Shi et al., 2019).

Partnerships that extend beyond the academy are also essential for supporting research that understands and informs decision-making processes (Cvitanovic et al., 2016b). This is critical as successfully tackling complex social-ecological challenges cannot be achieved through knowledge generation alone, but rather, the way in which new knowledge is applied to achieve tangible changes in theory and on practice (Reed et al., 2014). As one interviewee pointed out, strictly academic research questions do not necessarily produce information that can inform effective decision-making:

> *"We [academics] need to solve the problems they [decision-makers] want solved, so you do need to solve the problems we think need to be solved but you also need to solve the ones that they want solved, because that's not always the same"* (Interview 12)

Thus, it is clear that researchers must engage in meaningful two-way knowledge exchange with decision-makers and other stakeholders outside of academia. Doing so is critical for achieving both policy-relevant science, as well as evidence-informed decision-making processes (reviewed in Cvitanovic et al., 2015).

Our results specifically identified two strategies for working across knowledge systems. The first is the implementation of knowledge co-production, and the second is the use of science-policy boundary-spanners, such as knowledge brokers. The first of these sub-principles (i.e., co-production) is centered around notions of participatory research approaches (e.g., Meadow et al., 2015; Djenontin and Meadow, 2018). As defined by Norström et al. (2020), knowledge co-production is an iterative process that brings together diverse types of expertise, knowledge and actors to interactively produce new context-specific knowledge and pathways toward a sustainable future. This is achieved by actively engaging decision-makers and other relevant stakeholders (and knowledge systems) throughout the research process to ensure that they can contribute their knowledge experience and insights into all phases of the research activity including problem identification, framing and formulation (Cvitanovic et al., 2019).

The second strategy identified through our analysis for forging partnerships outside of academia is the practice of "boundary-spanning." Here, we define boundary spanning following Bednarek et al. (2018, p. 1176) as "work to enable exchange between the production and use of knowledge to support evidence-informed decision making in a specific context" and boundary spanners as the "individuals or organizations that specifically and actively facilitate this process." The importance of boundary spanning within the CMS was highlighted by one participant, who said:

> *"If you're looking to inform policy and practice then you need to have contacts and networks within the policy sphere and people who can work towards—so having people who can act as kind of a broker role is really important...someone to be able to translate from both sides to make it as successful as possible"* (Interview 10)

Within the sustainability sciences literature many types of boundary spanning functions have been identified, ranging from individual knowledge brokers (e.g., Reinecke, 2015; Cvitanovic et al., 2017) to large-scale boundary organizations (e.g., Bednarek et al., 2015; Hart et al., 2015; Meyer et al., 2015). Evidence suggests that when implemented effectively, boundary spanning efforts can, among other things, successfully facilitate new networks and partnerships among researchers and non-academic partners, as well as facilitate the exchange of knowledge throughout these networks (Posner and Cvitanovic, 2019).

Finally, our results also identified the need to build trust when engaging with partners outside of academia, and how this can be achieved by engaging partners from problem formation all the way through the research project. This was reflected by one respondent in our study who pointed out that engaging with partners before establishing a collaborative project can be useful to develop positive, trusting relationships:

> *"What I've learned is sometimes it's good to make contacts without making a bad impression. With the fisheries managers, I was able to meet them through volunteering just going and talking to kids about catching fish, which was a really good way to get a foot in the door and get to know the right people without offering them more than*

I could deliver or making a bad impression because I didn't know what it was that I was working on yet" (Interview 11)

Establishing trust has been identified as a critical pre-condition underpinning the success of research efforts that involve partners from outside of academia (Cvitanovic and Hobday, 2018). Building trusting relationships requires careful navigation as collaborators are getting to know one another, and to avoid the potential pitfalls of situations associated with a loss of trust, or even too much trust (reviewed by Lacey et al., 2018).

Principle 3. Develop Impact-Based Performance Metrics

The third principle identified through our analysis is the need to develop impact-based performance metrics. Impact in this context refers to research influence that extends outside the academy to achieve "an effect on, change or benefit to the economy, society, culture, public policy or services, health, the environment or quality of life, beyond academia" (United Kingdom Research and Innovation, 2019a). This is separate from the notion of academic impact, which describes the intellectual contribution of an individual (or group of individuals) to a particular field of study (Penfield et al., 2014) and is typically measured through metrics associated with publication rates, citations rates and other indices such as the h-index (Ravenscroft et al., 2017). This distinction is important for interdisciplinary research organizations that are explicitly oriented toward the identification of socially relevant solutions to complex social-ecological challenges (Lang et al., 2012). Thus, their central objective is not simply the pursuit of knowledge, but rather the pursuit of knowledge that informs how societies navigate associated with complex challenges such as climate change, biodiversity loss, water scarcity, and food insecurity (Nash et al., 2017; Pecl et al., 2017).

Calls for new metrics to adequately capture impact outside of the academy are not new. For example, Porter et al. (2006) identify the need to tailor promotion and tenure to account for interdisciplinary research contributions in order to support knowledge integration within universities. Similarly, a recent assessment of an interdisciplinary research team in Sweden, whose core goal is to link scientific knowledge to action to support the sustainable management of the Baltic Sea, identified the lack of suitable metrics as a key barrier to achieving tangible impacts on policy and practice (Cvitanovic et al., 2018a). Yet, despite widespread recognition of the need for new impact-based performance metrics, measuring interdisciplinary impact remains problematic (Palmer, 2018). This is associated with the ambiguity associated in defining what actually constitutes "impact" outside of the academy, the long time-lags between knowledge production and impact (i.e., often greater than 10 years), and the non-linear and multi-casual pathways by which impact can occur (Molas-Gallart et al., 2000; Chowdhury et al., 2016; Reed et al., 2018). In combination, these factors make it difficult to attribute an impact to an individual or team of interdisciplinary researchers, limiting progress to the development and implementation of novel impact-based metrics. The challenges associated with measuring practical impacts was highlighted by one study participant who said:

"Success is only a term. So we can discuss what success means for you. In the science world I would say success is publishing a lot of papers and I think we're doing quite well in this area. But we're also doing quite well in the non-scientific world with this open dialogue and just try to engage with stakeholders. And also in engaging with different disciplines. And I think this is, also, kind of success, just different, maybe harder to evaluate because you don't have an impact factor" (Interview 2)

Despite these difficulties, our analysis of participant experiences in the CMS identified two focal areas that could assist in the development of new impact-based performance metrics. First, participants in our study highlighted the need to develop explicitly *interdisciplinary indicators* to support monitoring and evaluation (M&E) frameworks. This was considered particularly important since the contributions of solution-oriented interdisciplinary research organizations can be missed by more traditional academic metrics (Stern, 2016). Specifically, the types of indicators suggested by CMS members included measures relating to the amount of time spent undertaking activities relating to science engagement and outreach, indicators to capture changes in social networks (e.g., to quantify growth in the network, increases in the cohesion of the network, or enhanced trust among members of the network), and formal recognition of non-academic publications (e.g., reports to industry or government) on equal footing with peer-reviewed publications. While this list is not exhaustive, it does show that it is indeed possible to develop new impact-based indicators of success and highlights the need for future research to more comprehensively understand what these indicators could entail (Maag et al., 2018).

Building on the above, participants in our study also highlight that making progress toward impact-based performance metrics will also require the identification of novel ways of actually *reporting impact*. Specifically, reporting frameworks for interdisciplinary research might include non-traditional metrics, such as case studies, testimonials from partners, and other more qualitative measures of impacts on policy and practice (Brown et al., 2015). Indeed, this supports recent evidence associated with the UK Research Excellence Framework (REF), which utilized narrative style case studies to help illustrate the impacts achieved by interdisciplinary research projects (Stern, 2016). Reflecting on the importance of impact assessment frameworks, like the UK's REF, a participant in this study noted:

"In the UK they have the Research Excellence Framework process, where you have to do impact case studies. Each organisation does an impact case study to look at how their research is contributing to policy or contributing to management change or things like that…. it would be really useful for CMS to go through that process, and actually identify if the research is actually contributing to management in whatever form that may be of industry or of conservation practice" (Interview 15)

Operationalizing these principles, and building the capacity of interdisciplinary research organizations to demonstrate real-world impact, will require institutional change. A main obstacle for interdisciplinary researchers is the fact that academic reward systems are still largely organized along disciplinary divisions (Hicks et al., 2010). As Belcher et al. (2016, p. 14) articulate "the lack of a standard and broadly applicable framework for the evaluation of quality in [interdisciplinary research] is perceived to cause an implicit or explicit devaluation of high-quality [interdisciplinary research] or may prevent quality [interdisciplinary research] from being done." That is, the lack of institutional recognition for research impact outside the academy can discourage researchers from engaging in solution-oriented, collaborative research (Shanley and López, 2009). Early career researchers may be particularly disincentivized to strive for impact outside the academy since early career stages tend to characterized by short-term contracts and job insecurity (Evans and Cvitanovic, 2018). Indeed, the requirement to return a fixed number of outputs per individual may encourage a focus on "safer" publication strategies, and this may involve short-termism in individual researchers' research strategies to enhance the likelihood of career progression and obtaining permanent employment (Stern, 2016). Thus, making meaningful progress toward impact-based performance measures must be underpinned by significant institutional reform among academic agencies to recognize and reward science engagement and outreach efforts in parallel with academic achievements (Cvitanovic et al., 2015).

Principle 4. Focus on Long-Term Funding

The fourth principle highlights the need to secure long-term funding to support successful interdisciplinary research. Funding plays a pivotal role in enabling academics to undertake high-quality research in all fields and disciplines, supporting a range of research items and activities, including field and laboratory costs, the salaries of PhDs and post-doctoral researchers, training and partnerships (Lyall et al., 2013). The importance of long-term funding (e.g., >5 years), however, is even more important within interdisciplinary research settings given the additional time required, and associated transactional costs, to build meaningful relationships founded upon mutual respect and trust among research team members (Cvitanovic et al., 2019). This is perhaps best described by Laura Meagher, an interdisciplinary coach in the UK, who reflected that "the most common mistake is underestimating the depth of commitment and personal relationships needed for a successful interdisciplinary project. You see people who think it's not much more than stapling a bunch of CVs to the back of a proposal, they don't realize that it takes time to build a relationship" (as quoted in Ledford, 2015, p. 310). Thus, conducting effective interdisciplinary research is often a long-term endeavor, which must be reflected in funding to allow the full development of relationships, and the actual (opposed to tokenistic) integration of different disciplines into the research process.

Our results highlight the ways in which long-term funding is particularly important during the design and establishment of an interdisciplinary research group. For example, as articulated by one participant:

> *"When [CMS] started out, there was funding to employ three Post Docs and pay for some PhD scholarships. there wasn't any money in the budget to start some exciting collaborations and I think that that was a massive oversight. You need to have the funds to spend on research collaborations. You need the funds to be able to pay for someone in admin or communication who is going to really bring that sense together from a logistical point of view. So, I would say that thinking very carefully about the money you need to really create a tangible centre"* (Interview 16)

As illustrated through this quote, ensuring adequate resources from the onset of an interdisciplinary endeavor is critical to facilitate the emergence of new collaborations, which in turn provides the basis for innovation, discovery and the advancement of knowledge. Securing long-term funding is also critical to allow the implementation of appropriate support processes, structures and resources that underpin success, such as the inclusion of communication and outreach experts to enhance the likelihood that research outputs are achieving real world outcomes.

Despite the importance of long-term funding to the success of interdisciplinary endeavors, interdisciplinary researchers have been challenged to secure funding. For example, a recent study that analyzed data from more than 18,000 proposals submitted to the Australia Research Council's Discovery Programme found that interdisciplinary research has consistently lower funding rates than disciplinary research (Bromham et al., 2016). Likewise, the Global Research Council's annual meeting identified a growing concern toward inadequate support for interdisciplinary research needed to address global challenges. The CMS specifically, for example, has been unsuccessful in two Transformation Research Hubs competition and one of the respondents attributes their failed record to the interdisciplinary nature of the center:

> *"The one place that I feel disappointed with CMS, and it's not CMS's fault, it's actually a funding constraint. For two years running now we've put out what's called a transformational training centre application in Australia, so that's to try and have industry-oriented training of post-graduate students. And we keep getting bumped because they don't get the idea of what the interdisciplinary stuff gives. It's very clear that if you have an engineering innovation centre that's teaching you engineering, what that brings, but it's hard for the reviewers to understand what CMS would bring"* (Interview 17)

Participants within our study highlighted that securing long-term funding to support innovative interdisciplinary research will require institutional reform by funders that explicitly recognize the additional challenges imposed by interdisciplinary research. Participants in our study identified longer-term grants and funding time together for collaboration as two promising pathways forward. Participants also highlighted the need for innovative funding models that support relationship building and provide opportunities for learning. Several respondents pointed to the National Socio-Environmental Synthesis Center (SESYNC) as a useful model, which employs an innovative funding model that supports newly formed collaborative teams to work together at its facility in the US to tackle complex challenges in novel ways (Palmer, 2018). We do, however, note that even funding schemes

like these, designed to support interdisciplinary research, can be challenging to obtain as highlighted earlier.

The need for longer-term grants is based on the recognition that interdisciplinary research typically takes longer than disciplinary research. Further, participants of our study also noted that most tangible impacts arising from interdisciplinary research often occur long after the research itself is complete. Yet, funding for interdisciplinary research often ends with a final project report, which misses the longer-term impact and sustainability of project outcomes (Blasiak et al., 2019). As such, longer-term funding would further enable the attainment of real-world impacts associated with interdisciplinary research (Blasiak et al., 2019).

Further, our results suggest that interdisciplinary research funding should also explicitly support face-to-face interactions between collaborators. As one respondent noted:

> *"The key point there is, it's not just funding for the research that we do that's necessary, but it's funding to create the socialising. Because, I mean, that's where the whole team gets together, and then the whole collaboration starts"* (Interview 1)

Bridle et al. (2013) propose that interdisciplinary encounters are an effective means to support the development of future interdisciplinary researchers, with a major advantage of this approach being the opportunity for open communication. They recommend that "funding bodies and other members of the research community should take note of the effectiveness of encounters to foster interdisciplinarity and generate space to develop more innovative and high-impact research that delivers solutions to the challenges facing humanity in the future" (Bridle et al., 2013, p. 30).

Principle 5. Build a Visible Brand

The fifth and final principle that emerged from our analysis is the potential power of effective branding for supporting interdisciplinary research organizations. For example, one respondent noted:

> *"It feels that [CMS] has become quite well established in the eyes of the rest of the world. Where if we now mention the Centre for Marine Socioecology, it has a presence…The name is part of the brand, isn't it? I mean, in the full sense of the word, the brand has a whole thing sitting behind it. It makes the centre directed and stronger in its coherence" (Interview 9)*

In this context, branding refers to the development of a unique name, design, and ethos that identifies and differentiates an organization (Vatsa, 2016). Developing a unique brand that clearly distinguishes an organization was considered by study participants as critically important given the present global proliferation of interdisciplinary research centres that share the broad goal of generating solutions to complex socio-ecological challenges.

Indeed, by looking across the existing literature it is clear that branding can play a pivotal role in building effective interdisciplinary research organizations. For example, research organizations can leverage a visible brand to establish their credibility, which in this context, refers to perceptions about the high accuracy, validity, and quality of research outputs (Cvitanovic et al., 2018a). Research has shown that institutional credibility can increase the uptake of research findings into policy and practice (Cvitanovic et al., 2018a). Establishing credibility is particularly important for research organizations tackling complex social-ecological challenges that are rife with conflicting emotional, financial, social, and political interests (Blythe et al., 2018). Building academic credibility is even more important as the legitimacy of science and research is increasingly questioned. As Irwin and Horst (2016, p. 1), recently pointed out "it does seem that trust in experts is in short supply with many commentators suggesting that 'facts' are losing out in their battle with 'opinion'."

Second, branding and the associated credibility it can inspire, is an important mechanism through which to broaden the real-world impact of interdisciplinary research. One of the central goals of interdisciplinary sustainability research is to inform real-world solutions, and thus the knowledge generated must be communicated beyond the academy (Lang et al., 2012). Credibility is believed to be one of three key traits of scientific knowledge (the others being legitimacy and salience) that underpin its uptake and integration into decision-making processes (Cash et al., 2003). Thus, an effective brand that helps to cultivate organizational credibility can also improve the extent to which the knowledge generated within the organization supports evidence-informed decision-making processes.

While the development of a unique name and ethos underpins the establishment of a brand, our results also highlight the importance of *promoting* your unique brand. In particular, participants in our study identified the need to promote your brand via non-traditional academic venues, such as the publication of academic papers and presentations at academic conferences. One respondent pointed out that novel communication strategies are required to increase the reach and audience of interdisciplinary research:

> *"I don't think we need another report. I really struggle with the meaning of reports. Because they don't get read. So, I think that they are other ways to increase visibility. Twitter and those sorts of things. Social media is quite important, for sure"* (Interview 1)

Indeed, many participants in our study reflected on the power of venues such as social media for building brand credibility and enhancing knowledge exchange. Evidence shows that research organizations with well-known and well-followed social media accounts, for example, can communicate research to a broad audience of other researchers, decision-makers, journalists, and the general public (Darling et al., 2013). For instance, a recent study found that scientists who Tweet to more than 1,000 followers reach non-academic audiences comprised of research and educational organizations, media, members of the public and decision-makers (Côté and Darling, 2018). Moreover, the audience of tweets can be amplified exponentially through sharing (re-tweeting) and shared via other social media platforms (Shiffman, 2012).

While the influence of effective branding is well documented in business and marketing research, empirical investigation of branding in social-ecological systems research is largely absent. This paucity suggests future research on effective branding

by research organizations represents a frontier for building effective interdisciplinary research organizations. For example, interdisciplinary scientists and organizations might learn how to build brand identity from well-established models in business or marketing (Ghodeswar, 2008).

CONCLUSION

In the context of the Anthropocene, interdisciplinary research is essential for identifying innovative solutions. In a recent review, Nicholas Stern concluded "as universities increasingly commit to addressing complex, intrinsically difficult "Grand Challenges" of global importance there is a clear recognition that *such issues and problems require a range of different perspectives that interdisciplinarity and collaboration can foster*" (Stern, 2016, p. 14, emphasis added). Despite broad consensus regarding the imperative for interdisciplinary approaches to inquiry, empirical evidence on how we can best build institutional capacity for interdisciplinary research is still lacking. Through in-depth, qualitative research this study identifies five principles pertinent to institutional design efforts to accommodate interdisciplinary research. The principles include: (1) support female leadership, (2) forge partnerships outside of academia, (3) develop impact-based performance metrics, (4) seek long-term funding, and (5) cultivate a visible brand.

While our investigation of the Centre for Marine Socioecology was a first step in generating empirically derived insights for building effective interdisciplinary research organizations, we would like to highlight several limitations that could be addressed in future research. Our case study focused on a single Australian organization, limiting the generalizability of our results and suggesting that our findings may be most applicable to organizations within similar contexts, such as Europe and North America. The principles may not translate to interdisciplinary organization in the Global South that operate in very different institutional contexts. Exploration of the applicability of these principles in other contexts represents an important area for future research. Indeed, the inclusion of more cases and authors from the Global South research has been identified an important frontier for marine interdisciplinary research (Blythe et al., 2020). Future work is also needed to more comprehensively understand each principle, and the institutional reforms needed for achieving them.

Irrespective, the five principles presented here represent a contribution to the important task of building interdisciplinary research organizations capable of tackling our most pressing challenges. In particular, our findings contribute to the growing body of literature on the institutional capacities that support interdisciplinary research organizations that engage in effective marine social-ecological systems research. We hope our findings might inform what Crow and Dabars (2017, p. 476) refer to as "institutional reconfiguration to promote interdisciplinarity." However, in proposing common principles we do not wish to deny the complexity, diversity, and internal differences of interdisciplinary research organizations. Nor do we imply that these principles should serve as prescriptions of a set of design strategies applicable in all contexts. Rather, we aim to call attention to the need for further research on institutional enablers of interdisciplinary research. Thus, we present these lessons from the Centre for Marine Socioecology in Australia as a starting point for further exploration and research into how to optimize the design and implementation of interdisciplinary research centres. Future engagement with these five principles, including exploration of how they translate across contexts, scales, and geographies, will be critical for building the interdisciplinary research capacity required to tackle our most pressing scientific and societal questions.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

This study has been approved by the CSIRO's Social Science Human Research Ethics Committee in accordance with the National Statement on Ethical Conduct in Human Research (2007). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JB and CC designed the research, collected and analyzed the data, and wrote the manuscript. Both authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Arctic Marine Data Collection Using Oceanic Gliders: Providing Ecological Context to Cetacean Vocalizations

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To achieve effective management and understanding of risks associated with increasing anthropogenic pressures in the ocean, it is essential to successfully and efficiently collect data with high spatio–temporal resolution and coverage. Autonomous Underwater Vehicles (AUVs) are an example of technological advances with potential to provide improved information on ocean processes. We demonstrate the capabilities of a low-power AUV buoyancy glider for performing long endurance biological and environmental data acquisition in Northern Norway. We deployed a passive acoustic sensor system onboard a Seaglider™ to investigate presence and distribution of cetaceans while concurrently using additional onboard sensors for recording environmental features (temperature, salinity, pressure, dissolved oxygen, and chlorophyll *a*). The hydrophone recorded over 108.6 h of acoustic data during the spring months of March and April across the continental shelf break and detected both baleen and odontocete species. We observed a change in cetacean detections throughout the survey period, with humpback whale calls dominating the soundscape in the first weeks of deployment, coinciding with the migration toward their breeding grounds. From mid-April, sperm whales and delphinids were the predominant species, which coincided with increasing chlorophyll *a* fluorescence values associated with the spring phytoplankton blooms. Finally, we report daily variations in background noise associated with fishing activities and traffic in the nearby East Atlantic shipping route. Our results show that gliders provide excellent platforms for collecting information about ecosystems with minimal disturbance to animals, allowing systematic observations of our ocean biodiversity and ecosystem dynamics in response to natural variations and industrial activities.

Keywords: underwater vehicles, glider, marine mammals, passive acoustics, ecology, seasonality

INTRODUCTION

In future decades, the highly productive Norwegian Sea is expected to experience an increase in anthropogenic activity (Gjøseter et al., 2010; Olafsen et al., 2012), accompanied by increased water temperature (ICES, 2010a,b), a shift in timing of the phytoplankton bloom (Rey, 2004), a decrease in the general zooplankton biomass (Huse et al., 2012), and changes in some of the most important commercial pelagic fish species' stock density and biomass distribution (Skjoldal, 2004; ICES, 2010b, 2011; Utne et al., 2012). As concerns for the effects of sea exploitation and climate change continue to increase, the potentially conflicting stressors require integrated management (Suberg et al., 2014). Species distribution and behavior provide indicators of ecosystem health, revealing patterns of change in biological communities, associated with alterations in physical conditions and processes. Changes in the quality, phenology, and abundance of key prey species may constrain efficient transfer of marine primary and secondary production to higher trophic levels, such as cetaceans, which will result in cascading implications for entire food webs (Lauria et al., 2012; Sydeman et al., 2013; Silber et al., 2017).

Several cetacean species occur along the coast of Northern Norway, including resident and seasonally migrating species. North Atlantic humpback whales (*Megaptera novaeangliae*) have been reportedly present from late October to early February in northern Norway, coinciding with overwintering Norwegian Spring Spawning (NSS) herring (Jourdain and Vongraven, 2017). Male sperm whales (*Physeter macrocephalus*), which inhabit continental slope areas from northern Norway to Svalbard (Øien, 2009) year around, can act as an indicator species for significant alterations in the inaccessible deep-sea environment (Steiner et al., 2012). Sperm whales are more predominantly present in deep-water canyons north of 65° N during the summer months. However, only few surveys performed in the summer have reported sperm whales south of the Arctic Circle. Smaller cetaceans also occur frequently along the Norwegian coast, including orcas (*Orcinus orca*), long-finned pilot whales (*Globicephala melas*), minke whales (*Balaenoptera acutorostrata*), white-beaked dolphins (*Lagenorhynchus albirostris*), and harbor porpoises (*Phocoena phocoena*). The distribution of these species appears to be linked to prey distribution along the Norwegian coast, though there is little knowledge on other drivers for their seasonal presence and regional migrations (e.g., NAMMCO, 2019). Fin whales have also been recorded in the vicinity of the survey area (Øygard, 2018), perhaps representing a small subset of the population that remains outside the coast of Norway during winter and spring (Haug, 1998). However, it is believed that the whales mostly visit this region during migrations to and from feeding areas.

In marine mammal research, the deployment of Passive Acoustic Monitoring (PAM) sensors has been highlighted as one useful approach to overcoming the limitations of visual observations (Cauchy et al., 2020). Marine mammals, and particularly cetaceans, are challenging to survey, as they spend a large portion of their time vocalizing under water. Thus, sensors capable of recording such vocalizations to document animal presence and behavior provide additional information that could not be otherwise obtained from the surface. Also, PAM systems can be deployed for extended periods and operate continuously irrespective of weather and light conditions, which can severely limit visual observations. Passive Acoustic Monitoring tools also provide measures of background sounds of biotic and abiotic origins.

Ocean gliders are autonomous underwater vehicles (AUVs) developed for the purpose of marine surveillance. They provide high resolution (sensor dependent) hydrographic profiles and perform long duration missions, unaffected by extreme weather events (Rudnick, 2016; Cauchy et al., 2018). The potential for glider deployments with PAM systems allows for data collection through varying water masses and for long periods of time. More recently, such sensors have been integrated onto gliders that can measure presence, abundance, and distribution, of higher trophic level organisms, e.g., fish and cetaceans (Baumgartner and Fratantoni, 2008; Ferguson et al., 2010; Klinck et al., 2012; Meyer-Gutbrod et al., 2012; Baumgartner et al., 2013; Marques et al., 2013; Send et al., 2013; Suberg et al., 2014; Cauchy et al., 2020). However, only a few studies have focused on deployments with simultaneous measurements of physical and biological components using gliders (e.g., Suberg et al., 2014; Benoit-Bird et al., 2018), particularly in terms of monitoring higher trophic organisms such as cetaceans. The purpose of this work is to show the capabilities of gliders in oceanic deployments and investigate cetacean ecology and background noise, while concurrently recording seawater characteristics and lower trophic-level features. By shedding light on a new aspect of glider surveys in integrating biotic and abiotic features, we provide an additional perspective to cetacean occurrence patterns in northern Norway.

MATERIALS AND METHODS

We describe the timing of whale vocalizations collected by a Seaglider^{TM} (Hydroid Inc.) AUV as it transitions through coastal shelf and shelf edge, and explore the ecological and physical context within which these vocalizations occur. This type of glider operates by moving through the water column in a saw-tooth motion induced by changes in buoyancy. The glider scanned the marine environment by diving up and down the water column, concurrently collecting data through its onboard sensors (see section "Seaglider Survey"). It is equipped with a suite of sensors that collect data while the glider is submerged and transmits these data during each surfacing period. The glider was equipped with multiple sensors, sampling at specific time resolutions (see section "Seaglider survey").

Survey Area

The Seaglider^{TM} operated in Northern Norway, between 68°N and 69°N (**Figure 1**) in the southern end of the Lofoten-Vesterålen (LoVe) region. This area is rich in fisheries resources and is a target for oil and gas exploration. The LoVe archipelago

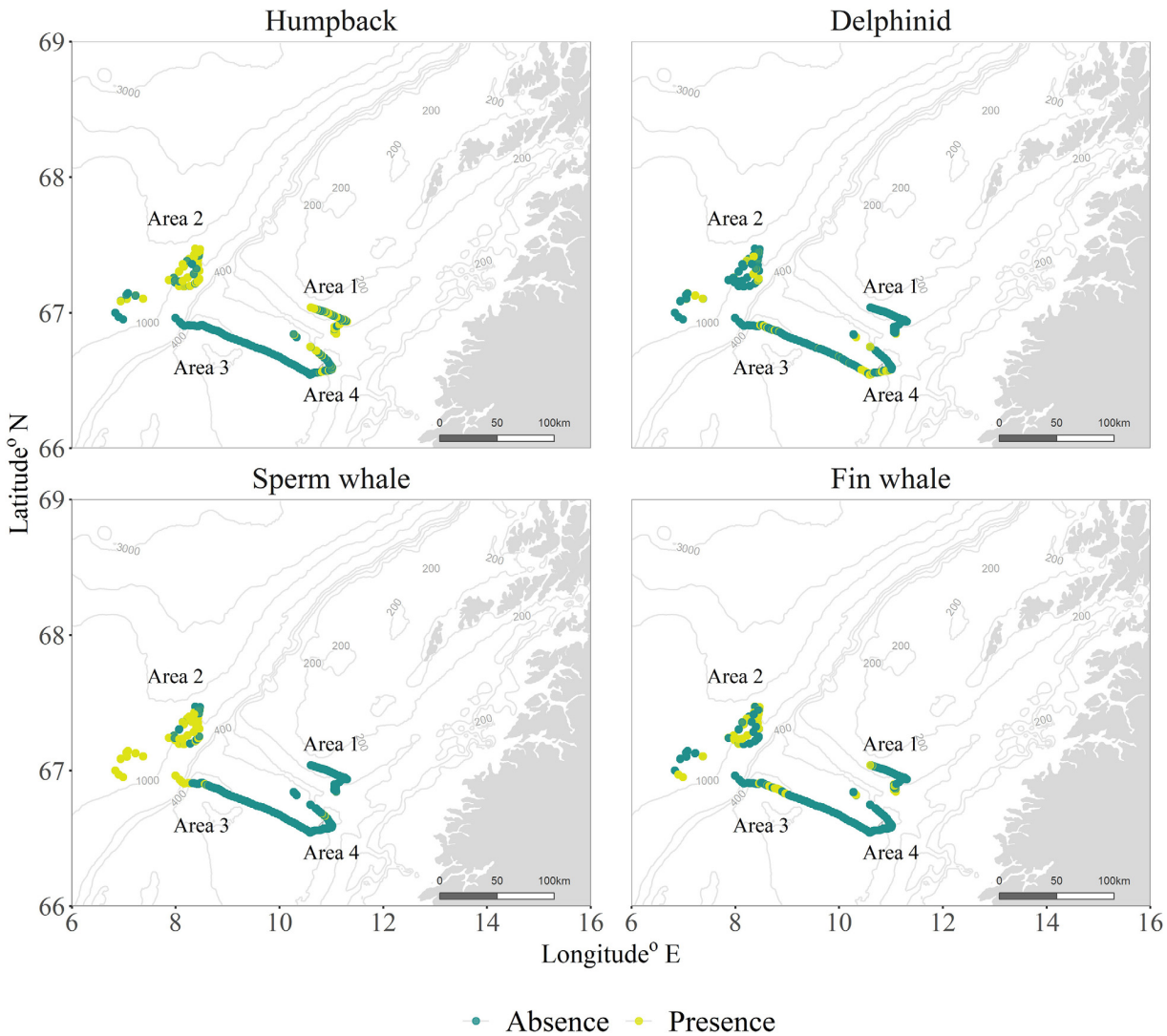

FIGURE 1 | Marine mammal detections (described as presence/absence) per area surveyed.

also has an important fishing and whale-watching tourism industry. The area therefore experiences intense maritime traffic as well as periodically occurring seismic explosions, which may affect local ecosystems.

Seaglider Survey

The Seaglider™ was deployed on March 15 and was recovered on May 1, 2018. A pre-programmed survey track was designed to cover both the continental shelf and the shelf break. The glider was equipped with a JASCO AMAR G4 hydrophone (JASCO Applied Sciences Ltd.) to detect and record cetacean vocalizations and other underwater noise, operating continuously during periods of 10 min during descent to 200 m depth. This was done in order to avoid the pump motor noise on ascent and preserve battery power. The hydrophone recording unit had a sampling frequency of 128 kHz and was mounted in the glider's aft wet space close to the buoyancy bladder, with the hydrophone on top of the glider just in front of the rudder. When at the surface, the glider would report its position through Iridium satellite and relay systems operation data and sensor data. Glider position data are used to allocate individual hydrophone data files correctly to time, depth and geographic position. The glider was also equipped with a CTD (SeaBird GPCTD), along with oxygen (Contros Hydroflash Optode) and fluorometer (SeaBird SeaOWL UVA) sensors, to measure physical properties of the water column and chlorophyll *a*, respectively, for every minute of operation. Dive duration was dependent on the location surveyed, with shorter dives in shallow waters and longer in deeper waters. On-shelf and shelf break sampling were occasionally interrupted to ensure sufficient battery longevity to cover the entire survey period. All acoustic data were stored internally as WAV files and recovered at the end of the deployment period.

Analyses

Passive Acoustic Monitoring data files were processed for marine mammal presence and species identification, using RavenPro 1.5 (Cornell Lab of Ornithology, Ithaca, NY, United States), relying on a Hamming window, 4096 DFT size, 7.81 Hz grid spacing, with 60% overlap for humpback whales; Hamming window, 2048 DFT size, 125 Hz grid spacing, with 70% overlap for delphinids and sperm whales; and Hann window, 2048 DFT size, 0.98 Hz grid spacing, with 67% overlap for fin whales. Based on calibration data provided by Kongsberg Maritime (calibration performed by GTI prior to deployment), a system sensitivity correction factor for the frequency band of interest was estimated to −165.1 dB. The hydrophone sensitivity was found to vary less than 1 dB below 10 kHz (+0.6 to −0.2 dB). We created a time series for species presence/absence throughout the sampling period (March 15 to April 26) and area, thus investigating migratory patterns timing and detection location. Additionally, we describe variations in water temperature, salinity, and chlorophyll *a* levels along the entire depth coverage of the Seaglider™ track. We categorized whale detections into different classes for different species (see **Table 1**) and removed all missing values from the dataset. We then applied a generalized mixed model, using R package glmmTMB (Brooks et al., 2017), to explore possible effects of glider depth, time of day and time of year, and survey section (see **Figure 1**) on our observations of whale occurrence. Given that above the Arctic Circle at this time of the year, the maximum sun angle at noon increases rapidly each day, we account for this relationship between date and sun elevation by including both daily maximum sun elevation and the period of the day when the recordings took place (day, night, dawn, dusk). We thus tested the effect of glider depth, maximum sun elevation and time of day (fixed effects) against humpback and fin whale occurrence. We limited this analysis to humpback and fin whales due to their distinctively seasonal migratory pattern and likely long vocalization range. Odontocetes, on the other hand, may be more prone to the influence of prey distribution and most likely have a less distinct migratory pattern at this time of year, so we used survey area rather than maximum sun elevation in their respective models. By separating survey period and location we also account for collinearity between the two variables (space and time).

The relationship between species' occurrences and depth was found to be occasionally curvilinear, and we therefore included glider depth in the model with a quadratic term for humpback and sperm whales (hence, linear term for the remaining species). Additionally, to correct for the possible influence of the thermocline on sound propagation at different depths, we included the glider location in relation to the depth of the thermocline for each glider dive (above, crossing, below) as a random effect in each model. The thermocline was calculated by first identifying a dive using the R package diveMove (Luque, 2007), and then using the *clined* function of the castr package (Irisson, 2020) to estimate the respective depth value for each dive. We dealt with temporal autocorrelation resulting from the transitory nature of glider surveys by implementing an autoregressive correlation error structure (AR 1) into each model. The autocorrelation in the models was designated by the dive id and date (day of the year, grouping parameter) to account for variability within dives occurring within the same day.

Seagliders are acoustically quiet platforms, however there are periods of intermittent platform noise due to the altimeter, buoyancy pump, and pitch/roll regulation, which needs to be identified and removed prior to analysis. All analyses were performed in Matlab (MATLAB™ version 2019b, Mathworks, Inc.). Spectrogram correlation was used to identify different types of self-noise throughout the data set and remove them from original wave files. In addition, the first minutes of each dive was removed, where the Seaglider™ was at the surface prior to descent. A new data set was created without Seaglider™ self-noise and concatenated to files of minimum 60 s duration. The new data set was manually scrutinized to ensure that all significant self-noise events were removed. The data set was resampled to 32 kHz and noise was analysed from 10 Hz to 10 kHz. The hydrophone is not expected to have a flat response below 20 Hz, and significant hydrodynamic noise is likely present in the dataset below 20 Hz. Acoustic power spectral density (PSD) was calculated using a 1-second Hann window, no padding or overlap, and spectral levels and corresponding probability distribution from 10 Hz to 10 kHz were calculated.

We investigated the potential interference of background noise on the species groups detected by incorporating band Sound Pressure Level (SPL) values into a separate model in order to avoid overparameterization of the original model for each species. The bands used reflected noise derived from ship traffic, turbulence, and other biological activity, occurring within the frequency range of vocalizations for the species groups in this study (50–1500 Hz, 1500–10,000 Hz, and 50–10,000 Hz for baleen whales, sperm whales, delphinids, respectively). Removal of periods of substantial glider self-noise meant that SPL levels could not be calculated for some sound files, which therefore had to be removed from statistical analyses. Though fin whales vocalize below 50 Hz (e.g., 20-Hz call) where there is also often ocean traffic noise, we set this as the lower limit for pressure level calculations due to the likely effects of flow noise and unknown hydrophone response at lower frequencies. The model was thus specified with whale occurrence as a function of the SPL band levels with the same covariance structure as above, though without the random effects for thermocline.

All statistical analyses were conducted using R software (version 4.0.1). Model selection was based on Akaike Information Criterion (AIC), and using the *dredge* function of the MuMIn package for R (Bartoń, 2019).

TABLE 1 | Number of files with species presence/absence (Presence: 1, Absence: 0) recorded between March 15 and April 26, 2018 per area surveyed on the shelf (Areas 1, 3, and 4) and shelf edge (Area 2).

	Area 1		Area 2		Area 3		Area 4	
Presence/Absence	***1***	**0**	**1**	**0**	**1**	**0**	**1**	**0**
Delphinids	9	150	32	180	46	205	51	74
Fin whales	34	125	87	125	41	210	5	120
Humpback whales	126	33	146	66	0	251	52	73
Sperm whales	1	158	164	48	35	216	7	118
Total	466	170	419	429	882	122	385	115

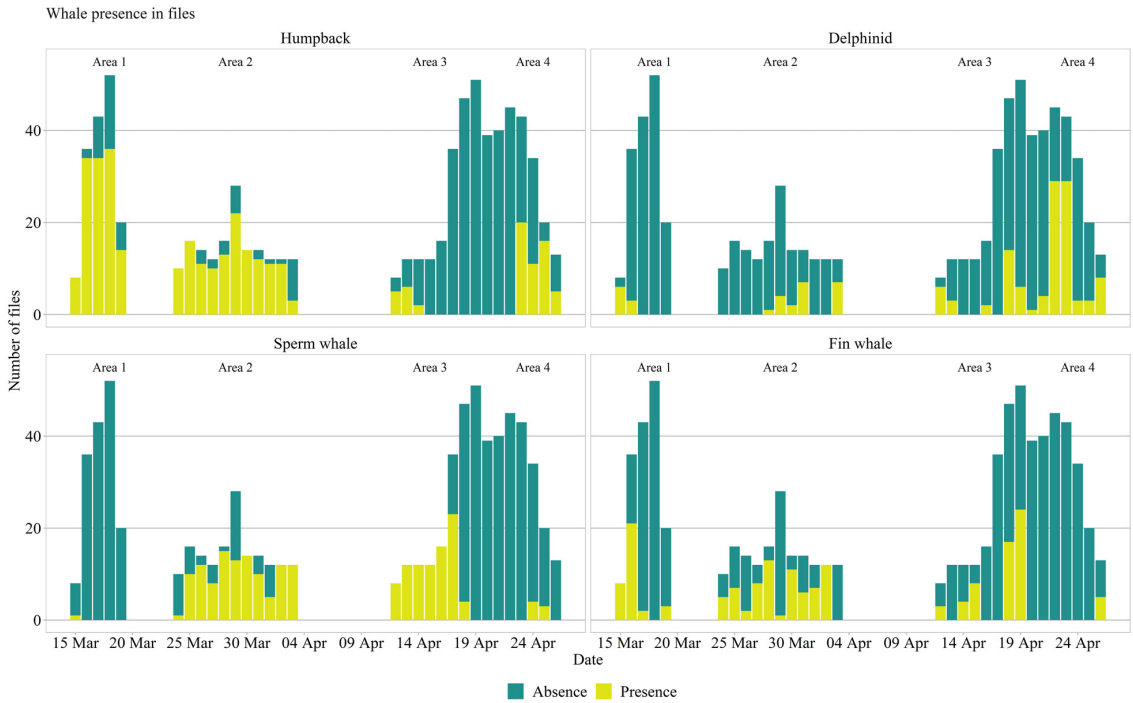

FIGURE 2 | Whale presence and absence detected in acoustic files per area.

RESULTS

Over the course of the two months of deployment, the glider performed a total of 284 dives (each dive comprising of one up and downcast), covering a total of 800 km (horizontal distance derived from GPS fixes). This resulted in over 108.6 h of hydrophone data, and 58496 fluorescence, CTD, and oxygen measurements. A total of 529 acoustic files contained whale vocalizations. We placed the detections in a time context to assess possible whale migration in the region and possible habitat selection, while estimating background noise levels for the same time period (**Figure 2**).

PAM Detections

The number of files with different species at the different survey areas is described in **Table 1**. We observed humpback whale detections throughout the entire spring, until late April both on the shelf and shelf edge. Sperm whales, on the other hand, were mostly detected at the opening and within a 400 m underwater canyon (**Figure 1**, bottom left, Area 2), coinciding with their preferred foraging habitat. The presence of delphinids was more sporadic, though with a more pronounced occurrence on shelf during the last week of survey. Fin whales were also present in the recordings, with a considerable presence in late March, early April, which gradually decreased as the glider moved from the shelf edge, toward the end of the sampling period.

Results from the best fit model showed that daily maximum sun elevation has a negative effect on the probability of occurrence of humpback and fin whales, indicating that the whales were more likely to be detected at the beginning of the survey. Humpback whales were the only species for which glider depth was found to have a considerable effect, suggesting that this species was more likely to be detected at shallower depths. No species were found to be affected by period of the day. See **Tables 2**, **3** for model output summary (further detail for model output including random effects in **Supplementary Tables 1**, **2**).

For the various survey areas, we found that sperm whales are more likely to be found at the shelf edge. The same was not evident for delphinids, However, there was a considerable positive effect of the last survey section (area 4). See **Tables 4**, **5** for

TABLE 2 | Model output for humpback whales.

Conditional fixed effects				
	Humpback whale absence/presence			
Predictors	**Odds Ratios**	**std. Error**	**Conf. Int (95%)**	***P*-value**
Depth^2	1.00	0.00	1.00–1.00	**0.019**
Max Sun elevation	0.61	0.13	0.47–0.79	**<0.001**
Day	4.56	1.45	0.27–78.41	0.296
Dusk	1.17	2.08	0.02–69.55	0.940
Night	1.34	1.46	0.08–23.29	0.841
$N_{where.thermocline}$	3			
$N_{jul.Day}$	28			
Observations	709			
Marginal R^2/ Conditional R^2	0.799/0.849			
AIC	454.139			

Bolded values indicate probability values below the statistical significance threshold of 0.05.

TABLE 3 | Model output for fin whales.

Conditional fixed effects				
	Fin whale absence/presence			
Predictors	**Odds Ratios**	**std. Error**	**Conf. Int (95%)**	***P*-value**
Depth	1.00	0.00	0.99–1.00	0.092
Max Sun elevation	0.72	0.11	0.58–0.88	**0.002**
Day	0.11	1.26	0.01–1.32	0.082
Dusk	1.83	1.93	0.04–81.15	0.755
Night	0.91	1.20	0.09–9.54	0.936
$N_{where.thermocline}$	3			
$N_{jul.Day}$	28			
Observations	709			
Marginal R^2/ Conditional R^2	0.757/NA			
AIC	389.254			

Bolded values indicate probability values below the statistical significance threshold of 0.05.

TABLE 4 | Model output for sperm whales.

Conditional fixed effects				
	Sperm whale absence/presence			
Predictors	**Odds Ratios**	**std. Error**	**Conf. Int (95%)**	***P*-value**
Depth^2	1.00	0.00	1.00–1.00	0.080
Area 1	0.00	4.08	0.00–0.00	**<0.001**
Area 3	0.00	3.48	0.00–0.00	**<0.001**
Area 4	0.00	3.98	0.00–0.00	**<0.001**
Day	2.31	2.03	0.04–124.61	0.680
Dusk	0.14	3.12	0.00–63.79	0.531
Night	10.20	2.13	0.16–668.34	0.277
$N_{where.thermocline}$	3			
$N_{jul.Day}$	31			
Observations	747			
Marginal R^2/ Conditional R^2	0.948/NA			
AIC	267.014			

Bolded values indicate probability values below the statistical significance threshold of 0.05.

model output summary (details for model estimates with random effects in **Supplementary Tables 3**, **4**).

Background Noise

Spectral levels from 10 Hz to 10 kHz over the duration of the glider mission is shown in **Figure 3** (top) along with the corresponding spectral probability distribution (**Figure 3** (bottom), SPD, Merchant et al., 2013). The spectrogram shows long periods of wideband noise associated with wind and rain (**Figure 3a**), turbulent flow noise (**Figure 3c**), and acoustic emissions from nearby vessels (**Figure 3d**) occurring as wideband noise and discrete harmonic banding. Periods of signals from seismic sources, and marine mammals with the exception of fin whales (**Figure 3b**), are not clearly seen in the figure.

TABLE 5 | Model output for delphinids.

Conditional fixed effects				
	Delphinid absence/presence			
Predictors	**Odds Ratios**	**std. Error**	**Conf. Int (95%)**	***P*-value**
Depth	1.00	0.00	0.99–1.00	0.121
Area 1	0.21	1.65	0.01–5.19	0.337
Area 3	1.57	1.51	0.08–30.03	0.765
Area 4	73.64	2.12	1.14–4741.01	**0.043**
Day	4.31	2.37	0.04–450.34	0.538
Dusk	51.35	2.78	0.22–11894.93	0.156
Night	7.34	2.40	0.07–803.25	0.405
$N_{where.thermocline}$	3			
$N_{jul.Day}$	31			
Observations	747			
Marginal R^2/ Conditional R^2	0.527/NA			
AIC	443.971			

Bolded values indicate probability values below the statistical significance threshold of 0.05.

The analysis of underwater noise effects on our detections of marine mammals revealed that detections of sperm whales and delphinids are affected by noise levels in the 1500–10,000 Hz band ($P = 0.016$, $P < 0.001$, respectively. See **Supplementary Tables 5**, **6**). For humpback and fin whales however, the model output showed no effect, which is likely due to the strong effect whale vocalizations have in the noise band between 50 to 1500 Hz (Humpback whales: $P = 0.22$; Fin whales: $P = 0.740$) and 1500–10,000 Hz (Humpback whales: $P = 0.64$; Fin whales: $P = 0.359$). See **Supplementary Tables 7**, **8** for further details on model output.

Physical Environment

The Seaglider™ predominantly sampled thermally stratified waters during its mission. In CTD measurements, a strong thermocline at 20–40 m depth was recorded (**Figure 4**). This was particularly evident in mid-March, when the Seaglider™ remained on the continental shelf. The deeper and longer dives performed off the continental shelf from the end of March did not allow for a clear distinction of water layers above 250 m during this period. However, we did observe changes in the salinity content at the end of the deployment (**Figure 4**), with lower concentrations at the continental shelf within a small 400-m deep underwater canyon. Levels of chlorophyll *a* fluorescence were more pronounced during April (**Figure 4**), nearly a month after the equinox (March 20, 2018), which is usually taken as the beginning of the primary production period in more southern latitudes.

DISCUSSION AND CONCLUSION

Ocean gliders are efficient and quiet platforms for measuring changes in the marine environment through PAM of marine mammals, with the additional capability of profiling the water column and providing sound speed profiles valuable

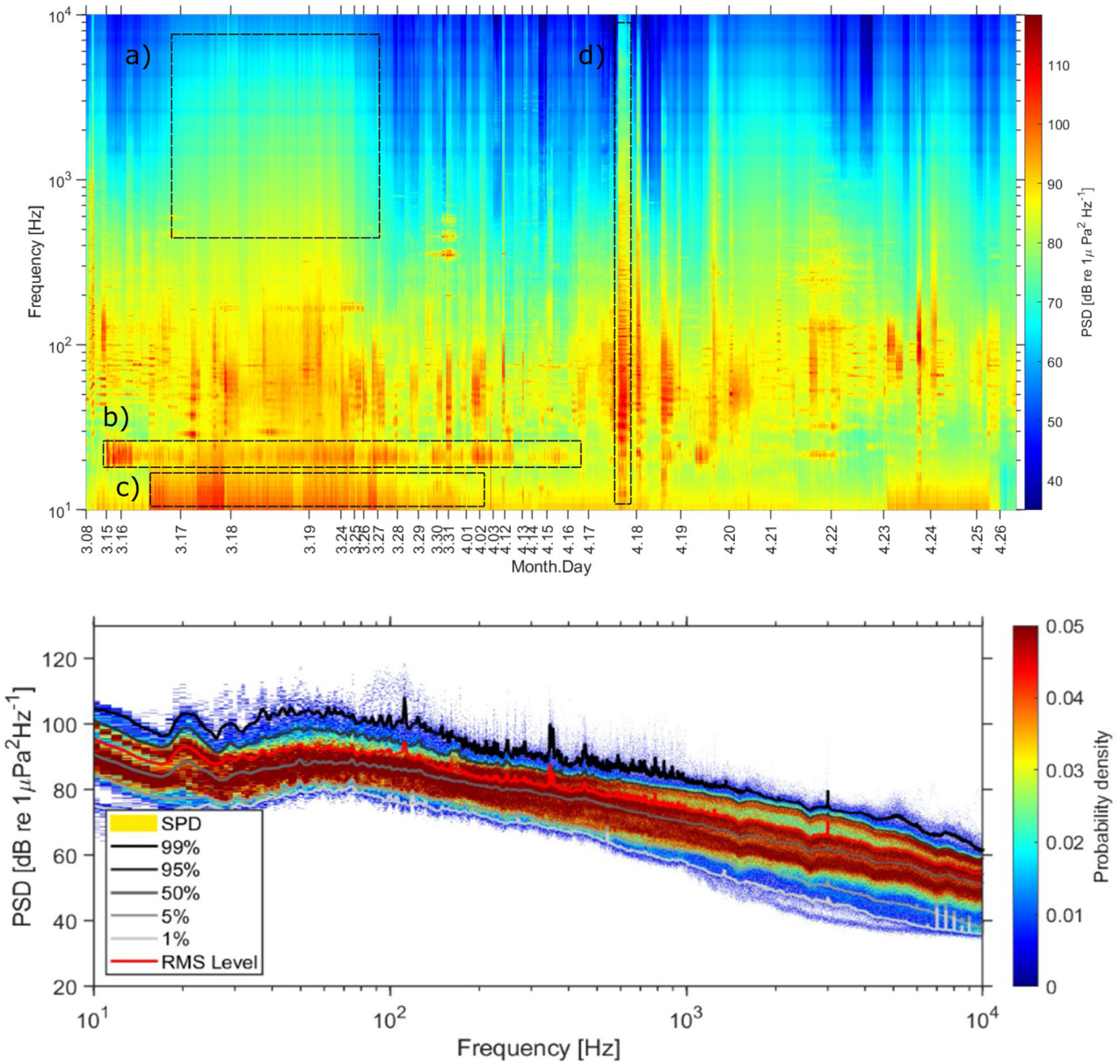

FIGURE 3 | Glider spectrogram (PSD, 1s Hann window, 60 s average) **(top)** and spectral probability distributions (SPD) of acoustic energy **(bottom)**. The different boxes indicate examples of the different sound sources; **(a)** wind and rain, **(b)** fin whale, **(c)** turbulent flow noise, **(d)** vessel in close proximity.

for underwater sound propagation modeling. The use of technological advances equipped with multiple sensors provides a unique view of the marine environment, and allows for improved understanding of marine animal ecology.

Temporal Variation of PAM Detections

In this study, we recorded humpback whales on the shelf and shelf edge, indicating that they tend to remain close to the shelf slope on their way to the breeding grounds. Though our analyses show that this species was more likely to be encountered on the continental shelf, prior to reaching the slope, these whales were detected until late April. This indicates that humpback whales remain in Norwegian waters longer than previously assumed (Broms et al., 2015; Ryan et al., 2015), likely foraging on herring. The assumption that the Norwegian Sea is a migratory corridor for this species (Jourdain and Vongraven, 2017) is therefore not valid, as such late departure from foraging grounds ultimately indicates either a delay in arrival at breeding grounds or that these animals may remain in foraging areas for periods when higher energetic reserves are required. Though our study represents a few months of a single year of whale acoustic behavior, sporadic observations reported on social media channels validate this finding (e.g., Bergersen et al., n.d.) across multiple years.

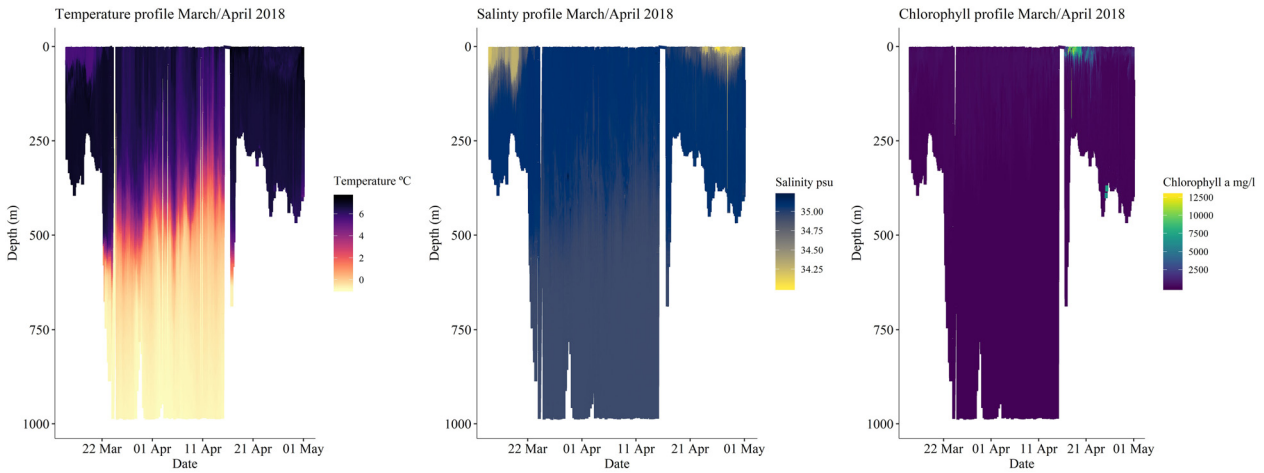

FIGURE 4 | Environmental conditions throughout Seaglider™ dives.

The recordings of sperm whale click at the opening of a small canyon and shelf edge represents foraging activity outside known locations above the Arctic Circle. Sperm whales in Norway appear to remain in foraging hotspots from May to September, though may also be present at those same areas during the winter (Rødland and Bjørge, 2015). The social structure of sperm whales is, however, poorly understood in the region and it is likely that bachelor groups disperse to other less-productive areas to avoid competition by larger males, or the survey region is a pit-stop on their way to better grounds.

Though we describe the surrounding environment through CTD and fluorometer data, we were unable at this stage to estimate detection ranges to the whales from the glider and assess spatial overlap. This was due to the fact that such estimates would require either triangulation for animals' geographical position or assumptions in species' source levels and calculations of sound propagation, which were beyond the scope of this work. Nevertheless, our analyses reveal variations in marine mammal detections throughout the sampling season, which may reflect changes in behavior and detectability. Levels of chlorophyll *a* fluorescence was more pronounced during April (**Figure 4**) and coincided with a higher rate of detections of delphinids and sperm whales though the opposite was observed for humpback and fin whales. Increases in daily sun elevation had a negative significant effect on the probability of obtaining either a humpback of fin whale presence, indicating that at the time of our survey, these species were likely migrating away from the survey region.

Spatial Variation of PAM Detections

The different sections of survey locations (survey area) were chosen based on the performed task of the glider (in transect or not) and on the actual location in relation to the coast to reflect different bathymetric features. Sperm whales and delphinids were found to be associated to different areas; Sperm whales were more likely to be close to the shelf edge, while delphinids were mainly associated with regions closer to the coast. Glider depth, i.e., recording depth, was only found to be significant for humpback whales, which may indicate a higher rate of surface vocalizations even though we corrected the effect of thermocline depth in our model as a random effect. There was no statistical evidence to suggest time of day (day, night, dawn and dusk) had any effect on the detection of any species. This contradicts previous studies on fin whale vocal activity (e.g., Víkingsson, 1997; Simon et al., 2010). We believe that this is mainly a result of different model structure, as we accounted for variability in both random effects and therefore temporal autocorrelation structure (by including glider dive and Julian day as random effects), which is necessary and relevant when investigating animal presence with temporal relationships.

The combined effect of spatio-temporal changes occurring as the glider progresses along the track can raise several questions as to the relevance of some of the variations observed in whale detections. This study shows a nearly two-month snapshot of whale detections in different areas, though the sampled areas were not revisited. Though some of the species identified are notoriously known for their migratory behavior, for which the space-time issue may be considerable, others (sperm whales and delphinids) seem to confirm known habitat preferences (Whitehead, 2018; Jourdain et al., 2019; NAMMCO, 2019). However, future glider endeavors are advised to sample the same study regions multiple times to allow clarity in measured variations across different habitats.

Background Noise

The noise spectrum is dominated by noise due to weather and near and distant vessels, with periods of seismic surveying also observed. Storms are common in this area during spring, and apparent in the dataset as broadband wind generated noise persisting for days. It has been shown that in shallow regions on-shelf Northern Norway the noise levels due to wind at lower frequencies (<400 Hz) are higher than expected from traditional Wenz curves (Ødegaard et al., 2019). The Seaglider™ operated in the area around the continental shelf break with the

major north-south shipping lane for large commercial vessels, which is apparent in the data set as broadband and tonal noise. The Seaglider^{TM} performed well for underwater noise measurements, however, self-noise (buoyancy pump, pitch/roll adjustment, altimeter) needs to be removed from the data set prior to analysis. In shallow water areas, and areas with high and variable current, such as on the continental shelf, the rate of self-noise is higher than off-shelf as the vehicle needs to use the buoyancy pump, altimeter and perform pitch/roll compensation more frequently. In addition, turbulent flow around the hydrophone results in flow noise proportional to the speed of the glider, particularly visible bellow 20 Hz, but likely present in the 5–50 Hz frequency band (dos Santos et al., 2016; Cauchy et al., 2018). This noise increases significantly above approximately 30 cm/s absolute velocity, indicating that for (a) reliable noise measurements at low frequencies (<50 Hz) and (b) high signal-to-noise ratio (SNR) for marine mammal detection at low frequencies, the glider should be operated with a low glide velocity when possible. The analysis of underwater noise revealed that detections of sperm whales and delphinids are affected by noise levels in the 1500–10,000 Hz band. Such results can originate from multiple factors, such as masking (i.e., the noise levels overlap with the whales' calls and these are no longer available for detection), animal behavior, and/or the spatio-temporal distribution of the glider in relation to these species. Naturally, such effects would require more detailed and controlled studies, dedicated to estimating the effects of background noise on marine mammal species.

Though marine mammals are often challenging to survey, this study shows that the use of autonomous PAM systems provides new insights on animal distribution that would otherwise be difficult to obtain in the Norwegian Sea. Though the pump and pitch/roll adjustment created noise during certain operations, the gliders were mainly silent throughout the entire survey. This allowed for very clear detections of marine mammal vocalizations. Detailed analysis of the background noise and potential consequences for marine mammal detection showed that odontocetes seem to be negatively affected by increasing noise levels in the 1500–10,000 Hz frequency band. However, it is worth noting that the same animal groups vocalize within this range and the results could also reveal effects of co-occurrence rather than background noise. Due to the fact that it was not possible at this stage to discard all animal vocalizations from the analyses, we only included in the analyses bands that represented a wide range of frequencies so that the assessment of potential effect would be more likely due to background noise rather than whale vocalizations.

Gliders are robust in poor sea conditions and their low power requirements allow them to remain at sea for several months. The use of oceanic autonomous platforms to investigate changes in both time and space represents therefore a great technological advance that can improve ecosystem-based management and conservation decisions. Advances in glider-based technology and its applications ultimately lead to improved long-term ecological monitoring over finer spatial scales and longer temporal scales. By conducting reproducible and multidisciplinary (combining physics, ecology, and engineering) sampling, glider-based studies provide systematic observations that can address questions concerning whale behavior and ecology, which are of high importance given the current pressures to natural marine environments.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available upon request to the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because the subjects were not under a protocol of experimentation. The purpose of this study was to survey animals in their natural habitat, with minimal disturbance to their natural behavior.

AUTHOR CONTRIBUTIONS

AA, GP, and LC conceptualized and designed this study with input of RP, UL, and MB. LC procured funding and conducted the field experiment with the support of GP. This study took place within the frame of the projects "Spatial and temporal analyses of marine mammal vocalizations using unmanned systems" led by ASA and the GLIDER project led by LC. AA performed the statistical analysis of the data, while GP performed analysis on background noise. UL provided estimates of sun elevation. ASA and GP led the writing of the manuscript with input of RP, MB, UL, and LC. All authors approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.585754/full#supplementary-material

Supplementary Table 1 | Conditional glmmTMB model random effects (html with results per dive) Humpback whales.

Supplementary Table 2 | Conditional glmmTMB model random effects (html with results per dive) Fin whales.

Supplementary Table 3 | Conditional glmmTMB model random effects (html with results per dive) Sperm whales.

Supplementary Table 4 | Conditional glmmTMB model random effects (html with results per dive) Delphinids.

Supplementary Table 5 | SPL glmmTMB model Humpback Whales.

Supplementary Table 6 | SPL glmmTMB model Fin whales.

Supplementary Table 7 | SPL glmmTMB model Sperm whales.

Supplementary Table 8 | SPL glmmTMB model Delphinids.

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Indicators of Coastal Wetlands Restoration Success: A Systematic Review

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Coastal wetlands restoration is an emerging field which aims to recover the ecological characteristics of degraded ecosystems to natural ones. The recent UN declaration of 2021–2030 as the "Decade on Ecosystem Restoration" will hopefully encourage global implementation of these projects. However, a lack of common indicators of restoration success hinders our knowledge on the ecological outcomes of restoration projects. We conducted a literature review to determine trends in monitoring indicators. We classified indicators following the Society for Ecological Restoration template, adapting it to coastal wetlands. We found that indicators on structural diversity (e.g., tree height, fish size) were the mostly commonly used. Indicators on ecosystem function were the second most investigated, with half of the assessed studies including them, especially those focusing on carbon, nutrient and sediment dynamics. We propose a recovery wheel framework adapted to coastal wetlands. Structural diversity indicators are generally easier to measure and often the traits that recover the fastest. However, ecosystem function indicators could be more important to assess the recovery of ecosystem services, which is a primary objective of restoration. Restoration objectives and goals are variable for each project, and we encourage future restoration projects on coastal wetlands to select the most appropriate indicators on the basis of the recovery wheel proposed in this study to plan a monitoring framework. Future studies assessing coastal wetlands restoration ecological outcomes should include ecosystem function indicators and monitor the sites over periods adequate to their recovery.

Keywords: coastal wetlands, restoration, indicator, monitoring, ecosystem functions

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INTRODUCTION

Coastal Wetland Restoration

Coastal wetlands, such as mangrove forests, saltmarshes, and seagrass meadows, are among the most valuable ecosystems in the world. They provide coastal populations with a wide range of ecosystem services such as improving water quality, sustaining coastal fisheries and mitigating floods (de Groot et al., 2012). However, coastal wetlands suffer various anthropogenic threats such as urbanization, reclamation, deforestation, eutrophication, and pollution (Orth et al., 2006; Duke and Maynecke, 2007). These threats have ultimately led to the global cover loss of an estimated 25–50%

of coastal wetlands over the past 50–100 years, making them one of the most endangered ecosystems on the planet (Waycott et al., 2009; Hamilton and Casey, 2016). Mitigation and protection have been the primary efforts to reverse this trend and conserve coastal wetlands and their ecosystem services. Nevertheless, the effectiveness of solely conserving wetlands in Protected Areas or their recognition in international treaties (e.g., RAMSAR) is still debated (Pendleton et al., 2018), partly, because the current degraded conditions might prevent their natural recovery (Perrow and Davy, 2002). Restoration and rehabilitation of natural conditions could play an important strategy for facilitating coastal wetlands recovery (Zedler and Kercher, 2005).

In the past, rehabilitation of an ecosystem had the objective of replacing ecosystem structure or function that has been lost or diminished (Field, 1998), while restoration focused on the return of the ecosystem conditions as close as the "original state" as possible (Jackson, 1995). While both terms have often been used ambiguously, they contrast with approaches such as afforestation or introducing forest in an area where they did not formerly exist in the historical past (Dale et al., 2014; Gann et al., 2019). The Society of Ecological Restoration (SER) was founded in 1988 with the objectives of "advancing the science, practice, and policy of ecological restoration to sustain biodiversity, improve resilience in a changing climate, and re-establish an ecologically healthy relationship between nature and culture" (SER, 2004). According to SER "ecological restoration aims to restore the integrity of ecological systems, therefore restoring a critical range of variability in biodiversity, ecological processes and structures, regional and historical context, and sustainable cultural practices (SER, 2004)".

Over the last 20 years, restoration projects have been increasingly implemented all over the world (Swan et al., 2016; Zhang et al., 2018; Basconi et al., 2020). Restoration science is anticipated to become one of the most important fields within conservation science of the twenty-first century (Hobbs and Harris, 2001). Ecological restoration is considered to be the main strategy to enable the return of ecosystem services (Bullock et al., 2011). While this strategy has been long claimed to be time and money consuming, new methods of ecosystem services valuation suggest that the economic benefits of restoration can outweigh their costs (Barbier et al., 2011; Bullock et al., 2011; Russell and Greening, 2015). The increased attention has led 2021–2030 to be recently declared the "UN Decade on Ecosystem Restoration." [1] However, increasing investment in restoration requires evidence of the effectiveness of the restoration projects (Ntshotsho et al., 2011; Browne et al., 2018).

When evaluating marine restoration success, most published studies on coastal ecosystems use the survival rate of the individuals restored (Bayraktarov et al., 2020b). The success of restoration has been estimated to range between 38 in seagrass and 65% in saltmarsh (Bayraktarov et al., 2016). Considering that marine restoration ranges from US$80,000 to $1,600,000, the projects might not seem cost-effective (Bayraktarov et al., 2016). The chance for success in restoring coastal ecosystems remains uncertain as this discipline is still at an "innovative phase" (Waltham et al., 2020). Organism short-term survival is not the best approach to assess restoration success as it is considered as an indicator of planting method success, and therefore does not assess ecosystem recovery (Wortley et al., 2013). Often metrics are used to measure the biological response of the organism to the restoration intervention rather than to measure a recovery of ecosystem function or services (Hein et al., 2017; Lee et al., 2019). The use of relevant indicators of marine restoration success is essential to produce an accurate estimation of project outcomes (Zhao et al., 2016).

Indicators of Coastal Wetland Restoration Success

Indicators are monitoring metrics that assess ecosystem attributes and can be linked to restoration goals and objectives (SER, 2004; Waltham et al., 2020), and the overall success of the project. A restoration project can reach success if it complies with the terms of agreement (compliance success), or if the ecosystem functions are recovered (functional success) (Kentula, 2000). However, both terms are usually used ambiguously (Zedler, 2007). In the past, indicators have been grouped in three ecosystem attributes including biodiversity (e.g., species richness), vegetation structure (e.g., tree density), and ecological process (e.g., sedimentation rate) (Ruiz-Jaen and Aide, 2005). Ecological processes such as nutrient cycling, carbon dynamics or sediment elevation are important as they provide information on the resilience of ecosystems (Ruiz-Jaen and Aide, 2005). Due to the strong link between processes and services, they are also used to integrate ecosystem services into conservation plans (Egoh et al., 2007). However, ecological restoration aims to facilitate the transition from a degraded ecosystem toward a natural state (SER, 2004). There is therefore the need to provide a target for the outcomes of ecosystem recovery, using reference sites.

A reference ecosystem is a model representing the approximate restoration target (SER, 2004). It is a critical aspect of achieving restoration success as it provides a clear depiction of goals of the restoration project and a development state to evaluate against (Wortley et al., 2013). These reference sites should be environmentally and ecologically similar to the project site, with minor degradation (SER, 2004). In the absence of suitable intact ecosystems in the vicinity of the restored site, it could also be based on historic data about the ecosystem or from modeled outputs (Mcdonald et al., 2016). Functional success of restoration can be ecologically evaluated through comparisons of ecosystem functions indicators in restored with those in reference sites (Zhao et al., 2016).

Recently, the SER created international standards for ecosystem restoration, including a monitoring framework to assess ecosystem recovery (Mcdonald et al., 2016). This recovery wheel propose the assessment of six key ecosystem attributes that restoration practitioners should monitor to evaluate restoration progress and success (Mcdonald et al., 2016). One of these ecosystem attributes is ecosystem functions, described as "the workings of an ecosystem arising from interactions and

[1] Available online at: https://www.decadeonrestoration.org/

relationships between biota and abiotic elements," including ecosystem processes (e.g., primary production, decomposition, nutrient cycling, and transpiration) and properties (e.g., competition and resilience) (Mcdonald et al., 2016). In addition to biodiversity (i.e., species composition), vegetation structure (i.e., structural diversity), and ecological processes (i.e., ecosystem function), they also integrate external exchanges, absence of threat and physical conditions as key ecosystem attributes. However, the use of this recovery wheel should be site specific, and therefore the indicators used to evaluate restoration success should vary depending on the ecosystem studied (Mcdonald et al., 2016). Based on the indicators assessed from the scientific literature, we propose to adapt the wheel to coastal wetlands to improve the relevance of the assessments.

Justification and Objectives

A series of prior reviews focused on assessing outcomes of ecological restoration of terrestrial and freshwater environments (Wortley et al., 2013; Meli et al., 2014; Kollmann et al., 2016). More recently, a literature review on marine coastal ecosystem restoration has been produced with data constrained by the search terms search terms "cost," "feasibility," and or "survival" (Bayraktarov et al., 2020b) which only displays a subset of the available restoration literature. There is a lack of information regarding the monitoring metrics used within the overall scientific community to assess the success of coastal wetlands restoration. In this study, we systematically reviewed the published literature to understand which metrics were used to assess coastal wetlands restoration success, and to elucidate the relation between the restoration of coastal wetlands and the recovery of their ecosystem functions. We specifically answer the following questions: (1) Which aspect of ecosystem recovery do scientific studies investigate when monitoring the outcome of coastal wetlands restoration? (2) Which indicators are used to assess functional success of coastal wetlands restoration? (3) How do these indicators relate to the SER international standards for ecological restoration?

MATERIALS AND METHODS

A systematic quantitative literature review was performed following the method outlined by Pickering and Byrne (2014). The search was conducted through the databases ISI Web of Knowledge (Core collection; Thomson Reuters, NY, U.S.A.) and Scopus (Elsevier, Atlanta, U.S.A.). These databases were searched through title, abstract and keywords using the research string: (seagrass* OR "sea grass*" OR saltmarsh* OR "salt marsh*" OR mangrove* OR "tidal marsh*" OR "tidal wetland*") AND (restor* OR rehab*) AND (monitor* OR assess* OR evaluat* OR measure* OR success* OR metric*). This research string was build following that created by previous quantitative reviews performed on restoration and coastal wetland ecology (Wortley et al., 2013; Kollmann et al., 2016; O'Connor et al., 2019). Available literature until February 2020 was included.

Eligible papers that monitor either saltmarsh, mangrove or seagrass ecological restoration projects were included by comparing the restored ecosystems to a natural reference site. Secondary sources such as reviews were excluded from the extraction of data because these sources generally do not provide the level of detail required for this analysis (Bayraktarov et al., 2020b). Created or constructed wetlands were also excluded as we focused on studies assessing the potential to restore ecosystem attributes that were once provided by coastal wetlands before their degradation. This study focuses on site specific monitoring; therefore, we did not include regional/national assessments as they often do not include reference sites and merge both natural and artificial restored coastal wetlands. Studies in which restored sites are used for production (e.g., timber production) were not included (Wortley et al., 2013).

TABLE 1 | List of attributes and sub-attributes classification for coastal wetlands restoration assessment indicators.

Attribute category	Sub-attribute category
Structural diversity A combination of species diversity and diversity of growth forms/strata. This category would also include (if assessed) habitat diversity, spatial mosaics, presence of structural habitat features (e.g., large snags, fallen logs, mangrove roots), trophic levels and functional groups.	Vegetation structure Fauna structure Bacterial structure Algal structure Food web
Ecosystem function The processes of ecosystems, involving interactions between biotic and abiotic elements. This includes process variables as well as raw variables that can be used to provide information on ecosystem function processes such as primary productivity, nutrient cycling, carbon cycling etc.	Primary productivity Secondary productivity Carbon dynamics Nutrient dynamics Sediment dynamics
Species composition The species present in an area and their relative abundance.	Fauna diversity and distribution Vegetation diversity and distribution Bacterial diversity and distribution Algal diversity and distribution
Physical conditions Physical conditions of the restoration site, including hydrological and substrate conditions.	Water physico-chemical variables Soil physico-chemical variables
Absence of threats The presence, absence or measurement of threats to the success of the restoration project.	Pollution Biological threats
External exchanges Linkages and connectivity for hydrology, fire, or other landscape-scale processes; and for habitat for migration and gene flow.	Hydrological connectivity

The methods and results section of each study was screened to extract the indicators used to assess the ecosystem recovery of coastal wetlands. We extracted indicators monitored in both restored and reference sites. Indicators (e.g., soil organic carbon density) were classified in sub-attributes (e.g., carbon dynamics) following a modified method based on Bayraktarov et al. (2020b). Sub-attributes were nested within broader attributes (e.g., Ecosystem function) (**Table 1**) defined by the International SER (Mcdonald et al., 2016). We did not include socio-economic indicators as this was out of the scope of this review; although we acknowledge that a similar study on their use in assessing restoration success could additionally contribute to this topic. We used the indicators found in the literature to adapt the SER recovery wheel[2] to coastal wetlands.

Additional information on restoration projects was also extracted, such as the time period between restoration activity and monitoring study and the gross domestic product of the country where the restoration occurred as defined by The World Bank (2014). Some studies report a range for the time period between the start of the restoration project and initiation of monitoring (e.g., 7–11 years) so we used the mean (9 years) of the period in the analysis. We also screened for any reference to the SER Primer (SER, 2004) or SER International standards (Mcdonald et al., 2016; Gann et al., 2019) to determine if the project was following these principles.

RESULTS

A total of 67 papers containing 133 restoration site observations were eligible to be reviewed in this study. Papers were spanned over 33 journals, with 12% being published by the journal *Restoration Ecology*. The number of publications increased along the 30 years period covered (1990–2019), with 63% of the papers published in the 2010–2019 decade and a spike in publications in 2019 with 11 papers published (**Supplementary Figure 1**). The papers reported studies from 16 countries (**Figure 1**), 40 of them with high income economies, 13 with upper-middle income economies, 14 with lower-middle economies, and none were from countries with low income economies (**Supplementary Figure 2**). Papers described studies carried on saltmarsh (29), mangroves (28), and seagrass (11). They were all exclusive of other ecosystems, apart for one study which simultaneously investigated the outcomes of saltmarsh and seagrass restoration in Spain (Curado et al., 2012). The period between restoration and monitoring was usually under 5 years (38%), with <15% studies carried out over 15 years.

We recorded the use of 238 indicators, that were classified within 18 sub-attributes nested in six broader attributes (**Supplementary Table 1**). The number of restoration outcome indicators assessed per study varied between 1 and 23, with a third of the studies including five or less indicators. The most common attribute investigated was structural diversity (91%), followed by ecosystem functions (55%), physical conditions (48%), species composition (46%), external exchanges (18%), and absence of threats (6%) (**Figure 2**). The most commonly measured sub-attributes were fauna and vegetation structure which were included in half of the studies each, and around a third of the studies reported on the sub-attributes fauna and vegetation diversity and distribution. The only external exchanges sub-attributes consisted in hydrological connectivity, investigated in 19% of the studies.

Ecosystem functions were classified into five sub-attributes related to ecosystem function, from which the most used were carbon (30%), nutrient (19%), and sediment dynamics (19%), followed by secondary (10%) and primary production (3%) (**Figure 3**). Thirty-two ecosystem function indicators were used to assess the outcomes of coastal wetlands restoration (**Figure 4**). Soil organic carbon density, organic matter, nitrogen density, nutrients and sediment elevation accounted for almost half (47%) of all ecosystem function indicators investigated. Only two studies investigated denitrification, and only one evaluated the greenhouse gas fluxes in restored coastal wetlands. We adapted the SER recovery wheel to coastal wetlands ecosystems, integrating indicators evaluated by scientific literature reviewed in this study (**Figure 5**). This recovery wheel is an example for future monitoring projects in these ecosystems, highlighting the need to adapt the recovery wheel to selected ecosystems. It uses evidence-based monitoring data, derived from coastal wetlands goals and objectives.

DISCUSSION

Coastal wetlands restoration is an emerging field in marine science, with an increased scientific literature investigating its outcomes over the last decade, in particular in 2019. The high number of papers published this year might have been triggered by the 1st March 2019 UN General Assembly declaration of 2021–2020 to become the "Decade of Ecosystem Restoration" (see footnote 1). There is encouraging evidence that scientific literature is increasing its efforts to investigate coastal restoration. However, there is a disparity of studies location with more than half of them being carried out in high-income countries and none in low-income countries. The absence of studies in low-income countries might be due to a lack of reporting, with high-income countries investing more in scientific research. However, countries with highest annual rate of deforestation have low-income economy, mainly in tropical Africa and Asia (Aronson et al., 2010). There is therefore a need to increase partnership between high-income and low-income countries to improve scientific investigation in places where restoration is most needed. Moreover, seagrass restoration assessment studies only accounts for a small proportion of the overall coastal wetlands despite covering a larger area (McKenzie et al., 2020). Finally, while long-term restoration assessment is desired, most monitoring was conducted for less than 10 years. This time period is too short to adequately assess ecosystem functions recovery (O'Connor et al., 2019). For instance, coastal wetlands have been evaluated to recover their carbon dynamics functions at a similar level to reference sites 17 years after their restoration, and mangroves have been estimated to recover

[2] Available online at: http://seraustralasia.com/wheel/index.html

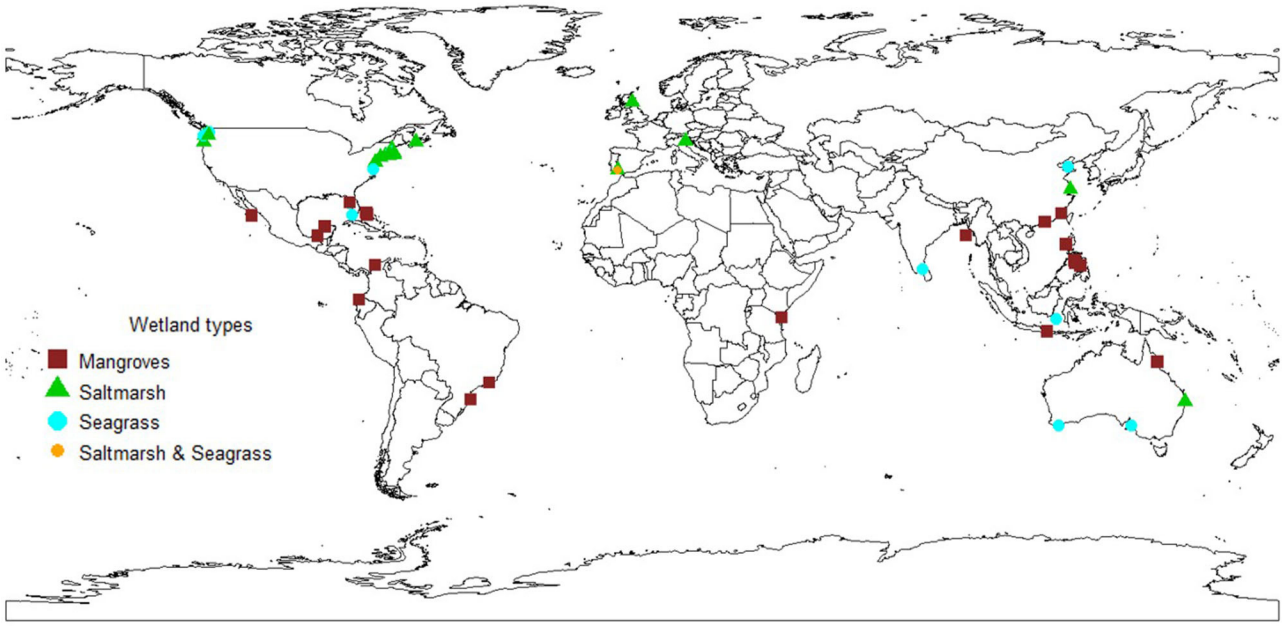

FIGURE 1 | Distribution of coastal wetlands restoration sites from studies reviewed.

their denitrification activity 12 years after restoration (Vovides et al., 2011; O'Connor et al., 2019). Unfortunately, due to a lack of ecosystem function monitoring over long term-period, it is difficult to estimate their recovery time.

The relative success of the restoration projects included in this study is difficult to estimate, mostly due to the wide range of metrics assessed. For instance, we found that more than fifty different indicators have been assessed to estimate the recovery of faunal structure (**Supplementary Table 1**). These indicators were assessing varied part of faunal structure such as nekton density (Bell et al., 1993), crab shell width (Russell et al., 2011), or fish age class distribution (Dibble and Meyerson, 2012). This diversity of indicators makes it difficult to estimate projects' success as the use of one metric over another can result in different outcomes (Basconi et al., 2020). There is a need to provide a common base to assess coastal wetlands restoration projects in order to obtain a clear and comparable success assessment. Gaps in coastal wetlands restoration research are still present, and it is important to resolve them to reach the objectives of the UN Decade on Ecosystem Restoration.

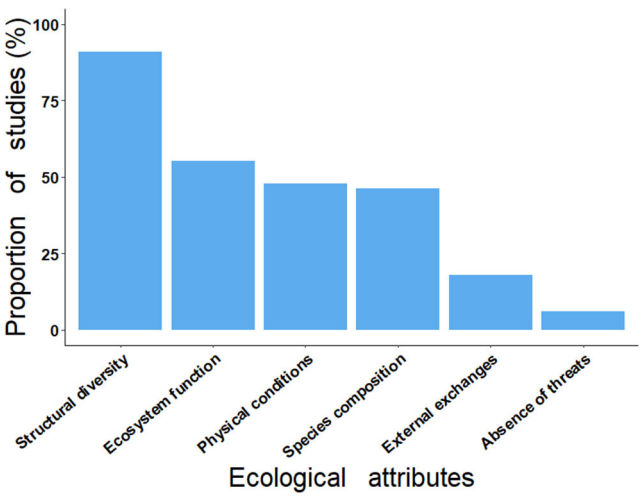

FIGURE 2 | Proportion of the studies investigating ecological attributes.

Ecological Attributes

Previous reviews on restoration outcomes highlighted an increase in measuring indicators of success informing on ecosystem function (Wortley et al., 2013; Kollmann et al., 2016). Our study confirms this trend, with 55% of the studies reporting on ecosystem function indicators. Ecosystem functions of coastal wetlands are being recognized as one of the main targets of restoration by the scientific community. However, most assessment studies are focused on indicators related to structural diversity. This might be because vegetation structure is usually the easiest and cheapest way to determine site condition, compared to ecosystem functions which are slower to recover (Ruiz-Jaen and Aide, 2005; Gibbons and Freudenburger, 2006). Structural diversity indicators are related to the complexity of the ecosystem, from the size of the vegetation to faunal biomass. For instance, Barnuevo et al. (2017) investigated the structural development of mangrove plantations using six structural

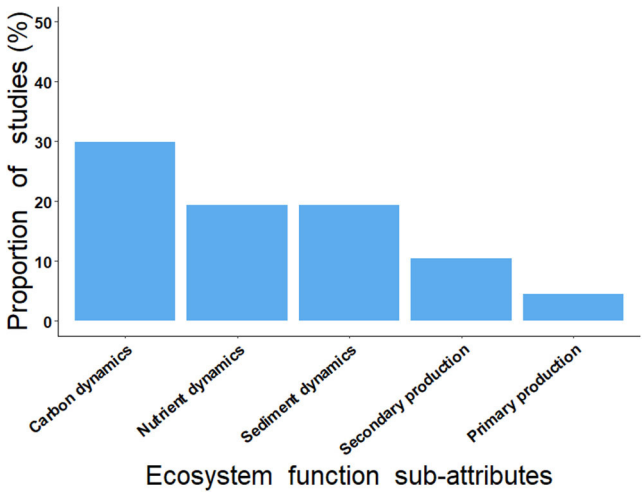

FIGURE 3 | Proportion of studies investigating ecosystem functions sub-attributes.

diversity indicators related to vegetation structure such as tree diameter or density, and Peck et al. (1994) investigated the structural development of restored saltmarsh fauna using six structural diversity indicators such as fauna biomass and density (**Table 1**). While structural diversity is an important attribute to monitor restoration progress, they are not always related to the provision of ecosystem services which is often stated as one of the rationales for undertaking restoration and ecosystem functions (Ntshotsho et al., 2011; Lee et al., 2019). There is therefore a need to improve the assessment of the functional success of coastal wetlands restoration using ecosystem function indicators such as carbon or nutrient dynamics (**Table 1**).

Ecosystem Functions

While coastal wetlands have been understudied for decades, scientific interest has been raised on their ecosystem functions and they are now increasingly studied (Orth et al., 2006; Richir et al., 2020). Coastal wetlands store organic carbon, improve water quality through nitrogen storage and denitrification, and mitigate coastal erosion, and these services have been the center of numerous studies (Alizad et al., 2018; Adame et al., 2019; O'Connor et al., 2019). The increased attention is confirmed by the number of studies investigating the outcomes of carbon, nutrient and sediment dynamics after restoration. Interestingly, carbon dynamics was the most studied ecosystem function, while previous reviews found it to be nutrient dynamics (Wortley et al., 2013; Kollmann et al., 2016). This is certainly due to the recognition of coastal wetlands as being global hotspots of blue carbon (Duarte et al., 2013).

Recent valuations of ecosystem services, linked to ecosystem functions, have potentially been a main driver of the increased scientific interest in coastal wetland restoration (Costanza et al., 1997, 2014; de Groot et al., 2012). Economists have demonstrated that restored, healthy habitats will generate value for both coastal populations and industry (Barbier et al., 2011). Valuation of ecosystem services led to the opening of alternative ways of funding, such as the emergence of carbon markets (Thomas, 2014). This carbon market can be integrated into payment for ecosystem schemes, through a reduction in emissions from deforestation and forest degradation set as international policies (Bullock et al., 2011; Locatelli et al., 2014). Coastal wetlands restoration projects are increasingly using this funding mechanisms, especially in mangroves as they possess the higher potential to store carbon (Wylie et al., 2016). It is therefore essential to understand the outcomes of restoration on the provision of ecosystem services such as carbon storage to facilitate stakeholders' involvement in this kind of projects (Basconi et al., 2020).

We emphasize here the importance of functional success as one of the main objectives of coastal wetlands restoration. Therefore, coastal wetlands restoration projects should include long-term monitoring programs, adapted for the recovery time frame of ecosystem functions. The period of observation is directly related to restoration success (Bell et al., 2014). There is however the need to underpin investment opportunities covering long-term monitoring costs (Waltham et al., 2020). International frameworks and national road maps are required to scale up ecological meaningful projects (Cormier and Elliott, 2017). Additional funding mechanisms such as payment for ecosystem services, biodiversity offset, carbon credits or water quality credit markets could facilitate the access to private capital and unlock major funding to cover the costs (Herr et al., 2015; Waltham et al., 2020). We encourage the use of carbon, nutrient and sediment dynamics success indicators in coastal wetlands restoration monitoring programs. These ecosystem functions are related to regulating services, such as waste treatment, erosion prevention and climate regulation (de Groot et al., 2012). Increased knowledge of project outcomes could facilitate the creation of global market of ecosystem services markets as it would further demonstrate that benefits from ecosystem restoration can outweigh their costs (Bullock et al., 2011).

Monitoring Framework

Among the 67 studies investigating coastal wetlands restoration outcomes, none have used indicators related to all six attributes of ecosystem recovery recommended by SER (Mcdonald et al., 2016). Only five percent of the studies referred to the SER Primer, yet none cited the recent international standards for ecological restoration. This discrepancy can be explained by 25% of the studies pre-dating the SER Primer, and 71% pre-dating the international standards (SER, 2004; Mcdonald et al., 2016). It would be interesting to keep tracking references to SER in the future to see if their principles are followed by the scientific literature. The lack of a common base for monitoring indicators is one of the main concerns associated with a relatively low success rate in restoration of <65% (Egoh et al., 2007; Bayraktarov et al., 2016; Zhao et al., 2016). With the upcoming decade of action, there is an urgent need to determine monitoring metrics and success indicators to assist restoration practitioners

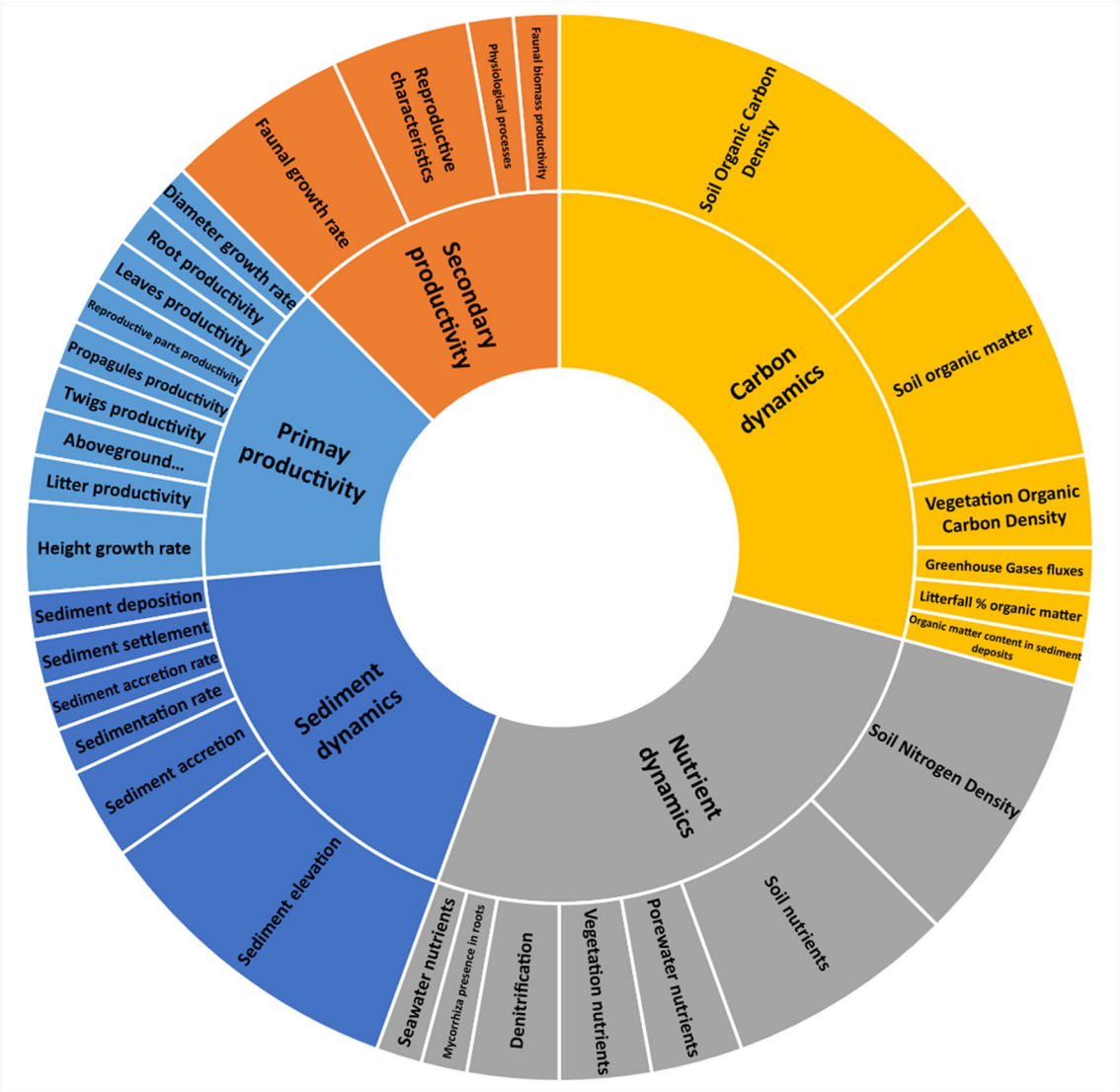

FIGURE 4 | Proportion of indicators (outer ring) nested within their sub-attributes (outer ring) assessed in the scientific literature.

assessing the ecological outcomes of restoration (Waltham et al., 2020). Restoration goals and objectives are dependent on the ecosystem restored (Borja et al., 2010) and the specific circumstances of the restoration sites (Bayraktarov et al., 2020a). The choice of monitoring indicators should be adapted to suit specific restoration sites (Mcdonald et al., 2016). Waltham et al. (2020) pointed out the difficulty to define clear and meaningful measures of success for the enormous range of coastal ecosystems restoration context. SER provided an important contribution to restoration through the creation of a general recovery wheel, but it also emphasizes the necessity to adapt this wheel to specific ecosystem studied (Mcdonald et al., 2016). The recovery wheel built in this study is a first step in the creation of a common monitoring framework for coastal wetlands restoration. We recommend future projects on coastal wetlands to use a recovery wheel based on the sub attributes and indicators presented in this study, and to adapt their monitoring framework to their specific objectives in order to obtain a clear assessment of their restoration outcomes (**Figure 6**).

Caveats

This study reviewed the efforts of the scientific community to assess the ecological outcomes of coastal wetlands restoration. However, most of the ecological meaningful restoration projects are carried by practitioners outside of the scientific field, such as NGOs or foundations, whom do not have the same incentive to publish in the scientific literature (Bayraktarov et al., 2020a). To achieve an overall view of the practice of restoration, we should strengthen the links between practitioners and academics to improve knowledge transmission. One way to do this would be to

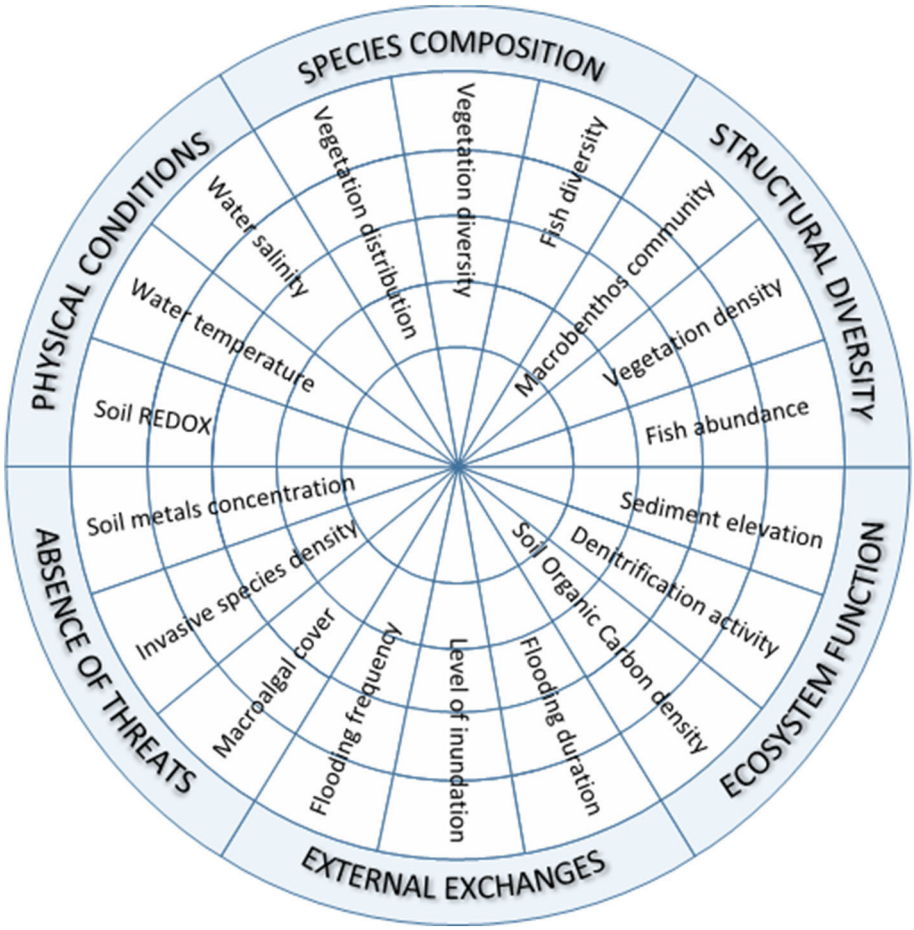

FIGURE 5 | Coastal wetlands recovery wheel including indicators found in the scientific literature.

survey restoration practitioners directly and get information and knowledge which would have been lost otherwise (Bayraktarov et al., 2020a).

We chose to focus on areas where the ecosystem restored previously existed and assessment studies including reference site and related as they aligned better with SER recommendations and therefore provide more meaningful information on coastal wetlands restoration success indicators. However, 90% of the marine restoration literature does not include a reference site; moreover created ecosystems account for a third of wetlands restoration literature (Moreno-mateos et al., 2012; Bayraktarov et al., 2020b). The exclusion of regional and national assessment might have caused the loss of highly relevant restoration data; however, these assessments often lack the monitoring details of site-specific studies required for this review. We also focused our review on English language, with some entries in Spanish, hence we could have missed about 35% of the literature published in different languages (Amano et al., 2016). Because of the limitations on published data globally available, this review is not exhaustive. However, it provides meaningful information on restoration success indicators employed by academics and proposes steps to improve the assessment of ecological outcomes.

CONCLUSION

Restoration ecology is an emerging field in conservation science. However, little is known about the ecological outcomes of restoration and how those have been assessed by measuring specific indicators. The UN Decade on Ecosystem Restoration seems to have encouraged the implementation of restoration projects and there is a need to assess their success. In the past, success was assessed mostly through structural diversity outcomes of restoration, but recent studies demonstrated the importance of measuring metrics related to ecosystem functions as they can be most closely associated with ecosystem services. We emphasize the importance of assessing functional success of coastal wetlands restoration as success indicators, for instance from carbon, nutrient and sediment dynamics assessment. We also recommend the implementation of long-term monitoring programs adapted to the recovery time frame of these ecosystem functions. Further studies on restored coastal wetlands ecosystem functions over long periods are still required to fully understand the outcomes of restoration on ecosystem services. This will facilitate stakeholder investment in coastal wetlands restoration, and the recovery of ecosystem services with economic, social and environmental benefits for all.

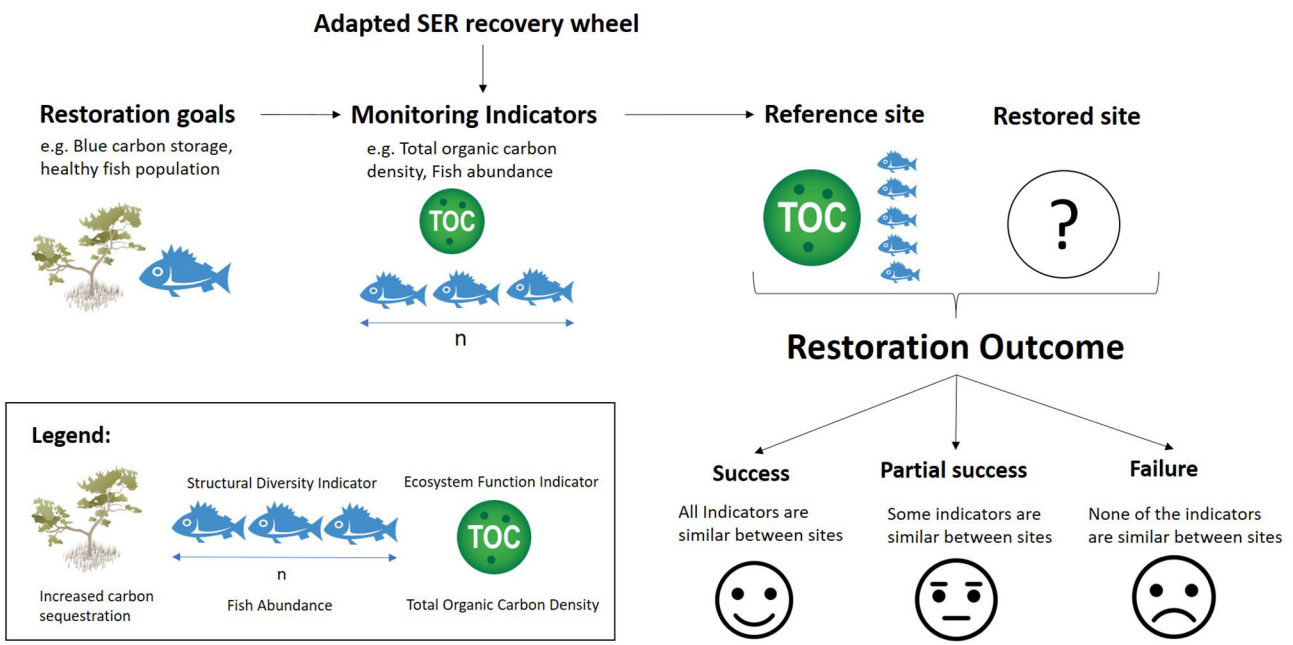

FIGURE 6 | Steps to assess restoration ecological outcome using structural and functional indicators.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Materials**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

CC conceived and developed this review methodology, reviewed and extracted data from literature, prepared the figures and tables, wrote the manuscript. EB contributed to the study conception and development of data extraction methodology and reviewed this manuscript. RP participated in the data analysis and creation of figures and reviewed this manuscript. MA contributed to the development of this review methodology, the creation of figures and reviewed this manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.600220/full#supplementary-material

Supplementary Figure 1 | Number of papers assessing ecological outcome of coastal wetlands per year.

Supplementary Figure 2 | Number of papers published per countries economy.

Supplementary Figure 3 | Number of restoration sites per age categories.

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Open Data, Collaborative Working Platforms, and Interdisciplinary Collaboration: Building an Early Career Scientist Community of Practice to Leverage Ocean Observatories Initiative Data to Address Critical Questions in Marine Science

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Ocean observing systems are well-recognized as platforms for long-term monitoring of near-shore and remote locations in the global ocean. High-quality observatory data is freely available and accessible to all members of the global oceanographic community—a democratization of data that is particularly useful for early career scientists (ECS), enabling ECS to conduct research independent of traditional funding models or access to laboratory and field equipment. The concurrent collection of distinct data types with relevance for oceanographic disciplines including physics, chemistry, biology, and geology yields a unique incubator for cutting-edge, timely, interdisciplinary research. These data are both an opportunity and an incentive for ECS to develop the computational skills and collaborative relationships necessary to interpret large data sets. Here, we use observatory data to demonstrate the potential for these interdisciplinary approaches by presenting a case study on the water-column response to anomalous atmospheric events (i.e., major storms) on the shelf of the Mid-Atlantic Bight southwest of Cape Cod, United States. Using data from the Ocean Observatories Initiative (OOI) Pioneer Array, we applied a simple data mining method to identify anomalous atmospheric events over a four-year period. Two closely occurring storm events in late 2018 were then selected to explore the dynamics of water-column response using mooring data from across the array. The comprehensive ECS knowledge base and computational skill sets allowed identification of data issues in the OOI data streams and technologically sound characterization of data from multiple

sensor packages to broadly characterize ocean-atmosphere interactions. An ECS-driven approach that emphasizes collaborative and interdisciplinary working practices adds significant value to existing datasets and programs such as OOI and has the potential to produce meaningful scientific advances. Future success in utilizing ocean observatory data requires continued investment in ECS education, collaboration, and research; in turn, the ECS community provides feedback, develops knowledge, and builds new tools to enhance the value of ocean observing systems. These findings present an argument for building a community of practice to augment ECS ocean scientist skills and foster collaborations to extend the context, reach, and societal utility of ocean science.

Keywords: big data, ocean observing, ocean response, data mining, COVID-19 pandemic, remote collaboration, middle Atlantic bight, early career researchers

INTRODUCTION

Ocean observatory data can enhance our capacity for addressing critical issues such as climate change, ecosystem variability, and ocean acidification. Exploring the coupling between the ocean and atmosphere, and biochemical cycles has historically depended on ship-based point measurements (e.g., Smith et al., 2019), which are limited in the timing and duration over which they are collected (e.g., Ganse et al., 2019; Venkatesan et al., 2019). Further, ship-based operations are limited by the number of contemporaneous observations, which depend on instrument availability and competition for time and space on research cruises. The move toward sensor-based, multi-annual ocean observing is essential for the collection of the collocated physical, biological, geological, and chemical measurements needed to holistically characterize these dynamic systems (Benway et al., 2019) and to validate and improve coupled physical-biogeochemical models (Fennel et al., 2006). Continued innovations in the miniaturization and automation of sensors, and introduction and improvement of observation platforms like tethered observatories and autonomous vehicles, have allowed remote collection of an increasingly diverse range of continuous datasets across large spatiotemporal scales and a wider range of conditions. Ocean observatory data are a solution to the scientific pitfalls of historical, ship-based data collection because they: (1) provide long-term sampling of a designated area, even during inaccessible time periods; (2) can be outfitted with sensors for interdisciplinary science (e.g., Davidson et al., 2019; Venkatesan et al., 2019); and (3) are built with the capacity to span research themes (e.g., National Science Foundation's Research Areas[1]) that have traditionally been funded through separate sources.

Ocean observing systems, such as the National Science Foundation's Ocean Observatories Initiative (OOI) arrays, measure key variables for describing drivers and exchanges from the air-sea interface to the seafloor. The high-quality data collected by the variety of sensors on the arrays is freely available, distributed in near real-time, and accessible to all members of the global oceanographic community. These arrays give scientists unprecedented access to explore the seafloor, water column, and air-sea interface over multi-year periods. Sea-state, weather, and vessel capability all limit data collection from ships to periods of relatively calm weather conditions resulting in data gaps during extreme weather events (e.g., Ondoa et al., 2019) that have a disproportionate influence on ocean systems (e.g., Ward et al., 2020), coastal infrastructure (e.g., Gough et al., 2019; Mendez-Tejeda et al., 2020), and coastal ecology (Adame et al., 2019; Yang et al., 2020). Ocean observing arrays are beginning to fill these gaps by continuously measuring parameters during these local or global events when observations would traditionally be limited. By improving coverage and consistency of data through remote observation, the ocean science community can better provide valuable information such as tsunami warnings, and potential impacts on human health and economically important fisheries (Ruhl et al., 2011).

The advantages of observatory data extend beyond traditional scientific merit by increasing the equitability of data access. For researchers and educators with resource limitations, observatory systems provide continuous access to state-of-the-art instrumentation and openly available data, which expands the opportunities for engagement with the larger research community. These observatory systems provide additional opportunities to include ocean data into undergraduate education and research (Greengrove et al., 2020) in a way that previously was only available to those who could collect data directly. For many scientists and educators at resource-limited institutions, lack of access to funding and instrumentation is common. Additionally, many with physical limitations traditionally cannot participate in fieldwork, even if the opportunity is provided (Nature Geoscience, 2015). During the current COVID-19 pandemic, this lack of access is being experienced even by those who typically have resources to permit and participate in expensive fieldwork (Geib, 2020; Nature Geoscience, 2020). While field work has been limited, ocean observatories have continued to provide direct observations for scientists, stakeholders, and students alike.

This democratization of ocean data offers distinct advantages to early career scientists (ECS) interested in addressing interdisciplinary problems. ECS are often on short-term

[1]https://www.nsf.gov/about/research_areas.jsp

contracts (i.e., the "postdoc treadmill," Radetsky, 1994) and need a high rate of research output for any hope of career advancement (e.g., Radetsky, 1994; Lawrence, 2003; Bodmer et al., 2019). Traditional costs associated with software, consumables, travel, cruise operations, and sample processing create obstacles which intensify the pressure to produce scientific results. Freely available observatory data provides an opportunity for ECS to explore important scientific questions without incurring many of the costs and challenges that are widely seen as barriers to career advancement and disproportionately impact the least privileged within the science community (Ginther et al., 2011).

Some of our most pressing oceanographic questions require interdisciplinary approaches that are well-suited for the application of ocean observatory data (Trowbridge et al., 2019). Though the quantity and breadth of sensor data currently available often require a range of expertise that few individual scientists possess, collaboration can be leveraged effectively to create useful interdisciplinary results. The ability to access, process, analyze, and interpret open-source observatories data can yield rich and interdisciplinary interpretation of results. Of great value to ECS, and the greater ocean science community, is the establishment of a clear pathway for developing interdisciplinary projects (e.g., networking, mentorship, training hubs) with workable, open-source analyses and effective communication pipelines.

Freely available data creates an incentive to harness a larger set of collective intellects and an opportunity to implement diverse approaches and experiences. Open-source community tools and resources permit science that depends more on innovation and ideas than on funding and past research success. In the age of 'big data,' data science skills are key to extracting important patterns; analytical techniques such as clustering, classification, anomaly detection, and frequent pattern mining make it feasible to extract useful information from oceanographic datasets that are often noisy or incomplete (Leung et al., 2014; Liu et al., 2017; Harris et al., 2019; Jiang et al., 2019). These techniques allow for efficient long-term time-series analyses over a range of frequencies to identify anomalous data and systematically identify co-variant patterns that require further investigation. These anomalous data also serve as a starting point for identifying previously unrecognized patterns and allow a systems-approach exploration of the unknown (Leung et al., 2014). Despite the volume and presence of collocated sensors on OOI platforms, modern data science workflows are still new to the oceanographic community, and thus efforts to address broad questions by mining OOI datasets for observations of interest have been limited. By leveraging the diverse skills and backgrounds of interdisciplinary research teams, we can better explore and interpret the results of these data-driven methods.

The OOI-ECS[2] is a community of ECS students, researchers, and faculty who bring backgrounds in geology, biology, chemistry, and physics, and a range of data analysis tools and experience. We lean on the collective background of OOI-ECS members to demonstrate the potential for ECS to perform open-source and interdisciplinary science, which takes advantage of the large data volumes collected by the OOI arrays. Here, we demonstrate the potential for these interdisciplinary approaches using OOI data by presenting a case study on the water-column impacts of anomalous atmospheric events (i.e., major storms) on the shelf of the Mid-Atlantic Bight southwest of Cape Cod, United States. Using data from the OOI Pioneer Array, we applied a simple data mining method to examine Gulf Stream dynamics in which we: (1) identify anomalous atmospheric events over a multi-year time range; (2) investigate the variability in ocean responses to those events; and (3) identify the dynamics of those responses over large spatial scales. This study aims to demonstrate the opportunity for ECS to make meaningful scientific contributions through the development and application of cutting-edge data-exploration techniques within a resource-limited environment.

METHODS FOR CASE STUDY

OOI Pioneer Array Site Overview

The Pioneer Array[3] (39° 40′N, 70° 40′W) footprint spans the outer continental shelf, shelfbreak, and upper slope of the Mid-Atlantic Bight southwest of Cape Cod, United States (Trowbridge et al., 2019). The array consists of seven sites, four cross-shelf sites on the downstream (west) transect and three upstream along a parallel cross-shelf transect, with an ocean depth range of 92–452 m (**Figure 1**; **Table 1**). Each site contains sub-surface profiler moorings, and three of these sites also contain buoys equipped with surface, near-surface, and seafloor instrumentation. All instruments are typically replaced during maintenance cruises each spring and fall.

The scientific motivation for the establishment of the Pioneer Array was to investigate how shelf/slope exchange processes structure the physics, chemistry, and biology of continental shelves (ORION Executive Steering Committee, 2007). This region of the northwest Atlantic is highly dynamic, with shelfbreak exchange driven by interactions with warm-core rings emanating from the Gulf Stream (Joyce, 1984), instabilities along the shelfbreak front (e.g., Lozier et al., 2002; Fratantoni and Pickart, 2003), and regional wind forcing (Lentz, 2008; Dzwonkowski et al., 2009). This exchange results in high levels of biological productivity driven by increased nutrient input (Hoarfrost et al., 2019). In addition to monitoring the impact of changing climate on the long-term variability of shelfbreak dynamics (Pershing et al., 2015; Gawarkiewicz et al., 2018; Harden et al., 2020), the Pioneer Array provides an opportunity to investigate short-term events with significant societal implications such as hurricanes and winter storms (Gawarkiewicz and Plueddemann, 2020). Fundamental questions exist about how severe storms and other episodic mixing processes affect the water column (ORION Executive Steering Committee, 2005)

[2]https://ooi-ecs.github.io/

[3]http://oceanobservatories.org/array/coastal-pioneer/

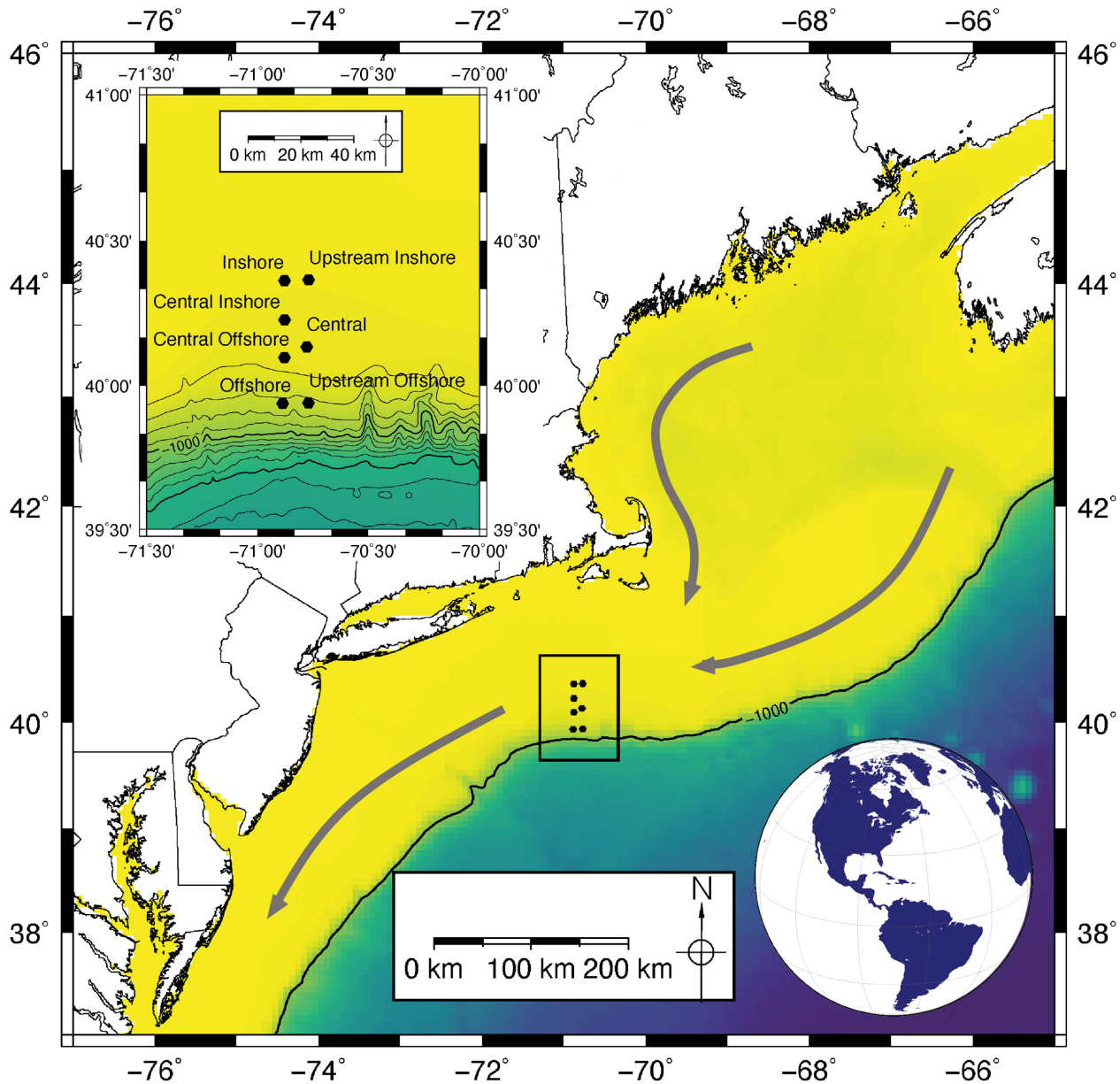

FIGURE 1 | Map of the northeast US continental shelf and slope with the location of the OOI Pioneer Array (black circles). The black box indicates the region of the inset map (upper left) showing the location and names of the moorings relative to the shelf slope. Gray lines indicate the approximate path and direction of the coastal current. Figure modified from Gawarkiewicz and Plueddemann (2020).

and how these storms are evolving in response to anthropogenic climate change (Collins et al., 2019).

OOI Datasets

To investigate the influence of low atmospheric pressure systems on surface and subsurface water-column responses on the shelf, we used measurements of sea surface temperature (SST), near-surface atmospheric humidity and temperature, wind speed and direction, barometric pressure, and latent and sensible heat fluxes recorded at surface moorings. Data obtained from the meteorological package, located 3 m above sea level on the surface moorings, at both the inshore and central mooring sites, were downsampled to a temporal resolution of 1-h and 3-h, respectively. Subsurface measurements of seawater temperature, salinity, dissolved oxygen (DO), and colored dissolved organic matter (CDOM) were recorded on wire-following profiler moorings across the array. Wire-following profilers moved through the water column from 3 m above the seafloor to 15 m below the sea surface at three-hour intervals for a total of 8 profiles a day. Instruments turned on at their parked depth for 2 min before moving upward through the water column. Once at 15 m below the sea surface, the profiler

TABLE 1 | Site summary of Pioneer Array moorings.

Site	Location	Water depth (m)
Upstream inshore	40.3649°N, 70.77°W	95
Central	40.1334°N, 70.7785°W	133
Upstream offshore	39.9394°N, 70.7708°W	452
Inshore	40.3619°N, 70.8783°W	92
Central inshore	40.2267°N, 70.8782°W	127
Central offshore	40.0963°N, 70.8789°W	148
Offshore	39.9371°N, 70.887°W	450

parked and sampled for 2 min before powering off for 5 min. Instruments were then turned back on for 2 min before the profiler moved downward through the water column. At its parked depth, the instruments continued to sample for 2 min before shutting down. While moving along the mooring riser, an instrument sampling at 1-Hz results in depth profiles with a vertical resolution of 0.25 m.

Anomaly Detection and Analysis

Low-pressure atmospheric anomalies were defined as all measurements below 3 times the standard deviation (e.g., Sagoolmuang and Sinapiromsaran, 2017) of the mean barometric pressure of the ∼4-year time series and identified at the inshore site (**Figure 2**). During this period from May 2015 thru August 2019, a total of 28 anomalous events were detected using all available instrument-recovered data (data not shown). The subset of data analyzed for this study were the eight anomalous atmospheric events detected in 2018, which was the last calendar year of instrument-recorded data available. These anomalous events included a bomb extratropical cyclone (Sanders and Gyakum, 1980), an extratropical storm, and several nor'easters, blizzards, and intense winter storms (**Figure 2**).

The specific events selected for this study were chosen based on coinciding data stream availability. Only data that passed the internal OOI quality assurance was used. To further investigate the integrity of the data, we compared overlapping data from the three scheduled maintenance cruises in November 2017, April 2018, and November 2018 (deployments 9 thru 11). Data quality issues were identified starting at the end of July 2018 that affected the 3-wavelength fluorometer on the wire-following profiler at the central offshore site. These issues continued until the recovery and replacement of the instrument in early November 2018. The improved performance of the new sensors deployed during this maintenance cruise (deployment 11) led to greater confidence in the data being acceptable for robust scientific analysis. Hence, the anomalous events of November 2018 (herein referred to as Event 1 and Event 2) were chosen for this study.

For each event, we compared the impact on subsurface conditions using water-column data from wire-following profilers for before, during, and after the event. A mean water-column profile from the up- and downcast closest to local noon (1600 UTC) on the day of the peak of the anomalous event was used for each event. Profiles were also taken both 48 h before and after each peak (also at local noon) to investigate ocean response. Data from wire-following profiles were also used to create two-dimensional time series of water-column profiles using a linear interpolation of water-column data at a 1.5-m depth interval and a 3-h time interval grid.

Auxiliary Datasets

Two auxiliary datasets were used to compare and verify oceanic data from the OOI array. First, climatological temperature, salinity, and DO for the month of November were obtained from the World Ocean Atlas 2018 (WOA18; Garcia et al., 2019; Locarnini et al., 2019; Zweng et al., 2019). WOA18 is a gridded climatological ocean analysis of subsurface ocean variables at standard depths that contains data from 1955 to 2017. The gridded resolution for the temperature, salinity, and DO data retrieved from WOA18 for this study were 0.25°, 0.25°, and 1°, respectively. Temporal averaging for temperature and salinity occurs over 2005–2017 whereas temporal averaging for DO is over the entire WOA18 time range (1955–2017). Second, daily satellite SSTs were obtained from the Jet Propulsion Laboratory's PODAAC Group for High Resolution SSTs (GHRSST) Level 4 MUR (JPL Mur MEaSUREs Project, 2015) to provide a broader spatial context to the variability observed across the Pioneer Array moorings. This product provides daily 1-km blended level 4 global SST analyses and was chosen for its high resolution and ability to resolve oceanic fronts and SST variability in cloudy environments (such as during storm events) through incorporation of microwave sensor data (Schowengerdt, 2007).

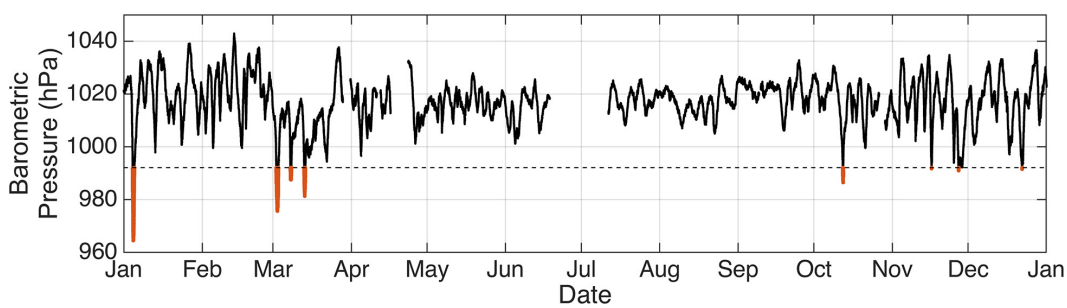

FIGURE 2 | Hourly barometric pressure measurements (hPa) from the surface buoy at the inshore site for 2018. Orange data points below the dashed line indicate anomalous events (see text for definition).

CASE STUDY RESULTS AND DISCUSSION

We detected two anomalous events of similar magnitude during November 2018 with barometric lows of 991.8 hPa and 991.0 hPa, respectively (**Figures 2**, **3A**). Event 1 occurred on 16 November 2018 and corresponded with the movement of a winter storm over the northwest Atlantic. Event 2 occurred on 27 November 2018. Analyses conducted for Event 1 span from 14 Nov 2018 to 18 Nov 2018; analyses conducted for Event 2 span from 26 Nov 2018 to 30 Nov 2018. "Pre-event" for Event 1 and Event 2 is 14 Nov and 26 Nov, respectively. "Post-event" for Event 1 and Event 2 is 17 Nov and 28 Nov, respectively.

Event Comparisons: Air-Sea Interaction

At the central surface mooring site, wind speed peaked (14.9 m s^{-1}) 12 h prior to the atmospheric pressure anomaly, indicating the onset of Event 1 (**Figures 3A,B**). Air temperature substantially decreased from 17.1°C (13 Nov 18Z) to 2.6°C (15 Nov 9Z) prior to Event 1. Increased winds and reduced air temperatures are associated with an increase in latent and sensible heat flux out of the ocean prior to Event 1 passage (peak values 369.1 W m^{-2} and 215.8 W m^{-2}, respectively, on 15 Nov 0Z). The synchrony between these two fluctuations and the peak in wind speed indicated a loss of ocean heat to the atmosphere (**Figures 3C,D**), which is supported by a small drop in pre-event SST observed at the array at the time of peak heat flux (12.8°C on 14 Nov 15Z to 12.7°C on 15 Nov 0Z, **Figure 3E**). Satellite SST (**Figure 4A**) confirmed this cooling was widespread, constrained not only to the mooring array but across the shelf and Gulf of Maine. By the time of Event 1, both air temperature and SST had warmed to similar values of 13.4°C and 13.5°C, respectively, causing a reduction in latent and sensible heat fluxes at the central surface mooring site to approximately 128.4 W m^{-2} and 0.0 Wm^{-2}, respectively. Satellite SST shows the presence of

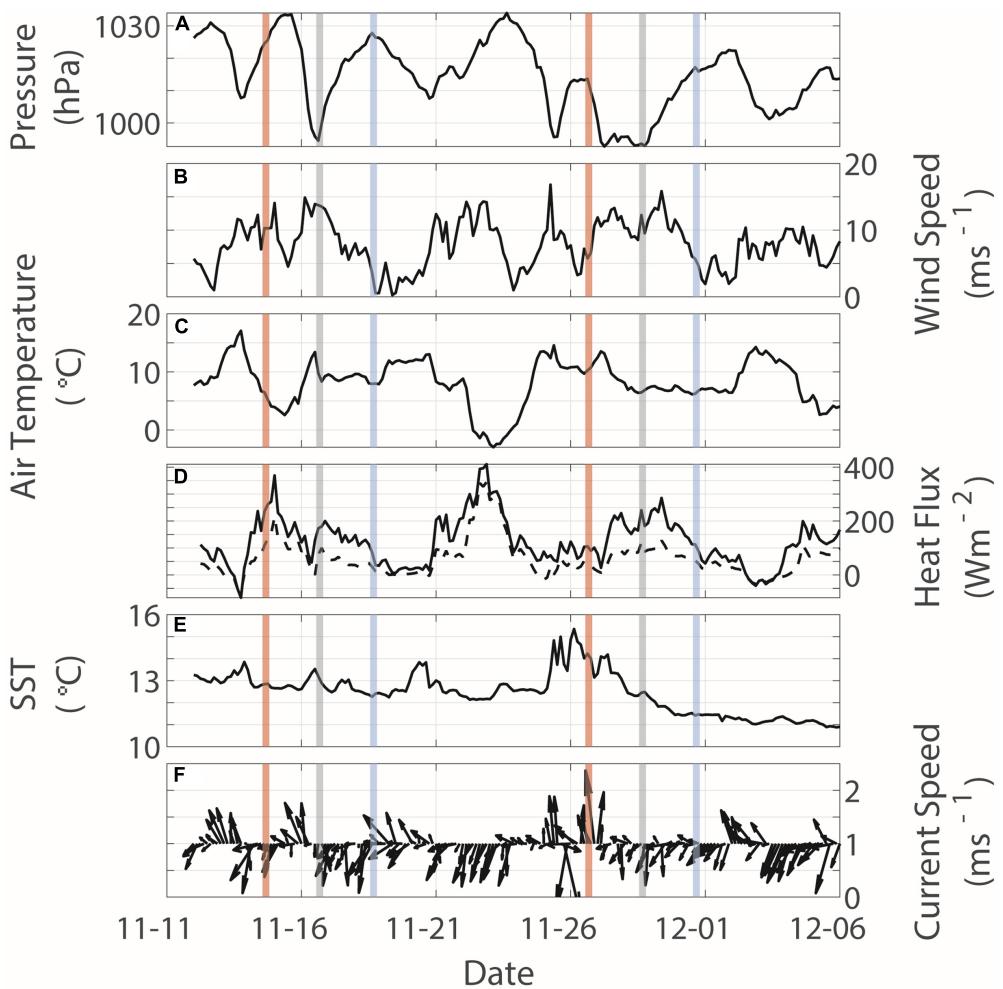

FIGURE 3 | Time series of **(A)** atmospheric barometric pressure (hPa), **(B)** wind speed (ms^{-1}), **(C)** air temperature (°C), **(D)** fluxes of latent (solid line) and sensible (dashed line) heat (Wm^{-2}), **(E)** sea surface temperature (SST, °C), and **(F)** surface current speed (ms^{-1}) and direction from central surface mooring site. Vertical lines indicate the time 48 h before (red), during (gray), and 48 h after (blue) each event.

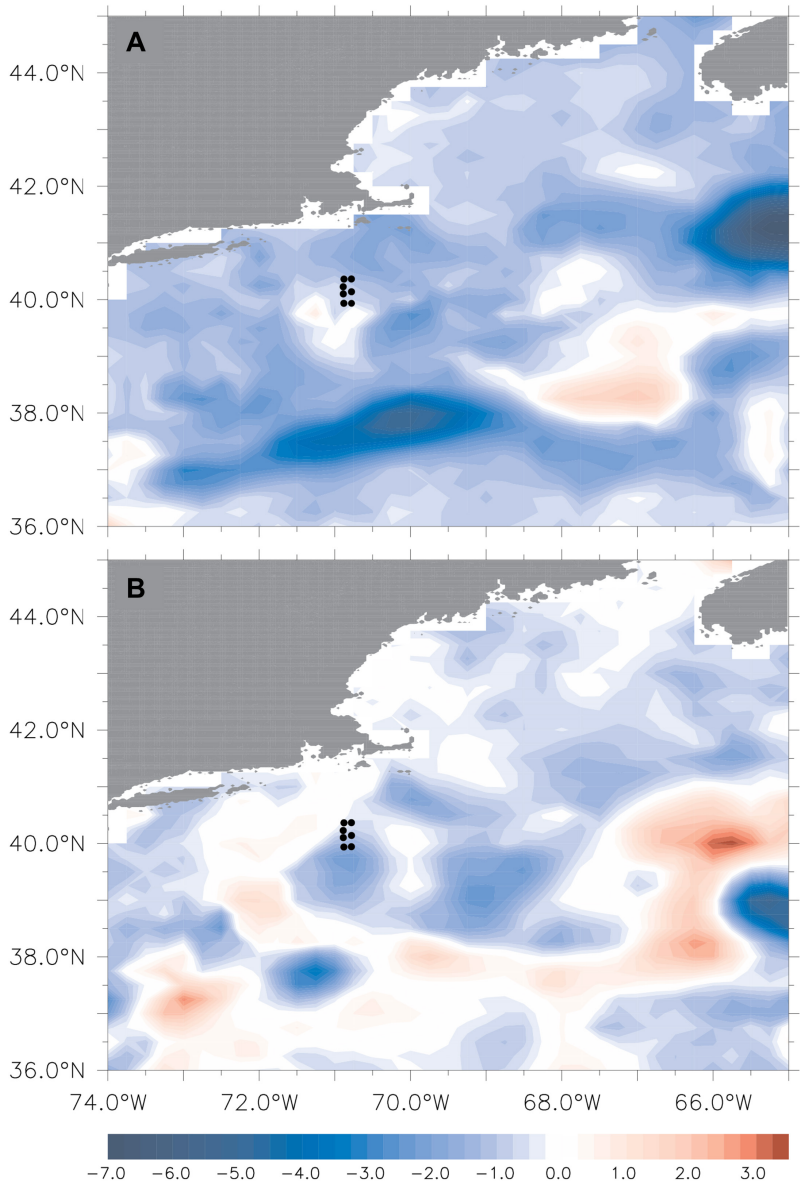

FIGURE 4 | Satellite sea surface temperature (SST) differences (°C) for **(A)** Event 1 and **(B)** Event 2. Differences for Event 1 and Event 2 are defined as (1) SST_{Nov18}-SST_{Nov14} and (2) SST_{Nov30}-SST_{Nov26}, respectively, such that positive differences indicate post-event SST warming and negative differences indicate post-event SST cooling. Black dots indicate locations of Pioneer Array Moorings.

a warm mesoscale feature just south of the mooring site during and after Event 1, which possibly led to anomalously warm SST observed during that time. Warming of SST during Event 1 from pre-Event 1 temperatures could possibly be tied to pre-event northwesterly surface currents (**Figure 3F**) advecting these warmer waters across the shelfbreak (further examined in section "Spatial Variations in Event Impacts").

Event 2 had a slightly lower wind speed (12.2 m s^{-1}) than Event 1, but a similar atmospheric pressure anomaly (991.0 hPa; **Figures 3A,B**). The substantial drop in atmospheric temperature observed prior to Event 1 was not observed prior to Event 2 (**Figure 3C**, 10.2). Air temperature during Event 2 was similar (13.2°C) to Event 1 but latent and sensible fluxes were slightly lower (239.8 W m^{-2} and 119.9 W m^{-2}, respectively). Peak latent and sensible fluxes (285.6 W m^{-2} and 127.9 W m^{-2}, respectively) occurred in the post-event stage (29 Nov 9Z) during a peak in wind speed (15.8 m s^{-1}) at that time rather than in the pre-event stage like Event 1. SST cooled rapidly by 2.8°C from pre-event to post event (**Figure 3E**), even though wind speed, air temperature, and latent and sensible heat fluxes were not indicative of such air-sea exchange as in Event 1. Satellite SST revealed a tongue of cold inner-shelf waters extending from the Gulf of Maine toward the mooring array (**Figure 4B**). Southwesterly surface currents during Event 2 (**Figure 3F**) indicated that observed SST

cooling was likely dominated by water mass advection rather than air-sea exchange.

Event Comparisons: Impacts on Water Column

A strong, persistent thermal inversion at 40–60 m (∼18°C) accompanied by saline (∼ 35.5) waters was evident at the central offshore site up to a week prior to Event 1 (**Figures 5B,C**, **6A,B**, **7D**). This inversion dissipated with the onset of Event 1 (11/15 12Z - 11/16 0Z) and was replaced by relatively cooler (∼13°C) and fresher (∼34°C) waters that were mixed down to 110 m (**Figures 5B,C**, **6A,B**, **7D**). Concurrently, DO increased and CDOM decreased down to depths of 110 m (**Figures 5D,E**, **6C,D**). The strong thermal inversion re-established approximately 5 days prior to Event 2 (11/22, **Figures 5B**, **6F**), extending from 40m to 80m. The properties of this inversion and the position along the seasonal pycnocline were consistent with salty intrusions typical of the continental shelf along the Mid Atlantic Bight (Lentz, 2003). The short decay time is expected given the rapid mixing of the water column, and future work could utilize the continuous measurements of the Pioneer Array to further explore the generation and decay mechanisms of these intrusions.

A constant layer of temperature, salinity, DO, CDOM and chlorophyll *a*, extending from the surface down to approximately 60m, was observed at the onset of Event 2 (**Figures 6F–J**), indicating intense turbulent mixing during the event. Much colder (<12°C), fresher (<33), and oxygenated (>250 μmol kg^{-1}) waters with an increased concentration of CDOM were observed in the upper 25 to 60 m starting 30 November 2018, two days after Event 2 (**Figures 6F–I**). Meteorological and ocean surface current observations from the central surface mooring, in addition to satellite measurements, indicate the cooling was associated with southward advection of cooler Gulf of Maine waters across the array (**Figures 3**, **4B**) rather than a widespread cooling as in Event 1 (**Figures 3**, **4A**).

Spatial Variations in Event Impacts

The impact of Event 1 on temperature and salinity varied spatially both across and along the shelf slope (**Figure 7**), while a uniform cooling response was observed across the array during Event 2 (data not shown). Observations from all seven profiler moorings indicated that conditions prior to Event 1 were highly variable across the shelfbreak. Variability along the shelf (90 m depth) at both the inshore (**Figure 7A**) and upstream inshore (**Figure 7B**) was low, with temperatures at both sites before, during, and after Event 1 ranging from 12.8–13.8°C. Minimal cooling (-0.3 and -0.6°C) was observed following Event 1 at both the inshore and upstream inshore sites.

The temperature inversion between 40 and 60 m observed at the central offshore site (148 m depth; **Figures 6A**, **7D**) during Event 1 was also observed at the central site (130 m depth;

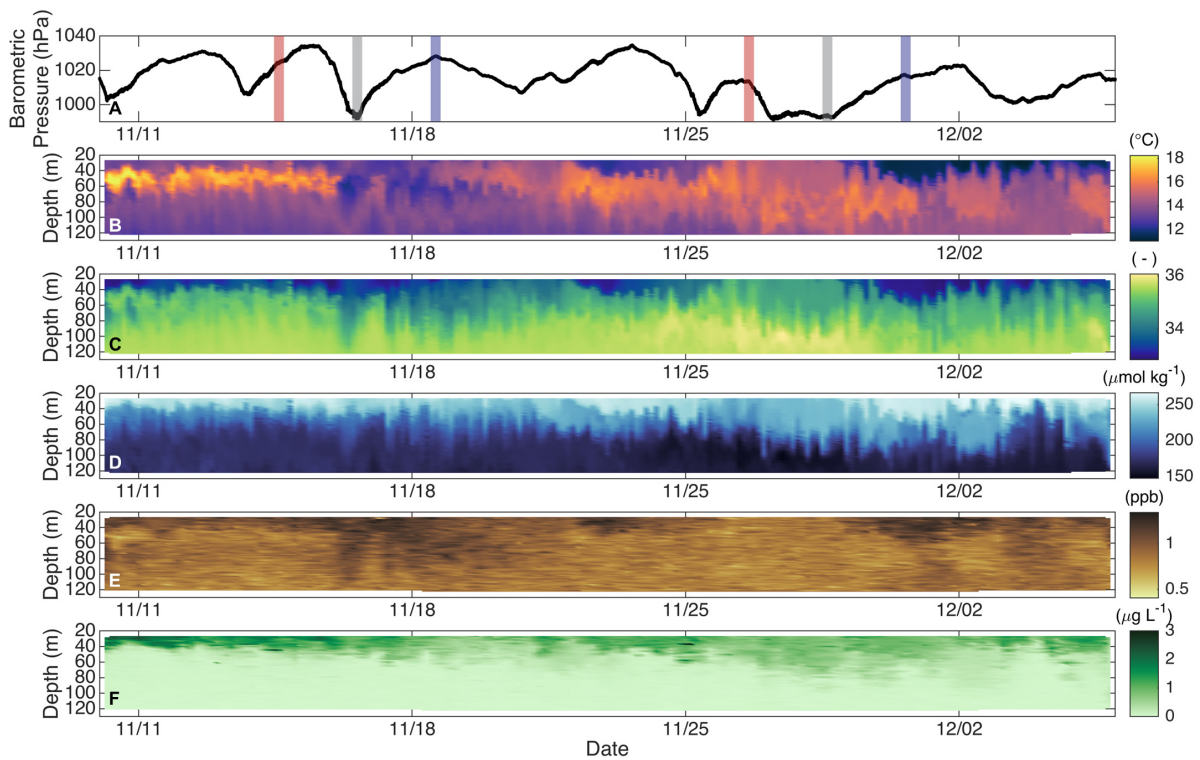

FIGURE 5 | (A) Barometric pressure from the inshore site for 10 November to 6 December 2018. Vertical lines indicate the time 48 h before (red), during (gray), and 48 h after (blue) each event. Water-column **(B)** temperature, **(C)** practical salinity, **(D)** dissolved oxygen, **(E)** color dissolved organic matter, and **(F)** chlorophyll *a* from the central offshore site for the same time period.

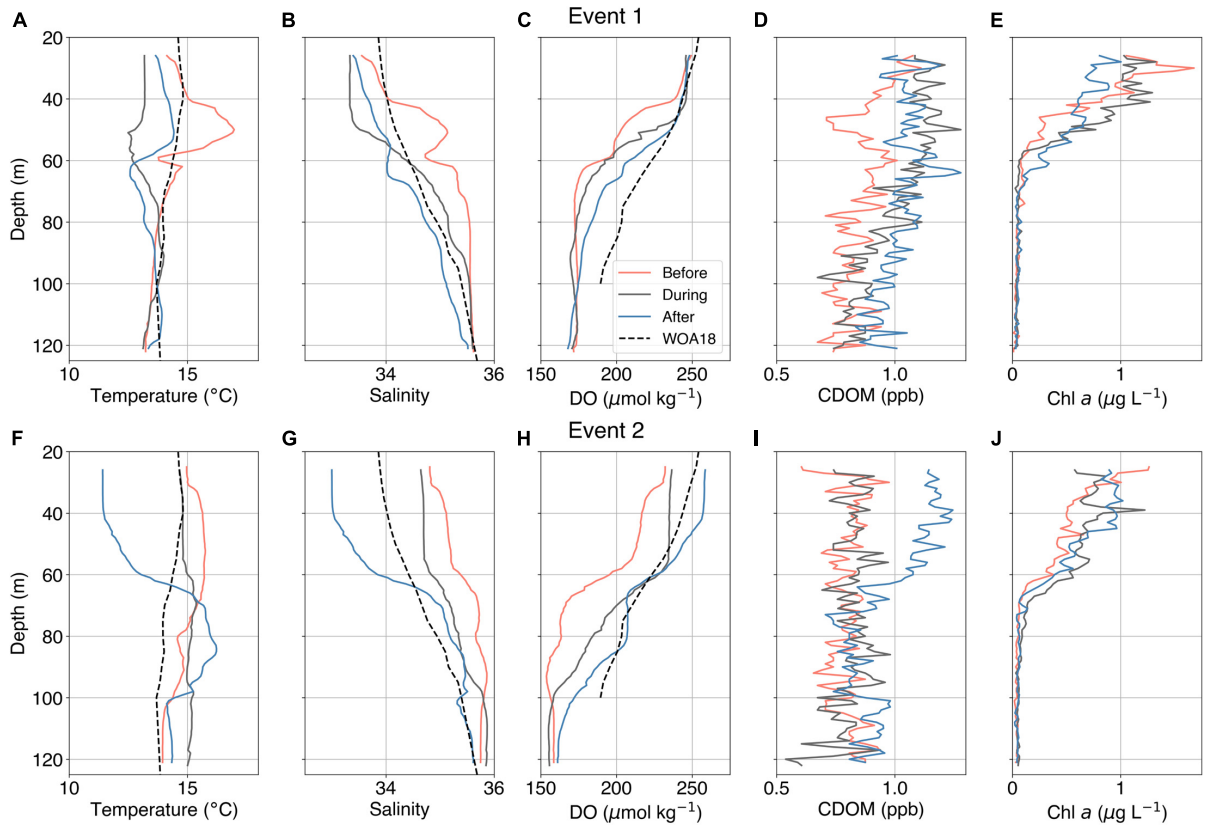

FIGURE 6 | Temperature, salinity, dissolved oxygen (DO), colored dissolved organic matter (CDOM), and chlorophyll *a* (Chl *a*) water-column profiles before (red), during (gray), and after (blue) Event 1 **(A–E)** and Event 2 **(F–J)** at the central offshore mooring site. WOA18 November climatological average profiles of temperature, salinity, and oxygen are indicated by the dashed lines.

Figure 7E) on the upstream (eastern) side of the array. Maximum temperatures between 40 and 60 m prior to Event 1 were 17.0 and 15.9°C at the central offshore and central sites, respectively, 2.3 and 3.2°C warmer than the corresponding inshore and upstream inshore sites. Maximum inversion temperatures were reduced by ∼3°C during Event 1, at which point the temperatures at the central offshore and central sites were <0.5°C warmer than the corresponding inshore and upstream inshore sites. Following Event 1, the central offshore site remained cool with a maximum temperature of 14.4°C between 40 and 60 m where the warm thermal inversion had been present (**Figures 6A**, **7D**). At the central site, the temperature inversion was once again present, with a maximum water temperature of 16.3°C (**Figure 7E**). We observed additional post-Event 1 warming on the upstream side of the array at the upstream offshore site (452 m depth); maximum water temperatures between 40 and 60 m increased from 14.8°C prior to Event 1 to 16.0°C after Event 1 (**Figure 7G**). Similarly, warm water remained present at the offshore site (450 m depth) where temperatures in the same depth range varied from 15.4 to 16.1°C during the same period (**Figure 7F**).

During and after Event 1, satellite-derived SST indicated an intrusion of warm surface water extending to 40° N (**Figure 4A**; **Supplementary Figure S1**). The SST and temperature/salinity properties within the warm inversion layer at the central and central offshore mooring sites, in addition to observed pre-event northwesterly surface current (**Figure 3F**), suggest mixing with slope/gulf stream water (e.g., Harden et al., 2020; **Figures 6A,B**). The temperature and salinity within the upper 80 m observed prior to and during Event 1 compare well with the slope eddy structure described in Gawarkiewicz et al. (2001). Both the offshore and upstream offshore sites remained influenced by slope water throughout the passing of Event 1 (**Figures 7F,G**). This water mass appeared to continue mixing onto the shelf slope at the central site following Event 1's passing, as exhibited by the warm post-storm temperatures observed at the central site reminiscent of the conditions prior to Event 1 (**Figure 7E**). This reemergence of the slope water mass following Event 1 was not observed to the west at the central offshore site (**Figure 7D**), perhaps either as a result of storm-driven mixing on the shelf slope or a movement of the slope front.

Summary and Implications of Event Variability

Latent and sensible heat fluxes prior to Event 1, and satellite SSTs indicated the presence of warm surface water over the central and offshore mooring sites (**Supplementary Figure S1**). Observations from the array indicated that during Event 1,

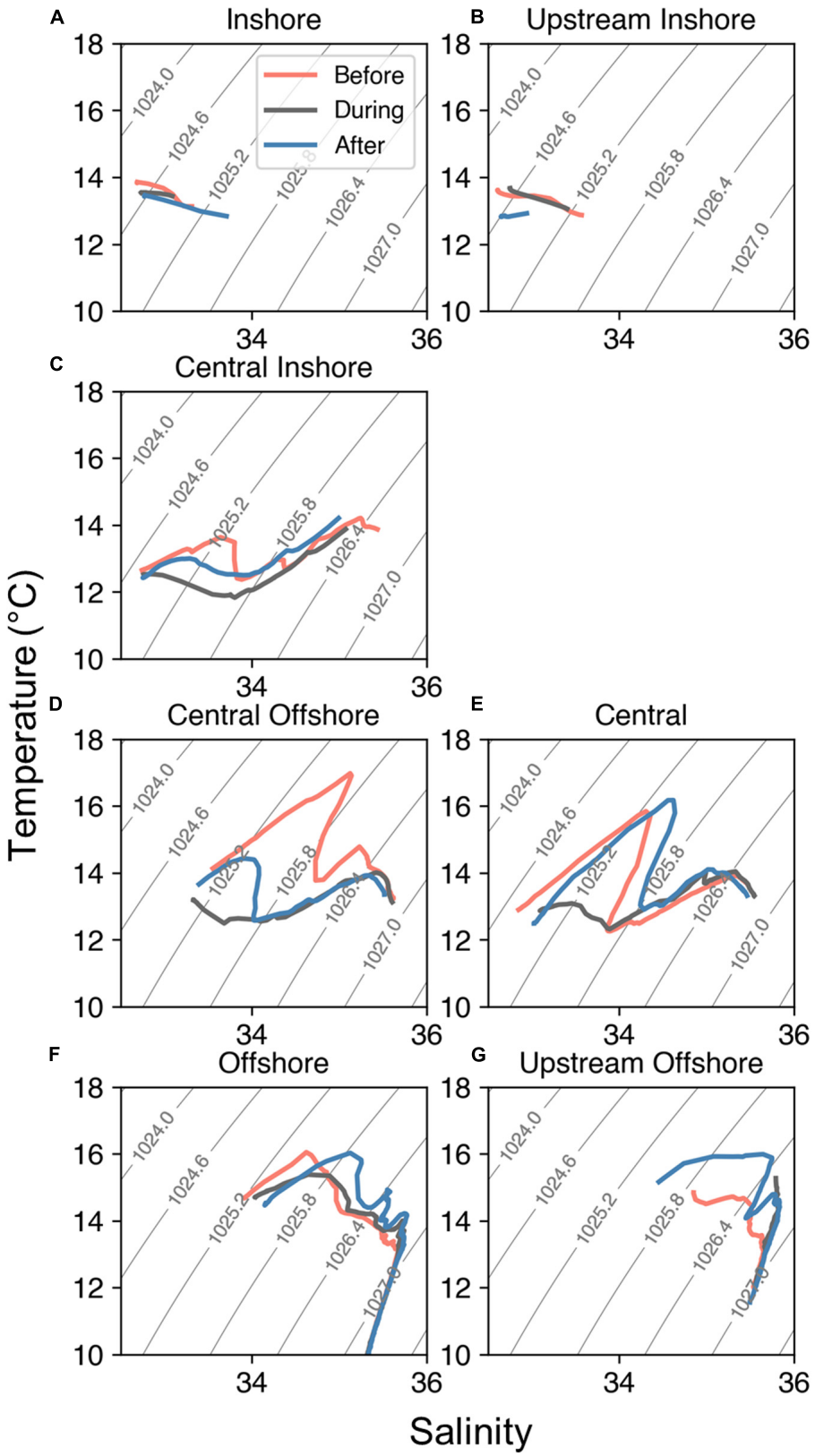

FIGURE 7 | Temperature and salinity of the water column before (red), during (gray), and after (blue) Event 1 at the **(A)** inshore, **(B)** upstream inshore, **(C)** central inshore, **(D)** central offshore, **(E)** central, **(F)** offshore, and **(G)** upstream offshore sites. Contours indicate potential density (kg m^{-3}).

latent and sensible heat fluxes to the atmosphere led to the widespread sea surface cooling, observed not only over the mooring array but also across the shelf and Gulf of Maine (**Figure 4A**; **Supplementary Figure S1**). The impact of event-driven mixing in the surface layer is also apparent in the deepening of the oxycline (**Figure 6C**). However, the magnitude of the cooling across the array was variable, and subsurface observations suggested the intrusion of a slope/Gulf Stream water mass throughout the passing of Event 1 which likely resulted in different water column temperature responses (**Figure 7**).

During and after Event 2, latent and sensible fluxes did not appear to account for cooling sea surface temperatures (**Figure 3E**). Instead, most surface cooling appeared to be associated with the advection of colder water into the shelf-slope region (**Figure 1**, **3F**, **4B**). Profiler observations revealed that the advected waters were colder, fresher, more oxygenated, and contained more CDOM than waters prior to Event 2 (**Figures 6F–I**). These patterns are indicative of coastal water from the Gulf of Maine being transported offshore via the coastal current (Mountain, 1977; **Figure 1**). As Event 2 passed, and SST cooled, chlorophyll *a* increased and the system appeared to return to pre-event conditions.

Overall, the investigation of these two events demonstrates our capability to address the importance of a multitude of interdisciplinary oceanographic processes including cross-shelf/along-shelf dynamics, biochemical interactions, and air-sea interactions before, during, and after pressure anomalies. The case study presented validate the conceptual design for the Pioneer Array (Trowbridge et al., 2019; Gawarkiewicz and Plueddemann, 2020) by leveraging multiple collocated continuous time series over a large spatial area. We demonstrated the potential for predictive analysis with an anomaly detection algorithm. Then, based on the identification of those events, we interrogated a wide range of data products available from the OOI to resolve the variability in and drivers of ocean response. The long-standing time series also allows for hypothesis-driven research such as climatology of the shelfbreak region, seasonal variability regarding Gulf Stream meanders and warm-core rings (Chen et al., 2014; Zhang and Gawarkiewicz, 2015), the influence of extreme events on shelf biogeochemical response (as demonstrated within the present case study), or the influence of a warming climate on shelf exchange. Historically, the number of datasets with repeat annual observations necessary to explore these potential shifts in climatology are limited in either number of variables (Forsyth et al., 2015) or temporal/seasonal coverage (Harden et al., 2020). The combination of high-resolution observations and temporal coverage of the OOI array should allow a much more detailed analysis of specific oceanographic processes contributing to the trends in warming and future shifts in these exchange processes (Harden et al., 2020).

As demonstrated, this framework is especially valuable because it uses data that can be collected even when ship-based science cannot be conducted (global pandemics, harsh weather, storms, or minor events that may otherwise go unnoticed). The availability of telemetered observatory data means that ocean response can also be monitored in near real-time in support of forecasting, co-occurring ship-based efforts, or to mobilize additional resources in response to interesting phenomena. These continuous observing systems provide real-world, broad applications to benefit society, including early tsunami warnings, weather and flooding events, El Niño periods, hypoxic events, and harmful algal blooms. Moreover, ocean observatories provide unprecedented access to the ocean, regardless of proximity. Development of a remote team science framework establishes a pipeline for virtual mentorship and education tools that use observatory data to communicate oceanographic concepts while building data skills and understanding of integrated applications (Greengrove et al., 2020).

Through engagement of communities outside of oceanography and the geosciences, it is possible to further expand the research potential and constructive applications of observatory data. As an example, we chose to use simple metrics for event detection to demonstrate the potential of more developed and complex algorithms for identifying patterns of interest. Data mining is an essential method for identifying signals in large and sometimes noisy datasets (Liu et al., 2017). The goal of our case study was to identify acute atmospheric pressure events which made it possible to focus on a single variable. Accordingly, we chose the commonly utilized 3-sigma rule as our algorithm for anomaly detection due to its simplicity and demonstrate that it could be used by non-atmospheric scientists without a detailed understanding of the region-specific atmospheric processes. Future work could include more extensive collaboration with the data science community to develop a more complex multivariate approach synthesizing many data streams (Wu and Zhang, 2003), identifying patterns from noisy data (Leung et al., 2014), and/or reducing long time series to key and compact features (Lee and Staneva, 2020).

DISCUSSION

Using this case study focused on Gulf Stream dynamics, we showed the utility of multidisciplinary collaboration of ECS using open-source data from a range of locations and sensor networks. Further, this work was performed across institutional and geographic boundaries, within a resource-limited environment and much of it during a global pandemic. In addition to insights into physical and biogeochemical processes across time and spatial scales, we demonstrated how ECS can overcome challenges in accessing and analyzing OOI data through close collaboration and interdisciplinary skill sharing.

Data synthesis is necessary to address ocean science questions, but interpretation of interdisciplinary data requires a variety of expertise. For instance, knowledge of the geographic region or system, instruments and sensor capabilities, data access, analysis, and visualization can all be compiled within a diverse research team. Within this project, our team consisted of ECS whose areas of expertise include physical, chemical, and biological oceanography, data science, marine geophysics, and coastal geology (**Table 2**). The inclusion of varied mastery enables a more comprehensive understanding of a system. This integrated outcome has been shown across research fields (Hall et al., 2018).

Open data has the potential to promote such integrative and collaborative interdisciplinary research, particularly among ECS (e.g., Carpenter et al., 2009). Although ocean science has been historically considered collaborative, ECS are particularly well-suited to move forward using team science. Formal team science (Bennett and Gadlin, 2012) allows for collaborative groups to form that span a wide range of skills and expertise. By engaging diverse scientists with differing skill sets from design to interpretation, we engendered a holistic approach to this study, which allowed scientists without an extensive background specifically in atmospheric or ocean science to explore air-sea interactions. This model also facilitated lateral mentorship and skill sharing, learning from the expertise of team members, regardless of professional standing. Through these research activities and mentorship, ECS gain skills that extend beyond the expertise of their own communities and the ability to produce more competitive proposals and future publications, potentially influencing the trajectory of their research agenda.

Despite the value of interdisciplinary collaborations, the benefits of participating in collaborative research are typically diminished for ECS. Traditional evaluation and reward systems built around specialization, funding limitations, and the importance placed on first authorship often disincentivize larger collaborative efforts, despite the potential scientific gains (Goring et al., 2014). As was true of the production of this work, ECS are typically not financially supported for research outside of their institute- or grant-directed programs. Thus, the work and time to establish these community-driven collaborations is largely uncompensated, and still requires outside support for expenses such as workshops and publication fees.

The remote nature of multidisciplinary and often cross-institutional collaborations also requires a set of tools for shared project management and execution. In addition to the scientific knowledge and data-specific skill set, we found skill sets such as communication, writing, and project management were imperative to maintaining progress, particularly as research was being done outside of typical institutional support (**Table 2**). Acknowledging these common constraints among ECS and developing guidelines for collaborations (e.g., OOI-ECS Code of Conduct[4]) alleviates many of these challenges by ensuring accountability and equity among collaborators. Additionally, the establishment of a community of practice, unified by a research agenda and shared toolkit (Wenger-Trayner and Wenger-Trayner, 2015), provides a platform for both research and networking that can be conducive to developing important team science skills among ECS. Our collaboration was facilitated by digital communication platforms (e.g., Slack, Zoom; **Table 2**), which allowed a range of interactions (e.g., file sharing/presentation, messaging, small/large meetings). For scientific analysis, a key component of our ability to collaborate remotely and across platforms and coding languages was the use of open-source data and development tools (e.g., Google Drive, GitHub[5]), which demonstrates the potential to implement similar techniques on publicly available computational platforms (e.g., OOICloud[6], Google COLAB[7], and National Research Cloud[8]). Although open access to data is not new, open access to cloud-based

[4]https://ooi-ecs.github.io/COC/

[5]https://github.com/ooi-ecs/ECS-Observatory-Collaboration

[6]https://www.ooicloud.org

[7]https://colab.research.google.com/notebooks/intro.ipynb

[8]https://hai.stanford.edu/blog/national-research-cloud-ensuring-continuation-american-innovation

TABLE 2 | Author skill, knowledge, and toolset contributions needed to conduct remote collaborative research.

Task	Authors	Skillsets/Knowledgebase	Toolsets
Project Development			
Project outlining	All	Communication, scientific writing, project management	Slack, Zoom, Google Docs
Data exploration	All	Data science, coding	Slack, Zoom, Google Colab
Case Study			
Data access	KF, RL, JR	Coding, experience with OOI data portal	Python, MATLAB, GitHub
Data quality assessment	KF, RL, JR	Sensor-specific knowledge, experience with OOI data	Python, MATLAB
Data analysis and interpretation	JR	Air-sea exchange, physical oceanography	MATLAB, Ferret
	KF	Time series analysis, chemical oceanography, biogeochemical cycling	MATLAB
	RL	Region-specific knowledge, biological oceanography	Python
	All	Communication, project management	Slack, Zoom, Google Docs
Manuscript Preparation			
ECS and observatory science	CR, DS, JW	Scientific writing	Google Docs
Case study results and discussion	All	Scientific writing	Google Docs
Figure preparation	All	Communication, graphics	Python, MATLAB, Ferret, Adobe Illustrator, Dropbox, Google Drive, GMT, Microsoft Office
Manuscript revisions	All	Scientific writing, peer review	Google Docs, Microsoft Office
Submission preparation	RL		Microsoft Office

computational resources and technical support from a robust and accessible data science community is lowering the barriers to working with ocean observatories data. These resources also ensure reproducibility and allow researchers to directly engage with datasets and analyses utilized by others in the community. That so much could be accomplished during the COVID-19 pandemic, and with limited traditional resources, illustrates the usefulness of observatory data for those with restricted access to historical oceanographic tools and platforms. This work demonstrates that future research exploring important oceanographic questions can be conducted from anywhere in the world with community-driven resources and tools to support further discovery.

By engaging larger and more diverse communities, we incorporate many perspectives and increase the potential to accelerate data-driven analyses and discoveries from ocean observatory data. The goals and strategies of such a collaboration, in close alignment with the OceanObs'19 Outcomes and Living Action Plan[9], relies on scientific engagement beyond oceanography. Incorporation of data mining expertise and techniques from the data science community would allow expansion of our framework to identify long-term trends in baseline data and provide a better understanding of anthropogenic impacts, such as ocean warming and acidification. The inclusion of biological data, such as species distributions, would further expand the application of observatory data to ocean management decisions (Cocquempot et al., 2019). Beyond marine science and technology, inclusion of law and policy researchers could lead to more effective integration of scientific findings into management, industry, and government actions. Ultimately, scientific endeavors are funded and undertaken in order to provide meaningful benefits to society – incorporating social science, indigenous, and community stakeholder perspectives in future endeavors would enable science that is truly translational, and both considers and highlights the human dimension.

CONCLUSION

1. Interdisciplinary research is most feasible when done as collaborative work among scientists with diverse specialties.
2. Collaborative research among ECS provides an opportunity to share and develop new skill sets while producing effective science that benefits from the inclusion of varied perspectives and skill sets. This range of insight increases the potential for scientific discovery and the application of findings.
3. Openly available ocean data provided by observatory systems improves the equity of access to scientific data for both research and education.
4. Open-access tools and software for data access, analysis, and peer-to-peer communication help facilitate collaborative research.
5. Institutional support and expanding the knowledge pool for such collaborative projects is needed to address global issues and maximize the potential of observatory systems.

[9]http://www.oceanobs19.net/living-action-plan/

DATA AVAILABILITY STATEMENT

Three publicly available datasets were used for the case study. The data for the OOI Pioneer Array can be accessed via the OOI Data Portal (first accessed 10 March 2020, https://ooinet.oceanobservatories.org/data_access/#CP). World Ocean Atlas 18 climatology is available via the National Oceanographic and Atmospheric Administration National Centers for Environmental Information (first accessed 27 April 2020, https://www.nodc.noaa.gov/OC5/woa18/woa18data.html). Satellite-derived sea surface temperature can be accessed via Jet Propulsion Laboratory's PODAAC Group for High Resolution SSTs (GHRSST) Level 4 MUR (first accessed 27 April 2020, https://podaac.jpl.nasa.gov/dataset/MUR-JPL-L4-GLOB-v4.1). The data, code, and further documentation of analyses are available at https://github.com/ooi-ecs/ECS-Observatory-Collaboration. An archive of all materials used in this study are included in Levine et al. (2020).

AUTHOR CONTRIBUTIONS

CR, DS, and JW were responsible for the "Introduction" and "Discussion." KF, RL, and JR were responsible for the "Methods for Case Study" and "Case Study Results and Discussion." Additional details of contributions can be found in **Table 2**. All authors contributed to the interpretation of case study findings, improved the manuscript, approved it for submission, and design and planning of the project.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.593512/full#supplementary-material

Supplementary Figure 1 | Satellite sea surface temperature (SST,°C) observed on **(A)** 14 November, **(B)** 16 November, and **(C)** 18 November during the passing of Event 1. SST observed on **(D)** 26 November, **(E)** 28 November, and **(F)** 30 November during the passing of Event 2. SST measurements are gridded to 1 km resolution, see section "Auxiliary Datasets" for additional details.

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frontiers in Marine Science

ORIGINAL RESEARCH
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An Assessment of How Australian Fisheries Management Plans Account for Climate Change Impacts

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For Australian fisheries to remain productive and sustainable (environmentally and commercially), there is a need to incorporate climate change considerations into management and planning, and to implement planned climate adaptation options. Here, we determine the extent to which Australian state fisheries management documents consider issues relating to climate change, as well as how frequently climate change is considered a research funding priority within fisheries research in Australia. We conduct a content analysis of fisheries management documents investigating categories and themes relating to Australian state fisheries, climate, and environmental change. We also reviewed recent Research Priorities from the major fisheries research funding body for reference to climate change related themes, and the number of subsequently funded projects which considered climate change or related topics. Results show that commercial state fisheries management documents consider climate only to a limited degree in comparison to other topics, with less than one-quarter of all fisheries management documents having content relating to climate. However, we find that the south-east and south-west regions of the Australian coastline have the highest incorporation of "climate" and "environmental protection considerations" in their fisheries management documents, and that fisheries are more likely to have more "climate-related mentions" within their related management documents, if they (i) primarily target species with higher economic commercial catch values, (ii) commercial catch weights, or (iii) a greater number of commercial fish stocks existing. Only a small number of recently funded fisheries research projects considered climate change, representing only a small proportion of fisheries research investment. Given the extensive climate-driven impacts recently documented among key Australian fisheries species and associated ecosystems, we conclude that there is a clear need for fisheries management in Australia to consider longer-term climate adaptation strategies for Australian commercial state fisheries to remain sustainable into the future. We suggest that without additional climate-related fisheries research and funding, many Australian agencies and fisheries may not be prepared for the impacts and subsequent adaptation efforts required for sustainable fisheries under climate change.

Keywords: adaptation, climate change, fisheries research, fisheries management, research priorities

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INTRODUCTION

Climate change is already having significant impacts on oceans globally, and this is affecting commercial (Brander, 2010; Cheung, 2018), recreational (Townhill et al., 2019), and Indigenous (Johnson and Welch, 2015; Sarkar et al., 2018) fisheries around the world (Barange et al., 2018). Many of the effects of climate change are greatest where waters are warming the fastest (Poloczanska et al., 2013), and Australia has some of the fast warming marine regions in the world (Hobday and Pecl, 2014). The south-east and south-west Australian coastlines are particularly vulnerable to the effects of climate change, due to rapid warming in these regions (Hobday and Pecl, 2014). Within these regions climate change is affecting marine systems and marine-dependent users (van Putten et al., 2016), including fisheries, through changes to the physical and chemical properties of the ocean, including water temperature, salinity, and acidity, as well as current and upwelling strength, for example (Brierley and Kingsford, 2009; Hobday and Lough, 2011; Pörtner et al., 2014; Weatherdon et al., 2016). In turn climate change can lead to changes in species characteristics, most commonly affecting species distribution, abundance, and phenology (Brierley and Kingsford, 2009; Johnson et al., 2011; Pecl et al., 2014b). Where harvest species are affected (directly or indirectly, e.g., indirectly via prey species or habitat being affected), this can lead to significant impacts on fisheries, causing changes to fishing location, duration or jurisdictional management processes (Hobday et al., 2018). We know fishers are already starting to adapt autonomously (Pecl et al., 2019a), and where adaptation options are available (Pecl et al., 2014a; Cheung et al., 2018; Ogier et al., 2020; Pinsky et al., 2020) they should be considered in all relevant areas of planning and management.

Australian commercial wild-catch fisheries are an important industry within Australia, employing ∼11,000 people (in fishing, hunting and trapping; **Figure 1**), and contributing significantly to the 341,272 tons of seafood eaten by Australians, and 50,741 tons (AUD1.58 billion) of exported edible seafood in 2017–18 (Steven et al., 2020). Wild-catch fisheries make up the majority of the gross value production (GVP) relating to commercial fishing and aquaculture industries (173,434 tons valued at AUD1.79 billion; 56% of economic value and 64% of weight of total Australian seafood production; **Figure 1**), with state wild-catch making up most of that production (122,344 tons valued at AUD1.40 billion; Steven et al., 2020). For fisheries to be productive and sustainable (both environmentally and commercially) into the future, fisheries management needs to be informed, flexible, and adaptive to respond to current and future climate changes (Hobday and Cvitanovic, 2017; Hobday et al., 2018). As climate change is likely to worsen existing fisheries management challenges (McIlgorm et al., 2010; Sumaila et al., 2011), it is an important factor to consider and address within management (Brown et al., 2012; Ogier et al., 2016). However, adaptation options need to be assessed in the context of current development and governance goals, as objectives may differ for various stakeholder groups (McIlgorm et al., 2010; Jennings et al., 2016).

Incorporating climate research and adaptation into fisheries management plans and practices will be a vital component to successful fisheries management, although this alone will not be sufficient to avoid or minimize all impacts of climate change on fisheries. In a country with an established and highly productive fisheries research sector (Hobday and Cvitanovic, 2017), climate-related literature relating to Australia's main fisheries harvest species still has large gaps (Pecl et al., 2014b), with only a third of species having any research on the biological or socio-ecological implications of climate change at all (Fogarty et al., 2019). Climate-related research effort among Australian fisheries species to date appears to be related to the number of fish stocks per species, and commercial catch weight, meaning that species fished on a larger scale tend to have greater investments of climate-related research effort (Fogarty et al., 2019). Fisheries research in Australia is funded by a variety of sources, however, applied fisheries research is largely organized by the Fisheries Research and Development Corporation (FRDC), which is a co-funded partnership between the Australian Government and the fishing and aquaculture sectors. Other fisheries research is funded by the Australian Research Council, however, this tends to be further from tactical needs (Ling and Hobday, 2018), and so is not covered here.

While the knowledge gaps relating to climate-focused fisheries research in Australian are documented (Fogarty et al., 2019), the extent to which climate change considerations are currently incorporated into fisheries management plans, or the degree to which climate research is a priority area within Australian fisheries research, has not been assessed. Filling this gap is important to also understand how prepared Australian fisheries managers and agencies are for the impacts of climate change to ensure the long-term sustainability of the sector. Thus, this study investigates (i) how extensively Australian state fisheries management plans and other directive management documents incorporate climate change (or climate variability) into current strategies and considerations, i.e., the willingness and preparedness to adapt to and/or consider climate change, and (ii) the extent that relevant research is being conducted and tactically funded in Australia that could inform fisheries management decisions, by examining the FRDC Research Priorities and funded research projects to see how many priorities and projects (underway and completed) include references to climate change.

METHODS

To address the aims of this study we used quantitative content analysis (as described in Bryman, 2012; Coe and Scacco, 2017)—a research method that systematically categorizes attributes of written text, visual, and aural material for analysis (e.g., Cvitanovic et al., 2014; Vourvachis and Woodward, 2015; Stecula and Merkley, 2019). Two sets of documents were analyzed to investigate the extent to which Australian commercial state fisheries consider long-term environmental changes such as

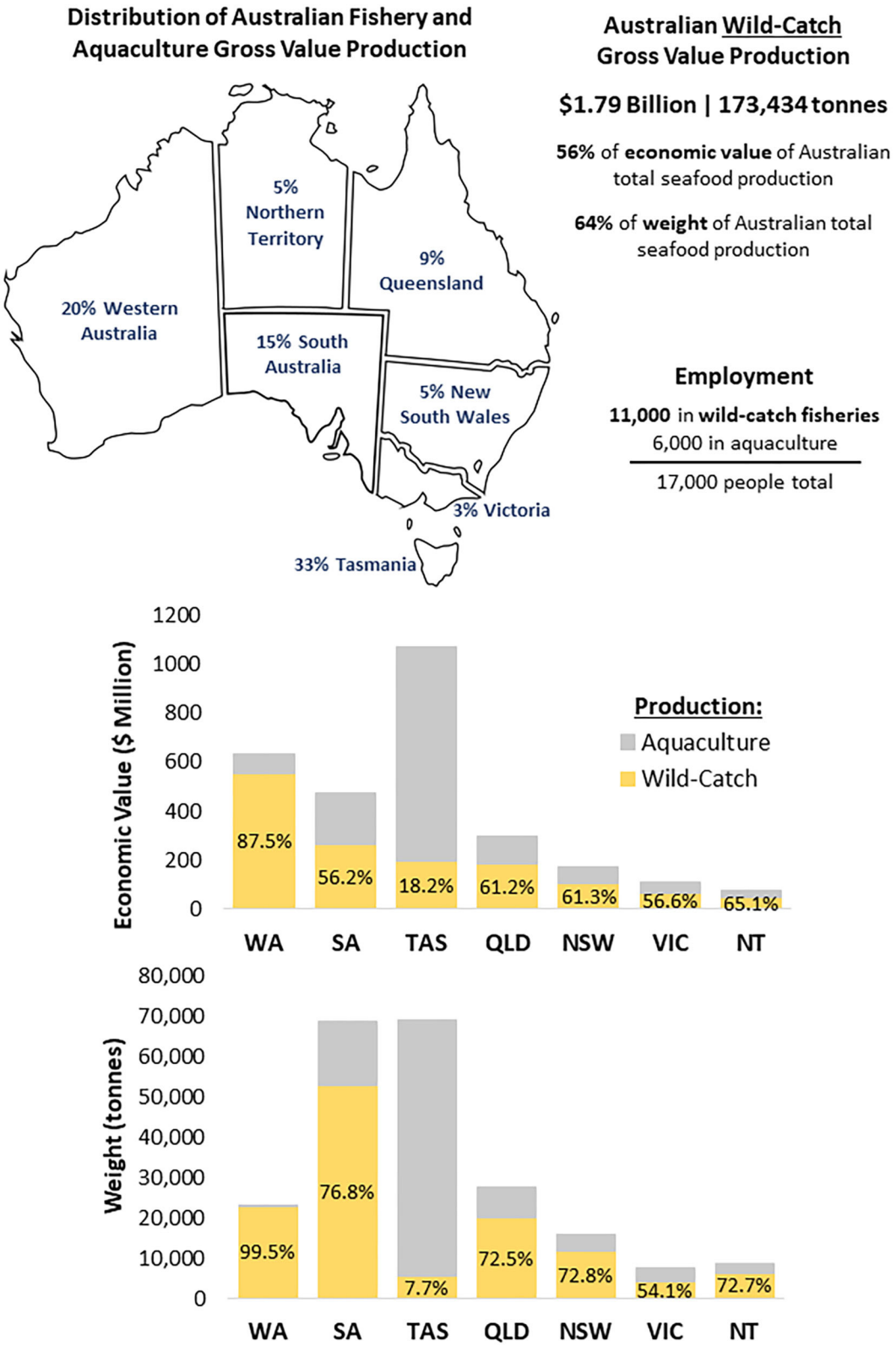

FIGURE 1 | Australian fisheries statistics for the 2017–18 fishing season, including Gross Value Production (GVP) and employment figures. Data labels over bar graphs show the wild-catch proportions of state seafood (fishery and aquaculture) production. Data from Steven et al. (2020).

climate change. The first were fisheries management documents that relate to Australian State fisheries. The second set of documents are those relating to FRDC research priorities, to understand the extent to which climate change related fisheries research is has been proposed and funded in Australia.

Fisheries Management Documents

The management documents that were included in the analysis were for species previously identified in Fogarty et al. (2019), which compiled a list of 99 species relevant to Australian fisheries from four national climate change and fisheries reports (Pecl et al., 2011; Welch et al., 2014; Caputi et al., 2015; Fulton et al., 2018). These species formed the basis of our analysis as they are the main commercially harvested species in Australian wild-catch fisheries. We compiled a list of state fisheries management documents gathered through searches on Australian state government websites, and individual searches of fisheries and target species (**Online Resource 1**). Here, we define "management documents" as the collective group of directive management documents we assessed, which included a wide range of document types (e.g., management plans, regulations, harvest strategies, etc.). Management documents were excluded where the document did not mention "commercial" fisheries, but were included where they alluded to the fact that they included commercial fisheries (i.e., they did not specifically rule out commercial fisheries as included, or they did not state that they were in reference to only non-commercial fisheries), and/or it was already known the document encompassed commercial fisheries. We used the latest available version of each management document, as many had been updated from their original format, and the latest versions were the most likely to include climate-related mentions. See **Figure 2** for a flow diagram for methods on investigating the extent that climate is included in fisheries management documents.

Content analysis of management documents was performed using NVIVO in two stages. First, all management documents were analyzed to understand their publication details. That is; the year of original publication of the management document; the year of publication of the most updated version of the document; the Australian state in which management document was published; type of management document (i.e., Act, Regulation, Rules, Management Plan, Management Strategy, Harvest Strategy, Operational Guidelines, Action Plan, Control Rules, Policy, or Policy and Procedure); and the Hierarchical Level of the Document [i.e., (1) Higher-Level = Acts, Regulations, Rules; (2) Mid-Level = Policy, Procedure, Guidelines, Harvest Strategy, Control Rules, Resource Report, Resource Allocation Report, Operational Guidelines, Strategy, Strategic Research Plan, Action Plan, Resource Sharing Framework; and (3) Lower-Level = Management Plan, Management Arrangements, Management Framework].

The second stage of the content analysis was focused on identifying specific mentions relating to "climate," to determine the frequency of their occurrence within the documents. To help with consistency and robustness of our methods, we used pre-determined terms to search the management documents for climate-related mentions (see **Online Resource 2** for the full list of search terms). Where these search terms were identified in text, they were then verified as correctly referencing climate and not another topic (for example, the term "impact" may have been discussing any range of impacts on a fishery or environment, not just climate impacts). Climate-related mentions were divided into four pre-determined categories: (i) "Direct Climate Mention;" (ii) "Indirect Climate Mention" (where climate-related topics were mentioned); and (iii) "Direct Climate Action;" and (iv) "Indirect Climate Action" (where actions either had knowledge to be acted upon, or involved reviewing the knowledge to identify new responses). In addition, we noted where the management document incorporated "Environmental Protection Considerations," such as implementing a "precautionary approach," or "ecosystem-based approach" (i.e., references relating to "environment," "precaution," and "protect," were all considered for this category). Climate-related mentions within each of these four pre-determined categories were further divided into "Overarching Themes" and "Sub-Themes," to identify trends within the data. Metrics used in this analysis included the total number of documents included the number of documents with climate mentions (direct or indirect), the number of documents with climate-related mentions (including "climate actions"), the number of documents with mentions on environmental protection considerations, the number of direct climate mentions, the number of indirect climate mentions, and state wild-catch production value (AUD million) (Mobsby, 2018).

To determine whether there were any relationships between fisheries species and the number of climate-related mentions in management documents, we first identified the target species groups and/or fisheries that were addressed in each management document, and categorized the management documents by those species groups or broader groupings. These were (1) "Single-Species Groups" (i.e., these management documents addressed the management of a single fisheries species or species group, such as abalone, crab, etc.), (2) "Multi-Species Groups" (i.e., these management documents addressed the management of one fishery that targets multiple species or species groups, such as commercial dive, finfish, or shellfish fisheries, etc.), and (3) "Multi-Fisheries" (i.e., these management documents addressed the management of multiple fisheries that targeted multiple species, such as developmental, trawl, or all state-wide fisheries, etc.). We then investigated the degree of climate preparedness relative to other fisheries categories using "Climate Sensitivity Scores" to climate change for individual species as assessed in a previous study (Fogarty et al., 2019), and calculated the "Number of Management Documents," "Number of Climate Mentions," "Number of Climate Actions," and the "Number of Environmental Protection Considerations" for each of the three fisheries categories above.

Next, we looked more closely at the individual fisheries species that could be assigned to Single-Species Groups (i.e., species that had or could be included in the "Single-Species Management Documents"), from the list of 99 Australian fisheries species (see Fogarty et al., 2019). We then calculated the "Number of Management Documents," "Number of Climate

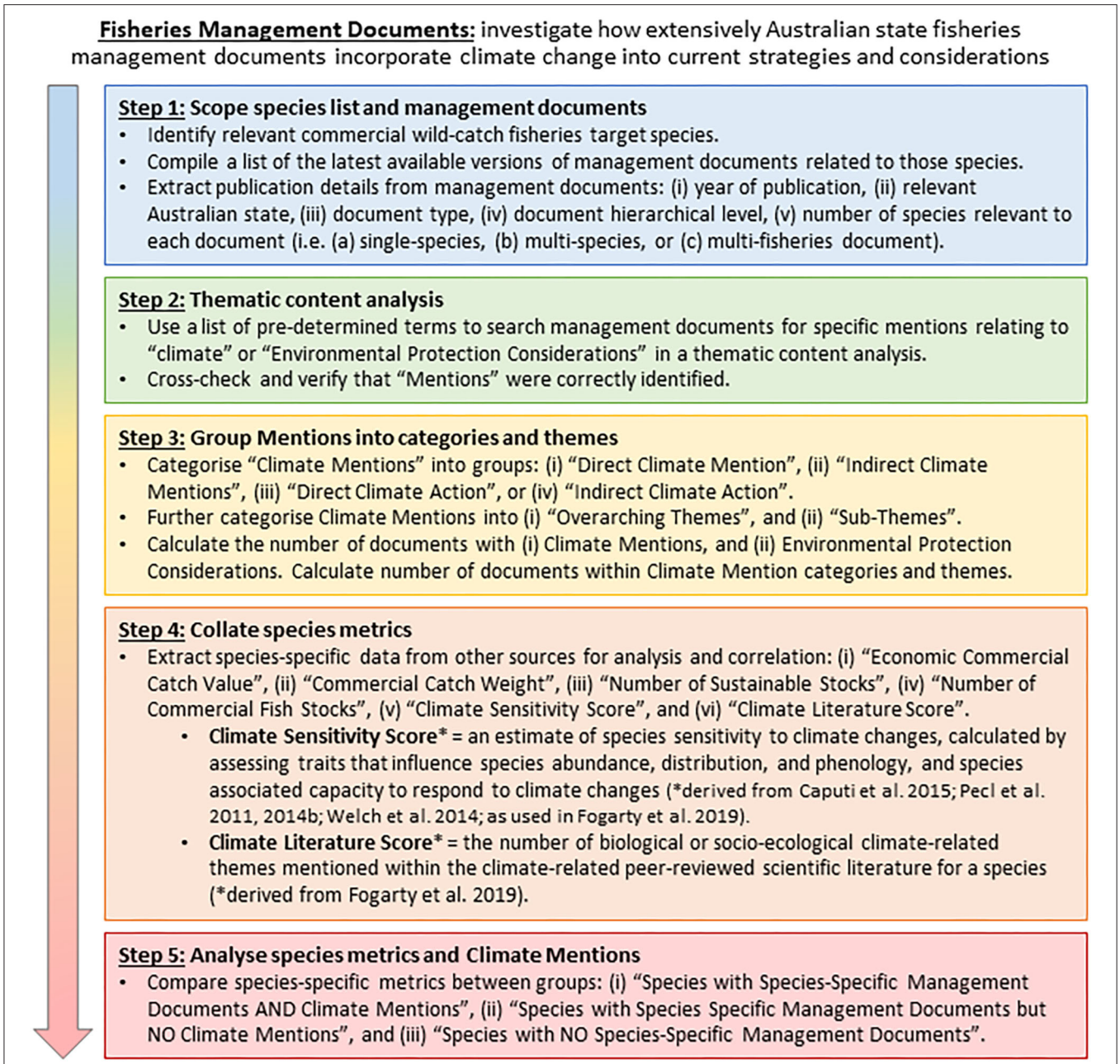

FIGURE 2 | Flow diagram summarizing the methods used for investigating the extent to which "climate" and climate-related themes are mentioned within Australian state fisheries management plans and other directive documents, and what factors may influence frequencies.

Mentions," and the "Number of Environmental Protection Considerations" for each Single-Species Group. Where available, we collected or assigned metric data for the Single-Species Groups, including "Economic Commercial Catch Value ($'000)" and "Commercial Catch Weight (tons)" (from Mobsby, 2018 in Fogarty et al., 2019), the "Number of Sustainable Stocks" (i.e., the number of sustainable or recovering commercial fish stocks, including Commonwealth stocks) and the "Number of Commercial Fish Stocks" (i.e., the total number of fish stocks, including Commonwealth stocks, that the species group had) [both collected in the Fogarty et al. (2019) study from the Status of Australian Fish Stocks Reports (SAFS; www.fish.gov.au); SAFS data is displayed as species-specific, but data for some species is not yet available], "Commercial Catch Weight (tons)" [i.e., commercial catch volume (tons), also collected in the in the Fogarty et al. (2019) study from the Status of Australian Fish Stocks Reports (SAFS; www.fish.gov.au)] was listed for individual

species, and was used in metric comparisons for the Single-Species Groups.

Single-Species Groups were also assigned a "Climate Sensitivity Score," which was an estimate of species sensitivity to climate changes, calculated by assessing traits and other factors that influence species abundance, distribution, and phenology, and their associated capacity to respond to climate changes, and therefore their level of risk [i.e., (1) low sensitivity-high capacity, (2) medium sensitivity-medium capacity, or (3) high sensitivity-low capacity]. Each species was allocated a score out of a possible maximum Climate Sensitivity Score of nine (from Pecl et al., 2011, 2014b; Welch et al., 2014; Caputi et al., 2015; as used by Fogarty et al., 2019). Where species occurred in multiple regions, the species Climate Sensitivity Scores sometimes differed according to regional differences, in which case species were assigned their highest score here for the purposes of this study. Single-Species Groups were also assigned a "Climate Literature Score" for the amount of climate-related peer-reviewed scientific literature discussion a species had (a measure assigned to the individual species in Fogarty et al., 2019, identified there as "Total Literature Score"). This score was calculated from the number of climate-related "themes" that were mentioned within the peer-reviewed literature for each of the 99 fisheries species. There were 20 different themes, related to either the biological or socio-ecological impacts of climate change related to a species. See Fogarty et al. (2019) for full methods on Climate Sensitivity Scores and Climate Literature Scores. We compared these overall metric values for the 99 species divided into three further groups: (i) "Species with Species-Specific Management Documents AND Climate Mentions" (i.e., climate mentions in the management documents), (ii) "Species with Species-Specific Management Documents but NO Climate Mentions," and (iii) "Species with NO Species-Specific Management Documents."

FRDC Research Priorities and Funding

We investigated the extent to which the FRDC (Fisheries Research and Development Corporation) is funding climate-related fisheries research, which could be used to inform fisheries management climate adaptations. Firstly, we investigated how many climate-related research priority areas have been identified in recent years through applications for research priority areas to the FRDC by various jurisdictions (i.e., research advisory bodies/committees, subprograms, and reference groups). We compiled a list of recent FRDC Calls for Applications for Research Priorities which were supplied to the authors by the FRDC. We assessed nine Calls for Research Priorities over 7 years (2013, 2014, 2015, 2016, 2017, 2017 May, 2017 Nov, 2018 Apr, and 2019 Apr), and we present the data here as years with multiple calls combined to just the year (i.e., we combined the 2017, 2017 May, and 2017 Nov calls as "2017"). Years prior to 2013 were unavailable for comprehensive assessment. We then conducted a second content analysis in NVIVO of these Research Priorities, searching for climate-relevance using the same pre-determined search terms identified earlier for the first management documents content analysis. See **Figure 3** for flow diagram of methods for investigating FRDC research priorities and projects. See **Online Resource 3** for a list of jurisdictions and climate-related FRDC research proposals.

Next, we investigated the number of climate-related research projects (underway or completed) that have been funded by the FRDC (i.e., through Tactical Research Funding). Climate-related projects were extracted from the FRDC website (FRDC "Marine climate change adaptation projects" http://www.frdc.com.au/Industry-and-Environment/Climate-change/Marine-climate-change-adaption-projects accessed 10/4/2019; and FRDC "Climate Adaptation Program" http://www.frdc.com.au/en/Industry-and-Environment/Climate-change/Climate-Adaptation-Program accessed 10/04/2019). In addition, the FRDC provided the authors a list of all FRDC funded projects (both completed and underway), omitting administration projects and projects with IP restrictions, from which we extracted projects between 2009 to mid-2019. See **Online Resource 4** for a list of the climate-related FRDC-funded research projects.

After establishing a relative level of priority given to "climate change" as a research topic funded by the FRDC, we collated the text from the "Topic," "Objectives," "Need," and "Background" sections of all FRDC funded research project proposals (1,208 projects) between 2009 and 2019 (supplied to us as a list by the FRDC), and used it to conduct a keyword search, from which we determined the number of times a word was used (i.e., "keywords"). The text was converted to all lower-case to minimize duplication of words based on the case used, and "filler" words (i.e., words which helped to complete a sentence, e.g., "will," "need," "can," "within," "including," "using," etc.), plurals or word variations (leaving the word with the highest use, e.g., "results," "result," "resulted," "resulting," etc.) were removed. Next, we looked at the keywords that were used in the project proposals more frequently than the word "climate" (i.e., had a higher weighted value). We further removed less informative words that did not add any richness or context to the research topics (for example, "FRDC," "aquatic," "Australian," "national," "species," etc. did not add richness to the research topics). The remaining top keywords were then grouped by color into similar or relating themes, to reveal trends in research topics. To provide further context of the in-text use of these keywords, we searched for key word combinations (*key phrases*) using the search function ("Ctrl+F") in Microsoft Word, and noted the number of times keywords such as "climate" were used in conjunction with other words. See **Online Resource 5** for a list of other commonly used keyword combinations and their frequencies.

RESULTS

Analysis of Fisheries Management Documents

Of the 125 Australian state fisheries management documents included in the content analysis, 37 (29.6%) made no mention of "climate," or "Environmental Protection Considerations" (**Figure 4A**). Another 25 documents (20%) mentioned both "climate" and "Environmental Protection Considerations" and

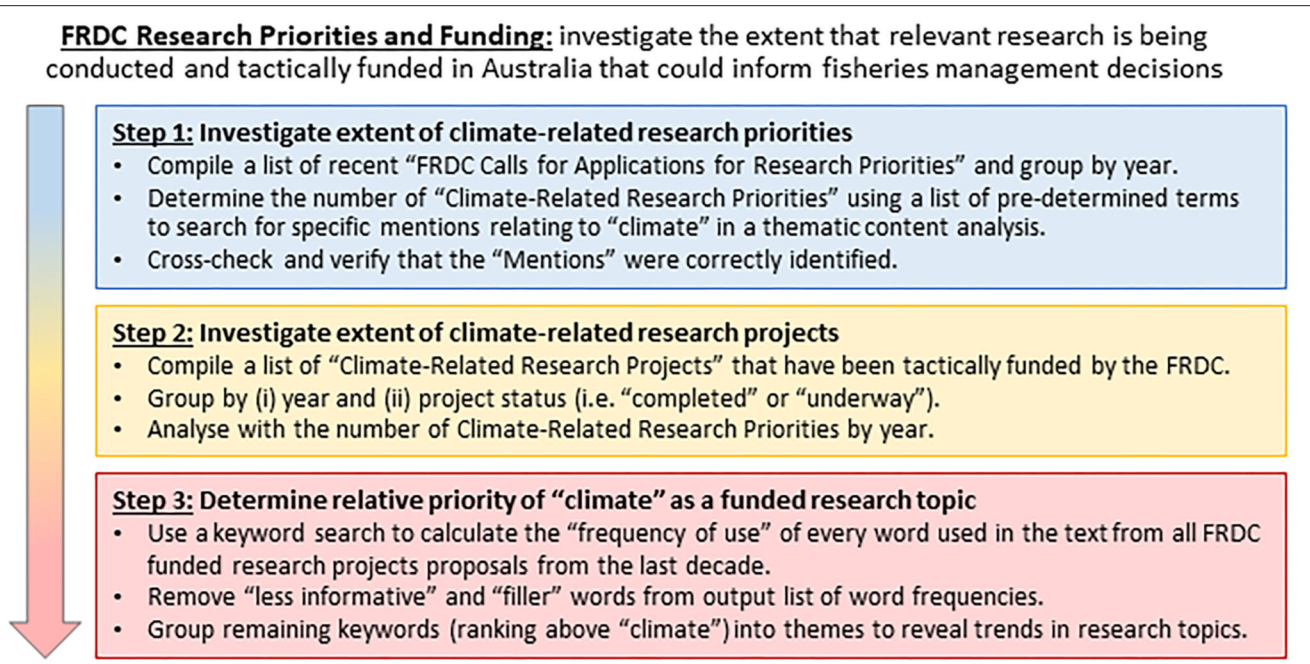

FIGURE 3 | Flow diagram summarizing the methods used for investigating the FRDC research priorities and tactically funded projects for climate-related mentions, and to determine the relative priority level of "climate" as a funded research topic.

were more likely to be Mid-Level or Lower-Level documents, primarily from South Australia, followed by Victoria and Queensland (**Figure 4**). Meanwhile, 98 documents (78.4%) did not mention "climate" and were more likely to be recent and Higher-Level documents, mostly from Tasmania, Western Australia, New South Wales, and the Northern Territory (**Figure 4**). We found 86 documents (68.8%) mentioned "Environmental Protection Considerations," increasing with year of publication, and were proportionately mostly Mid-Level documents from Western Australia, followed by New South Wales and Northern Territory (**Figure 4**). The Northern Territory was the only region to have no climate-related mentions at all, followed by Tasmania having only 2 documents with climate-related mentions (**Figure 4D**). However, 81.8% of Northern Territory documents did mention Environmental Protection Considerations (**Figure 4D**). As the number of documents produced increased over the study period, the proportion of documents mentioning climate decreased, even though the actual number of documents mentioning climate increased (**Figure 4B**, **Online Resource 1**). See **Online Resource 1** for more details on the fisheries management documents included in this study.

Results of the content analysis showed there were 108 individual climate-related mentions (total) from the 27 management documents *with* climate-related mentions, divided into 14 overarching themes (total), and 52 sub-themes (total) (**Tables 1**, **2**). The category "Direct Climate Mentions" had 44 mentions from 20 fisheries management documents, split into 7 overarching themes and 19 sub-themes (detailed in **Table 1**). Meanwhile, "Indirect Climate Mentions" had 35 mentions from 18 management documents, split into 3 overarching themes and 24 sub-themes (detailed in **Table 1**). "Indirect Climate Actions" had 29 mentions from 11 management documents, split into 4 overarching themes and 9 sub-themes, making up just under a third of all climate-related mentions (detailed in **Table 2**). We found no mentions to be classed as "Direct Climate Actions," as we found no actions aimed at specifically addressing or adapting to the effects of climate change on fisheries.

Investigating these categories more closely, we found the most frequent "direct" reference to climate within the management documents was identifying climate change as a key threat to fisheries, followed by themes of management considerations and goals to respond to climate change (**Table 1**). "Indirectly," the most frequent reference to climate related to identifying oceanographic conditions as risks affecting fisheries performance (**Table 1**). Actions to ("indirectly") address climate change predominantly focused on fisheries and ecosystem management changes that could be implemented, followed by increasing and improving research on climate change (**Table 2**). Perhaps unsurprisingly, 24% of the indirect climate actions identified were to "review the threat of climate change in a few years or at the next major assessment" (**Table 2**).

When investigating the fisheries management documents in relation to the fisheries species more specifically (i.e., 99 Australian fisheries species previously identified), we grouped the management documents into 19 "Single-Species Groups," 13 "Multi-Species Groups," and five "Multi-Fisheries" categories. Single-Species Groups and Multi-Fisheries had a similar number of management documents, while Multi-Species Groups had just less than half of these (**Figure 5**). The Number of Climate

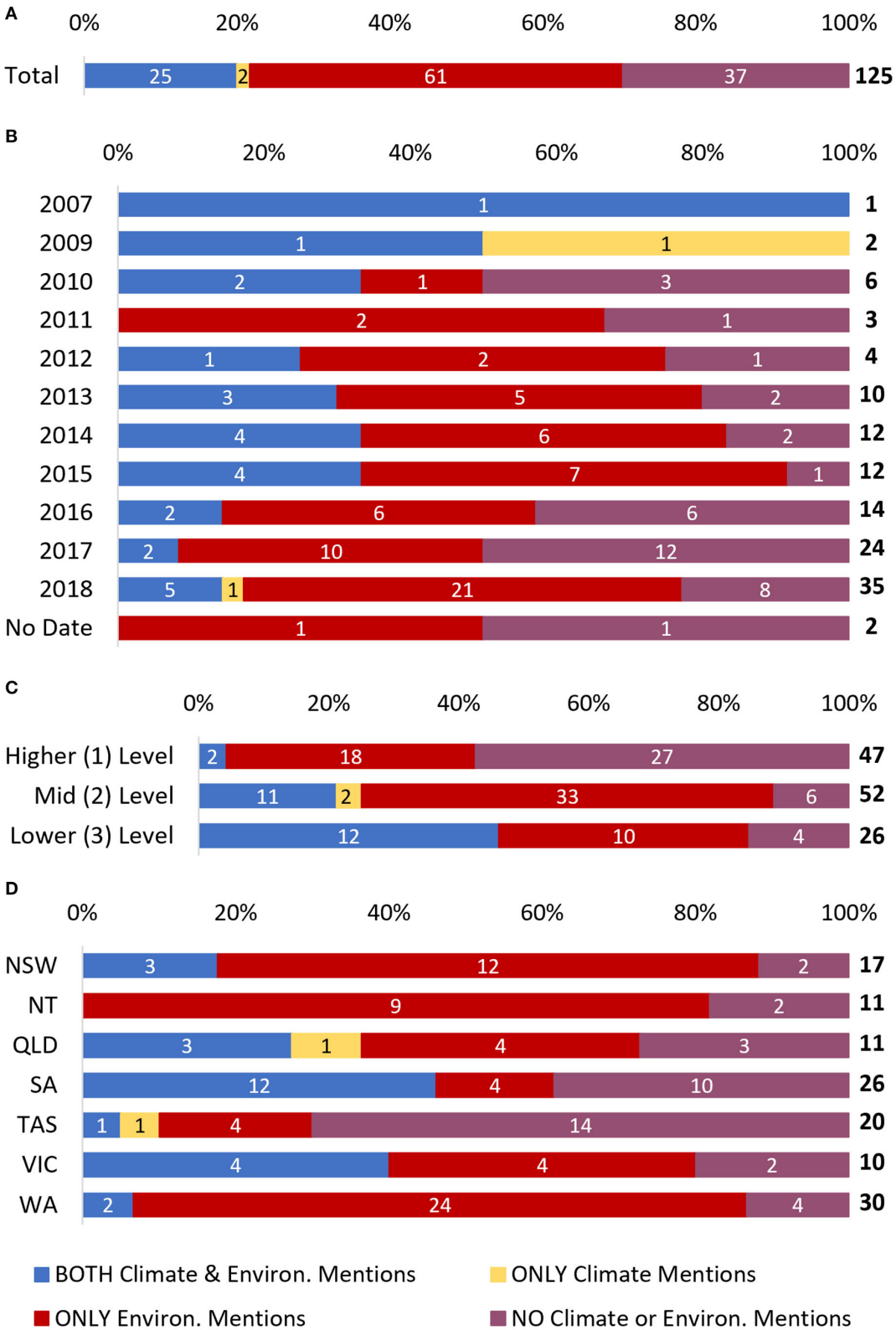

FIGURE 4 | The percentage and count of the number of fisheries management documents with climate-related mentions ("climate"), mentions of environmental protection considerations ("environ."), or none of the above, separated by; **(A)** All documents as one group; **(B)** The year of publication of the current document version; **(C)** Hierarchical level of management document; and **(D)** Australian state where the document is relevant to. NSW, New South Wales; NT, Northern Territory; QLD, Queensland; SA, South Australia; TAS, Tasmania; VIC, Victoria; WA, Western Australia. Data labels represent the count of documents for each category, with the labels to the right of the bars representing the overall counts of management documents.

TABLE 1 | The numbers of "direct climate mentions" and "indirect climate mentions" identified in the content analysis of the fisheries management documents, detailed by overarching theme and sub-themes.

Overarching themes	Sub-themes	Mentions (*n*)
	Direct climate mentions	
1. Climate change as a key threat to fisheries	1.1. Climate change is a key process threatening fisheries	9
	1.2. Issue = climate change; Risk/Priority = High	7
	1.3. Issue = climate change; Risk/Importance Rating = Moderate	4
	1.4. Issue = climate change; Risk/Priority = Negligible	2
	1.5. Climate change: high risk rating; development of objectives and management strategies that directly mitigate the effects of climate change is limited, and therefore the risk is not referred to in objectives and strategies	1 (Theme 1 Total Mentions = 23)
2. Management goals to respond to climate change	2.1 Goal: Management adaptive to climate change	4
	2.2 Operators to have clear contingency plans in place to respond to climate change events	1 (Theme 2 Total Mentions = 5)
3. Considerations for management of climate change	3.1 Avoiding/taking into account the effects of development on climate change	3
	3.2 Knowledge area for effective management: impacts of climate change	1
	3.3 Key consideration for management: climate change/climate-induced events; Unsuitable for management within this policy	1 (Theme 3 Total Mentions = 5)
4. Climate changes lead to changes in species dynamics and habitats	4.1 Climate change affects long-term sustainability of fishery/species	2
	4.2 Transition in ocean currents/climate leads to varied/complex habitats and species	1
	4.3 Climate variability: risk affecting water temperature and ocean currents, leads to changes in species survival, growth rates, and distribution	1 (Theme 4 Total Mentions = 4)
5. Buffers against climate change impacts	5.1 Refugia definition = habitats where fish are able to survive the impacts of climate change	2
	5.2 Stock rebuilding as a buffer against climate change	1 (Theme 5 Total Mentions = 3)
6. Climate change definition as physical oceanographic changes/intricately related to other physical factors	6.1 Climate change: altering ocean temperature, chemistry, sea level, storm frequency and severity, amount of freshwater entering aquatic systems and patterns of regional oceanography	1
	6.2 Climate is intricately linked to other physical factors	1 (Theme 6 Total Mentions = 2)
7. Climate change studies/research	7.1 Department involved in regional climate change studies	1
	7.2 Area a critical baseline to measure climate change effects	1 (Theme 7 Total Mentions = 2)
Total overarching themes = 7	**Total sub-themes = 19**	**Total mentions = 44**
	Indirect climate mentions	
1. Issue = Oceanographic conditions (water temperature, weather, upwelling) affecting performance of fishery [-20pt]	1.1. Issue = Weather; Risk/Priority = Moderate	4
	1.2. Issue = Oceanographic conditions; Risk = Moderate	2
	1.3. Issue = Oceanographic, Temperature, Weather; Risk = Moderate	2
	1.4. Issue = Oceanographic (Temp, Weather, Upwellings); Risk/Priority = Moderate	2
	1.5. Issue = Temperature; Risk = Moderate	2
	1.6. Issue = Upwelling; Risk = Extreme	2
	1.7. Issue = Upwelling; Risk/Priority = Moderate	1
	1.8. Issue = Temperature, Weather, Upwelling; Risk/Priority = Negligible	1
	1.9. Fishery subject to oceanic influences, including bad weather (swell and wind), and cold upwelling events	1
	1.10. Fishery/catch weather dependent—access to certain areas	1
	1.11. Changing ocean temperatures and strengthening of the EAC may lead to a significant shift in the distribution of many marine species	1
	1.12. Distribution influenced by wind patterns and tidal currents	1 (Theme 1 Total Mentions = 20)
2. Goal/Recommendation for environmental/ecosystem drivers/changes to be considered in fishery management	2.1. Goal—Manage fishery as part of the broader ecosystem	2

(Continued)

TABLE 1 | Continued

Direct climate mentions		
Overarching themes	**Sub-themes**	**Mentions (*n*)**
	2.2. Glossary: Environmentally limited stock—biomass reduced due to environmental change	2
	2.3. Management considerations: changing environmental conditions/environmental changes	2
	2.4. Management considerations: Environmental changes, habitat changes, effects of weather	1
	2.5. Environmental drivers to be considered in management	1
	2.6. Ecosystem changes to be considered in management	1
		(Theme 2 Total Mentions = 9)
3. Extreme/adverse events/conditions affecting fishery, species, and area	3.1. Species vulnerable to natural catastrophic environmental impacts: freshwater floods, temperature extremes	1
	3.2. Area vulnerable/susceptible to environmental impacts/changes	1
	3.3. A resilient system will bounce back from adverse environmental conditions (floods, bleaching, cyclones)	1
	3.4. Fishery impacted by extreme stress events: bleaching events	1
	3.5. Issue = Stormwater, Hypersalinity (desaliation); Risk/Priority = Low	1
	3.6. Sea level rise—setback coastal development	1
		(Theme 3 Total Mentions = 6)
Total overarching themes = 3	**Total sub-themes = 24**	**Total mentions = 35**

"Mentions (n)" in column 3 = the number of "climate-related mentions" found that related to each category. "(Total=n)" = the sum of "climate-related mentions" in each overarching theme. Sub-Themes listed are variations of quotes lifted from the management documents.

Mentions, Climate Actions, and Environmental Protection Considerations identified within the documents were all mostly from Single-Species Group management documents (**Figure 5**). In addition to having a high number of management documents, Multi-Fisheries also had middle values of Climate Mentions and Environmental Protection Considerations (still proportionately high) but had the lowest number of Climate Actions.

One third (34 of 99) of species from the list of Australian fisheries species could be assigned into the "19 Single-Species Groups" that had management documents relating specifically to them or their species groups. Of these 34 individual species, 19 (making up nine Single-Species Groups) had Climate Mentions within management documents, while 25 individual species (17 Single-Species Groups) had Environmental Protection Considerations mentioned within management documents relating specifically to them or their species group (**Figure 6**). Additionally, a second grouping of 19 (out of the 34) individual species were also found to have "peer reviewed climate-related species literature" in Fogarty et al. (2019). Of these two different groups of 19 individual species, 13 species overlapped, having both Climate Mentions in their management documents *and* climate-related species literature in Fogarty et al. (2019). These 13 individual species were from five Single-Species Groups "Abalone," "Crab," "Lobster," "Prawn," and "Sardines," of which the first four Single-Species Groups had the majority of management documents (58%), Climate Mentions (61.5%) and/or Environmental Protection Considerations (60.5%; **Figure 6**). Furthermore, 16 of the 65 individual species in the present study without *single-species* management documents did have climate-related species literature in Fogarty et al. (2019). These 16 individual species, however, were almost all Perciformes ("Perch-like") fish species (e.g., finfish), and therefore their management was covered by management documents for Multi-Species Groups and/or Multi-Fisheries.

Of the 19 Single-Species Groups with management documents, "Economic Commercial Catch Value" and "Commercial Catch Weight" data were located for 11 species groups (Mobsby, 2018), while the "Number of Commercial Fish Stocks" data were located for eight (from SAFS, www.fish.gov.au), and Climate Sensitivity Scores were assigned for 12 species groups. Among the Single-Species Groups data, we found the strongest apparent relationship between having higher Economic Commercial Catch Value, and having more management documents, Climate Mentions and/or Environmental Protection Considerations, as the five Single-Species Groups with both climate-related management *and* climate-related scientific literature (identified above) also held the top five highest Economic Commercial Catch Values (i.e., Economic Values ranking order: 1. *Lobster*, 2. *Prawn*, 3. *Abalone*, 4. *Crab*, 5. *Sardines*, 6. Scallop (italics used to identify the five Single-Species Groups identified earlier); **Figure 6**). In addition, species having increased climate sensitivity (or even having had a Climate Sensitivity Score calculated at all), also tended to have more management documents, Climate Mentions, and/or Environmental Protection Considerations, with four of the five Single-Species Groups noted above ranking within the top six for Species Climate Sensitivity (i.e., Climate Sensitivity ranking order: 1. Sea Cucumber, 2. *Lobster*, 3. *Abalone*, 4. *Prawn*, 5. Scallop, 6. *Crab*; **Figure 6**). Furthermore,

TABLE 2 | The numbers of "indirect climate actions" identified in the content analysis of the fisheries management documents, detailed by overarching themes and sub-themes.

Indirect climate actions		
Overarching themes	**Sub-themes**	**Mentions (*n*)**
1. Fisheries and ecosystem management changes: influence and implement management processes	1.1. Management: set annual TACC within sustainable levels; precaution/precautionary principle	4
	1.2. Develop flexible fisheries to adapt to change	3
	1.3. Influence other management processes that impact on ecologically sustainable development of the fishery	2
	1.4. Combination management: develop flexible fisheries, influence other management processes, set TACC precaution, ensure sufficient information to inform management decisions	2 (Theme 1 Total Mentions = 11)
2. Increase and improve research on climate change	2.1. Promote, support, and undertake additional research	5
	2.2. Ensure sufficient information for informed management decision (e.g., surveys)	2
	2.3. Monitor environmental changes	2 (Theme 2 Total Mentions = 9)
3. Review threat in a few years/at next major assessment	3.1. Review threat in a few years/at next major assessment	7 (Theme 3 Total Mentions = 7)
4. Increase/promote engagement between fisheries managers and RD&E, water resource management agencies, and infrastructure authorities, etc.	4.1. Increase/promote engagement between fisheries managers and RD&E, water resource management agencies, and infrastructure authorities, etc.	2 (Theme 4 Total Mentions = 2)
Total overarching themes = 4	**Total sub-themes = 9**	**Total mentions = 29**

"Mentions (n)" in column 3 = the number of "climate-related mentions" found that related to each category. "(Total=n)" = the sum of "climate-related mentions" in each overarching theme. Note: no "Direct Climate Actions" were found in any documents. Sub-Themes listed are variations of quotes lifted from the management documents.

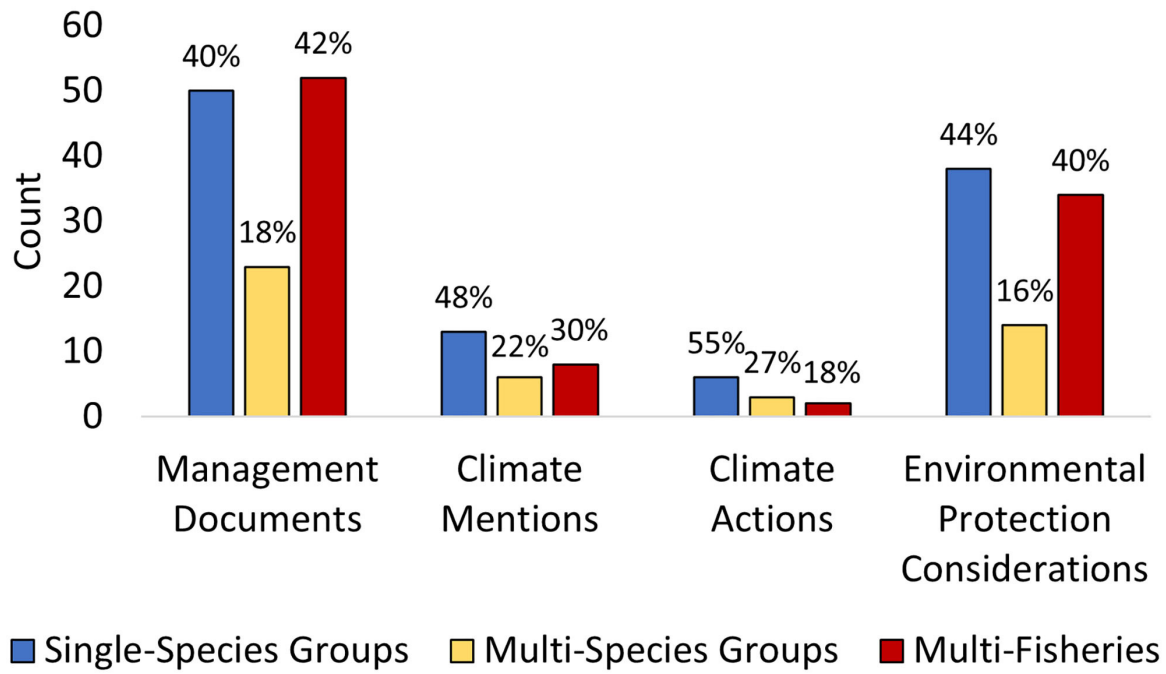

FIGURE 5 | The numbers (and proportions) of Management Documents, Climate Mentions, Climate Actions, and Environmental Protection Considerations for (1) Single-Species Groups, (2) Multi-Species Groups, and (3) Multi-Fisheries.

these five Single-Species Groups were also among the top six Single-Species Groups with the highest Commercial Catch Weights (i.e., Catch Weights ranking order: 1. *Sardines*, 2. *Prawn*, 3. *Lobster*, 4. Scallop, 5. *Crab*, 6. *Abalone*; **Figure 6**), and three of these five groups had the highest Number of Commercial Fish Stocks (i.e., Fish Stocks ranking order: 1.

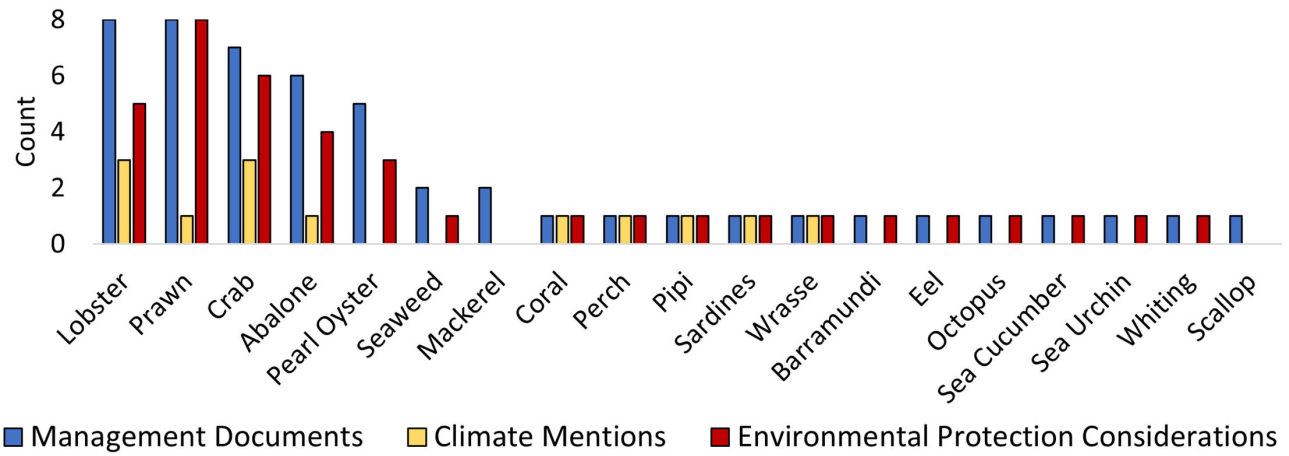

FIGURE 6 | The Number of Management Documents, Climate Mentions, and Environmental Protection Considerations for each of the 19 Single-Species Groups. Species name orders are by highest to lowest Number of Management Documents, then by highest to lowest Number of Climate Mentions, and then by highest to lowest Number of Environmental Protection Considerations.

Prawn, 2. *Crab*, 3. *Abalone*, 4. Mackerel, 5. Barramundi, 6. Whiting; **Figure 6**).

Finally, we compared metrics from Fogarty et al. (2019) between three groups for the 99 individual fisheries species: (1) "Species *with* Species-Specific Management Documents AND Climate Mentions" (19 of 99 species); (2) "Species *with* Species-Specific Management Documents but NO Climate Mentions" (15 of 99 species); and (3) "Species with NO Species-Specific Management Documents" (65 of 99 species). Species-specific metrics included Climate Sensitivity Score, the Number of Sustainable Stocks, Commercial Catch Weight, and Climate Literature Score. The first group of species (19 species) had the greatest Climate Sensitivity Scores, more sustainable commercial fish stocks, larger Commercial Catch Weights, more Commercial Fish Stocks, and the most peer-reviewed climate-related species literature per species (**Table 3**, first column). Within this first group, 11 species (57.9%) had over 1,000 tons Commercial Catch Weight (from SAFS), while four species (21.1%) were missing catch weight data from SAFS. The second group of species (15 species) held the middle values for Climate Sensitivity Scores, the Number of Sustainable Stocks, Number of Commercial Fish Stocks, and Climate Literature Scores per species, but had the lowest average value for Commercial Catch Weight (**Table 3**, second column). Within this group, only 2 species (13.3%) had over 1,000 tons of commercial catch weight, while four species (26.7%) were missing catch volume data from SAFS. The third group of species (65 species) held the lowest values for Climate Sensitivity Scores, the Number of Sustainable Stocks, the Number of Commercial Fish Stocks, and Climate Literature Scores, but held the middle value for Commercial Catch Weight, partly increased due to a single species outlier (Pilchard) having a much greater Commercial Catch Weight at 38,671.5 tons (**Table 3**, third column). In fact, this group had only six species (9.2%) with Commercial Catch Weights over 1,000 tons, while 38 species (58.5%) were missing catch weight data from SAFS.

FRDC Research Priorities and Funding

From seven years of FRDC Calls for Applications for Research Priorities (a total of nine Calls), there was a total of 351 research priority applications included from a total of 21 jurisdictions (see **Online Resource 3** for list of jurisdictions; not all jurisdictions were included in Calls every year). We found nine research priority applications with a reference to climate (**Online Resource 3**), which were divided into seven "direct" climate references (each proposed by the major state Fisheries Research Advisory Body (FRAB) or Research Advisory Committees (RAC): 1x from Tas FRAB 2014, 1x WA FRAB 2015, 1x Commonwealth RAC 2017, 1x NT RAC 2017, 1x Q RAC 2017 Nov, 1x SA RAC 2017 Nov, 1x Vic RAC 2019 Apr), and 2 "indirect" climate references (1x WA RAC 2015, 1x Tas RAC 2018 Apr). These nine climate-related research priorities identified came from only seven jurisdictions, with New South Wales being the only state with a "jurisdiction" that did not propose a climate-related research priority. With so few climate-related research priority applications it is difficult to see a trend over the years, however, the number of climate-related priorities does mirror the number of jurisdictions and total research priorities each year to some extent, with higher values in 2015 and 2017 (**Figure 7**).

Investigation of the projects funded by the FRDC found 36 completed climate-related projects, and 19 underway climate-related projects between 2009 and 2019, out of 1,208 funded projects assessed (**Online Resource 4**). It is evident that the number of climate-related projects, relative to the total number of FRDC funded projects varies over time, peaking in 2014 and 2015 (11.7 and 11.5% of FRDC funded projects are climate-related, respectively), with the number and proportion of climate-related projects decreasing in the years after, down to between 0 and 1.9% of projects each year (**Figure 7**). The year 2010 follows as having the next highest proportion of climate-related research projects, with 8.8% of projects funded that year being climate-related. Overall, 4.6% of the research projects assessed within the research

TABLE 3 | Mean/modal data for the Climate Sensitivity Score (i.e., a measure of species risk and capacity to respond to climate changes), Number of Sustainable Fish Stocks, Number of Commercial Fish Stocks, and Commercial Catch Weight, for the 99 Australian fisheries species, divided into three categories based on whether they had species-specific management documents and Climate Mentions within those management documents.

	Species with species-specific management documents AND climate mentions (*N* = 19)	Species with species-specific management documents but no climate mentions (*N* = 15)	Species with NO species-specific management documents (*N* = 65)
		Climate Sensitivity Score (_/9)	
Mode	**6.75** (highest = 7.25)	**6.25** (highest = 8)	**5.5** (highest = 7.75)
		Commercial Fish Stocks (SAFS)	
Mean	**5.3** (highest = 13)	**4.1** (highest = 9)	**3.4** (highest = 10)
		Sustainable Stock Status (SAFS)	
Mean	**3.5** (highest = 8)	**3.1** (highest = 7)	**2.1** (highest = 4)
		Commercial Catch Weight (t) (SAFS)	
Mean	**2082.6** (highest = 6,050 t)	**436.9** (highest = 2142.8 t)	**1978.2** (highest = 38671.5 t)
		Climate Literature Score (_/20)	
Mean	**4.5** (highest = 12)	**2.4** (highest = 12)	**0.9** (highest = 11)

Red, highest value; orange, middle value; yellow, lowest value.

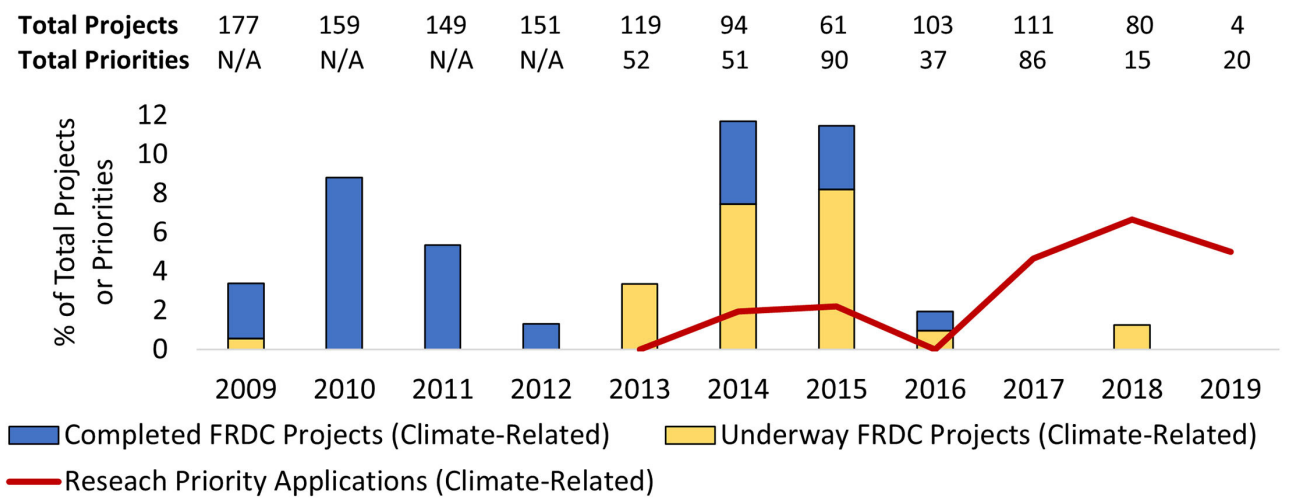

FIGURE 7 | FRDC support in climate-related fisheries research by year (2009–2019), presented as the percentages of completed and underway climate-related research projects, and climate-related research priorities extracted from the FRDC Calls for Applications for Research Priorities each year (2013–April 2019), with data labels above presenting the total number of FRDC funded research projects each year, and the total number of research priority applications overall each year.

period were climate-related, with a mean value of 4.4% calculated from the proportions of projects each year. The number of total projects funded by the FRDC does decline in the latter half of the decade. Additionally, the proportion of climate-related research priority applications significantly increases over time, and it appears that almost no funded climate-related research projects in the last 3 years paradoxically corresponds with an increase in climate-related research priority applications (**Figure 7**).

Investigating which research topics or themes may have been a higher priority than "climate" within fisheries research, "climate" was the 36th most commonly used word within the "Topic," "Objectives," "Need," and "Background" sections of 1208 research projects funded by the FRDC between 2009 and 2019, when all "filler" words and "low context" words (i.e., less informative words) were removed. From a similar theme, "environmental" and "sustainable" placed 20th and 33rd, respectively, in frequency of their use (**Figure 8**). Grouping these top 36 keywords into similar themes or topics showed seven research themes of interest (**Figure 8**). The category "commercial fisheries topics" had the highest number of top keywords identified as relating to the theme (11 keywords), followed by "climate and environmental considerations" (7 keywords), "community (non-commercial) and social aspects of fisheries" (5 keywords), "fisheries management and planning" and "fisheries knowledge and assessments" (both themes with 4 keywords), "fisheries economics" (3 keywords), and "health and disease" (2 keywords; **Figure 8**). Finally, we investigated key phrases using the keywords, in particular "climate," to give more context to the keywords. "Climate-change" was the third most used key phrase that included at least one of the top 36 keywords, with 427 uses,

coming below "fisheries-management" (548 uses), and "seafood-industr(y/ies) (534 uses). Other key phrases identified that used the word "climate," included "climate-varia(bility/tion)" with 18 uses, "changing-climate" with 16 uses, and "climate-impact(s)" with 13 uses. With a similar theme, key phrases identified using the keywords "environmental" and "sustainable" included "environmental-conditions" with 89 uses, "sustainable-development" with 88 uses, "ecologically-sustainable" with 73 uses, "sustainable-fish(ing/eries/ery)" with 54 uses, "sustainable-management" with 48 uses, and "environmental-change(s)" with 32 uses. See **Online Resource 5** for a further list of key phrases.

DISCUSSION

Fisheries Management Documents

In this study we undertook a content analysis of Australian fisheries management documents to assess how they account for and incorporate climate change impacts. Our assessment showed that for wild-catch fisheries only 21.6% of all documents specifically had "climate-related" content, and that these tended to be (i) more recently published; (ii) largely from South Australia, followed by Victoria; and (iii) were Lower-Level or Mid-Level documents (in terms of their directive aims). This was reflected by Single-Species Groups management documents having a greater number of Climate Mentions, while Multi-Species Groups had a large proportion of Climate Mentions in relation to the lower proportion of management documents within that group. Multi-Fisheries documents did however have a high proportion (40%) of the Environmental Protection Considerations that were identified within the text, which may reflect that a fishery that is well managed does not degrade the natural environment, thereby in looking after and responding to environmental changes, fisheries management may simultaneously respond to climate change, as a well-managed fishery is best able to adapt to climate change (McIlgorm et al., 2010; Ogier et al., 2016).

The documents with no mention of "climate" or "Environmental Protection Considerations" were predominantly from Tasmania and South Australia. In contrast, the Northern Territory, Western Australia, and New South Wales did have a high proportion of documents with Environmental Protection Considerations, which may indicate that climate is more indirectly addressed and incorporated into their respective management strategies. It is therefore worth noting that a state having little-to-no mention of climate in their fisheries management documents may not necessarily mean that they do not have ground-level actions in place that assist their adaptation to climate change, or that they are unprepared for climate change, but rather it may be a reflection of the style of writing and/or format the management documents are written in. For example, many of the Tasmanian management documents related to specific fisheries, but were set out as legislation, and therefore did not provide the same background information and/or deeper context that other state management documents did. This may be a result of comparative resourcing and funding allocations to fisheries management departments in each state, which would allow for deeper contextual management documents. Resourcing and funding levels in each state may be influenced by GVP proportions that wild-catch fisheries account for in each state, for example, although Tasmania has the highest total seafood GVP (33%) in Australia, Tasmanian wild-catch fisheries have the third highest dollar value (AUD194.3 million) of all Australian states (behind Western Australia and South Australia), and proportionately the lowest catch value (18.2%) and weight (7.7%) of any state (**Figure 1**; Steven et al., 2020). However, how relative fisheries resourcing and funding levels influences management in each state requires further investigation into the future.

Another interesting correlation is that the fastest warming waters in Australia are the south-east and south-west coastlines (Hobday and Pecl, 2014), which tended to have higher proportions of climate-related mentions and Environmental Protection Consideration. These two climate "hotspot" regions include the coastlines of South Australia and Victoria, which had the two highest proportions of climate-related mentions, and New South Wales and Western Australia, which had the two highest proportions of Environmental Protection Considerations, therefore potentially indicating that climate vulnerability may factor into respective climate preparedness and adaption implementation (Ling and Hobday, 2018). Species climate sensitivity has also previously been found to have a positive influence on research effort, as species with higher industry value or importance are more likely to have higher (and more accurately determined) climate sensitivity scores (Fogarty et al., 2019). Similarly, we find here that species with higher climate sensitivity are also likely to have higher numbers of management documents, and Climate Mentions and Environmental Protections Considerations mentioned within the management documents. This could be interpreted positively, as greater climate considerations are desirable for more climate-vulnerable species. However, it would also be beneficial to increasingly incorporate climate adaptations into more (if not all) species fisheries management documents, as there are still climate-vulnerable species with no Climate Mentions and/or species-specific management documents.

After thematically categorizing the individual climate-related mentions from the content analysis of the management documents, we found "Direct Climate Mentions" to be the largest category, followed by "Indirect Climate Mentions." The most frequent "direct" references to climate within the management documents were identifying climate change as a key threat to fisheries, and management considerations or goals to respond to climate change, while the most frequent "indirect" reference to climate related to identifying oceanographic conditions as risks affecting fisheries performance. Actions to ("indirectly") address climate change predominantly focused on fisheries and ecosystem management changes that could be implemented, as well as increasing and improving research on climate change. In addition, one-quarter of the indirect climate actions identified were to "review the threat of climate change in a few years or at the next major assessment," which means that on ground climate adaptation for that fishery is still some time away. Similarly, another recent study also found a lack of climate action within management plans of Regional Fisheries Bodies (RFB), with a large portion of RFBs placing climate change "permanently

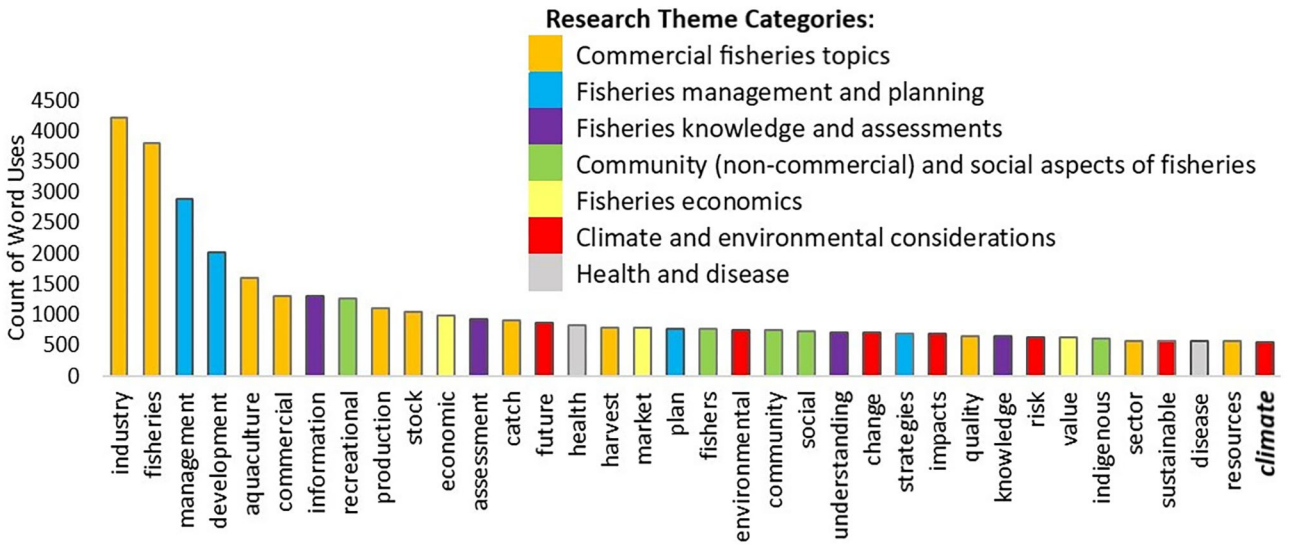

FIGURE 8 | The count of uses of the top 36 most *informative* keywords including and above "climate" (i.e., filler words and *less* informative words removed). Colors represent seven categories of similar or related research themes.

on the agenda for attention" (Sumby et al., 2021). It is likely the uncertainty of climate change which encourages the use of short planning horizons to focus on immediate problems, and supports the dangerous idea that mitigating actions can wait until more information is available (McIlgorm et al., 2010). Although different species and fisheries have differing levels of vulnerability or sensitivity to climate change, there is an increasing need to increase the frequency of inclusion of Climate Mentions and Climate Actions within fisheries management documents.

The combination of results from the current study and Fogarty et al. (2019) indicates that economically important fisheries species are more likely to be better prepared for climate change in terms of scientific climate knowledge availability as well as climate management implementation/adaptations. We also found a correlation between species having climate-related peer-reviewed scientific information available, and those species having more climate-related content identified within their respective management documents, meaning that species with more climate-related peer-reviewed literature available also had associated management documents that were more scientifically informed on climate changes. This finding reinforces the importance of having scientifically informed fisheries management to allow for better preparation and adaptation to climate change. Further investigation of the individual Australian fisheries species that the management documents might relate to found that of the 34 species (out of 99) which could be assigned to the Single-Species Group, 56% (19 species) had Climate Mentions within those management documents. We also found another 19 species within the Single-Species Groups that had climate-related species literature published, of which 13 species overlapped having both Climate Mentions within management documents in the current study, *and* peer-reviewed climate-related species literature in Fogarty et al. (2019). These were identified as species of abalone, crab, lobster, prawn, and sardines, and we therefore determine that their respective fisheries are the most prepared or equipped to adapt to climate change, in terms of knowledge and implementation. These five Single-Species Groups also had some of the highest Economic Commercial Catch Values, Commercial Catch Weights, and Numbers of Commercial Fish Stocks, indicating that these factors, in particular Economic Catch Value and Commercial Catch Weight, may influence which species have the most climate-prepared fisheries management. This is a similar result to our previous study (Fogarty et al., 2019) which found these factors influenced species climate-related research effort and direction, that these species were also more likely to have higher climate sensitivity and were less likely to have species data missing from the SAFS database, compared with other species assessed. It is possible that species *with* Climate Mentions in this study having higher proportions of sustainable fish stocks is due to the fact they also have more peer-reviewed climate-related literature available (Fogarty et al., 2019), *and* Climate Mentions within their management documents, therefore leading to better management of these fisheries. Species *with* Climate Mentions are also likely to be "more important" fisheries species, as they had greater Commercial Catch Weights, and have more resources (i.e., time and money) invested into better management of those fisheries. Furthermore, species that did not yet have data in the SAFS database were most likely to have no species-specific management documents, indicating that those species are "less important" to the fishing industry.

Based on our analysis, we argue that the fishing industry would benefit from having proactive policies which pre-emptively put in place planned emergency responses and adaptations for climate change, in addition to other management directives. The lack of climate-related mentions in fisheries management documents assessed here may be reflective of: (i) insufficient knowledge exchange among scientists and managers about the

ways we can manage climate change in Australian fisheries; (ii) lack of political will for addressing climate change; and/or (iii) a lack of adaptive capacity within fisheries management due to many of the management documents being older and updated so infrequently that there is no scope to revise them as new knowledge is generated. Mechanisms to overcome some of these issues include implementing strategies that foster greater collaboration and knowledge exchange among fisheries scientists and managers (i.e., principles underpinning successful knowledge exchange between marine scientists and decision-makers are provided by Cvitanovic et al., 2016; Hobday and Cvitanovic, 2017). For example, through institutional level changes that facilitate and promote engagement activities such as those embodied by notions of co-production (Norström et al., 2020), using "hot desk" rotations of staff from other institutions (i.e., "embedding," see Roux et al., 2019), increasing boundary organizations (Cvitanovic et al., 2018), and by increasing the use of knowledge brokers to act between institutions (Fazey et al., 2012; Cvitanovic et al., 2015). Directing a more concerted effort toward engaging a wide range of stakeholders (e.g., the public) to foster support for climate-ready fishery policies and programs may also overcome some of these barriers and encourage adaptive capacity (Hobday and Cvitanovic, 2017; Le Cornu et al., 2018).

FRDC Research Priorities and Funding

The FRDC has annual targets for research expenditure for five program areas, being 40% Environment, 40% Industry, 10% People, 8% Adoption, and 2% Communities (FRDC, 2015). Climate-related projects may fall within any of these five program areas, however, the FRDC expenditure in the Environment program area is relatively high, and likely includes projects researching environmental protection. This does not necessarily mean that climate-related fisheries research is not occurring within Australia, as research may be occurring that is funded within universities, state fisheries departments or the R&D departments of fishing companies, rather than by the FRDC. However, the low levels we find in this study suggest that there is currently a lack of up-to-date climate-related fisheries research available to inform fisheries managers and decision-makers on fisheries adaptations to climate change in Australia, although some regions (such as the south-east and western Australian coasts) are more prepared than others (Fogarty et al., 2019). As the number of climate-related research priority applications submitted to the FRDC, and FRDC-funded climate-related research projects are low in recent years, it may indicate that climate is not a high priority when it comes to fisheries research in Australia. This could be because (i) climate change is not considered the most pressing issue by FRDC, (ii) Australia already has a strong legacy of fisheries climate science and FRDC want to invest in other things, (iii) climate change is not yet a high priority topic for fisheries stakeholders and communities, and/or (iv) previous climate-relating funding cycles have led to the perception that climate research has been "done" already.

Our study shows keywords such as "climate" and "environment" were not discussed at the same frequencies as more common topics such as fisheries "production" and "stock" within research priority applications submitted to the FRDC. Even so, we found two peaks in the number of climate-related FRDC-funded research projects in our analysis which may be explained by several concerted efforts to boost climate-related fisheries research around those times. For example, the National Climate Change Adaptation Research Facility (NCCARF) was established in 2007, and its' key role is to coordinate the development of National Climate Change Adaptation Research Plans (NARPs) across a range of priority areas (Hobday et al., 2017). One of these priority areas was addressed by the Marine NARP in 2010 (Mapstone et al., 2010), which has since been updated twice (Holbrook et al., 2012; Hobday et al., 2017). The Marine NARP identified research knowledge gaps with respect to helping marine systems adapt to climate change, and developed research priority questions to enable researchers to focus their efforts on filling these gaps. Following this, there were 26 Marine NARP-funded research projects undertaken from 2010 to 2015 (described in Creighton et al., 2016), 17 of which addressed priority questions on fisheries. At the same time, the FRDC led and funded the "Climate Adaptation Program" from 2010 to 2014, in partnership with Australian and State Governments, CSIRO, and universities (FRDC, 2020).

In the more recent years since these peak funding periods for climate-related fisheries research, our analysis found only low counts of both FRDC funded projects and priority research topics proposed to the FRDC that related to climate, but a small increase in proportions of climate-related research priorities from 2017 onwards. This is not to say that there has been little climate-related fisheries research, as there has in fact been an increased volume of peer reviewed climate-related species literature from 2012 onwards (Fogarty et al., 2019). The 2017 update of the Marine NARP (Hobday et al., 2017), IPCC Climate Report released in 2018 (IPCC, 2018), 2019 UN Climate Action Summit (United Nations, 2019), and the 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019), may have helped to stimulate and keep interest in climate-related research going. Nevertheless, we find that the injection of funds into climate-related fisheries research in Australia has been limited in recent years (Ling and Hobday, 2018). It is evident that future initiatives like the FRDC-led Climate Adaptation Program or Marine NARP climate research funding will help stimulate climate-related research in the field.

Furthermore, to help funders know where to invest money for Australian fisheries in response to climate change, and to help guide national priorities, we propose that future research may seek to undertake a horizon scan of fisheries research needs in Australia, such as those conducted by Holder et al. (2020) and Wilson et al. (2010), to understand what the key climate-related fisheries questions are. This will in turn lead to an increase in climate-related fisheries literature that fisheries management can draw from when updating management directives. In addition, future research is required to investigate more specifically which topics are discussed more frequently than "climate change" in management documents, research project descriptions, priority applications, or other similar documents, to determine whether research priorities need to be re-evaluated.

The small proportions of climate-related FRDC-funded research and research priority proposals may reflect a deeper

problem than just a lack of climate-related research being funded, but rather that climate change is not yet a priority for fisheries stakeholders and communities, as such, leading to fewer climate-related research projects being proposed, and fewer climate-related research projects to fund. This may be part of a cycle within fisheries management and climate change. For instance, fisheries management does not have many "climate-related mentions" and focuses more on maintaining a sustainable industry by responding to environmental and stock changes (e.g., short-term, annual fluctuations). A component of fisheries management is about managing people and navigating politics (Hoel, 1998; Fulton et al., 2011). As fisheries stakeholder and communities do not yet prioritize climate-research highly, research priority applications largely focus on topics other than climate change, and therefore FRDC does not fund many climate-related fisheries research projects. This leads to fisheries management having access to minimal climate-related fisheries research to inform decisions around climate adaptation, and therefore only incorporating climate change into fisheries management to a limited degree, and so on. However, a well-managed fishery should be capable of easily adapting to climate change through the implementation of flexible management measures that can be rapidly changed to address rapid environmental or stock changes. By increasing community and fisheries stakeholder engagement in climate-related research, we can increase awareness and concern of climate-related marine impacts. For example, citizen science programs such as Redmap Australia (see www.redmap.org.au; Pecl et al., 2019b) have been shown to increase public education and engagement on scientific issues (Nursey-Bray et al., 2017, 2018), by giving participants a sense of ownership over the data they have helped collect (Martin et al., 2016) which is then able to be used by various user groups such as scientists (Pecl et al., 2019b; Adler et al., 2020). By increasing public engagement on the issues of climate change, and how it will affect industries such as fisheries, could be beneficial in increasing funding and resourcing in this area, and improve fisheries "social license to operate" (Kelly et al., 2017; van Putten et al., 2018). Although this research focuses on Australian state wild-catch fisheries, our results may also be relevant to other commercial and recreational fisheries, and aquaculture, both in Australia and internationally.

CONCLUSION

The south-east and south-west regions of the Australian coastline have previously been identified as being "most prepared" to implement climate-related scientific information into fisheries management (Fogarty et al., 2019). Here we find that these two regions also have the highest incorporation of "climate" and "environmental protection considerations" in their fisheries management documents, led by South Australia and Victoria (for climate-related content), and New South Wales and Western Australia (for environmental protection content). We also identify that fisheries are more likely to have more climate-related mentions within their associated management documents, if they target species with (i) a higher Economic Commercial Catch Value (primarily), (ii) higher Commercial Catch Weight, or (iii) greater Number of Commercial Fish Stocks. Overall, although our results may have found that "climate" is not necessarily a highly discussed topic within fisheries management documents, research projects, or priority applications (relative to other topics), it may be assumed that "climate" is captured through the discussion of other related topics (e.g., "environmental protection" or "sustainability"), and that if fisheries are managed well, through flexible and scientifically-informed strategies, then climate change and its' associated impacts may be inadvertently addressed by day-to-day fisheries management. However, we argue that the fishing industry would benefit from also having more proactive policies in place which pre-emptively put in place planned emergency responses and adaptations for climate change. It is also evident that initiatives promoting climate-related research, such as the FRDC-led Climate Adaptation Program, or Marine NARP climate research funding, do help stimulate climate-related research, which has the potential to lead to more expert-informed fisheries management, and therefore fisheries that are better prepared for climate change. We believe that climate-related fisheries research in Australia needs to be accelerated for Australian fisheries management to overcome and adapt to future climate changes. Without climate-related fisheries research and funding continuing and increasing into the future, many management agencies and fisheries may not be adequately prepared for the long-term implications of climate change.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

HF, CC, AH, and GP conceived and designed the study. Data collection and analysis was undertaken by HF, who also led the drafting of the manuscript with input from all authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.591642/full#supplementary-material

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Lessons From the Trenches: Students' Perspectives of Their Own Marine Transdisciplinary Education

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Recent environmental changes have demonstrated that the Earth has entered the Anthropocene. In this new age, complex interactions between human and natural systems exacerbate "wicked problems" that challenge researchers to engage both deep disciplinary expertise and broad integrative knowledge to address these societally relevant problems. Researchers and practitioners are making an increased effort to bridge the divide between human and natural systems research by facilitating multi-, inter-, and transdisciplinary collaborations. Despite 21st century changes to the research environment, the structure of a typical graduate education remains largely unchanged over the past several decades. Wicked problems necessitate communication and collaboration expertise; innovative transdisciplinary training and research opportunities can equip graduate students with these necessary skills. Oregon State University has offered such an opportunity through an NSF-funded Research Traineeship Program (NRT) for students focusing on Risk and Uncertainty Quantification and Communication in Marine Science. Herein, we reflect on the experience of graduate students who successfully completed the NRT and assert that support for transdisciplinary training and research at the graduate stage is urgently needed. We present five lessons learned from our year-long transdisciplinary project focused on the development of an approach for integrating diverse data sets within a social-ecological systems framework to reach a broader understanding of the interconnections between a marine reserve system, people, and the environment. Finally, we present current challenges and paths forward to enhance the success of early career transdisciplinary research.

Keywords: social-ecological systems (SES), graduate education, wicked problems, transdisciplinary training, marine reserves, qualitative network analysis

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INTRODUCTION

Growing populations, large-scale industrialization, increased consumption, and globalization of human systems have drastically altered interconnections between society and the environment. These changes have given rise to the Anthropocene, characterized by global, human-caused environmental changes (Lewis and Maslin, 2015). Complex interconnections currently span

multiple scales and systems, intensifying *wicked problems*: persistent issues that span multiple dimensions (e.g., environment, economics, and human activity), and require collaborative problem-solving (Rittel and Webber, 1973; Jentoft and Chuenpagdee, 2009). The marine environment is rife with wicked problems due to an incomplete understanding of the interconnections between highly dynamic dimensions (e.g., a variable and changing ocean, limited resource pool, and multiple user/knowledge holder groups). Many examples of these wicked problems are globally recognized for their complexity, and include the threats of ocean acidification, prevalence of microplastics, and the sustainability of fisheries (United Nations (UN), 2015).

Traditional disciplinary methods provide a one-dimensional understanding of these complex challenges; this limited perspective is often insufficient to develop effective societal solutions. Therefore, applied scientists, managers, and policymakers are increasingly focused on coordinating collaborative strategies that align multiple knowledge systems at the intersection of multiple dimensions (Blickley et al., 2013). Despite the clear and urgent need for boundary-crossing research, most graduate programs continue to focus on developing deep disciplinary expertise (Ciannelli et al., 2014). As a result, graduate students often lack the necessary skills to integrate across different disciplines and knowledge types, collaborate with non-academics, and pursue diverse career paths (Campbell et al., 2005). A recent report on the status of science, technology, engineering, and mathematics graduate education identified that graduate students are increasingly interested in pursuing careers outside of academia (e.g., government, policy) or working beyond disciplinary interfaces but are lacking the necessary collaboration and communication skills (Cyranoski et al., 2011; Alberts et al., 2014; National Academies of Sciences, Engineering, and Medicine (NASEM), 2018).

In this context, we present the experiences of four graduate students who participated in a National Science Foundation transdisciplinary research traineeship program at Oregon State University (OSU). Our team consisted of four graduate students representing disciplinary expertise in ecology, statistics, public policy, and fisheries oceanography. Though each student brought a different perspective to the team (e.g., personal biases, educational background, career path, and degree timeline), we reflected on the context in which we each came to the project and identified the shared vision of incorporating transdisciplinary processes into our dissertations, theses, and future careers. Our experiences illustrate the benefits of early exposure to transdisciplinary research and provide suggestions for the continued implementation of transdisciplinary programs, both of which are necessary to solve wicked problems. In the paper, we summarize differences between disciplinary, multi-, inter-, and transdisciplinary research, present five lessons learned along our path to transdisciplinarity, and reflect on two challenges that underscore the importance of collaboration and communication training. We hope that sharing these experiences will reduce obstacles for future transdisciplinary endeavors, especially those focused on human-natural systems in marine environments.

A SPECTRUM OF INTEGRATION

Variation in the amount of integration across dimensions exists on a spectrum ranging from disciplinary to transdisciplinary research (Klein, 1990; Rosenfield, 1992). Literature outlines four distinct levels of collaboration along this spectrum: disciplinary, multidisciplinary, interdisciplinary, and transdisciplinary (**Table 1**; Klein, 2014). We define transdisciplinary research as different academic disciplines working together with non-academic collaborators (e.g., stakeholders, practitioners, and tribal nations resource managers) to integrate knowledge and methods to develop and accomplish co-created research goals under one unified conceptual framework (drawing from Stember, 1991; Rosenfield, 1992; Tress et al., 2005; Lang et al., 2012; Mauser et al., 2013; Ciannelli et al., 2014; Kelly et al., 2019). Transdisciplinarity is particularly useful to a research process when the goal is to solve complex or "real-world" problems (Stokols, 2014; Lemos et al., 2018). Additionally, transdisciplinary collaboration may increase in importance as recent societal disruptions impose novel challenges to graduate degree requirements (e.g., COVID-19; Pardo et al., 2020).

TRANSDISCIPLINARY TRAINING FOR GRADUATE STUDENTS

Oregon State University was awarded a grant through the National Science Foundation Research Traineeship Program (hereafter called the NRT) to support transdisciplinary graduate education, facilitate collaborative research, and explore "Risk and Uncertainty Quantification and Communication in Marine Sciences." The NRT aims to engage graduate students in education, professional experiences, and research to address wicked problems in marine systems. Each academic year, the NRT faculty select graduate students who have been in an existing academic program for at least 1 year, and place them, based on their research interests, into transdisciplinary research teams. These teams participate in a year-long training program composed of four elements: (1) an intensive field course, (2) a graduate specialization in risk and uncertainty, (3) an internship, and (4) a collaborative research project culminating in a transdisciplinary report (authored by all the students in the group) and individual interdisciplinary thesis chapters. Training components are centered on three core concepts that are used to characterize wicked problems in the marine environment: Risk and Uncertainty, Big Data, and Coupled Human-Natural Systems.

The NRT recognizes that navigating the pathway to transdisciplinarity is challenging and takes specific action to minimize barriers (Andrews et al., 2020). The research project and the internship facilitate experiential learning and are valuable opportunities for students to develop new skills, build confidence, and make professional connections that support their future career goals. Additionally, the NRT connects graduate students to mentors with diverse interests, disciplines, and identities. For graduate students, especially those interested in interdisciplinary research, a successful education depends

TABLE 1 | Spectrum of integration across disciplinary, multi-, inter-, and transdisciplinary collaboration with associated definitions, supporting references, and examples.

Level of collaboration	Definition	References	Level of Integration	Example
Disciplinary	Research conducted in one field of study	Rosenfield, 1992; Stokols et al., 2008	None	A fisheries stock assessment that relies solely on the biological information about the species
Multidisciplinary	Collaboration between researchers from various disciplines to work in parallel on a shared problem	Rosenfield, 1992; Stokols et al., 2008; Disis and Slattery, 2010	None or weak/temporary combination of disciplinary contributions	A fisheries assessment led by a multidisciplinary committee that has an explicit requirement for sociological and economic input from the outset
Interdisciplinary	Researchers from various disciplines collaborate and exchange ideas extensively to meet shared research goals and achieve a real synthesis of approaches	Klein, 1990; Stember, 1991; Tress et al., 2005; Christie, 2011; Clark et al., 2011; O'Rourke et al., 2019; Andrews et al., 2020	Integrate knowledge types, theories, skill sets, and methods across disciplines	Fisheries scientists working with fishing communities, industries, and management agencies to situate problems and propose solutions in dynamic social, cultural, economic, and political contexts of change
Transdisciplinary	Different academic disciplines working together with non-academic collaborators (e.g., stakeholders, practitioners, tribal nations resource managers) to develop and accomplish co-created research goals under one unified conceptual framework	Stember, 1991; Rosenfield, 1992; Tress et al., 2005; Lang et al., 2012; Mauser et al., 2013; Ciannelli et al., 2014; Kelly et al., 2019	Integrate knowledge types, theories, skills sets, and methods among researchers and practitioners	The process of developing a decision support tool for a fishery, where knowledge was drawn from fisheries scientists, social scientists, fishing industry representatives, and federal, state, and tribal resource managers

on the student-faculty relationship (Ellis, 1992; Andrews et al., 2020), and the most effective mentors have experiences in diverse contexts and relationships (Thomas et al., 2007). NRT students are supported by all faculty members engaged in the program, representing over 20 subdisciplines and a variety of career paths.

THE NRT IN RETROSPECT

Our team was initially assigned with integrating data from ecological, human, and oceanographic dimensions to holistically explore the effects of marine protected areas (MPAs) on ecosystems and communities. An MPA is a clearly defined geographical space, recognized, dedicated, and managed to achieve the long-term conservation of nature with associated ecosystem services and cultural values (IUCN WCPA, 2018). Beginning in 2012, Oregon has been implementing MPAs as part of the coastal management strategy. To study these areas, we collaborated with the Oregon Department of Fish and Wildlife Marine Reserves Program (MRP), a state agency who manages Oregon's 11 MPAs. We focused on the five MPAs that prohibit all development and extraction; these are considered fully protected and are hereafter referred to as marine reserves (Lubchenco and Grorud-Colvert, 2015). The goals of Oregon's marine reserve system are threefold: (1) to conserve marine habitats and biodiversity, (2) to serve as scientific reference sites, and (3) to avoid adverse impact to ocean users and coastal communities (Oregon Ocean Policy Advisory Council, 2008). To meet these goals, the MRP employs a variety of scientific tools to monitor the ecological, human, and oceanographic dimensions of the reserve system over time. Marine reserves are dynamic systems that exist at the intersection of ecology, policy, social science, oceanography, and economics, necessitating that our team take an approach that incorporates multiple perspectives and transcends disciplinary boundaries. In our team's partnership with the MRP, we sought to define mutually informative research questions, to develop an approach that could be used to integrate diverse data sets, and ultimately, to contribute to a broader understanding of the interconnections between the marine reserve system, people, and the environment. We achieve this through the development of three tools: a social-ecological system (SES) framework specific to the Oregon marine reserve system, exploratory data visualization of broad trends, and a flexible modeling tool for complex interactions. In this section, we highlight key lessons learned through this transdisciplinary process (**Table 2**).

Lesson #1: Appreciate Process and Retain Flexibility in Outcomes and Products

Many research environments strongly emphasize end-products (e.g., peer-reviewed publications; Goring et al., 2014). In contrast, the structure of the NRT placed emphasis on training and process and provided funding and support for flexible outcomes. This shift in focus is a key enabling condition for transdisciplinary processes (Lang et al., 2012; Angelstam et al., 2013; Brandt et al., 2013); it allowed our team to experiment with different research approaches before agreeing upon research goals and meaningful outcomes. For example, at an advanced stage of our project we recognized that data limitations and system complexities weakened the strength of our methodological approach. Additionally, our team's partnership with a state agency required mutual investment in relationship-building,

TABLE 2 | Benefits, challenges, and supporting practices for five key lessons learned during a year-long, student-led transdisciplinary research project.

Lesson		Benefits	Challenges	Supporting practices
	Appreciate process and retain flexibility in outcomes and products.	• Focus on integrating across multiple dimensions, engage with practitioners, maintain societal relevance • Build lasting relationships	• Institutional focus on end-products • Securing funding for projects with flexible timelines • Relationship building is time consuming	• Institutional rewards for process development • Training-focused programs • Support timeline flexibility • Develop communication competencies • Develop team culture and identity
	Shared conceptual frameworks inspire meaningful communication and integration.	• Align diverse data sets • Identify and investigate novel interconnections • Inform future data collection • Co-create research questions with practitioners	• Multiple types of knowledge, experience, evidence, and data • Relationship building is time consuming	• Use of boundary objects • Review and adapt existing frameworks • Develop communication competencies
	Exploratory data visualization is a powerful method for characterizing broad trends.	• Methodological starting point • Inform future data collection and/or research questions • Elicit multiple perspectives from researchers and practitioners • High-level understanding of system	• Data with multiple temporal and/or spatial scales • Many statistical tools may not be applicable • May not find statistically significant evidence • Iterative, time-intensive process	• Frequent engagement with practitioners to discuss: o Scale of questions o Data aggregation o Expectations for statistical evidence
	Flexible modeling approaches are compelling tools to understand complex interactions.	• Incorporate multiple data types and perspectives • Can have relatively low computing power • Can be user friendly • Simulate several model structures • Measure system responses to simulated perturbation	• Often rely on user assumptions (e.g., literature review or expert knowledge) • Mix of qualitative and quantitative results	• Practice communication of results: o Avoid jargon o Clarify role of user assumptions o Discuss model process and uncertainty
	Maintain relevance for end users throughout the transdisciplinary process.	• Balance scientific credibility with salience and legitimacy to stakeholders • Practitioner empowerment	• Reaching consensus about research process and application of results is time consuming	• Communication and community engagement training • Consider audience values and goals • Identify methods compatible with current management strategies

References are drawn from 'The NRT in Retrospect' and 'Transdisciplinary Education: Challenges and Paths Forward' sections.

which is often challenged by timelines and processes that differ between academics and practitioners (Brandt et al., 2013). These experiences took time; however, we understood from the outset that the significant value added from our transdisciplinary endeavor lays in the process of drawing from multiple dimensions, engaging with practitioners, and maintaining societal relevance (Lang et al., 2012). We suggest that research modifications and relationship building be viewed not as detours that detract from progress toward a fixed product, but instead as necessary elements of transdisciplinary process, and that timeline flexibility is built in accordingly.

Lesson #2: Shared Conceptual Frameworks Inspire Meaningful Communication and Integration

A fundamental challenge of transdisciplinary research is integrating different types of knowledge, experience, evidence, and data to clearly frame a project and co-create research questions with practitioners (Jahn et al., 2012; Lang et al., 2012). Our team identified that using a shared conceptual framework as a shared point of reference, or boundary object (Gorman, 2002), was key. Because our project focused on the ecological, human dimensions, and oceanographic aspects of marine reserves, we used Ostrom's SES framework (Ostrom, 2009) as the grounding theory and boundary object (as in Gurney et al., 2019) for our work, though many other SES frameworks exist (see review by Binder et al., 2013). Ostrom's framework has been applied to several marine systems (e.g., Cinner et al., 2012; Leslie et al., 2015; Martone et al., 2017; Botto-Barrios and Saavedra-Díaz, 2020) and suggests that analyzing the sustainability of an SES requires the description of core subsystems (e.g., Resource Units, Resource System, Governance System, and Users), their interactions, outcomes, and larger ecosystem or socio-political context. Our team coalesced existing data streams from various agencies and institutions (see Lesson #3: Exploratory data visualization is a powerful method for characterizing broad trends) relevant to the Oregon Marine Reserves SES. Through iterative conversations that transcended each of our epistemologies, we reached consensus about the

placement of each data stream within the framework. The significance of this process and product lies in the ability to align diverse data sets, investigate novel interconnections, identify areas for future data collection, and co-create research questions with MRP.

Lesson #3: Exploratory Data Visualization Is a Powerful Method for Characterizing Broad Trends

Transdisciplinary research commonly encounters different types and spatiotemporal scales of data. Our team utilized several datasets related to the marine reserve system: qualitative and quantitative human dimensions data (e.g., wellbeing), ecological data (e.g., species diversity), and oceanographic data (e.g., temperature). Data were collected on seasonal (e.g., visual surveys), annual (e.g., census), and opportunistic (e.g., workshops) time scales, and at different spatial scales ranging from single locations (e.g., oceanographic moorings) to coast-wide (e.g., upwelling). Identifying available features in the data and hypothesizing what relationships may exist can provide a starting point for constructing visualizations. Our team learned that data visualization is an iterative, time-intensive process that facilitates the transdisciplinary process by generating discussion about variable types, spatio-temporal scales, and questions of interest between researchers and practitioners. We found exploratory data visualization to be productive methodological starting point and we propose that it be used as a standardized approach in transdisciplinary research (Brandt et al., 2013).

Many frameworks that evaluate ecological or social change over time require a time-series of predictor and response variables with sufficient replication over space and time to identify statistically significant differences. Our team studied a relatively new marine reserve system with developing monitoring capacity. Marine reserve literature suggested that we should not expect to find statistically significant evidence for change over this time period (Micheli et al., 2004; Babcock et al., 2010; Gill et al., 2017; Nickols et al., 2019). Thus, we focused on high-level integration and asked broad questions (e.g., "What is the effect of the marine reserves system on people and the environment?"). Accordingly, we aggregated data to a high level at the expense of statistical power. We identified broad patterns and trends which were important tools for engaging with experts, eliciting multiple perspectives, and achieving a more holistic understanding of the system. These conversations could then be used to inform future, more specific, research projects where statistically significant evidence is more appropriate. We suggest that transdisciplinary teams dedicate time early in their process to discuss the scale of their questions, appropriate levels of data aggregation, and expectations for statistical evidence with practitioners.

Lesson #4: Flexible Modeling Approaches Are Compelling Tools to Understand Complex Interactions

Flexible modeling techniques, such as qualitative network analysis (QNA), are compelling tools for simulating complex interactions, especially in data limited systems (Melbourne-Thomas et al., 2012; Harvey et al., 2016; Martone et al., 2017). QNA is often used when the data are disparate (e.g., scales are mismatched); thus, user assumptions (e.g., literature review or expert knowledge) inform network characteristics. We developed a hypothetical network where nodes were represented by variables from the ecological, human, and oceanographic dimensions of our SES, and linkages between nodes were informed by literature review. We utilized QNA to simulate interactions in our SES framework by qualitatively measuring the ripple effect of perturbations throughout the network, thereby elucidating system responses.

We recommend that transdisciplinary teams do not overlook flexible modeling tools such as QNA because they can incorporate multiple data types, require relatively low computing power, and can simulate several model structures in real-time. Additionally, user-friendly models provide the unique opportunity to solicit perspectives from different academic disciplines or stakeholder groups and engage in participatory model construction (Kosko, 1986; Gray et al., 2015; Vasslides and Jensen, 2016).

Lesson #5: Maintain Relevance for End Users Throughout the Transdisciplinary Process

The past four lessons emerged, in part, from our dedication to maintaining relevance across a wide range of audiences. From the outset of our project, we intended for our findings and products to support marine reserve management. Consideration of our end users shaped our transdisciplinary experience by encouraging us to embrace a flexible process, identify boundary objects, utilize visual communication tools, and apply methods compatible with current management strategies (Lang et al., 2012; Yates et al., 2015; Kelly et al., 2019; Andrews et al., 2020). These processes, tools, and the conversations they evoked helped to balance the scientific credibility of our research with salience and legitimacy in the eyes of practitioners (in this case, the MRP; Cash et al., 2003), as the definition of transdisciplinarity outlines. The significance of this approach lies in practitioner empowerment (Krütli et al., 2010), a central but challenging goal of transdisciplinary science where practitioners are given decision-making authority in the research process and application of results (Brandt et al., 2013). Therefore, we suggest that transdisciplinary teams consider their audience's values and goals throughout each step of the research process. Transdisciplinary training programs can support this effort through specialized coursework in science communication and community engagement.

TRANSDISCIPLINARY EDUCATION: CHALLENGES AND PATHS FORWARD

Our experiences completing the NRT program highlighted two practical challenges that may face future transdisciplinary educators and students. If they are overcome, transdisciplinarity

is more enjoyable and attainable (Cundill et al., 2019; Kozlowski and Bell, 2019).

Overcoming Disciplinary Differences

Typically, researchers involved in transdisciplinary collaborations have already developed strong disciplinary expertise rooted in subject matter, specialized language, research orientation, and disciplinary culture (Pohl and Hadorn, 2008; Stone, 2014; Szoslak, 2014). After devoting significant time and mental fortitude to a specific discipline, these factors coalesce to shape an epistemology (Stone, 2014). Embarking on transdisciplinary research forces interactions with differing epistemologies, which can be perceived as uncomfortable, adversarial, or even academically disloyal (Bennett and Gadlin, 2019). True transdisciplinarity requires the consideration and appreciation of disciplinary differences in order to transcend disciplinary boundaries and uncover novel solutions (Stone, 2014). While these feelings may be taxing, this challenge cannot be resisted; instead, the solution is to *lean in*. Our experiences and prior research suggests that this solution is most effective when team members practice reflection of their own disciplinary biases, remain open to new ideas, and appreciate and compromise around disciplinary differences (Borrego and Newswander, 2010; Szoslak, 2014; Kelly et al., 2019; O'Rourke et al., 2019).

Conscientious communication provides a foundation for exploring disciplinary boundaries. Many researchers and practitioners encounter communication conflicts within their own discipline; transdisciplinary communication presents unique challenges that compound with these conflicts. Past research highlights various communication competencies that promote constructive dialog among a transdisciplinary team: active listening (National Research Council, 2015; Nurius and Kemp, 2019), avoiding jargon (O'Rourke et al., 2019), reflexivity (Thompson, 2009; Read et al., 2016), identifying boundary objects (Gorman, 2002), and optimizing communication technologies (National Research Council, 2015).

Developing Relationships

Relationship building is a key component of transdisciplinarity because it establishes trust and team cohesion and sets a foundation for the aforementioned communication competencies. With the development of personal relationships comes empathy, understanding, and human connection. Team science literature explains that relationships are created during the forming phase of group development (Tuckman, 1965) and establish a baseline for transdisciplinary interactions. Over time, these deliberate actions create a distinct team culture that persists throughout other stages of team science (Tuckman, 1965; Cheruvelil et al., 2014). Team culture is critical for long-term collaboration because it establishes realistic structure and expectations (Cheruvelil et al., 2014). It also supports a cohesive team identity, which has been positively associated with transdisciplinary team performance (Barsade, 2002; Beal et al., 2003) and negatively associated with team conflict (Bennett and Gadlin, 2019). In our team's experience, building our team culture and identity was a worthwhile time investment, increasing our ability to articulate shared expectations and overcome differences in individual goals and graduate education timeline.

CONCLUSION

The need for transdisciplinary training and research opportunities during the early stages of graduate education is immediate and unavoidable. Wicked problems are only increasing in magnitude and complexity, and the next generation of marine researchers and practitioners must be equipped with collaborative skills to solve them. The challenges we have addressed in this piece confront current academic structures and are intellectually, emotionally, and financially demanding. Their solutions require flexibility, innovation, and endurance. The NRT program represents one possible solution: expanding the scope of OSU graduate education by building institutional capacity (e.g., specialized courses, connection to diverse mentors, and student funding) to support a transdisciplinary research track. In order to support similar transdisciplinary training opportunities, higher education must adapt to support transdisciplinary education. Our experiences as graduate students illustrate the value gained: we have developed the skills and experience necessary to address wicked problems with a transdisciplinary approach and are now poised to use them in our future careers. Finally, it is our hope that by sharing our lessons learned on the path to transdisciplinarity, we inspire conversation and action toward the advancement of transdisciplinary education and research.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors designed and conducted the research. MW coordinated the writing effort. All authors edited and contributed with text.

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Fine-Tuning Climate Resilience in Marine Socio-Ecological Systems: The Need for Accurate Space-Time Representativeness to Identify Relevant Consequences and Responses

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Climate change triggers a wide mosaic of regional and local responses, often different to the large-scale variability in magnitude and direction. Because of the psychological connections (cognitive and emotional) with the frequency, intensity and age of a climatic event, people may have the capacity to recognize key variations at lower scales, especially those from which they perceive risk. Yet, the anticipatory actions and social engagement to respond or adapt to climate change are difficult to achieve, mostly when there exists a long psychological distance to climatic phenomena. Research about climate change communication provides clues about the relevance of place-based discussion to gauge risk perception and improve response protocols, their design and prioritization. It argues that strategies and actions required to face climate risks may widely differ depending on the scale and accuracy of the local representations displayed during discussions of climate impacts. This work examines how local attributes (from climate to social) operate and control place-specific risks and priorities, by comparing coastal communities in two locations, Cabo Pulmo, Mexico and Zanzibar, Tanzania, which are subject to different climate dynamics. This paper discusses the need to identify relevant climate risks/responses at the local level and how psycho-social factors (e.g., psychological distance, collective memory, and social engagement) may operate positively for building climate resilience. We also illustrate a workflow to increase and enhance collaboration between researchers and local people by promoting dialogue, participation and narratives that rigorously consider the local knowledge.

Keywords: socio-ecological resilience, risk perception, climate adaptation, climate risk, coastal communities, adaptive capacity, anticipatory governance

INTRODUCTION

Climate resilience is the multidimensional capacity of the system itself to absorb, adapt and respond to climate risks (Perry et al., 2010; Welle et al., 2014). Building climate resilience in marine social-ecological systems (MSES) is of general interest due to their global importance for food production, livelihoods, and future sustainability (Charles, 2012). The climate may alter the state of marine ecosystems and coastal communities in terms of physics, ecology, economy, security, people health, and wellbeing (Barange et al., 2010). To achieve global resilience depends on resilience at smaller scales, where climate consequences manifest, and also where responses and adaptations occur (IPCC, 2007; Perry et al., 2010). This paper discusses the need to identify relevant climate risks/responses at the local level and how psycho-social factors (e.g., psychological distance, collective memory, and social engagement) may operate positively for building climate resilience.

Representation of Climate Variability and Change

Climate change is not homogeneous on Earth; there is a wide variety of regional and local responses. In many instances, these responses do not follow large-scale trends (IPCC, 2007; Cooney, 2012; Saldívar-Lucio et al., 2015). Conclusions based on predictions from global models can generate inadequate representations of climatic variations for local actors (e.g., managers, coastal people, and fishers, etc.). These smaller scale representations are critical because they are the basis for the recognition and perception of risk for the local response to specific situations (Sheppard et al., 2011) and for taking adaptive action (Shackeley and Deanwood, 2002; Jones et al., 2017). Generally, this problem is exacerbated by incomplete knowledge about local consequences of climate variability together with complicating factors such as the dissemination of inaccurate data (e.g., media misinformation) (Furness et al., 1998; Sheppard, 2005).

Despite notable advances in the simulation of the climate system of our planet, including the possibility to assess multiple scenarios of change (Cooney, 2012), there are well documented difficulties in communicating the potential impacts of climate change. This might be due to the level of abstraction of scientific climate models. A consequence is that people distance themselves from model abstractions or scenarios: they do not mirror their own experiences and perceptions causing a so called "psychological distance." This term refers to things, persons or events that are not registered in the direct experience of reality (Liberman et al., 2007). The psychological distance may vary according to the intensity that any given climatic event impacts on cognitive and emotional components of human psychology (Spence et al., 2012; Trope and Liberman, 2012). When the psychological distance is short (psychologically close), the emotional and cognitive engagement increases, then people may recognize and feel connected to the event. However, if only a vague or long psychological distance (psychologically distant) is generated (e.g., a weak hurricane or a coarse model), people will find it difficult to establish cognitive and emotional connections (Lorenzoni et al., 2007; Steynor et al., 2020).

In this context, some researchers have warned about the possible need of new climate-driven calamities to change the collective perception of risk and induce people and governments to take action (Tickell, 2002). Sheppard (2005) demonstrates that realistic landscape visualizations (showing potential future scenarios) reduce the psychological distance by engaging emotions and may substantially enhance awareness-building about the consequences of climate change. This kind of visualizations may also help to motivate behavioral change at individual and societal levels. However, it has been suggested that climate change representations (e.g., animations or scenarios) should not be chaotic or threatening. Instead they should strengthen the link between people and everyday concerns and emotions (O'Neill and Nicholson-Cole, 2009). Kolb and Kolb (2009) discuss that an experiential learning may be better achieved by focusing on concrete, locally relevant impacts, and responses to climate change.

Risk Perception, Collective Memory, and Social Engagement

Another important consideration in risk perception is the connection between the collective memory and the frequency, magnitude and temporal length of climate events (Bellelli et al., 2007; Viglione et al., 2014). Perry et al. (2010), page 2-3 describe an example of such connection: "*. . .over a typical human life of 50 years in a fishery, a fisher in the Pacific can be expected to experience several ENSO (El Niño Sorthern-Oscillation) events, and at least one event occurring at interdecadal time-scales. Variability on multidecadal and longer time scales may not be experienced by individual fishers but is likely to have been encountered by family forebears and/or by the community, and so will be embedded in local and traditional local knowledge.*" Even when memories of climate impacts may be maintained in the traditional knowledge, the response capacity (if any) will fade out with the gradual increase of the temporal distance of the event (Trope and Liberman, 2012).

The temporal distance, spatial distance, and uncertainty about whether the climate event will happen or not, are key factors defining the perception of climate risks because they govern the psychological distance of individuals and communities with respect to the event. Therefore, psychological distance influences the collective memory and resilience: the more familiarity to particular climate events, the greater the tendency to generate adequate responses by individuals and communities. In contrast, a poor collective memory associated with infrequent events induces higher levels of vulnerability (Steynor et al., 2020).

The psychological distance is also influenced by aspects of communication strategies. For example, there are difficulties with respect to the effective communication of climate threats, partially because narratives are focused on globally catastrophic consequences, implying inadequate representations of local climate dynamics and the corresponding local consequences. Individuals play an important role in responding to climate change, whether they are common citizens, government

representatives, or leaders who can initiate climate action (Wolf and Moser, 2011). But the kind of delocalized communication strategies (inadequate representation of local climate) can seriously increase the psychological distance because of the difference in the communicated message with every day experienced climate conditions. Such difference eventually can induce perception of no climate risks, thus preventing engagement with related topics, policies or activities (Wibeck, 2014; Steynor et al., 2020). In the current context, "engagement" is the personal connection with climate change, comprising cognitive, emotional, and behavioral aspects (Lorenzoni et al., 2007).

In addition to the many factors modulating individual and collective willingness to get involved in climate action, such as collective memory, psychological distance, or social engagement, there is a general gap in knowledge regarding the set of procedures necessary to face particular climatic events (Asrar et al., 2013). This set of procedures or response protocols (defining specific responsive actions) needs to be designed and implemented to co-exist latently with daily life, in order to avoid new climatic tragedies. Developing a good response capacity demands understanding how local climate relates to everyday human perceptions and activities, which is a keystone for building the social engagement required to implement local responses and associated protocols. In this context, the next section shows how local attributes (from climate to social) operate and control place-specific risks and priorities, thus demanding tailored response protocols.

MODELING LOCAL CLIMATE RESPONSES FOR BUILDING RESILIENCE

The Climate Sets the Scene and the (Social) Actors Play Their Roles

We engaged with the questions above by illustrating with two case studies from one of our ongoing projects (The SEAgender project, PI Maricela de la Torre, Stockholm University, all co-authors are participants), both are coastal communities located in tropical seascapes and embedded in a marine protected area (MPA): Cabo Pulmo (México) and Unguja Ukuu (Zanzibar, Tazania; **Supplementary Figure 1**). These two sites were selected for having (to some extent) similarities, but different economic levels, institutional set-ups and donor history. Thus, selection of cases for comparison was done according to the most similar, ecological features, and the most different in terms of developmental levels and socioeconomic activities. We included this comparative exercise (between sites) to exemplify how local characteristics/circumstances determine the consequences of climate events, thus the kind of response and priority required (in all socio-ecological dimensions: form physics to social).

In addition to our previous knowledge on these coastal communities, having worked there for almost two decades, we used direct observations in the field, conversations with local people, group discussions and literature review, to disentangle and conceptualize how local climate dynamics influence on ecological, social and psychological factors (e.g., economic activities and perceptions). Such climatic influences define not only the specific vulnerabilities to climate variability and change, but also provide the necessary clues for fine-tuning adequate responses, as part of local response protocols (a critical tool toward climate resilience).

First we schematized a conceptual model (workflow) to guide a hypothetical process of social-academic interactions (e.g., workshops) for building climate resilience in MSES, by promoting dialogue, meaningful participation and trust (**Figure 1**). All this with the aim of decreasing the psychological distance and ensuring the integration of local perceptions in the process. The proposed workflow in **Figure 1** manifests the need for accurate space-time representativeness for both climate events and local conditions, in order to identify relevant consequences and responses. This is the point at which it becomes relevant the use of place-based representations (e.g., photographs, maps, videos, and documentaries), in order to operate in a desired direction the aforementioned psycho-social factors: psychological distance, collective memory and social engagement.

Then, we simulated a process of identifying and prioritizing risks/responses (**Table 1**), by comparing Cabo Pulmo and Unguja Ukuu. We started aligning climate events to local impacts at multiple temporal scales. At each temporal scale, risks identification was based on the interactions of climate events (first column, **Table 1**) with every dimension of the social-ecological system where there was experience of past events (local knowledge), or documented impacts (literature review). Each climate impact was ranked in magnitude with a corresponding color code (green, yellow and red) and risk level (Low, Medium and High), accordingly to the experience of the locals and/or as a result of group discussions (based on scientific knowledge and experience at the sites). Specific circumstances of each social-ecological system were considered (**Table 1**).

From these exercises, we obtained a list of ranked climate risks, so specific responses may potentially be formulated according to the needs and priorities from each place. With **Table 1** we also exemplify how different a response protocol may be from one site to another -depending on the required set of responses and priorities-. The general idea of the simulation exercise is to illustrate that locally identified problems allow centering discussions around pertinent actions in the local context. The graphs, maps and photographs used as place-based representations are expected to substancially reinforce the effects of psychological and social factors described above.

This approach is in contrast to identifying solutions from a global problem (or global model): the global problem/priority may not apply at the site or the solution may not be suitable for every locality. For example, some communities may not be willing to adopt such a proposed solution because of environmental, cultural or socio-psychological reasons (Stoll-Kleemann et al., 2001). Therefore, appropriate response protocols are expected to emerge from the aggregation of tailored responses at each local context.

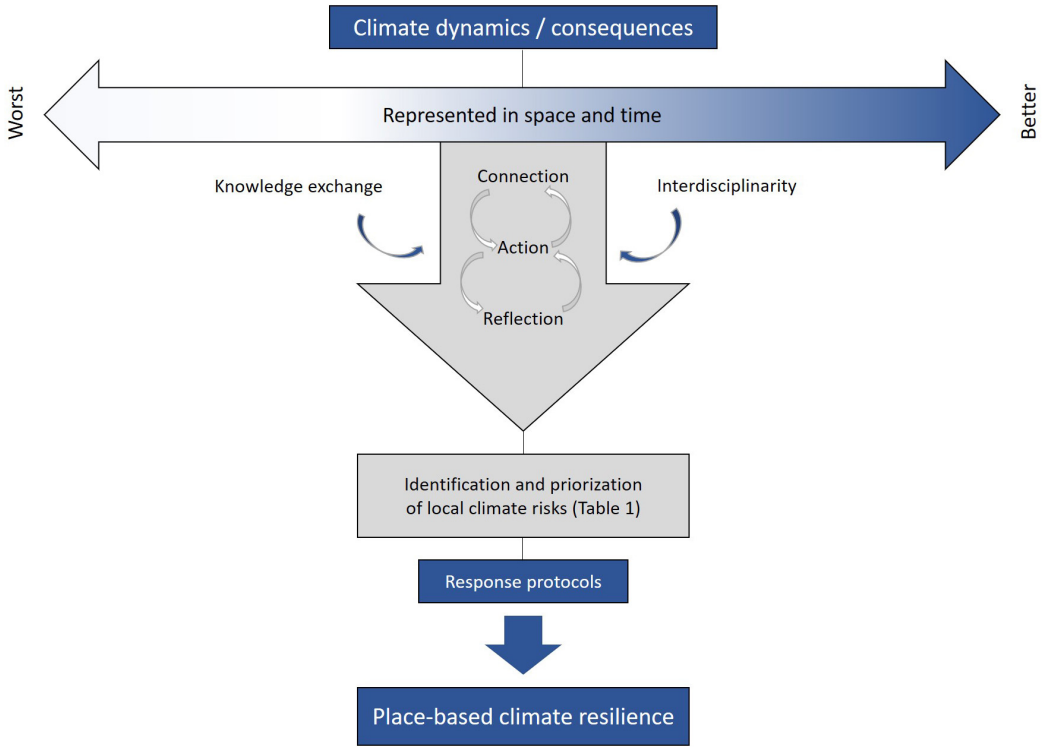

FIGURE 1 | Schematic workflow to support place-based climate resilience in MSES.

To exemplify how local climate dynamics and socio-ecological aspects are integrated and why they should be considered in a process of building climate resilience, we describe the physical and social characteristics of the two chosen cases: Unguja Ukuu and Cabo Pulmo.

Unguja Ukuu, Zanzibar, Tanzania

Unguja Ukuu is located at 6°S of latitude and 39°E of longitude, in the southwest of Unguja Island, the biggest one of the Zanzibar archipelago, on the Tanzanian coasts in East Africa. Average annual air temperature in the region is about 27°C, with minor seasonal variation (Rohli et al., 2019). In contrast, the wind shows clear seasonal shifts: the southeast monsoon (locally known as "*kusi*") usually occurs from April to October, while the northerly monsoon ("*kaskazi*") blows from November to March (Mahongo et al., 2011). The monsoons influence local wind direction and speed, air and sea temperature, rainfall and coastal hydrography (Newell, 1957). Sea surface temperature ranges from 25 to 30.5°C along the year, presenting significant decreases during intense rainfall (Nyandwi and Dubi, 2001). According to Rohli et al. (2019), the rainfall regime corresponds closely with the monsoonal circulation.

The mean seasonal patterns may significantly vary in response to larger scale forcing. However, the seasonal change domains over another patterns of climate variability (e.g., interannual or decadal). The multidecadal increase of sea level registered for all the East African coast seems to be ameliorated by the frontal reef barrier in the locality (**Supplementary Figure 1**). Unguja ukuu is influenced by the dynamics of the large-scale circulation of the Indian Ocean, particularly from the warm North Equatorial current. The region has a moderate exposure to variability associated to El Niño/La Niña. Tsunamis have been registered with minimum to moderate ecological and economic impacts, with loss of human lives (Jidawi, 2019 personal communication). The Zanzibar archipelago is near the path of hurricanes but has not been impacted by any such storm for the past 50 years National Oceanic and Atmospheric Administration (NOAA) (2020).

Artisanal fishing is the most important economic activity in the community. Women, children and men have long walks during low tide, fishing, and gathering at the intertidal zone or to reach fishing boats. These harvesting activities are possible because the tidal range is larger than 5 m and the intertidal is protected by the extensive barrier reef. The main fisheries resources are tropical seascape related fishes, mollusks, gastropods, lobsters, and octopus. Like most MPAs in Zanzibar, the MPA in Unguja Ukuu has social objectives beyond pure conservation because it provides fresh fish and other marine products to commercialize in local markets. The livelihoods of the Unguja Ukuu community are highly dependent on a healthy ocean but fshing activites are not well regulated, wtih a lack of, or inadequate, enforcement (Jiddawi and Öhman, 2002). There is an ongoing revision of marine and fisheries regulation in Zanzibar, especially since the early 2000

TABLE 1 | Comparing climate-social interactions/priorities to build response protocols based on local-climate consequences in two Marine Socio-ecological Systems (MSES).

Scale	Climate event	Socio-ecological component	Potential consequences	Priority of action	
				Unguja Ukuu	Cabo Pulmo
Multidecadal	Sea Level Rise	Physical	Beach loss	H	M
		Economical	Touristic infrastructure damage	H	M
			Community infrastructure damage	H	H
	Ocean warming/cooling	Ecological	Species distribution	L	H
			Coral bleaching	H	M
			Biodiversity change	H	M
		Economical	Touristic attractions damage	L	H
			Fisheries yield trends	H	L
Interannual	Hurricanes	Societal	Human lives	L	H
		Ecological	Seascape damage	L	H
		Economical	Infrastructure damage	L	H
	El Niño / La Niña	Ecological	Species distribution	M	H
			Biogeographic proportions	L	H
		Economical	Target species	L	H
			Fisheries yield	H	L
Seasonal	Wind	Physical	Mixing and turbidity	L	H
			Upwelling	L	H
		Ecological	Marine productivity	M	H
		Economical	Number of navigating days	M	H
	Sea surface temperature	Physical	Stratification	M	H
			Nutrients	M	H
		Ecological	Reproductive success	L	H
			Species composition	L	H
			Biogeographic proportions	L	H
		Economical	SCUBA divers satisfaction	L	H
	Rain	Physical	Turbidity	M	H
			Eutrophication	L	H
		Ecological	Marine productivity	L	H
			Species dominance	L	H
		Economical	Visitors satisfaction	L	H
			Fishing yields	H	L
Random	Tsunamies	Societal	Human lives	M	L
		Ecological	Transitory effects	L	L
		Economical	Infrastructure damage	M	L
			Boats loss	M	L
				⇩	⇩
				Response protocol	Response protocol

Color code shows priority: Red, high (H); Yellow, moderate (M); Green, low (L).

when the World Bank provided a large amount of financial resources for the formation of MPAs (Ruitenbeek et al., 2005; de la Torre-Castro, 2012). The region is growing at an accelerated pace due to tourism-related immigration as well as local demographic growth.

Cabo Pulmo, México

Cabo Pulmo is a National Marine Park located on the Mexican Pacific, at the west coast of the Gulf of California in the 23.5° N of latitude and 109° W of longitude. It is the only extensive coral reef of the Gulf of California and the northernmost of the Eastern Pacific (Álvarez-Filip et al., 2006). The tidal range is about 2 m and wave activity are attenuated by a reef barrier located a few hundred meters from the coastline. Cabo Pulmo is part of a subtropical-temperate transition zone with two seasons contrasting in average sea surface temperatures, wind regimes, and circulation patterns. During the summer, prevailing southeastern winds promote upwelling activity and nutrient-rich surface waters (Álvarez-Borrego and Lara-Lara, 1991; Lavín and Marinone, 2003). There

is a large interannual variability, mainly produced by El Niño/La Niña oscillations that modulate ecological attributes (e.g., fish diversity and biogeographic composition) and influence hurricane activity and extreme rains/droughts over the entire region (Magaña et al., 2003; Álvarez-Filip et al., 2006). The influence of the California Current and atmospheric teleconnections imposes decadal to multidecadal climate patterns in the NE Pacific, but environmental variability in Cabo Pulmo is dominated by seasonal to interannual changes (Lavín et al., 2003; Lluch-Cota et al., 2010). The long-term sea-level trends in the region are positive but small (Climate Change Initiative (CCI), 2020). In recent years there are informal reports of coastal erosion and some damage to shoreline infrastructure, associated with seasonal variability, from the passage of hurricanes in the summer to the northwesterly winds in the winter.

Cabo Pulmo enjoys a worldwide reputation as a successful conservation site because of the recovery of fished species in the past and other ecological attributes (e.g., biodiversity), in combination with the beauty of seascapes and an unusual history of human/nature interactions (Cariño-Olvera et al., 2008; Langle-Flores et al., 2017; Anderson, 2019). This National Park has persisted as an effective no-fishing zone for 25 years, thanks to the active community engagement in protecting the environment, the relative isolation of the village, and the flourishing of local-owned business benefited from ecotourism (e.g., scuba diving, snorkeling, and whale watching). Unfortunately, all the positive social and ecological aspects relevant for the resilience of the community are being threatened by aggressive touristic developers and land speculation, thus compromising the community organization, local development, and environmental conservation (Cariño-Olvera et al., 2008).

From Climate Impact to Response Design

In comparing Unguja Ukuu and Cabo Pulmo, it is clear that climate variability interacts in different ways with the local ecological and social attributes. These interactions shape different climatic risks. For instance, hurricanes are not a problem in Zanzibar since none has landed in the last 50 years. Meanwhile, hurricanes approach every summer to Cabo Pulmo region, representing a very frequent, and high, risk because of their potential threat to human lives and to the integrity of the coral barrier and near-shore infrastructure. Cabo Pulmo is not impacted by another kind of interannual variability in social and economic terms since its economy depends on tourism, not fisheries. In contrast, Unguja Ukuu population depends highly on fisheries, reporting low fishing yields associated with interannual environmental changes (e.g., El Niño/La Niña). Hence, such a phenomenon may have a significant impact on local food security, livelihoods and adaptive capabilities (**Table 1**).

From the comparison exercise we can conclude that each local circumstance provides opportunities for a detailed analysis of the potential consequences driven by climate variability and change, in addition to helping with the prioritization of the required actions (**Table 1**). Better representations of MSES attributes in space and time are expected to improve the identification of local climate risks and designing better response protocols. This is based on the highest chance to activate the collective memory, reduce the psychological distance and increase social engagement and willingness to operate response protocols. Therefore, in contrast to approaches based on digital media-visualizations or chaotic narratives inducing fear to reduce psychological distance, we posit that building response capacities would require bi-directional knowledge exchange (e.g., between civil society and academy), and engaging with the local realities. The knowledge-exchange exercises may include place-based representations of the climate dynamics and their potential impacts over appreciated elements at the target territory. The elements present in the territory may include biodiversity, landscape, infrastructure and economic activities, among others (Kolb and Kolb, 2009; O'Neill and Nicholson-Cole, 2009).

Documenting local conditions is an important first step to connect with the collective memory and people's interests, pointing to motivate participatory argumentations that look for solutions and adaptations to deal with change. An example of the power behind capturing local circumstances to induce social change is the documentary film by Julia Dahr: "Thank you for the Rain" released in 2017[1]. Unlike many climate change films, this is a personal story of a Kenyan farmer transitioning from the hardship to empowerment in climate-induced challenges. In addition to videography, many different tools may be used for documenting and displaying local attributes (whatever it maintains the focus of collective discussions on local climate consequences), for example, imagery from satellites (e.g., local physics), drones (e.g., spatial use of the ecosystem) or photography (e.g., local biodiversity and local activities). In consequence, an accurate and careful representation of local attributes in space and time may boost processes of knowledge exchange because it has the potential to reduce psychological distance and activate the collective memory; the raw materials to build not only engagement but also response capacities and resilience (Shaw et al., 2009; Sheppard et al., 2011).

Climate resilience cannot purely consider responses for the known threats, it needs to consider innovation, learning, and anticipation for the expected impacts of a changing climate (Welle et al., 2014). Many negative consequences of climate variability and change might be prevented in the presence of local capacities to anticipate and respond (Knopman and Berg, 2017; Marshall et al., 2019). Analyzing anticipatory governance, Croxatto et al. (2020), page 12 concluded that: *"preventive actions, together with transparent operational response frameworks, could significantly improve resilience and adaptability of local knowledge systems and institutions dealing with climate change adaptation."*

The achievement of global resilience is depends on resilience at lower scales because the local scale is where climate consequences are manifested, but also from where responses and adaptations

[1]https://thankyoufortherain.com/

are born (IPCC, 2007; Perry et al., 2010). A global-scale climate resilience requires networks of local resilience builders, armed with tools that promote participatory argumentations by those social actors in the target territory. Strategies to build climate resilience are being tested and reproduced all around the world. In this context, the present paper calls attention about the importance of place-based spatial and temporal representativity of climate dynamics defining interactions with MSES. This work complements resilience-building approaches like those based on human-rights, livelihood, co-management, anticipatory governance, or social transformation.

Finally, we propose a conceptual model (workflow) expressing the role of place-based representativity applied in developing climate resilience at small scales. **Figure 1** emphasizes the importance of a better representation of local climate dynamics and consequences to establish connections with the memories, emotions, interests, and worries of individuals and communities. Such connections can determine how good the climatic risks are identified and prioritized, therefore rule on how pertinent a response protocol is for a particular MSES. The connection, action and reflection labels inside the vertical gray arrow, represent a strong dependence of the all process (from climate to resilience), on how finely are captured and displayed the local climate dynamics and consequences. **Figure 1** also suggests that all intervention process should be accompanied by interdisciplinary exchange of knowledge. The final output of the figure (bottom blue rectangle) represents how the integration of previous elements can be exploited in a process of building place-based climate resilience. In section "Suggested Steps to Apply the Conceptual Model (Workflow) in **Figure 1**," we detail some components for each stage embedded in the proposed workflow: (1) Connection, (2) Action, and (3) Reflection.

Suggested Steps to Apply the Conceptual Model (Workflow) in Figure 1

Stage 1: Connection (identifying and prioritizing risks).

(i) Scrutiny of valued assets in the target territory (e.g., discussing the valued elements in the territory using imagery from satellites, video or photography of seascapes and landscapes).
(ii) Compile the collective memory of historic climate events/impacts.
(iii) Analyze specific cases (impacts/responses). Learn and enhance responses.

Stage 2: Action (designing responses).

(i) Prioritize responses according to risk level.
(ii) Design specific protocols for each impact/response.
(iii) Designate local committees/initial response (social engagement).

Stage 3: Reflection (enhancing all process).

(i) Understanding climate dynamics/impacts: local processes and manifestations in the territory + mechanisms connecting to large-scale dynamics.
(ii) Integrate interactions of climate with other factors of physical and social change.
(iii) Extend knowledge in space and time: encourage narratives and interpretative power of local dynamics/climate-forced changes/adequate responses.

CONCLUSION

Achieving sustainability in MSES demands improving multiple response capacities under contexts of uncertainty and change, with the additional complexity that the climate interacts with socio-ecological components (e.g., ecological function and structure, economic activities) at different temporal and spatial scales (Perry et al., 2010; Charles, 2012). Building place-based resilience requires tools to motivate participation and argumentation by those social actors at the target territory, generating the necessary social engagement (Wibeck, 2014). Here, "engagement" is the personal connection with climate change, comprising cognitive, emotional, and behavioral aspects (Lorenzoni et al., 2007). At social levels, engagement drives collective participation, which can be motivated by reducing the psychological distance (Kolb and Kolb, 2009) and stimulating the collective memory (Steynor et al., 2020), by using locally relevant components and dynamics captured in adequate narratives and visualizations (e.g., maps, graphs, video and photographs) (Sheppard et al., 2011; Jones et al., 2017; Marschütz et al., 2020). The better represented (in space and time) the local components and dynamics, the more empathy and connection with social actors, thus the better integrated and designed response protocols (e.g., Kolb and Kolb, 2009; Marshall et al., 2019). Thanks to the interconnections among the collective memory, psychological distance and social engagement – as key concepts to build local capacities and operate response protocols – the expansion of place-based strategies seems promising in the context of building response capacities, regardless if they are applied to climate resilience or beyond (Shaw et al., 2009; Charles, 2012; Marshall et al., 2019; Marschütz et al., 2020).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

MT-C and LL led logistics and collective discussions. AT-C, NJ, MT-C, RC, LL, SJ, JF, and RS-L contributed to collective

discussions and further inputs for manuscript. MT-C, LL, RC, SJ, JF, and AT-C provided conceptual framework and feedback. NJ, MT-C, LL, and AT-C provided data and field observations. RS-L conceived the original idea, led writing, and version control. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.600403/full#supplementary-material

Supplementary Figure 1 | Key characteristics of the coastal MSES used to exemplify the analysis (in text: relevant physical characteristics, in photos: the seascapes, activities and key livelihoods). To the left, Unguja Ukuu, a coastal village situated in the south of Zanzibar, Tanzania. To the right, Cabo Plumo, México. This community is located in the southeast side of the Baja California Peninsula (west having Gulf of California as reference). Photographs by the authors.

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Nitrogen in Atmospheric Wet Depositions Over the East Indian Ocean and West Pacific Ocean: Spatial Variability, Source Identification, and Potential Influences

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Atmospheric deposition is the dominant pathway for the loading of exogenous nitrogen (N) to open ocean. Here, rainwater samples were collected from 31 stations in the equatorial East Indian Ocean (EIO) and West Pacific Ocean (WPO) to explore the spatial variability of N species, potential sources, and related ecological influences. Among two oceans, nitrate (NO_3^-) and ammonium (NH_4^+) were the main components in the rainwater N inventory. NO_3^- concentrations varied from 0.19 to 100.5 μM, whereas NH_4^+ concentrations ranged from 0.54 to 110.6 μM. Among all stations, low concentrations of NO_3^- and NH_4^+ appeared in the remote ocean, whereas high concentrations were observed at the stations near the Malacca Strait and New Guinea, coupled with an enhancement of non-sea salt major ions, e.g., calcium ions (Ca^{2+}) and sulfate (SO_4^{2-}), revealing the influence from coastal human activities, such as coal and gasoline combustion. In the remote ocean, $\delta^{15}N$–NH_4^+ ranged from −5.7 to −9.3‰, whereas it dropped to -15.5‰ near coasts. A logarithmic decay between $\delta^{15}N$–NH_4^+ and NH_4^+ concentrations in rainwater samples was obtained, suggesting a shift from natural source (seawater emission) in oceanic precipitation events to anthropogenic source (chemical fertilizer volatilization and vehicle exhaust) in coastal rainwaters. $\delta^{15}N$–NO_3^- in the remote ocean varied between −1.7 and 0.4‰ with low levels found in the WPO, likely related to the ascending air flow driven by the Walker Circulation. In coastal oceans, $\delta^{15}N$–NO_3^- ranged from 1.5 to 3.5‰. The linkage between $\delta^{15}N$–NO_3^- and NO_3^- concentrations varied in two oceans, resulting from difference in biological and fossil fuel combustion contributions. Compared with ocean surface water, N in the rainwater was markedly enriched, suggesting that N from atmospheric wet depositions could rapidly enhance the dissolved N availability in ocean surface water. However,

the N redundancy according to the Redfield–Brzezinski ratio (N:Si:P = 16:16:1) in the rainwater might benefit from the growth of N-preference phytoplankton species and microbes. As the first study on N concentrations, sources, and stoichiometry balance in rainwater over the equatorial WPO and EIO, the results could be a support to the global N budget estimation and oceanic primary production modeling.

Keywords: atmosphere, nitrogen, Indian Ocean, Pacific Ocean, precipitation, stable isotope

INTRODUCTION

Nitrogen (N) is essential for the biosynthesis of amino acids, phospholipid, nucleic acids, etc. Since preindustrial times, the reactive N storage in the biosphere has rapidly increased due to anthropogenic N fixation (Kuypers et al., 2018). Given the high solubility and chemical activity, reactive N intensively transports among different systems in the biosphere (Galloway et al., 2008). Though the importance in biological actives, excessive N frequently leads to negative ecological feedbacks, especially in aquatic systems, such as harmful algae blooms, benthic hypoxia, and phytoplankton community succession. Accordingly, N cycling with regard to transport and transformation receives great attention from the scientific community.

On a global scale, the magnitude of N deposition flux to terrestrial systems is relatively well gauged based on monitoring projects in continents (e.g., Loÿe-Pilot et al., 1990; Fenn et al., 2003; Duan et al., 2016). In contrast, the impacts of N deposition to oceans are less evaluated, with sporadic measurements and limited spatial coverage archived in the past several decades (e.g., the tropical Atlantic Ocean, Baker et al., 2007; Bermuda, Altieri et al., 2013; the North Pacific Jung et al., 2013). In those unexplored oceans, our knowledge of atmospheric N deposition, with regard to concentration, species, and sources, is highly scarce. This knowledge gap adds great uncertainties in global N budget estimations, such as oceanic N storages and N reaction rates. In addition, the limitation of oceanic N deposition data also produces the difficulty in ecological explanation on the variability of N-related phytoplankton community structure (Li et al., 2015). Furthermore, the lack of oceanic N deposition data also hampers the understanding of carbon cycles because of the reaction linkage of the sequestration capability of atmospheric CO_2 *via* primary producers (Capone, 2001).

In the present study, wet deposition (rainwater) samples from two cruises covering tropical areas in the East Indian Ocean (EIO) and West Pacific Ocean (WPO) were obtained (**Figure 1A**). The sampling area in the EIO is adjacent to the Peninsular Thailand and Indonesia Archipelagoes on the east and the Indian Subcontinent and Sri Lanka on the north. In those regions, dense population (>1.5 billion) and intensive agriculture/manufacture are characterized. From May to September, the south-west monsoon introduces significant precipitation to South Asia, whereas the east wind from November to April introduces substantial land-derived matter from the Indian Subcontinent to the EIO (Sinha et al., 2019). For the sampling region in the WPO, it is surrounded by tropical islands, e.g., Guam, Borneo, and New Guinea. Walker Circulation (latitudinal) and Hadley Circulation (meridional) related east wind is prevailing at the eastern boundary of this sampling region, whereas the west wind from the Sulawesi Sea introduces terrestrial compounds derived from the Borneo and Indonesian islands (**Supplementary Figure S1**). The equatorial EIO and WPO have been identified as global sea ranches for tuna and squid catching more than 30 years (Takashi and Tsukada, 1988), whereas the primary productivity in seawater frequently remains a low level due to oligotrophic status (**Supplementary Figure S2**). During these two cruises, 31 rainwater samples (13 from EIO and 18 from WPO) were collected. Coupled with *in situ* measurement of precipitation amount and rainwater pH, concentrations of major ions and dissolved inorganic N species [ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-)] were determined. More importantly, multiple N isotopic signatures ($^{15}N–NO_3^-$, $^{18}O–NO_3^-$, $^{15}N–NH_4^+$) and water stable isotope fractions ($^2H–H_2O$, $^{18}O–H_2O$) in these rainwater samples were determined, in order to identify different sources of NH_4^+ and NO_3^- during these precipitation events (e.g., volatilized fertilizer, vehicle exhaust, and lighting production) according to their significant variability in isotopic fractions (e.g., Felix et al., 2015; Elliott et al., 2019; Zeng et al., 2019). Together with the backward trajectory mode from the National Oceanic and Atmospheric Administration (NOAA) (**Figure 1A**), we aimed to: (1) determine the spatial variability of N species in wet precipitations in the equatorial EIO and WPO and dynamic linkage with the Walker Circulation and Hadley Circulation; (2) identify potential sources of rainwater N and evaluate the influence of anthropogenic activities from adjacent coasts on rainwater N inventory; and (3) explore the potential ecology/environment impacts from wet deposition derived N on the equatorial EIO and WPO.

MATERIALS AND METHODS

Sample Collection

The EIO cruise was conducted from 17th March 2018 to 12th May 2018 on the Shiyan III R/V, whereas the WPO cruise ranged from 15th November 2018 to 30th January 2019 on the Kexue R/V. Atmospheric temperature and wind speed were automatically recorded on board during both campaigns. Rainwater samples were collected with an acid-prewashed container at an open area of the top deck. The collection ranged from 2 to 6 h in each site. After rainwater gathering, the precipitation amount (unit: mm) was estimated, and then the collected rainwater was used for filtration and pH measurement (sketch in **Figure 1B**). The filtration was conducted at air-cleaning environment, using polycarbonate membrane filter

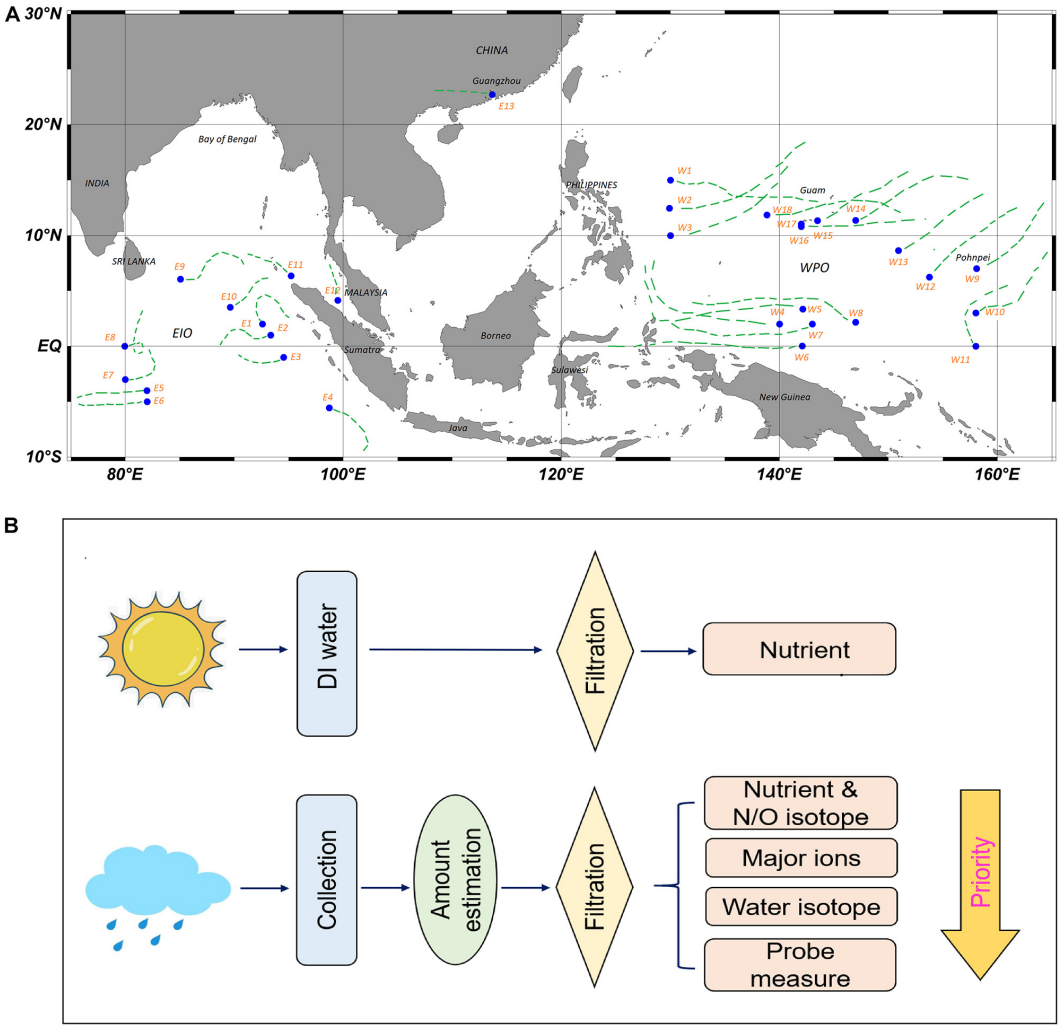

FIGURE 1 | Sampling sites in both EIO and WPO cruises **(A)**, the dash lines indicate 72 h transport pathway of atmospheric particles at an altitude of 1,000 m (back-trajectory analysis). **(B)** Sketch of the sampling procedure, including atmospheric blank analysis (only WPO) and rainwater collection/filtration.

(0.4 μm pore size, Whatman®). The filtrate was stored in acid-prewashed high-density polyethylene (HDPE) bottles at −20°C environment for major ions, nutrients, and N stable isotope fractions. Water stable isotope samples were stored in air-tight vacutainers at 4°C environment (Jiang et al., 2017). Occasionally, the volume of collected rainwater was limited. In these cases, nutrients and major ions collection were priority targets. The pH of the rainwater (unfiltered) was measured with a calibrated WTW multi-function probe (350 type, Germany) on board. After each collection, the sampling container was cleaned using ethanol (analytical reagent purity) and deionized (DI) water (resistance: 18.2 MΩ.cm) and then resettled on the top deck. In total, 13 rainwater samples were collected from the EIO cruise (E1–E13), and 18 rainwater samples were obtained from the WPO cruise (W1–W18; **Figure 1A**). In addition, during both cruises, a series of blank experiments was conducted to quantitively determine the bias introduced from the filtration system (test 1st and 2nd) and seawater spray on the collected rainwater (test 3rd–6th). In practice, 100 ml DI water was filtered and then stored in acid-prewashed sampling bottles to determine the bias from the filtration system. For the seawater spray influence, approximately 500 ml DI water was injected into the container and received sunlight exposure at the sampling spot for 1 (3rd, 4th, 5th) and 3 days (6th). Subsequently, the water was filtered and analyzed with rainwater samples together. Notably, the filtration blank was conducted in both EIO and WPO cruises, whereas the spray effect was only determined in the WPO.

Chemical Analyses

After thawing, concentrations of NH_4^+, NO_2^-, NO_3^-, soluble reaction phosphorus (SRP), and dissolved silicate (Si) in water samples were determined on a flow injection system (SKLAR + +, the Netherlands) with the standard colorimetric approach. The method precision for all species was <5%. The concentration of total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) was quantified on the identical

system after 30 min at 121°C digestion with alkaline potassium persulfate solution. Dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) were assumed to be the concentration difference between TDN and dissolved inorganic nitrogen (DIN), as well as TDP and SRP, respectively (Jiang et al., 2019). Both $\delta^{15}N–NO_3^-$ and $\delta^{18}O–NO_3^-$ were determined *via* transforming NO_3^- to N_2O using a denitrifier with the reference of USGS-32, USGS-34, and IAEA-N3 (Sigman et al., 2001) after removing NO_2^- (Weigand et al., 2016). The produced N_2O was concentrated in a Thermo-Fisher Precon system at liquid nitrogen environment, and the signal of N_2O was detected in a Thermo-Fisher Delta V Advantage Isotope Mass Spectrometer (Jin et al., 2020). The method detection limit was approximately 1 μM, and the method variation for $\delta^{15}N–NO_3^-$ <0.2‰ and $\delta^{18}O–NO_3^-$ <0.5‰ was based on the long run. The $\delta^{15}N–NH_4^+$ was determined *via* transforming NH_4^+ to N_2O using the sodium hypobromite–sodium azide method with the reference of USGS-26, USGS-25, and IAEA-N1 (Zhang et al., 2007). The detection limit was ca. 2 μM, and the method variation was approximately 0.5‰. The water stable isotope fractions ($^2H–H_2O$) and ($^{18}O–H_2O$) were analyzed on an Elementary Analyzer-Isotope Ratio Mass Spectrometer. The concentration of major ions, including sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulfate (SO_4^{2-}), and fluoride (F^-), was tested using ion chromatography (Dione ICS-2000). The eluent was potassium hydroxide solution (25 mM) for anions and methanesulfonic acid solution (20 mM) for cations, with the flow rate of 1 ml min^{-1}. The detection limit was approximately 0.01 mg L^{-1} for all species. The precision for major ions was below 4%.

Data Analyses

The linear regression, cluster analysis, and Spearman's rank correlation were conducted in the Minitab software (version 17.5). The redundancy analysis (RDA) was conducted in the Canoco 5 software. The statistical significance was assumed to be $P \leq 0.05$. Chlorophyll *a* concentration in the sampled ocean areas was estimated from the remote sensing and downloaded from the online database[1]. The visualized atmospheric circulation (wind speed and direction) information (altitude of 850 hPa, approximately 1,500 m height; download from https://earth.nullschool.net) on two sampling regions was invoked to validate the long-range atmospheric dispersion (e.g., Yang et al., 2017). To identify the origin of aerosol particles *via* atmospheric transport, back-trajectory analysis has been performed (dash lines in **Figure 1A**). The trajectory of aerosol particles was back to 72 h at an altitude of 1,000 m (e.g., Zhang et al., 2004; Sinha et al., 2019).

RESULTS

Meteorology

During the EIO cruise, the atmospheric temperature was 20°C at Guangzhou, China (**Supplementary Figure S3**). Temperature ranged from 26.2 to 34.3°C during the EIO cruise. Concurrently, the wind speed varied from 0.96 to 14.8 m s^{-1} (**Supplementary Figure S3**). The wind direction was northeast at 850 hPa with eddies (**Supplementary Figure S1**). Both temperature and wind speed showed insignificant variations during precipitation events. The precipitation amount ranged from approximately 0.4 to 22 mm, and pH in the EIO rainwater varied between 4.3 (Guangzhou) and 6.6 (remote ocean). Chlorophyll *a* concentration in surface EIO was <8 mg m^{-3} (**Supplementary Figure S2**). During the WPO cruise, the atmospheric temperature increased from 9°C at Qingdao to approximately 29°C at the equatorial WPO. Wind speed varied between 1.6 and 14.1 m s^{-1}. The east wind was prevailing, whereas several sites near the New Guinea coast were influenced by the west wind (**Supplementary Figure S1**). The precipitation amount varied between 0.3 and 32 mm, and the pH ranged from 5.2 to 6.4. Similar with the EIO, insignificant variations in both temperature and wind speed during precipitation events and low-level chlorophyll *a* concentration in the equatorial WPO were found (**Supplementary Figure S2**).

Blank Test

In the filter blank, nutrient concentrations were below the detection limit (**Supplementary Table S1**). For the 1-day exposure, concentrations of NH_4^+, NO_2^-, and NO_3^- slightly increased, reaching 0.54 μM. After the 3-day exposure, approximately 20% of DI water was evaporated. N species and dissolved Si increased, whereas the level of SRP and DOP remained low. Excluding the influence from evaporation, the addition rate for nutrient species ranged from 1.3 to 13.0 nmol L^{-1} h^{-1}. Considering that the rainwater collection only lasted 6 h (maximum) at each site, the exogenous nutrient concentration from seawater spray introduced into the sampling container should be <0.12 μM, indicating an insignificant influence.

N Concentrations and Isotope Fractions

NH_4^+ concentration in rainwater samples from the EIO cruise varied between 1.8 and 110 μM, peaking at Guangzhou (**Figure 2**). Enrichment of NH_4^+ was also found at sites near the Malacca Strait. In the WPO, the NH_4^+ concentration ranged from 0.9 to 12.3 μM (**Figure 2**). High concentrations were observed between the W4 and W8 sites (near New Guinea). $\delta^{15}N–NH_4^+$ in the EIO cruise ranged from -7.5 to 15.5‰ that the lowest value was still found at Guangzhou. In the WPO, $\delta^{15}N–NH_4^+$ ranged from -5.4 to -14.7‰ (**Figure 2**). In both EIO and WPO, $\delta^{15}N–NH_4^+$ showed a logarithmic decay with NH_4^+ concentrations (**Figure 3A**).

For NO_3^- concentration, it varied from 0.6 to 55.6 μM in the EIO apart from the highest level at Guangzhou (100.5 μM). During the WPO cruise, NO_3^- concentration ranged from 0.5 to 66 μM. High-level NO_3^- spatially co-occurred with NH_4^+ enrichments (**Figure 2**). In the EIO, an exponential increase was obtained between NH_4^+ and NO_3^- concentrations (**Figure 3B**), whereas rainwater samples in the WPO were comparatively enriched of NO_3^- than NH_4^+, suggesting a potential reduction of terrestrial NH_4^+ inputs. Under the low pH condition, the

[1]https://giovanni.gsfc.nasa.gov

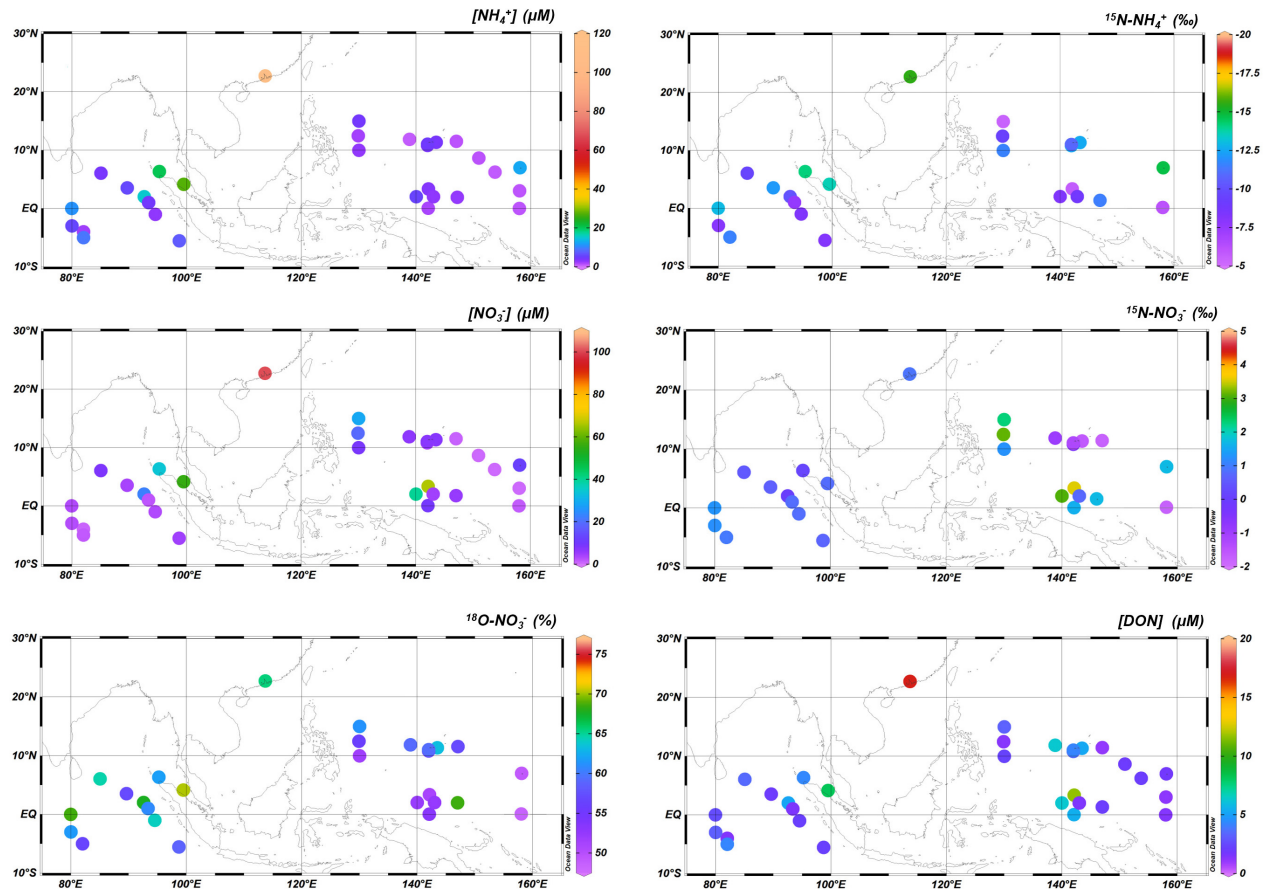

FIGURE 2 | Spatial variability of NH_4^+, NO_3^-, and DON concentrations and their isotope fractions in both EIO and WPO.

NO_3^- content in wet precipitations was likely in the chemical form of HNO_3 (**Figure 3E**). For $\delta^{15}N$–NO_3^-, it varied from 0.03 to 1.3‰ in the EIO and from -1.6 to 3.5‰ in the WPO (**Figure 2**), whereas the linkage between $\delta^{15}N$–NO_3^- and NO_3^- concentrations was variable among two oceans (**Figure 3C**). An insignificant linkage was obtained between $\delta^{18}O$–NO_3^- and NO_3^- concentrations (**Figure 3D**).

NO_2^- was the minor portion in the rainwater DIN inventory, likely due to the rapid transformation from NO_2^- to nitric acid. The concentration of NO_2^- in both EIO and WPO was frequently < 1 μM. For DON, it varied from 1.4 to 16.9 μM during the EIO cruise and from 1.1 to 11.6 μM during the WPO cruise (**Figure 2**). In addition, a significantly linear correlation was identified between DON and NO_3^- concentrations in rainwaters from both oceans (**Figure 3F**). Based on the N compound compositions and concentrations (**Figures 4A,B**), the rainwater in the EIO and WPO was assigned into three clusters (the Euclidean-distance similarity), namely, the low N (<7.8 μM in the EIO, <4.1 μM in the WPO), moderate N (11.6–17.2 μM in the EIO, 8.7–18.6 μM in the WPO), and high N groups (>17.3 μM in the EIO, >18.7 μM in the WPO). The RDA also identified the variation of N inventory among different groups during two cruises (**Figures 4C,D**).

P Species and Dissolved Si

For SRP and DOP, the concentration in rainwaters was frequently below 1 μM (**Table 1**). Apart from NO_2^- content, positive correlations among SRP/DOP and N species were observed in both oceans (**Table 2**), especially for the high N groups and P species (**Figures 4C,D**). Dissolved Si accounted for a low level in rainwater compared with N content. The highest concentration was 2.3 μM, whereas the remaining was <1 μM (**Table 1**). Such low-concentration P and Si contents led to stoichiometric N-redundancy in all samples based on the Redfield–Brzezinski ratio plot (N:Si:P = 16:16:1; **Figure 5A**).

Water Stable Isotopes

δ^2H–H_2O and $\delta^{18}O$–H_2O in oceanic rainwater were significantly linearly correlated (**Figure 5B**). In the EIO, the slope (8.2) of the regression curve was similar to the global meteoric water line (GMWL, slope 8), whereas the intercept (15.8) was much higher (GMWL, intercept 10). In contrast, in the WPO, both slope (6.5) and intercept (9.7) of the curve were slightly smaller than those of the GMWL. Such difference suggests the variability of hydrologic cycle between seawater and atmospheric water vapor in the EIO and WPO. In addition, significant correlations were found between $\delta^{15}N$–NH_4^+ and $\delta^{18}O$–H_2O

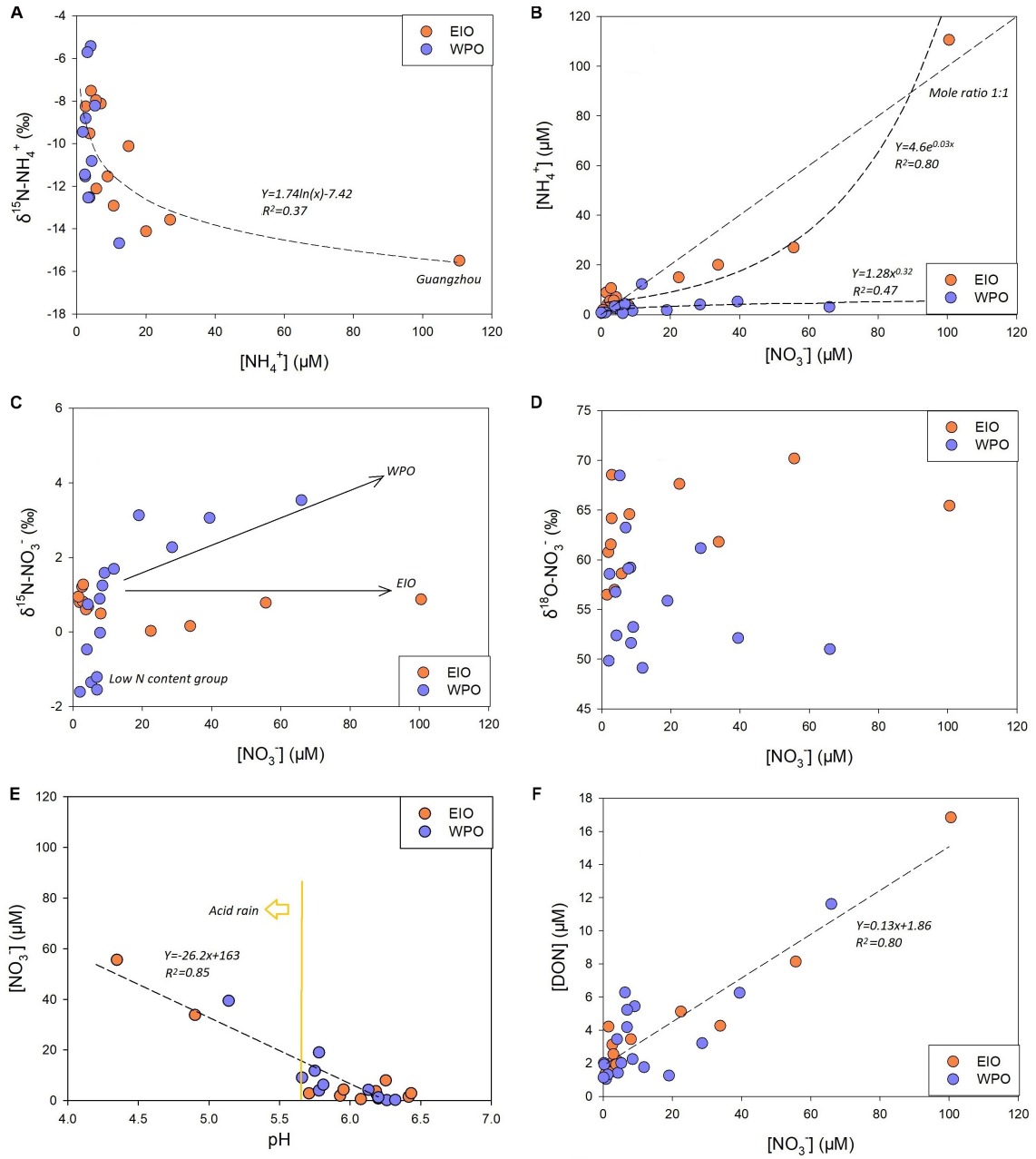

FIGURE 3 | (A) Correlation between NH_4^+ concentration and $\delta^{15}N–NH_4^+$. **(B)** Correlation between NH_4^+ and NO_3^- concentrations in rainwater, showing significantly different curves between two oceans. **(C,D)** The insignificant trend between NO_3^- concentration and $\delta^{15}N/^{18}O–NO_3^-$. **(E,F)** Correlation between pH/DON and NO_3^- concentrations in rainwater from two oceans.

in the WPO, as well as $\delta^{15}N–NO_3^-$ and $\delta^{18}O–H_2O$ in the EIO (**Figures 5C,D**). For $\delta^{18}O–H_2O$ and $\delta^{18}O–NO_3^-$ (**Figure 5E**), the plot clearly separated rainwater samples from two oceans though $\delta^{18}O–NO_3^-$ in rainwater samples likely increased with $\delta^{18}O–H_2O$ enhancements.

Major Ions

Na^+ was the most abundant cation in the rainwater. The concentration in the rainwater collected from the EIO ranged from 1.2 to 123 mg L^{-1} (**Table 1**). In the WPO, Na^+ concentration varied between 0.5 and 275 mg L^{-1}. The highest level of Na^+ was obtained in the moderate and high N groups, with a similar distribution pattern of K^+, Ca^{2+}, and Mg^{2+} (**Table 1**). In the WPO, the Cl^- concentration in rainwater reached 460 mg L^{-1}, much higher than the level of SO_4^{2-} and F^-. After removing the sea salt in rainwater based on the standard seawater composition (Zhang et al., 2011), the concentrations of non-sea salt (nss) K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and F^- markedly

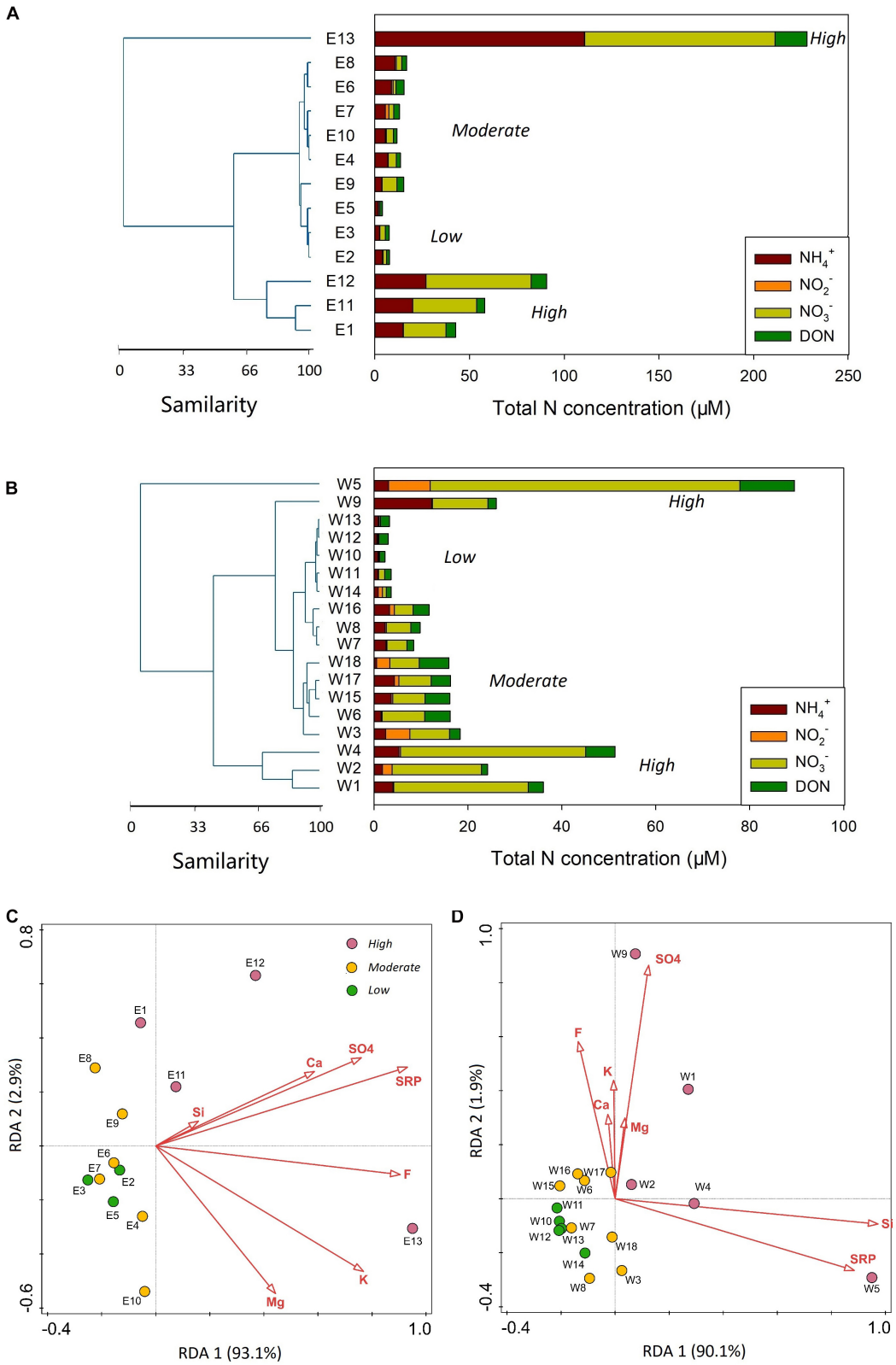

FIGURE 4 | (A,B) Cluster analyses for rainwater samples from both EIO and WPO based on concentrations of different N species. In both cluster analyses, three clusters are identified, namely, the low N, moderate N, and high N groups. **(C,D)** RDA results for the EIO and WPO rainwater samples, highlighting the difference among the low, moderate, and high N groups.

TABLE 1 | Range of phosphorus, dissolved silicate, and major ions in rainwater collected from two cruises.

	SRP	DOP	Si	Na^+	K^+	Mg^{2+}	Ca^{2+}	F^-	Cl^-	SO_4^{2-}
L-EIO	B.D.–0.07	0.01–0.12	B.D.–0.07	2.4–23.2	0.18–0.93	0.35–2.6	0.48–1.4	0.03–0.08	4.42–41.9	0.96–6.1
M-EIO	B.D.–0.28	0.11–0.22	B.D.–0.55	1.2–123	0.12–4.6	0.22–14.9	0.41–4.9	0.02–0.11	2.1–75.1	0.57–12.3
H-EIO	0.35–0.92	0.25–0.98	0.13–0.56	8.3–13.8	0.57–1.3	1.1–1.7	1.7–2.4	0.08–0.41	14.6–25.6	4.3–5.9
L-WPO	B.D.–0.71	0.06–0.22	B.D.–0.17	0.5–4.2	0.08–0.24	0.07–0.54	0.14–0.45	0.02–0.05	0.57–6.9	0.33–1.3
M-WPO	B.D.–0.22	0.09–0.28	B.D.–0.56	0.7–86.2	0.47–3.3	1.2–9.8	0.79–4.8	0.04–0.30	17.0–141	2.9–20.3
H-WPO	0.09–4.4	0.14–7.4	0.27–2.3	37.3–275	1.5–10.7	4.3–31.6	2.41–21.7	0.02–0.31	61.3–460	11.1–78.8

The concentration range is listed in low (L), moderate (M), and high (H) N groups. The unit for SRP, DOP, and Si is μM and major ions is mg L^{-1}. B.D. is below the detection limit.

TABLE 2 | Coefficients from Spearman's rank correlation tests between non-sea salt fraction of major ions and nutrients, as well as precipitation amount (mm) in rainwater.

	nss-K	nss-Mg	nss-Ca	nss-F	nss-SO_4^{2-}	Si	NO_3^-	NO_2^-	NH_4^+	SRP	DON	DOP
nss-Mg	0.638**											
nss-Ca	0.697**	0.413*										
nss-F	0.499**	0.253	0.513**									
nss-SO_4^{2-}	0.640**	0.345	0.815**	0.471*								
Si	0.821*	0.615*	0.761*	0.326	0.723**							
NO_3^-	0.762**	0.368	0.713**	0.498**	0.825**	0.728**						
NO_2^-	0.363	0.560**	0.447*	−0.051	0.224	0.448*	0.066					
NH_4^+	0.300	−0.237	0.395*	0.322	0.511**	0.333	0.492**	−0.117				
SRP	0.626**	0.398*	0.517*	0.270	0.576**	0.674**	0.766**	0.025	0.431*			
DON	0.429*	0.098	0.604**	0.599**	0.577**	0.379*	0.662**	0.137	0.426*	0.405*		
DOP	0.554**	0.225	0.469*	0.362	0.333	0.408*	0.591**	0.038	0.360	0.729**	0.441*	
Amount	−0.349	−0.205	−0.414	−0.338	−0.310	−0.508*	−0.331	−0.113	−0.201	0.130	−0.264	−0.107

*The unit for these major ions and nutrients is mg L^{-1}, and nutrient is μM, respectively. * indicates $P < 0.05$ and ** indicates $P < 0.01$.*

decreased (e.g., **Figures 5F,G**). Several nss-cations and nss-anions were correlated, e.g., F^- vs. K^+ and SO_4^{2-} vs. Ca^{2+} (**Table 2**). More importantly, the enrichment of nss fractions varied between the EIO and WPO. In particular, both nss-Mg^{2+} and nss-F^- were relatively enriched in the WPO. Significant correlations were also obtained between nss-ions and nutrient species (**Table 2**), such as the exponential increase between nss-SO_4^{2-} and NH_4^+ (**Figure 5H**). Notably, the mole ratio between NO_3^- and nss-SO_4^{2-} in the EIO and WPO frequently ranged between 1/3 and 2, whereas the ratio in three sites was >2, indicating nss-SO_4^{2-} as the dominant solute in acid rains (**Figure 5I**).

DISCUSSION

Wet Deposition N in the EIO

In the EIO, high atmospheric temperature (>26°C, **Supplementary Figure S3**) accelerated the seawater evaporation and introduced 13 precipitation events. Given the variability of rainwater N inventory, low, moderate, and high N clusters were identified (**Figure 4A**). The low-level N group includes three sites with the lowest content found in the remote ocean (E5 in **Figure 1A**), where received west-direction wind. At the E5 site, NO_3^- and NH_4^+ were key species in N inventory, but their concentrations were <3 μM. The west wind also produced the remaining two low-level N sites near the coast of Sumatra Island (E2 and E3). Low concentrations of N species in these sites are comparable to observations made in other oceanic environments, such as the record made in the North Pacific Ocean and the Bermuda Island (**Figure 6**). In the low-level group, the concentrations of nss-cations and nss-anions were also frequently <2 mg L^{-1}, which was 1–2 orders of magnitude lower than the measurement at Guangzhou (E13 in **Figure 1A**), further suggesting a minor influence from terrestrial sources (e.g., coal combustion and agriculture emission, sketch in **Figure 7**). Consequently, NH_4^+ in the low N group can be assumed to be the product of NH_4^+ emission from the surface seawater, whereas NO_3^- mainly resulted from lighting fixation (**Figure 7**). The $\delta^{15}N$–NH_4^+ directly supports that NH_4^+ in the low N group derived from oceanic surface water emission was the main source of NH_4^+. In particular, $\delta^{15}N$–NH_4^+ in the surface seawater was approximately -0.5‰ (Hoch et al., 1994). Accordingly, the oceanic emission of $\delta^{15}N$–NH_4^+ was found to be -0.5 to -9‰ (Lin et al., 2016), as highlighted in **Supplementary Figure S4**. Due to the positive correlation between temperature and emitted $\delta^{15}N$–NH_4^+ (Elliott et al., 2019), $\delta^{15}N$–NH_4^+ derived from oceanic emission in equatorial regions tended to be higher in this range, which fitted our observation in the remote ocean. Furthermore, lighting fixation may also produce a small quantity of NH_4^+ *via* the combination between N and H molecules (NOAA site)[2]. $\delta^{15}N$–NH_4^+ produced from nitrogen gas (N_2) *via* lighting fixation is still approaching

[2]https://www.esrl.noaa.gov/gmd/education

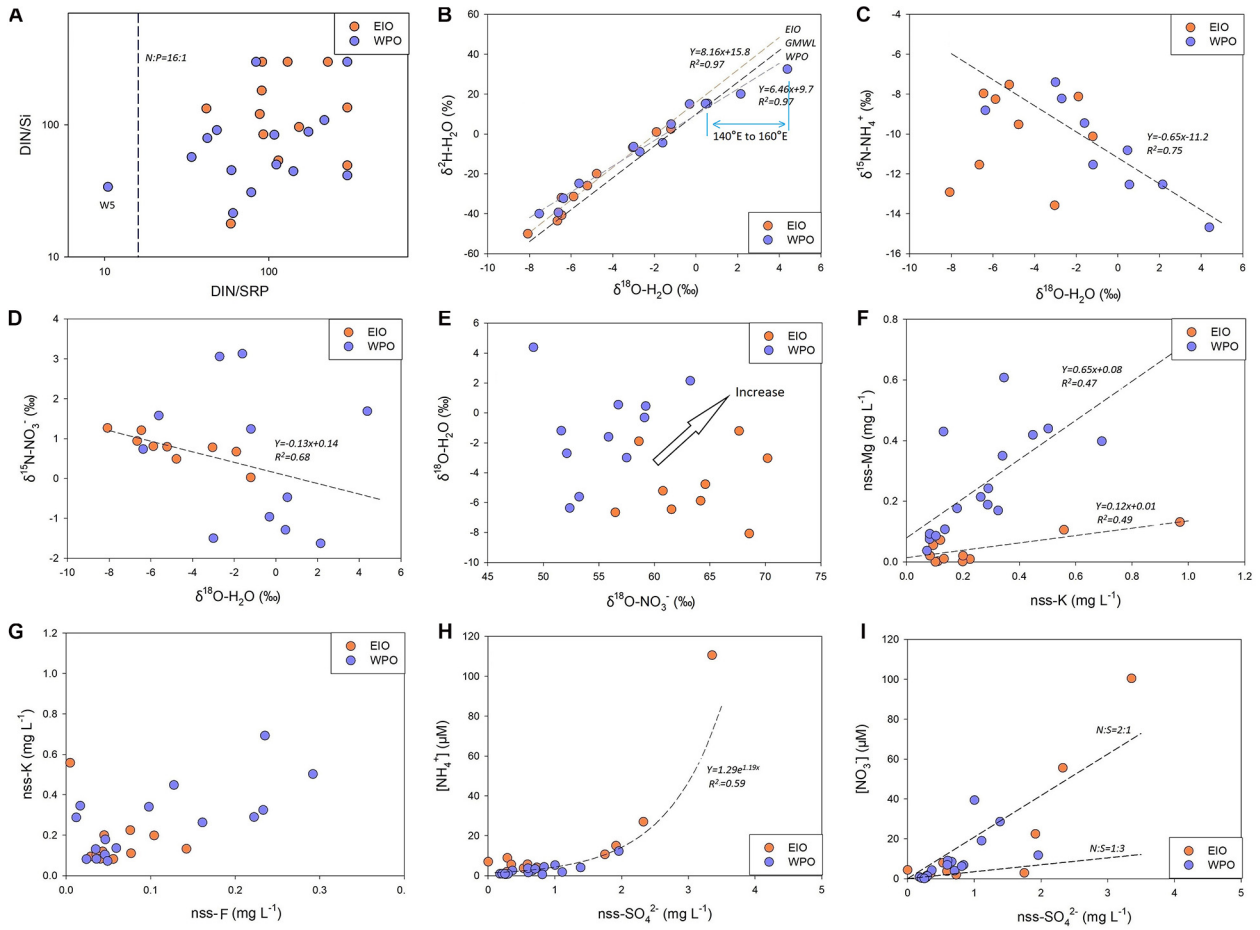

FIGURE 5 | (A) The comparison between DIN:SRP and DIN:Si. Most sites are characterized as P-limitation, and W5 site is characterized as Si-limitation based on the Redfield–Brzezinski ratio. **(B)** The correlation between δ^2H–H_2O and $\delta^{18}O$–H_2O in rainwaters. GMWL is the global meteoric water line with a slope of 8 and an intercept of 10. Different curves are found in the EIO and WPO. **(C,D)** $\delta^{15}N$–NH_4^+/$\delta^{15}N$–NO_3^- and $\delta^{18}O$–H_2O from samples obtained in the WPO and EIO, respectively; it shows the regression curve between $\delta^{15}N$–NH_4^+ and $\delta^{18}O$–H_2O in the WPO **(C)**, as well as $\delta^{15}N$–NO_3^- and $\delta^{18}O$–H_2O in the EIO **(D)**. **(E)** $\delta^{18}O$–NO_3^- vs. $\delta^{18}O$–H_2O in both EIO and WPO, highlighting the increasing trend. **(F,G)** Correlations between nss-K^+ and nss-Mg^{2+}/nss-F^- concentrations. **(H,I)** Correlations between NH_4^+/NO_3^- concentration with nss-SO_4^{2-}.

0, which could not significantly change the $\delta^{15}N$–NH_4^+ in oceanic environments. By contrast, $\delta^{15}N$–NH_4^+ from volatilized fertilizer [e.g., $(NH_4)_2SO_4$, NH_4Cl] frequently hosts a more negative isotope value (dropping to -56‰; Pan et al., 2018). In addition, during the atmospheric transport from inland to remote oceans, terrestrial NH_4^+ could be easily loosed during the long-range transport (Lin et al., 2016), and $\delta^{15}N$–NH_4^+ tends to be decreasing due to the "washout" of heavy isotopes from aerosols (Agnihotri et al., 2011; Altieri et al., 2014). In the EIO low N group, $\delta^{15}N$–NH_4^+ was markedly higher than $\delta^{15}N$–NH_4^+ reported in terrestrial precipitation events, e.g., Toshima, Japan (mean: -25‰, Uchiyama et al., 2017) and Guiyang, China (mean: -15‰; Xiao et al., 2012), also confirming its oceanic origin. In the low N group, the oceanic NO_3^- is the oxidation product of lighting-produced NO and NO_2 (NO_x; Altieri et al., 2013). These gas products host $\delta^{15}N$ of 0 (Hoering, 1957), indicating that the oceanic $\delta^{15}N$–NO_3^- should be 0 with a small variation after transformation (**Supplementary Figure S4**). In these samples, $\delta^{15}N$–NO_3^- was 1‰, suggesting that the lighting-induced reaction was the dominant source.

When sampling sites were approaching the Indian Subcontinent and Malaysian Peninsular (**Figure 1A**), N concentrations in rainwater samples increased and created the moderate and high N concentration groups (**Figure 4A**). The NH_4^+ concentration is similar to the rainwater collected from the Bay of Bengal (**Figure 6**). Such high-level NH_4^+ is beyond the requirement of neutralization (NH_4^+ to neutralize nss-SO_4^{2-} and NO_3^-; **Supplementary Figure S5**) when ammonium available index (AAI) is introduced (Szép et al., 2018). Large AAI indicates the excessive NH_4^+ from intensive human activities (Szép et al., 2018). Concurrently, nss-ions, e.g., Ca^{2+} and K^+, also markedly increased, suggesting the input from terrestrial materials into the rainwaters (Martino et al., 2013). In particular, Ca^{2+} was the byproduct of coal combustion in India (Singh et al., 2007), whereas K^+ was identified as the product of biomass burning (Srinivas et al., 2011). Accordingly,

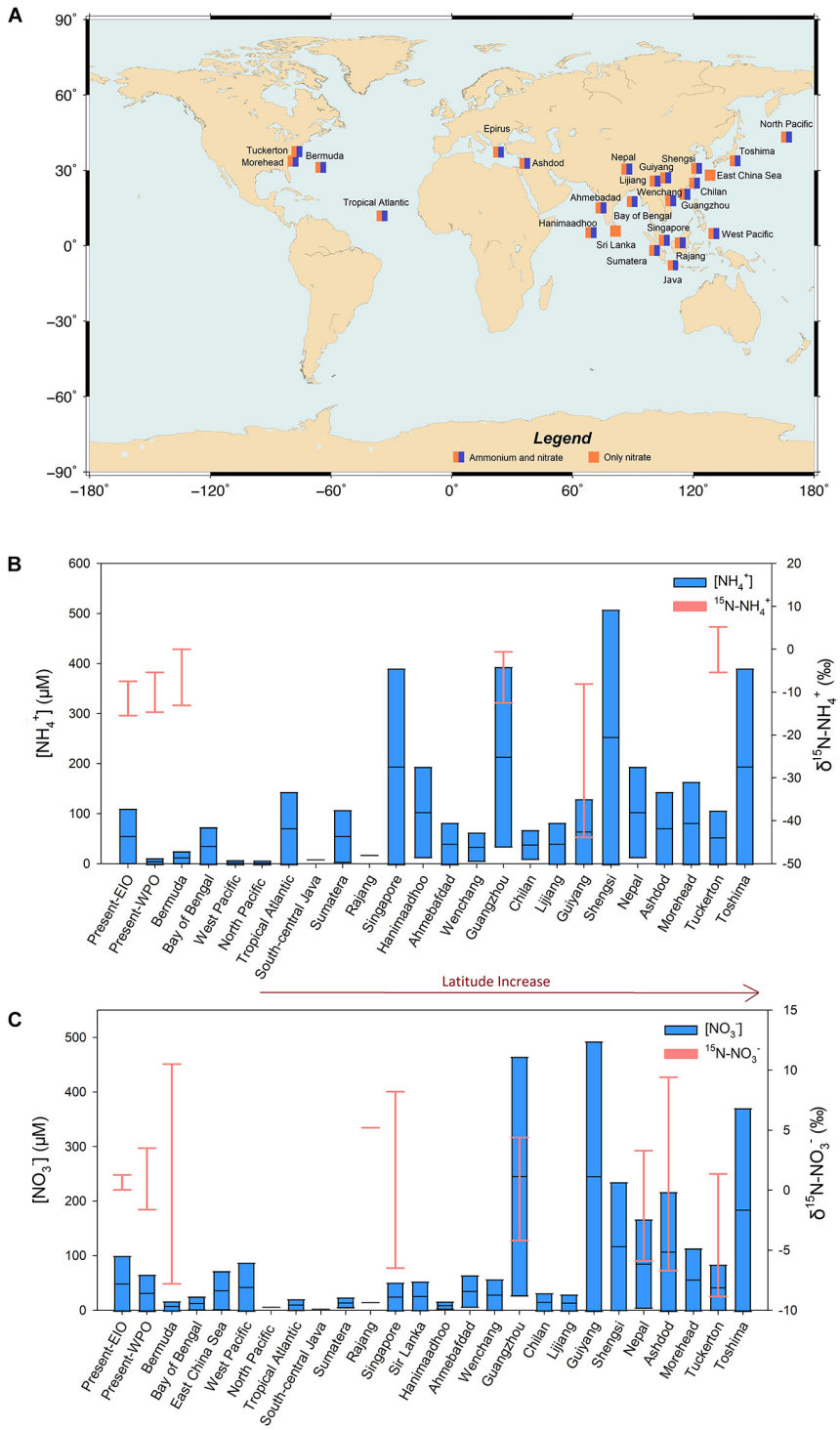

FIGURE 6 | Global comparison of NO_3^-/NH_4^+ concentrations and isotopes among different study sites (**A**: location, **B**: NH_4^+ comparison, **C**: NO_3^- comparison; detailed references in **Supplementary Table S2**). The majority of them are around the EIO and WPO. Notably, the NO_3^-/NH_4^+ concentration range in the EIO excludes the value obtained from Guangzhou.

the increase of NH_4^+ concentration in rainwater was deemed to be responsible for anthropogenic activities. Given the isotopic information, atmospheric NH_4^+ likely resulted from several activities. The fertilizer volatilization is assumed to be a key factor for atmospheric NH_4^+ (Xiao et al., 2020). In the Indian Subcontinent, a significant amount of chemical fertilizer,

e.g., urea, NH_4Cl, and $(NH_4)_2SO_4$, is intensively applied to enhance the yield. For instance, the 16.9 million tones N yr^{-1} fertilizer was applied to the Indian farmland in 2014[3] and the application amount kept increasing in the recent 20 years. The fertilizer application in China is also prominent. The redundant NH_3 in soils is easily volatilized into the atmosphere coupled with the high temperature and air humidity (Sommer et al., 1991). In addition, approximately 45% of fertilized urea was transformed to NH_3 and then increased atmospheric NH_3 concentration (Trierweiler and Bishop, 1983). In the atmosphere, with the combination of acid materials, such as H_2SO_4 from petrochemical industry, steelmaking, thermo power stations, and volcanic activities (Martino et al., 2014), NH_3 is transformed to NH_4^+ (Jia and Chen, 2010). The positive increase in both sulfide and NH_3 led to the accumulation of atmospheric NH_4^+ (**Figure 7**), which, in turn, increased NH_4^+ concentration in the wet deposition. Apart from agriculture, traffic (vehicle exhaust) was also a significant source of atmospheric NH_4^+, which increased $\delta^{15}N$–NH_4^+ in precipitations (Chang et al., 2016) due to the significant positive values (**Supplementary Figure S4**). In the surrounding coasts, the 1.5 billion population in India, Bangladesh, Thailand, etc., could be a key contributor of fossil fuel NH_3 *via* daily transport. Notably, based on the logarithmic decay between NH_4^+ concentration and $\delta^{15}N$–NH_4^+ (**Figure 3A**), the contribution from chemical fertilizer seemed to be stronger than that of vehicle exhaust on the rainwater NH_4^+ enrichment, indicating the necessity of fertilizer application regulation and management.

Different from NH_4^+, the increase of NO_3^- concentration in the moderate group did not significantly influence $\delta^{15}N$–NO_3^- and $\delta^{18}O$–NO_3^- in the EIO (**Figures 3C,D**), indicating multiple sources for terrestrial NO_3^- in these precipitation events (**Supplementary Figure S4**). Notably, human activities could not directly introduce NO_3^- but add the precursor of NO_3^-, i.e., NO_x, into the atmosphere (**Figure 7**). NO_x is rapidly transformed to NO_2^- in humid environment. Due to the instability of NO_2^- and the presence of O_3, the majority of NO_2^- could be transformed to NO_3^- (Elliott et al., 2019), typically as the nitric acid under low pH condition (e.g., low pH conditions in **Figure 3E**). The combustion of fossil fuels, mainly as gasolines from vehicles, is a significant source of NO_x. Anthropogenic NO_x is usually positive in $\delta^{15}N$, ranging from 3.7 to 13‰ (Jia and Chen, 2010) and from 5 to 25‰ (Felix et al., 2015). In contrast, NO_x from soil microbiota is usually negative in $\delta^{15}N$ (-20 to -50‰; Felix et al., 2015) due to the preferential utilization of ^{14}N compounds in metabolism (Harrison et al., 2007). In addition, thermo power plants, especially in India, also markedly contribute to anthropogenic NO_x emissions (Ghude et al., 2012). Coupled with north direction wind (**Figure 1** and **Supplementary Figure S1**), the terrestrial NO_x is transported along the meridional direction into the equatorial EIO, as evidenced by the significant correlation between $\delta^{15}N$–NO_3^- and $\delta^{18}O$–H_2O (**Figure 5D**). On the other hand, the intensive chemical fertilizer triggered active nitrification and denitrification in terrestrial soils, especially in the Indo-Gangetic Plains where intensive agriculture has been conducted (Ghude et al., 2012), leading to an active production of NO_x (Pathak et al., 2002). This clearly introduces biological NO_3^- in the rainwater N inventory. Accordingly, the mixing of these sources likely compensates the isotopic variation of NO_3^-, leading to the distribution pattern observed in **Figures 3C,D**. When the samples were collected in coastal zones (<1 km distance), such as the Malacca Strait and Guangzhou, China (**Figure 1A**), the influence of anthropogenic activities peaked (both soil emission and fossil fuel combustion; **Supplementary Figure S4**), producing high-level N compounds, as well as nss major ions (e.g., SO_4^{2-}). The increase of these compounds markedly decreased rainwater pH (**Figure 3E**) and further accelerated the transformation from NH_3 to NH_4^+ and from NO_x to NO_3^-, eventually leading to the significant enhancement in NH_4^+ and NO_3^- in precipitation.

Wet Deposition N in the WPO

Similar with the EIO, three categories in the WPO were observed (**Figure 4B**). The low N group was obtained in the east boundary of the sampling area, where received east trade wind driven by the Hadley Circulation (**Supplementary Figure S1**). Both NH_4^+ and NO_3^- concentrations in the low N group were < 2.7 μM, which was highly comparable to the record in the EIO (**Figure 4A** vs. **Figure 4B**). In addition, the nss portion of ions in the low N group between oceans was similar (cf. **Figures 5F,G**). Accordingly, marine sourced N should be identified as the dominance in these samples. In the low N group, $\delta^{15}N$–NH_4^+ varied between -10 and -6‰, which was in line with the range found in the EIO samples (**Figure 3A**), as well as the range (-0.5–9‰) in the Atlantic Ocean (Lin et al., 2016), reinforcing that the seawater emission can be identified as the major source of NH_4^+ in oceanic samples. For NO_3^- in the WPO low N group, both $\delta^{15}N$–NO_3^- and $\delta^{18}O$–NO_3^- were more negative (–1.5–0) compared with the EIO, indicating a potential difference during the transformation of NO_x to NO_3^- in atmospheric environments.

Apart from influence from "isotope washout" during long-range transport, as a reaction mainly oxidized by O_3 (Altieri et al., 2013; Elliott et al., 2019), the concentration of O_3 might be a key for the NO_3^- isotopic signature. Between two oceans, the hydrologic cycle impacted by the Walker Circulation deeply influences atmospheric O_3. In particular, the water stable isotopes (δ^2H–H_2O vs $\delta^{18}O$–H_2O) usually decrease from the equatorial ocean to high-latitude oceans (Field et al., 2010). The slope and intercept of the regression line is a mirror of hydrologic cycle on a local scale (Vallet-Coulomb et al., 2008). Compared with the EIO, small values in regression slope and intercept were found in the WPO (**Figure 5B**), indicating the unsteady isotopic fractionation during the precipitation (Gat, 1996). This unsteady state is linked to the environment characterized as evaporation with strong ascending air, termed as "sub-cloud secondary evaporation" (Xia et al., 2019). These sites with $\delta^{18}O$–H_2O > 0 also appeared in the WPO (**Figure 5B**), adding the evidence of ascending air flow in tropical systems (e.g., Gonfiantini et al., 2001; Vallet-Coulomb et al., 2008). In the WPO, such environment settings result from the Walker Circulation, which continuously pumps moisture from the warm pool into

[3]https://ourworldindata.org/fertilizers

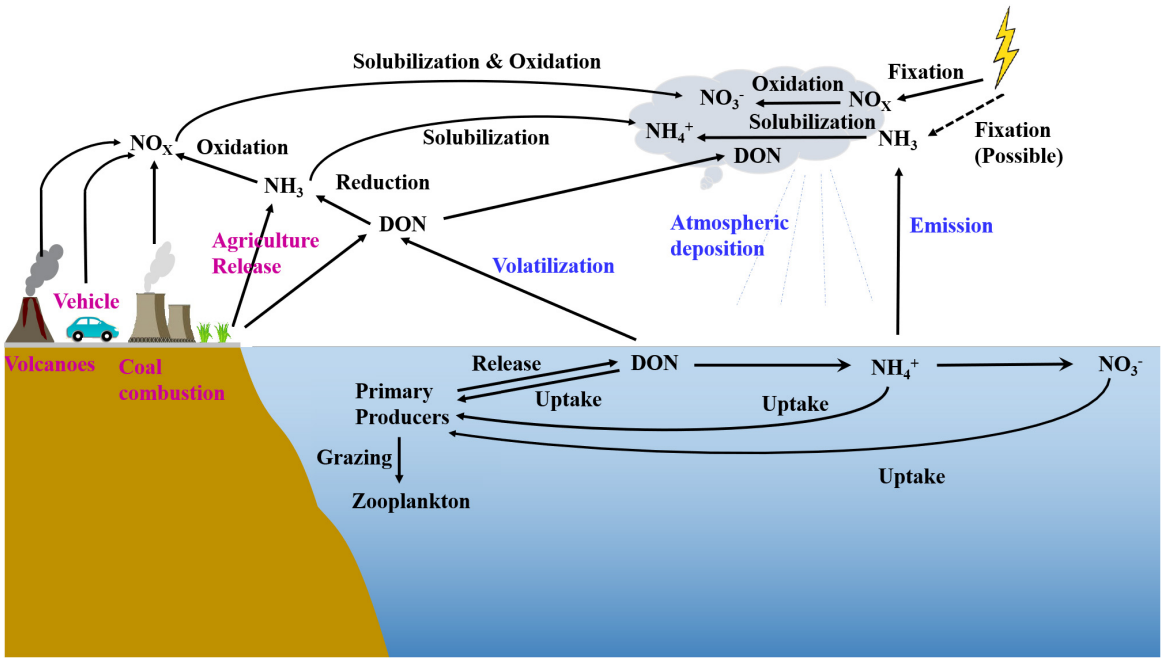

FIGURE 7 | Sketch of N sources, atmospheric transport, and reaction pathways in oceanic precipitation events (modified from Cao et al., 2021).

the atmosphere (Stechmann and Ogrosky, 2014). This ascending flow likely dilutes the atmospheric O_3 in the turbulently mixed sublayer, as the low-level O_3 from 0 to 2 km altitude in the tropical Pacific Ocean (Singh et al., 1996). According to the dynamic balance between NO_x and O_3 (Elliott et al., 2019), low-level O_3 likely produced a weak oxidation with the preference of ^{14}N compounds (Altieri et al., 2013), hence leading to a more negative value of $\delta^{15}N$–NO_3^-. In addition, $\delta^{18}O$ in O_3 ranges from 90 to 122‰ (Johnston and Thiemens, 1997). The reduced reaction potential also decreased $\delta^{18}O$–NO_3^-, creating a drop of both $\delta^{15}N$–NO_3^- and $\delta^{18}O$–NO_3^- in the WPO low N group (**Figure 3D**), as well as different correlations in water stable isotopes (**Figure 5E**).

In contrast, the rainwater samples collected from the west boundary of WPO hosted the high concentration of N compounds (**Figure 4B**). From W1 to W4, the short distance to the Philippines/Indonesia coasts and seaward wind introduced a significant amount of terrestrial materials (**Figure 1A**), leading to the enrichment of land-derived NH_4^+ (low-level ^{15}N signals) with the longitude signal (**Figure 5C**). This west wind that drives the air flow toward the Pacific Ocean center also results from the Walker Circulation (Stechmann and Ogrosky, 2014) and further leads to the increase of NH_4^+ concentration at sites near New Guinea. Interestingly, though the impacts of anthropogenic influence, the enrichment of NH_4^+ in the WPO was relatively weak than that in the EIO (e.g., AAI in the WPO < 100%, **Supplementary Figure S5**). In addition, the NH_4^+ concentration in aerosol $PM_{2.5}$ particles detected in the northwestern Philippines was approximately 0.5 μg N–NH_4^+ m^{-3} (Bagtasa et al., 2018), which was significantly smaller than the value found in the Bay of Bengal (2.8 μg N–NH_4^+ m^{-3}; Srinivas et al., 2011). This likely results from variation of chemical fertilizer application during local agriculture activities in the Philippines, Malaysia, and Indonesia. Specifically, in these three countries, the agriculture activities mainly include the rubber and oil palm plantations (Sia et al., 2019), which produce a low-level application of N fertilizer in agriculture compared with South Asia[4]. However, the requirement on magnesium fertilizer is intensive in peatlands at tropical countries (e.g., Panhwar et al., 2014). As a response, we observed the pattern of low NH_4^+ enrichment but the high-level nss-Mg^{2+} in the WPO precipitation events.

Interestingly, NO_3^- concentrations in the WPO high N group were comparable to the EIO high N group, excluding the Guangzhou site (**Figures 3B**, **6**). However, the total population in the Philippines, Malaysia, and Indonesia is much smaller than that in India, Thailand, and Bangladesh[5], indicating a low contribution of NO_x to the atmosphere on fossil fuel combustion from economic activities. Accordingly, NO_3^- concentration in the WPO samples should be significantly reduced. This contradiction might be resulted from the multiple sources of atmospheric NO_x from terrestrial systems in Southeast Asia (Li et al., 2020). In particular, the Indonesian volcanic activities are an important source for NO_x with $\delta^{15}N$ from N gas compounds of 0.1–4.0‰ (Sano et al., 2001), which is similar to the range found in the WPO (**Figure 2**). During December 2018, the Dungusan Soputan Volcano erupted (Indonesian Geology Bureau)[6] and added a significant amount of ashes into

[4]https://ourworldindata.org/fertilizers
[5]https://data.worldbank.org
[6]http://vsi.esdm.go.id/

the atmosphere (reaching 7,000 m height). The enrichment of nss-F^- (easily evaporated element; **Figure 5G**) in the WPO samples could be a support of the volcanic activities. In addition, croplands in Indonesia are also a hotpot of NO_x with a significant annual increase in NO_x emission (Takakai et al., 2006). Besides, a significant fraction of peatland in Southeast Asia has been changed to oil palm plantations (Jiang et al., 2019). The releasing rate of N_2O from these peatlands is significantly higher (emission factors: 2.4–2.7%) than the IPCC standard on a global scale (1%; Rahman et al., 2019). Though low-level application of chemical fertilizer, the rapid and active production from peatland could contribute to atmospheric NO_x. Emissions from the biomass burning, e.g., rice straw burning after harvesting (Bagtasa et al., 2018; Xiao et al., 2020) and forest/peatland fire events induced from high temperature and accidents (Kumar et al., 2019; Szép et al., 2019), are also an unneglectable source for atmospheric NO_x. Coupled with west wind driven by the Walker Circulation, the terrestrial NO_x is easily delivered into the equatorial WPO. In addition, the volcano activities may also introduce a significant amount of atmospheric nss-SO_4^{2-} (Martino et al., 2014). Such high-level nss-SO_4^{2-} drove the acid rain event in the WPO as the SO_4^{2-}–NO_3^- mixing type (**Figure 5I**). In the WPO high N group, the W9 site is located in the east boundary of the sampling area (**Figure 1A**). This sample was collected at Pohnpei, Micronesia, directly receiving the anthropogenic influence. However, the population in Pohnpei is only approximately 35,000. In addition, the manufacture and agriculture activities in Micronesia are less developed, and citizens are mainly dependent on imported food (Connell, 2015). Compared with NO_3^- and NH_4^+ in the wet precipitation collected at Guangzhou (**Figure 2**) and other coastal sites with millions of population residence, e.g., Wenchang, China (Liu et al., 2011) and Toshima, Japan (Uchiyama et al., 2017), the N content in the Pohnpei harbor is minor, reinforcing that the major driver of wet precipitation N inventory is population-based anthropogenic activities instead of latitude effect driven by the Hardly Circulation.

Budget Estimation and Ecological Implications

Compared with the surface seawater in remote ocean, DIN concentrations in the rainwater were frequently higher, indicating a significant influence on ecological structure from precipitation (Zhang et al., 2004). The estimated precipitation amount in the equatorial EIO was approximately 1,900 mm yr^{-1}, whereas it increased to 2,000 mm yr^{-1} in the equatorial WPO (Béranger et al., 2006). By the mean precipitation rate and the lowest rainwater DIN concentration, the wet precipitation conservatively introduced 66.5 and 47.6 kg N-DIN km^{-2} yr^{-1} into the remote EIO and WPO, respectively. Such conservative contribution from wet deposition events is comparable to the WPO dry deposition (132 kg N-DIN km^{-2} yr^{-1}; Martino et al., 2014). As aforementioned, in the remote ocean, biological fixation and atmospheric disposition are only pathway for the replenishment of N. Biological N fixation is frequently constrained by the input of P and trace elements, such as iron (Großkopf et al., 2012). In the equatorial EIO and WPO, the estimated biological fixation would be <280 kg N km^{-2} yr^{-1} (Deutsch et al., 2007), indicating wet depositions in the EIO and WPO as a key N contributor. Coupled with the surface seawater mixing, the deposited DIN could be rapidly diluted and assimilated by phytoplankton communities (Zhang et al., 2004). Excluding the influence from nutrient stoichiometric balance, the completely biological consumption of rainwater DIN could produce 378 and 270 kg C km^{-2} yr^{-1} sequestration in the EIO and WPO at the conservative scenarios, respectively. The carbon sequestration capability induced by the wet precipitation could easily go to the magnitude of 2,000 kg C km^{-2} yr^{-1} in those regions that received terrestrial materials, such as the area near the Malacca Strait and New Guinea coasts (**Figure 1A**), which is highly comparable to the estimated results in the continental margin of the East China Sea (1,825–3,650 kg C km^{-2} yr^{-1}, Zhang et al., 2004).

Currently, the source of DON in the atmospheric wet deposition is still under debate (reviewed by Cape et al., 2011). Terrestrial source is assumed to be significant in many investigations (e.g., Mace et al., 2003 at Cape Grim, Australia; Luo et al., 2018 at North Pacific Ocean). In the present study, based on the tight linkage between DON and NO_3^- (**Figure 3F**), a significant portion of DON is estimated to be terrestrial emission. Though DON compounds frequently account for a small portion in the oceanic aerosol and wet precipitation N inventory (Cornell et al., 2001; Matsumoto and Uematsu, 2005; Luo et al., 2018) and the recalcitrant nature, DON in surface oceans might also be important by primary producers after phytodegradation (Deutsch et al., 2007), enhancing the carbon sequestration capability. Apart from stimulation on the growth of primary producers (Paerl, 1985), the enrichment of DIN in the rainwater may also add negative effects to the oceanic ecological system, mainly resulting from the imbalanced stichometry ratio among DIN, P, and Si. In particular, the DIN content was constantly redundant in rainwaters from both EIO and WPO, as outlined in **Figure 5A**. Such significant N-redundancy might significantly benefit from the growth of N-preference species in oceanic environments (Rocha et al., 2002). In the equatorial EIO and WPO, the dominant phytoplankton species was mainly picophytoplankton, such as *Synechococcus* and *Prochlorococcus* (Li et al., 2015; Wei et al., 2019). The *in situ* incubation in the WPO has revealed an enhancement in the biomass of diatom and dinoflagellates with excessive N loading (Li et al., 2015). Accordingly, the long-term N excess from the wet atmospheric deposition potentially triggers the ecological succession of phytoplankton species, which should receive further attention.

CONCLUSION

The present study investigated the N inventory in rainwaters obtained from the EIO and WPO. NH_4^+ and NO_3^- frequently accounted for the dominant species with highly variable concentrations. Accordingly, three clusters, namely low, moderate, and high N groups, were identified. In both oceans,

the sites included in the low N group were located in the remote ocean. Main N sources were oceanic NH_4^+ emission and lighting fixation (NO_3^-). In contrast, the sites near the coastal line frequently host the higher N concentrations, especially subject to the west wind driven by the Walker Circulation in the WPO. The enhancement of NH_4^+ concentration in rainwater resulted from the intensive application of chemical fertilizer and daily transport, especially in EIO surrounding countries. The enrichment of NO_3^- is deemed to be responsible for the microbial reactions in terrestrial soils and combustion of fossil fuel. Different contributions from these two sources produced variable correlation between NO_3^- concentration and $\delta^{15}N–NO_3^-$ in rainwaters. Together with the precipitation, 66.5–47.6 kg N km^{-2} yr^{-1} could be introduced into the EIO and WPO, respectively, acting as an important source to support the oceanic CO_2 sequestration. Notably, compared with N content, SRP and Si in rainwater were relatively insufficient based on the Redfield–Brzezinski ratio. As the major path for the exogenous N input, the wet precipitation likely benefits from the growth of N-preference phytoplankton and eventually modifies the ecological structure in tropical oceans. This deserves further attention from the scientific community.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

ShaJ: field survey, laboratory analyses, and data analysis. JJ, YW, and SL: laboratory analysis and data analysis. ShuJ, JW, ZZ, and JZ: field survey and data analysis. JC and YC: data analysis. LW: laboratory analysis. All authors contributed significantly on this manuscript.

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SUPPLEMENTARY MATERIAL

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Spatio-Temporal Assessment of the European Hake (*Merluccius merluccius*) Recruits in the Northern Iberian Peninsula

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The protection of fish nurseries has been recognized as a useful tool to efficiently manage fisheries given that protected areas enhance the recruitment of target species. To identify and locate potential nursery areas, a solid understanding of species-environment relationships and their spatio-temporal dynamics is needed. Within this context, in this study we assess where European hake (*Merluccius merluccius*) recruits persistently aggregate in the northern continental shelf of the Iberian Peninsula. Hake recruit data collected during scientific trawl surveys between 2005 and 2016 were analyzed using Bayesian hurdle hierarchical spatio-temporal models, considering the environmental variables bathymetry, sea bottom temperature and salinity. Additionally, three different spatio-temporal structures (i.e., persistent, progressive, or opportunistic) were compared to assess the temporal persistence of nurseries over time. Among all the environmental variables analyzed, bathymetry was the most important. The preferential habitat of recruits was found to be within a bathymetric range of 120–200 m. Our findings clearly show that there is a temporally persistent main nursery located along the continental shelf of the Artabrian gulf (off La Coruña) in addition to several areas with high aggregations of hake recruits but with strong inter-annual variability. We argue that the analytical framework applied in this study allowed us to identify European hake nurseries in the northern continental shelf of the Iberian Peninsula, as well as their spatio-temporal fluctuations throughout the study period (2005–2016), and to assess which environmental factors, among bathymetry, sea bottom temperature and salinity, influence the occurrence and abundance of recruits in the study area. Results of our models also produce a new abundance index that could be useful for improving traditional stock assessment models.

Keywords: bayesian models, European hake, hurdle-model, recruits, stock assessment, spatial ecology, INLA approach

1. INTRODUCTION

Contemporary sustainable fisheries management advisory panels have acknowledged the importance of fisheries restricted areas (FRA) as a complementary tool to conventional stock management policies (FAO, 2016). Increased overfishing can lead to fluctuations in species stock abundance, and therefore, fully accounting for the age-structure and natural growth potential of fish stocks is crucial, being recruitment one of the most vulnerable phases (Diekert et al., 2010). There are some measures to protect this life stage, such as increasing mesh size or using a different net geometry (Carlucci et al., 2009), but other technical measures that involve protecting spatial or spatio-temporal FRAs may be key to accomplishing sustainable management (Colloca et al., 2015; Paradinas et al., 2015) as they are less susceptible to annual assessment strategies or political agreements (Pitchford et al., 2007).

European hake (*Merluccius merluccius*) is one of the most important commercial species in the northeast Atlantic and is assessed by the International Council for the Exploration of the Sea (ICES) in two units: the northern and the southern stocks. Despite the recovery plan for the southern stock implemented in 2006 (EC 2166/2005) and the Multiannual Management Plan for Western Waters (EU, 2019), the fish mortality rate is still above the maximum sustainable yield (Fmsy), even though the spawning stock biomass is above precautionary levels (ICES, 2018a). Diverse spatial studies have identified nursery areas for this species and stock (Casey and Pereiro, 1995). Sánchez and Gil (2000) found persistent nursery areas in the northwest coast of the Iberian Peninsula, while a more recent study by Pennino et al. (2019) identified four areas with different levels of overlap with the past study. This difference in results demonstrates the importance of dynamic spatio-temporal modeling, given that the effect of environmental conditions over time can vary the distribution, shape and abundance of hake nursery grounds.

Several studies have assessed whether different physical, environmental and biological factors can affect growth and survival rates of European hake during the early life stages (Alvarez et al., 2001, 2004; Bartolino et al., 2008; Korta et al., 2015). In the northeastern Atlantic, previous studies have determined that recruitment success has a direct relationship with regime shifts expressed through the sea surface temperature and the Ekman's transport index (Goikoetxea and Irigoien, 2013). Along the continental Galician shelf, random variations in the physical environment, such as North Atlantic Oscillation (NAO) and the upwelling, have been observed to directly affect the growth and size of mature hake females (Domínguez-Petit et al., 2008). Moreover, the interplay of westward larvae transport within anticyclonic eddies that collide with the shelf grounds favors high recruitment to nursery areas at depths of between 90 and 180 meters in the western shelf of the Cantabrian Sea (Sánchez and Gil, 2000).

Valuable information regarding ecological hake dynamics is being addressed both through various studies and the stock assessment working group developed by ICES, which relies on information from commercial landings and oceanographic surveys provided by research centers, such as the "Instituto Español de Oceanografía" (IEO) and the "Instituto Português do Mar e da Atmosfera" (IPMA). Since 2014, this data has been used as an input to the GADGET (Globally applicable Area Disaggregated General Ecosystem Toolbox) model (length based), which is currently one of the most complete methods to study the state of a population over time (ICES, 2018b). However, most of these stock assessment studies maintain the same assumption that spatial and environmental variability is implicitly intrinsic in the data, and therefore, it is not explicitly taken into consideration in assessment models. Survey abundance indices are used to calibrate dynamic models assuming some proportionality between survey abundance and modeled abundance. To guarantee that this proportionality is constant on time the sampling design is kept the same every year, allowing a random selection of hauls in each strata. However, changes on fish distribution can happen from year to year affecting the design based abundance estimation. If these abundance indices ignore spatial structures in estimates it can lead to biased results (Shelton et al., 2014; Cao et al., 2017).

Studying the spatial distribution of a species like hake over time is a medium-large scale process, which is influenced by changing environmental features. Geostatistical models take into account spatial autocorrelation, which allows spatial dependency between neighboring locations to be incorporated, following the principle that nearby locations are more similar than distant ones (Tobler, 1970; Dormann, 2007). Similarly, when analyzing time series data consecutive measurements of months and/or years are more similar than separated ones, and therefore, display temporal autocorrelation (Tsitsika et al., 2007). Taking explicitly spatial and temporal correlation in models into account is essential since observations are often collected close in time and space and are subject to similar environmental characteristics (Hurlbert, 1984; Hefley et al., 2017). Ignoring spatial and temporal dependence in this type of analysis can generate misleading results (Latimer et al., 2006; Agostini et al., 2008; Fahrmeir and Kneib, 2008). Recently, the use of Bayesian hierarchical spatio-temporal models has demonstrated to be a convenient approach when modeling species habitat preferred conditions (Muñoz et al., 2013) and also to identify species nurseries (Colloca et al., 2009; Paradinas et al., 2015, 2020), given their ability to incorporate the spatio-temporal correlation as well as the associated uncertainties. Moreover, to be useful for fisheries management, the identified nurseries need to be areas that persist over time (Fiorentino et al., 2003; Garofalo et al., 2011; Colloca et al., 2015; Druon et al., 2015). A variety of research approaches have been proposed to assess temporal persistence: Colloca et al. (2009) proposed Bayesian kriging maps by year associated to aggregation curves that identify the level of persistence; Paradinas et al. (2015) proposed a Bayesian approach that compared two spatio-temporal structures, one fitting persistent scenarios (i.e., spatial distributions that do not change with time), and the other accommodating opportunistic scenarios (i.e., spatial distributions that change unrelatedly across subsequent time events). Recently, Paradinas et al. (2017, 2020) enhanced the latter approach by including a third spatio-temporal structure to fit progressive processes (i.e., distributions that are neither totally persistent nor opportunistic but change progressively over time).

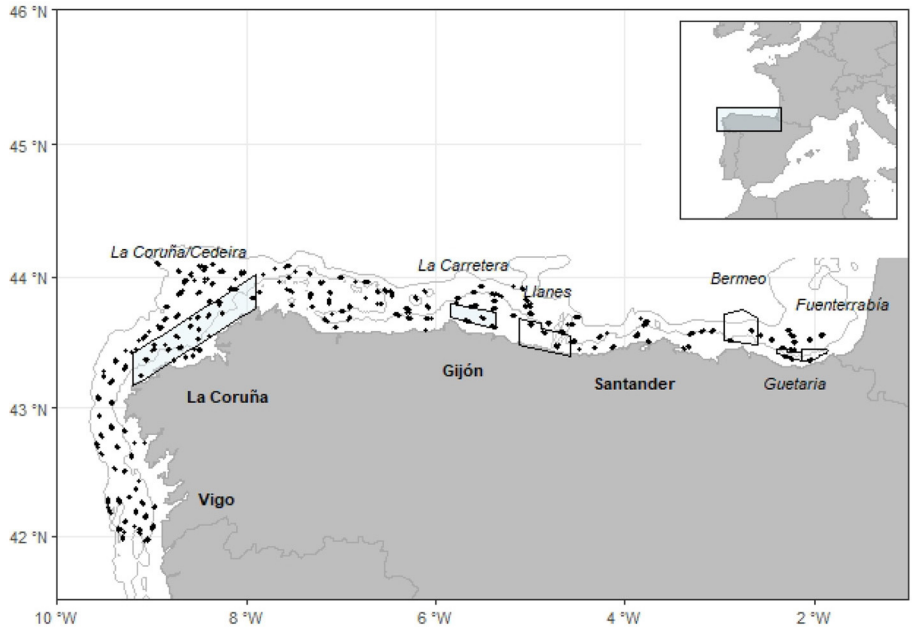

FIGURE 1 | Sampling locations (black dots) of SP-NSGFS Q4 surveys (2005–2016). Bathymetric lines indicate the 100 and 800 m isobaths. Closure areas to trawl in Galician and Cantabrian Sea Waters. Colored polygons are permanent closed while White areas correspond to the temporal ones (BOE, 2015).

Within this context, here we apply a Bayesian hierarchical spatio-temporal hurdle-model (B-HSTHMs) to (1) identify European hake nurseries in the northern continental shelf of the Iberian Peninsula and their spatio-temporal fluctuations over time (2005–2016); (2) assess which environmental factors, among bathymetry, sea bottom temperature and salinity, influence recruit occurrence and abundance in the study area, and (3) produce a new habitat-based abundance index of recruits for traditional stock assessment models.

2. METHODS

2.1. Study Region

The region of interest for this study is the northern continental shelf of the Iberian Peninsula (see **Figure 1**), a narrow area (10–60 km) of almost 18,000 km^2 that is characterized by important and marked hydro dynamism (Abad et al., 2019). Over the shelf, currents are driven by regional factors, such as tides and wind (Gil and Sánchez, 2003). In the winter, a warm and saline poleward current moves eastward along the Cantabrian coast and enters the Bay of Biscay (Korta et al., 2015). In addition, the coastal upwelling off the Galician and Portuguese coasts appears during spring and summer which, combined with hydrographic mesoscale activities, has a strong influence on the primary production of the area (Sánchez and Olaso, 2004).

In this area, hake is caught by trawls, gillnetters, long-liners, and artisanal fleets (ICES, 2018a). The bottom-trawling fleet operate throughout the year exploiting the fishing grounds, but seasonal and permanent spatial closures for this fleet have been implemented since before 2000 (BOE, 1996, 2015). Specifically, the fishing grounds with seasonal closures for hake recruitment are La Coruña/Cedeira, where trawling is forbidden from October to January, and La Carretera, where trawling is forbidden from September to March (**Figure 1**).

2.2. Data Collection

Data on hake recruits were collected by the IEO for the scientific survey series SP NSGFS Q4, which is carried out annually in autumn (September to October), and the study period includes data from 2005 to 2016. This survey used a stratified sampling design based on depth with three bathymetric strata: 70–120, 121–200, and 201–500 m. Moreover, some samples from additional trawls at greater depths were also included. Sampling stations consisted of 30 min trawling hauls located randomly within each strata at the beginning of the survey design (**Figure 1**). Approximately 115 hauls divided between the three bathymetric strata were performed every year in this zone, using baka 44/60 gear (ICES, 2017) and following the International Bottom Trawl Survey Working Group protocols (IBTSWG) of ICES.

All individuals smaller than 21 centimeters were considered recruits (Murua, 2010). It should be noted that the fishing gear used is well-designed to catch recruit individuals (cod-end mesh size 10 mm), who settle at the bottom with about 10 cm (Sánchez and Gil, 2000).

Two different response variables were analyzed to characterize the spatio-temporal behavior of European hake recruits. First, we considered a presence/absence variable to measure the occurrence probability of the species. Second, we used the total number of individuals standardized by 30 min of trawling (i.e., number per unit effort, NPUE) as an indicator of the conditional-to-presence abundance of the species.

TABLE 1 | Summary of fitted spatio-temporal models $U(s, t)$.

Model	Notation	Description
Opportunistic	$U(s,t) = \boldsymbol{W}_t$	Different and uncorrelated realizations of the spatial field every year.
Persistent	$U(s,t) = \boldsymbol{W} + f(t)$	A common realization of the spatial field for all years and an additive temporal trend $f(t)$.
Progressive	$U(s,t) = \boldsymbol{W}_t + \rho U_{st-1}$	Spatial realizations change over time through a first order autoregressive model. ρ controls the level of correlation between subsequent time events.

$\boldsymbol{W}$ represents a geostatistical spatial field, $f(t)$ is a temporal trend function and ρ is an autoregressive correlation parameter bounded to [0,1].

Due to the demersal nature of this species, only three environmental variables were considered to be potential drivers. Two oceanographic variables, Sea Bottom Temperature (SBT in °C) and Sea Bottom Salinity (SBS in PSU), and bathymetry (in meters).

SBT and SBS were added to the analysis as they are strongly related to marine system productivity given that they affect nutrient availability and water stratification (Muñoz et al., 2013). SBT and SBS values were collected during the survey with a sounding CTD SeaBird (conductivity, temperature and depth) in different random sampling points of the study area. Average SBT (**Supplementary Figure 1**) and SBS (**Supplementary Figure 2**) maps for the months of the survey (September–October) over the entire area were obtained for each year of the period studied with the Radial basis functions (RBF) tool in ArcGIS 10.1.

Bathymetry (**Supplementary Figure 3**) was obtained from the European Marine Observation and Data Network with a spatial resolution of 0.02 × 0.02 decimal degrees. In order to ensure the same spatial resolution, all environmental data were aggregated to the lower spatial resolutions (0.05 × 0.05 decimal degrees) using the raster package (Hijmans, 2018) in the R software (R Core Team, 2017).

All covariates were explored for collinearity, outliers, and missing values following the approach of Zuur et al. (2010) before being included in the models. Correlation among variables was tested using the Spearman's correlation (**Supplementary Figure 4**), whereas collinearity was computed using Generalized variance-inflation factors (GVIF) (Fox and Weisberg, 2011) (**Supplementary Figure 5**). To avoid numerical confounding within the model selection, the explanatory variables were standardized (difference from the mean divided by the corresponding standard deviation) (Gelman, 2008).

2.3. Characterizing the Spatio-Temporal Behavior of European Hake Recruits

This study used the spatio-temporal geostatistical model structure comparison proposed by Paradinas et al. (2017) to categorize the spatio-temporal behavior of European hake as either opportunistic, persistent or progressive (see **Table 1** and **Figure 2**). These models use a geostatistical term that accounts for spatial autocorrelation in the data and can easily include different spatiotemporal extensions. In particular, opportunistic structures indicate that species change their spatial patterns every year without following any specific pattern, persistent structures imply that species have a spatial distribution that does not change every year, and progressive structures indicate that species change their spatial patterns in a correlated way from 1 year to another. The progressive structure contains an autoregressive ρ_t parameter (see **Table 1**) that controls the persistence level of the spatial effect. This ρ_t parameter is bound to $[0, 1]$, where parameter values close to 0 represent more opportunistic behaviors and parameter values close to 1 represent more persistent distributions over time.

The spatial field (W_s) (see **Table 1**) was modeled as a normal multivariate distribution with a zero mean and a Matérn covariance function that depends on its range (r_w) and variance (σ_w). The temporal trend $f(t)$ could follow any suitable function, for example, a linear effect, a smooth effect, an unstructured random term, etc.

2.4. Modeling European Hake Occurrence and Abundance Distribution

Spatio-temporal fisheries abundance data often involves a large proportion of zeros in observations, i.e., zero inflated data. These data are generally tackled using independent two-part models, also known as hurdle models. In these models, the occurrence and conditional-to-presence abundances (NPUE) are modeled independently. However, the variables abundance and detection probability are often related (Kéry et al., 2005), which violates the independence assumption in classic delta models. This study acknowledges that both processes could be related by fitting shared environmental and/or spatio-temporal effects through joint modeling techniques (Hogan and Laird, 1997; Held et al., 2005). We have a semi continuous dataset regarding the presence/absence and abundance data, as both processes are measured in the $[0, \infty)$ interval (Paradinas et al., 2017). Moreover, the proportion of zeros in the data gets close to 30% for some of the years. Within this context, the application of a hurdle model enables that the first process determines the occurrence and the second the intensity when the response is non-zero, what makes the modeling process more informative.

Specifically, $Y(s, t)$ and $Z(s, t)$ denote the spatio-temporal distribution occurrence and the conditional-to-presence abundance (NPUE), respectively, where $s = 1, \ldots\ldots, n_t$ is the spatial location and $t = 1, \ldots, T$ the temporal index, with $i = 1, \ldots, I$ representing the environmental variable in location s. As is generally done with these kinds of variables, we used a Bernoulli distribution to model the occurrence of $Y(s, t)$. With respect to NPUE $Z(s, t)$, we chose to model it with a gamma distribution, which is a probability distribution that helps to capture any possible overdispersion in the data. The mean of both variables was then related via the usual link functions (logit and log, respectively) to the environmental and

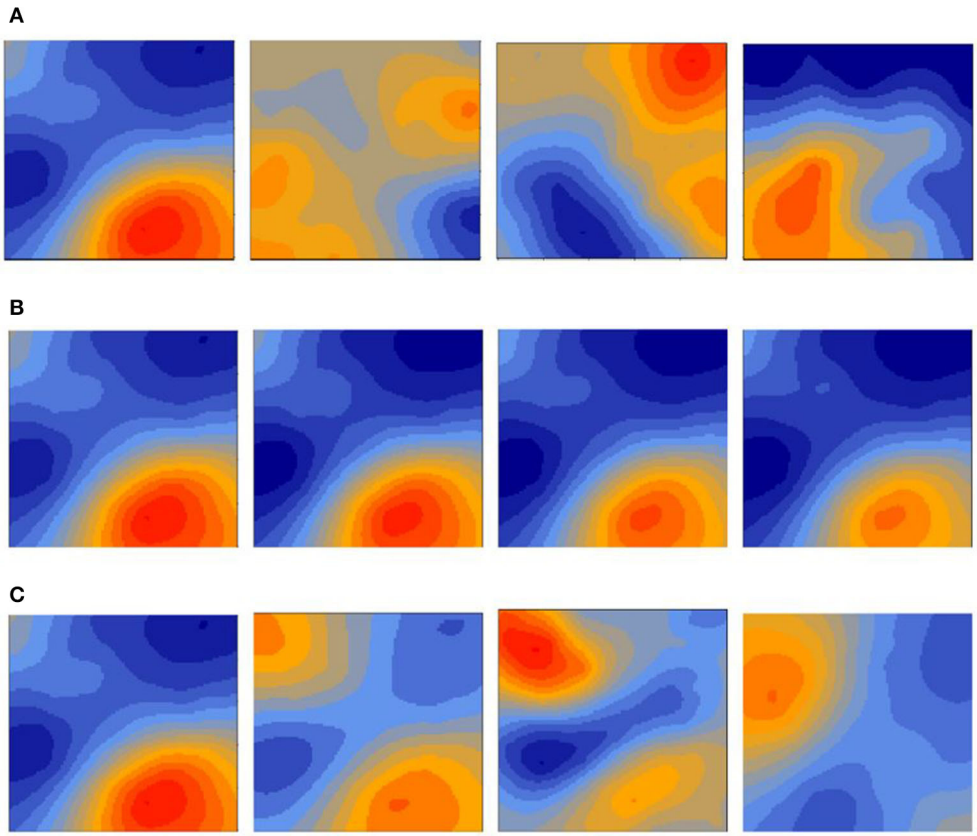

FIGURE 2 | Simulated spatio-temporal scenarios extracted from Paradinas et al. (2017). An opportunistic distribution shows big unrelated changes in the spatial structure among neighboring times. A persistent scenario has very similar spatial structures at every time. A progressive scenario has correlated spatial realization changes over time. **(A)** Opportunistic distribution. **(B)** Persistent distribution with trend. **(C)** Progressive spatio-temporal distribution.

spatio-temporal effects:

$$\begin{aligned} Y(s,t) &\sim \mathrm{Ber}(\pi(s,t)) \\ Z(s,t) &\sim \mathrm{Gamma}(\mu(s,t),\phi) \\ \mathrm{logit}(\pi(s,t)) &= \alpha_Y + \sum_{i=1}^{I} f_i(X_i(s,t)) + U_Y(s,t) \\ \log(\mu(s,t)) &= \alpha_Z + \sum_{i=1}^{I} \theta_i f_i(X_i(s,t)) + \theta_U U_Z(s,t) \end{aligned} \tag{1}$$

where $\pi(s,t)$ represents the probability of occurrence at location s at time t, and $\mu(s,t)$ and ϕ represent the mean and dispersion of the conditional-to-presence abundance. The linear predictors, which indicate how parameters $\pi(s,t)$ and $\mu(s,t)$ behave in space and time, are formed by: α_Y and α_Z, i.e., the terms representing the intercepts of each variable; $f()$ represents any function applied to our environmental variables X_i, which in our case were either a constant function (fixed effects) or a second order random walk (RW2) function to fit non-linear relationships (Fahrmeir and Lang, 2001); and the final terms, $U_Y(s,t)$ and $U_Z(s,t)$ refer to the spatio-temporal structure of occurrence and the conditional-to-presence abundance, respectively, and may follow any of the three spatio-temporal structures described in the previous section. The scale parameters θ_i and θ_U permit differences in scale across both linear predictors in shared effects. It is important to note that sharing occurrence and conditional-to-presence abundance information to fit common environmental effects may not always improve the models, thus we tested all possible model combinations.

Vague prior distributions with a zero-mean and a standard deviation of 100 were implemented for all the fixed effects, the abundance process variance, and the scaling parameter (θ) of the shared effects. PC priors (Fuglstad et al., 2018) were used to describe prior knowledge of hyperparameters of the geostatistical terms and the ρ parameters of the RW2 functions. These priors were set as follows: if the prior probability of the spatial range was smaller than 0.5, it was set at 0.05, if the probability of the spatial variance was larger than 0.6, it was also set at 0.05, and if the probability that the precision of the RW2 effects was larger than 0.5, it was set at 0.01. A sensitivity analysis of the choice of priors was performed by verifying that the posterior distributions

TABLE 2 | Spatio-temporal structures comparison for the conditional-to-presence abundance distribution European hake recruits' model based on WAIC and LCPO scores.

Model	WAIC	LCPO	Time (s)
Persistent shared effects	15879.45	2.90	80.91
Persistent not shared effects	16001.28	2.92	118.08
Opportunistic shared effects	16095.17	2.95	59.82
Opportunistic not shared effects	16231.99	2.95	79.56
Progressive shared effects	16774.70	3.05	401.62
Progressive not shared effects	**15846.09**	**3.11**	**7138.10**

Time scores refer only to the estimation process of the model. The best model is highlighted in bold.

TABLE 3 | Environmental effects comparison for the conditional-to-presence abundance distribution European hake recruits' model based on WAIC and LCPO scores.

Model PNSE	WAIC	LCPO	Time (s)
B shared effects	**15659.88**	**3.02**	**13667.78**
SBS shared effects	15848.98	3.11	7168.39
SBT shared effects	15800.53	3.15	11032.17
B + SBS shared effects	15655.22	3.05	16488.46
B + SBT shared effects	15657.85	3.07	17097.45
SBS + SBT shared effects	15804.95	3.16	11683.53
B not shared effects	15668.76	3.03	10143.00
SBS not shared effects	15852.73	3.11	10662.15
SBT not shared effects	15798.90	3.14	9416.98
B + SBS not shared effects	15672.92	3.03	14104.07
B + SBT not shared effects	15672.60	3.06	15135.95
SBS + SBT not shared effects	15805.43	3.14	11152.92

B, Bathymetry; SBS, Sea bottom salinity; and SBT, Sea bottom temperature. Note all models include the selected Progressive Not Shared Effects spatio-temporal structure (PNSE). Time scores refer only to the estimation process of the model. The best model is highlighted in bold.

concentrated well within the support of the priors (Zuur et al., 2017).

Model selection was performed by testing all possible combinations among the possible spatio-temporal structures and variables using the Watanabe Akaike Information Criterion (WAIC) (Watanabe, 2010) for goodness of fit and the mean logarithm of the Conditional Predictive Ordinate (LCPO) (Roos et al., 2011) as a predictive quality measure. For both measures, the smaller the score, the better the model. All models were fitted using the integrated nested Laplace approximation (INLA) (Rue et al., 2009) approach in the R-INLA software. The R-INLA code for the applied models can be found on this GitHub repository.

From the final spatio-temporal model output we obtained the mean yearly habitat-based recruits abundance index. For comparison purposes, we created a stock assessment strata-based index for the number of hake recruits (<21 cm), standardized for the area of their corresponding bathymetric strata (from 70 to 500 m) (ICES, 2017).

Finally, we defined hake nurseries as high recruit aggregation areas which are persistent over the time. Thus, for the average of a given n-years period we are able to identify potential nursery areas with the contour polygon based on the NPUE above 90th percentile, as described in Paradinas et al. (2020).

3. RESULTS

3.1. Spatio-Temporal Structure Selection

With respect to the spatio-temporal structures, the shared components showed better goodness of fit in the opportunistic and persistent models (**Table 2**). However, the best structure was the progressive model with non-shared spatio-temporal effects. This means that the spatial occurrence and abundance patterns of recruits change in a correlated way from 1 year to the next, but that both sub-processes behave considerably different from one another. This structure was selected for the final model because it had the lowest WAIC value. It should be mentioned that the progressive structure had the largest computational time, with a notable difference (**Table 2**).

3.2. Variable Selection

Concerning the environmental variables, bathymetry was the most important predictor to defining the distribution occurrence and abundance of hake recruits in the study area (**Table 3**). Although, in terms of WAIC, the best models were those that included bathymetry and either SBS or SBT, the difference between these models and the model that only included bathymetry was rather negligible (i.e., lower than 5 units). This means that the variability of the hake recruit abundance is mostly affected by bathymetry and spatio-temporal effects. Therefore, and following a parsimony principle, the selected model included only a shared bathymetric effect as a covariate.

3.3. Final Model

Given that the only relevant variable included in the final model was bathymetry, original scale units were used to facilitate interpretation of the partial effect. There is an optimum bathymetric range between 140 and 200 m for both the occurrence and abundance of hake recruits (see **Figure 3**). This means that hake recruit abundance decreases gradually with bathymetry, as presented in **Figure 3**.

The selection of an autoregressive temporal term in the model suggests the presence of a certain degree of temporal persistence in the spatial distribution of hake recruits in the study area. These results were supported by the high temporal correlation parameters (ρ) of the progressive spatio-temporal structures (0.99 and 0.96 for the occurrence and conditional-to-presence abundances, respectively).

With respect to the posterior distribution mean of the occurrence spatial effect, only slight changes were observed between years (**Figure 4**). This result highlights a clear stable structure for the presence of hake recruits in the study area that remains constant throughout the whole period. However, the mean spatial effect for abundance had high inter-annual variation, thereby reflecting changes to recruit concentration areas over the time (**Figure 5**). We can observe similar patterns in the standard deviation maps of the posterior distribution of

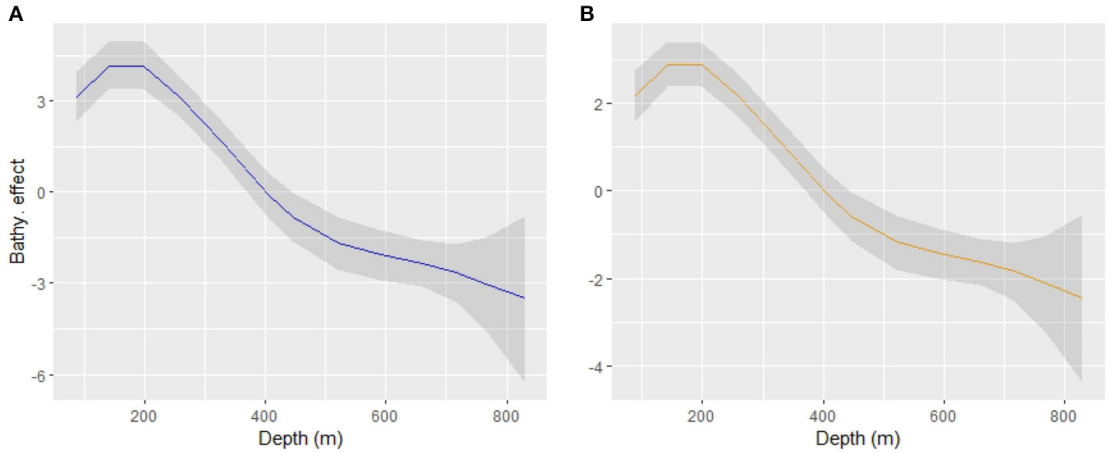

FIGURE 3 | Smoothed bathymetric effect ("RW2") for the sub-process Binomial **(A)** and Gamma **(B)** in the linear predictor scale (logarithmic link).

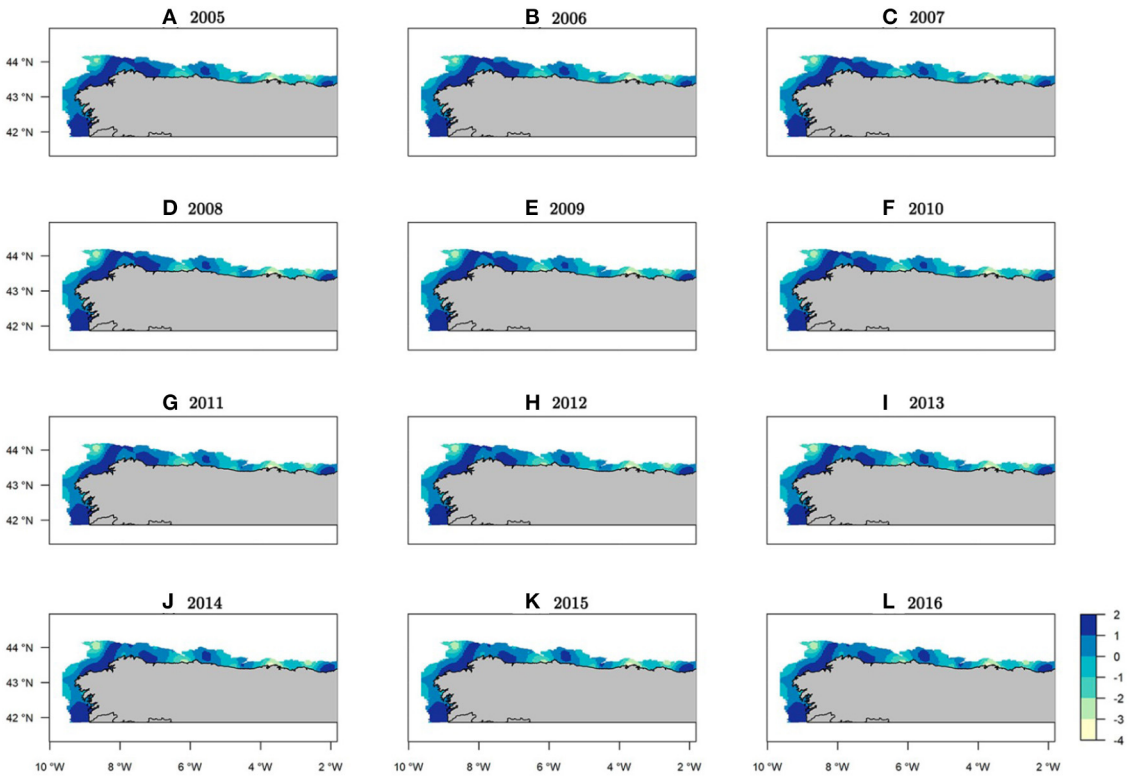

FIGURE 4 | Spatio-temporal occurrence maps for *Merluccius merluccius* recruits in the northeast Atlantic showing mean spatial effects (log-scale) for the probability of presence.

the spatial effect for both the occurrence and abundance sub-processes (see **Supplementary Figures 6**, **7**).

The median of the posterior predictive distribution for the occurrence revealed that the areas with the presence of hake recruits have a constant spatial pattern over time (**Figure 6**). However, abundance did not show the same spatio-temporal behavior. Indeed, we found areas with a persistent high concentrations of recruits over time, as well as intermittent zones (**Figure 7**).

Within the study area, the northwest area of the Iberian Peninsula presented the highest concentration of recruits

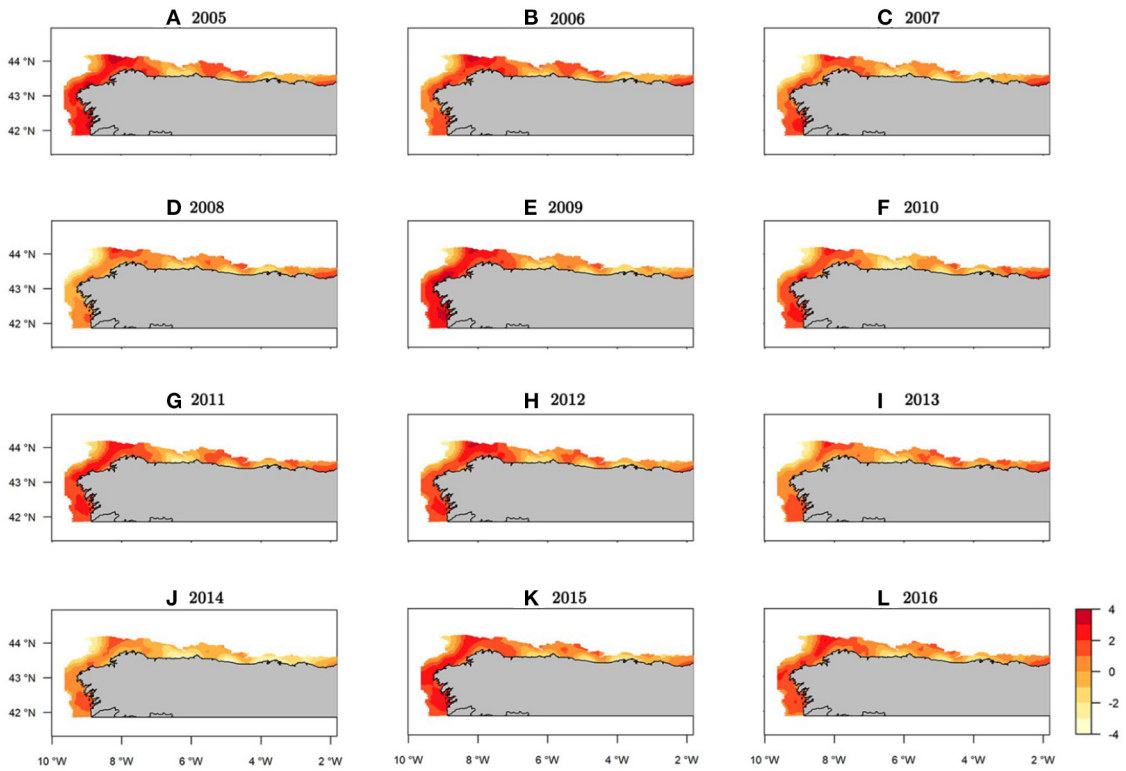

FIGURE 5 | Spatio-temporal abundance (NPUE) maps for *Merluccius merluccius* recruits in the northeast Atlantic showing mean spatial effects (log-scale).

throughout the entire period (**Figure 7**). Specifically, from west to east three persistent areas were identified: the area in front of Vigo, the Artabrian gulf (off La Coruña) and La Carretera (**Figures 7**, **1**). Three intermittent areas were identified: one in front of Santander and the other two corresponding to the Bermeo and Guetaria-Fuenterrabía spatial closure areas (**Figures 7**, **1**). The years with the greatest hake recruit abundance were 2005 and 2009, whereas the years with the lowest values were 2008 and 2014 (**Supplementary Figure 8**).

Regarding the variability of the generated predictions, estimates corresponding to the first and third quartiles showed a spatial pattern very similar to the predicted posterior median, thereby suggesting a good degree of accuracy with respect to the uncertainty of the model for both the occurrence and abundance of recruits (**Figure 8**). The yearly maps that correspond to the three quartiles for occurrence and abundance can be found in **Supplementary Figures 8–13**. In addition, we identified the main aggregation areas with a NPUE above the 90th percentile to be potential hake nurseries, taking into account the average of all study years (2005–2016) (**Figure 8**). The overlapping area between the FRA of La Coruña and the main identified nursery area is about the 27.46% (800.250 km^2) (see **Supplementary Figure 14**).

The mean predicted posterior abundance trend of European hake recruits was similar to the trend of the designed strata-based index that would be commonly used as an input for stock assessment models. However, the output from our model showed lower mean abundance values within the entire study period, specifically for the years 2009 and 2015, where the strata based index values were high (**Figure 9**).

4. DISCUSSION

In order to implement fisheries restricted areas (FRAs), a spatial characterization of the key life–cycle habitats of commercial stocks, such hake nursery or spawning grounds, is required. Here, we apply a methodological approach to identify nursery grounds based on the spatio–temporal persistence of recruit aggregation areas.

Coinciding with Paradinas et al. (2017), the best spatio-temporal structure was the progressive one with non-shared effects. This result suggests that hake recruitment data is generated in two different steps : (1) identifying the probability of observing hake recruits, and if present, (2) identifying their abundance. However, the nature of the process under study leads us to believe that this apparent independence is a consequence of the survey sampling effort, rather than a result of two different processes. The SP-NSGFS Q4 survey trawls a relatively big area, and therefore the probability of observing at least one individual of an abundant fish species, such as hake, is quite high in environmentally not-too-challenging areas. However, if effort had been increased to deeper areas, the detection probability

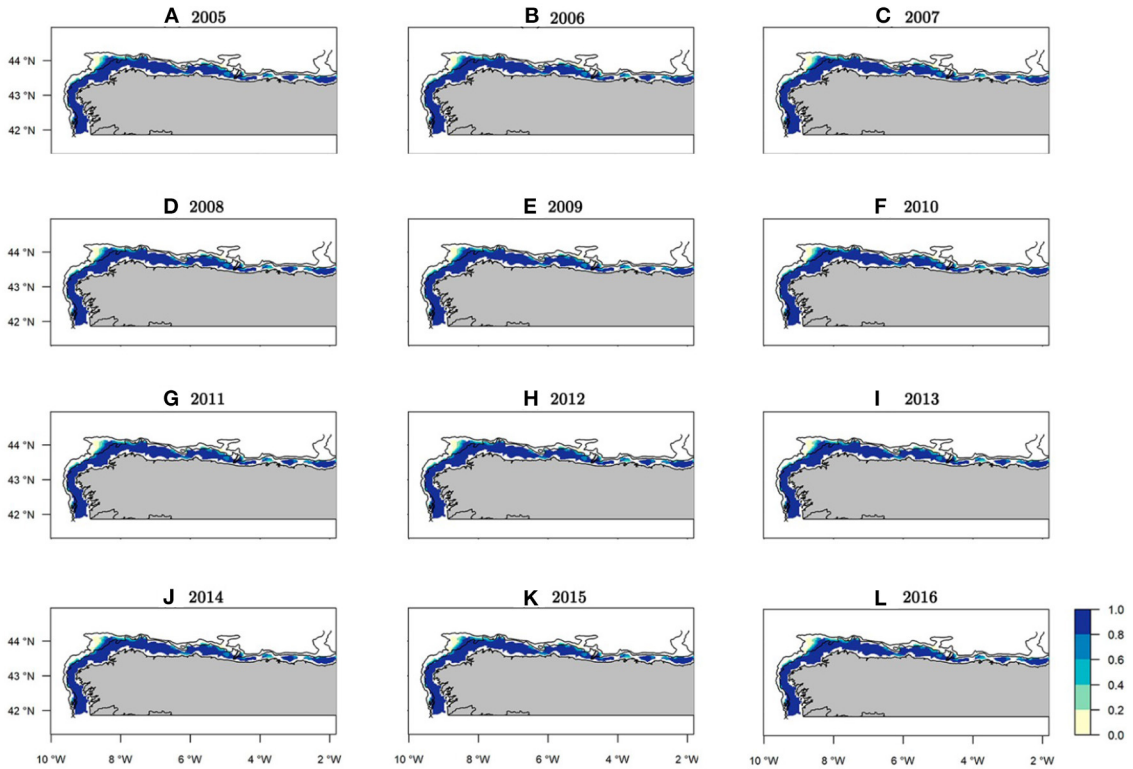

FIGURE 6 | Median occurrence probability maps of the posterior predictive distribution for European hake recruits within the study period. Bathymetric lines correspond to 200 and 800 m isobath.

would have decreased proportionally, and thus, generated a lot more zeros in our dataset. Occurrence and abundance have been shown to respond equal and differently depending on the environmental variables, as it has been observed for different elasmobranch species in the Mediterranean, therefore, they are modeled by semi-independent processes (Lauria et al., 2015). This result is highly related to the life habits of a species and their age-size, since the individuals have a wide spatial distribution range where they are present, but they can be more abundant in areas where environmental preferred conditions take place (i.e., trophic niche). In our case of study, due to the benthic habits of European hake recruits, we consider that the occurrence, abundance and environmental variables are modeled by the same generating process.

Among all the covariates tested, SBS and SBT were the least relevant at explaining the occurrence and abundance of hake recruits in the study area. Similar results were observed by Paradinas et al. (2015), who found that surface temperature and type of substrate were not relevant to recruiting hake in the Mediterranean. However, different results have been reported in literature. A study of regime shifts carried out by Goikoetxea and Irigoien (2013) found that temperature increase anomalies had a positive effect on hake recruitment from the northeast Atlantic. In the Ligurian Sea northern hake nursery area, Abella et al. (2008) found a negative correlation between the North Atlantic Oscillation (NAO) index and recruitment success. In the Mediterranean, high peaks in water temperatures during summer resulted in a decreased abundance of hake recruits in autumn (Bartolino et al., 2008), therefore demonstrating that the changes produced in a given month have indirect effects on the abundance of individuals in subsequent months. Results from the present study indicate that SBT did not have a big influence on recruitment in the same month, however, it would be interesting to test environmental variables with temporal lags for future studies.

Regarding bathymetry, in recent studies it has been observed to be an important variable that contributes to explaining the spatial distribution of both hake recruits (Sánchez and Serrano, 2003; Abella et al., 2005; Colloca et al., 2015; Paradinas et al., 2015; Pennino et al., 2019) and adults (Agostini et al., 2008). The final model predicted the highest occurrence and abundance probabilities of hake recruits to be at a range of between 100 and 250 m deep, with a constant optimum range between 140 and 200 m. The same bathymetric range for hake at age 0 along the shelf break was identified by the authors Colloca et al. (2015) in Mediterranean nurseries. In contrast, our results differ from the study carried out by Sánchez and Gil (2000) for the southern hake stock in the study area, which found a range between 90 and 180 m deep with a maximum peak of abundance at 100 m. However, these authors analyzed a previous period of years and the defined size of the recruits was <17 cm instead of <21 cm. These differences could be

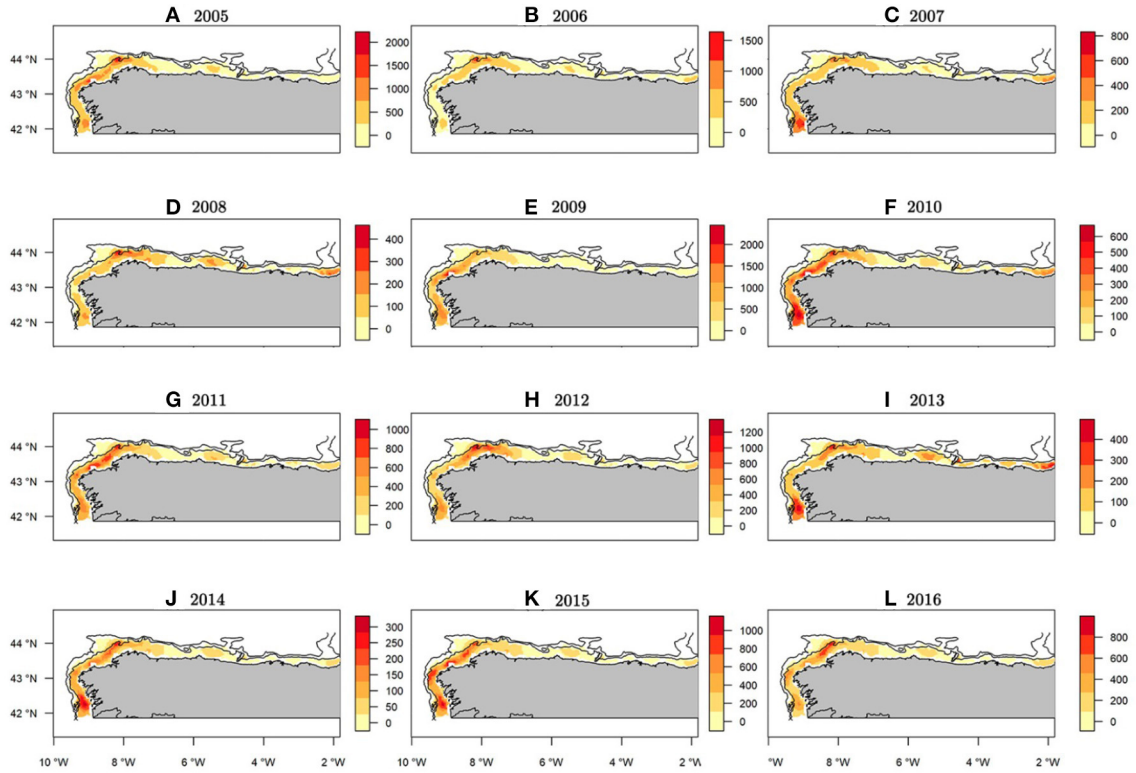

FIGURE 7 | Median abundance (NPUE) maps of the posterior predictive distribution for European hake recruits within the study period. Bathymetric lines correspond to 200 and 800 m isobath. Note each year has it's own scale in order to show where the spatial hotspots are located along the study period.

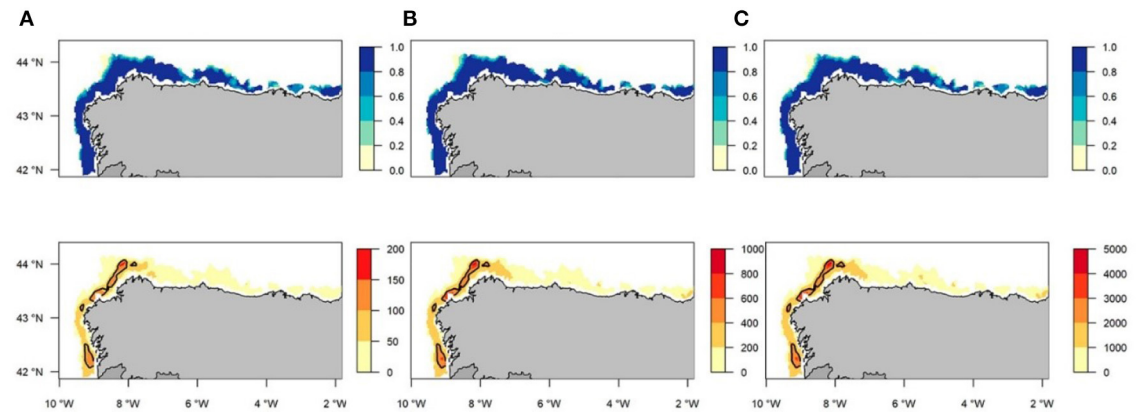

FIGURE 8 | Total mean for all years (2005–2016) correspondent to the first **(A)**, second **(B)**, and third **(C)** quartiles for occurrence probability (blue) and abundance (orange) of European Hake recruits posterior predictive distribution maps. Contour lines indicates potential nursery areas identified with abundance (NPUE) above the 90th percentile.

associated with the ontogenetic deepening phenomena, as the average size of individuals could increase with depth over the time. Ontogenetic deepening in the northeast Atlantic has been reported for different species by Baudron et al. (2019), whereby the depth of medium and large northern hake presented a decreasing trend between 2000 and 2004, followed by lower values than the previous time period analyzed. However, further research in hake size-depth should be carried out to test this hypothesis given that we only analyzed a single size, and thus, other factors could be influencing this process, such as optimal growth temperatures, predation, or fishing pressure (Audzijonyte and Pecl, 2018).

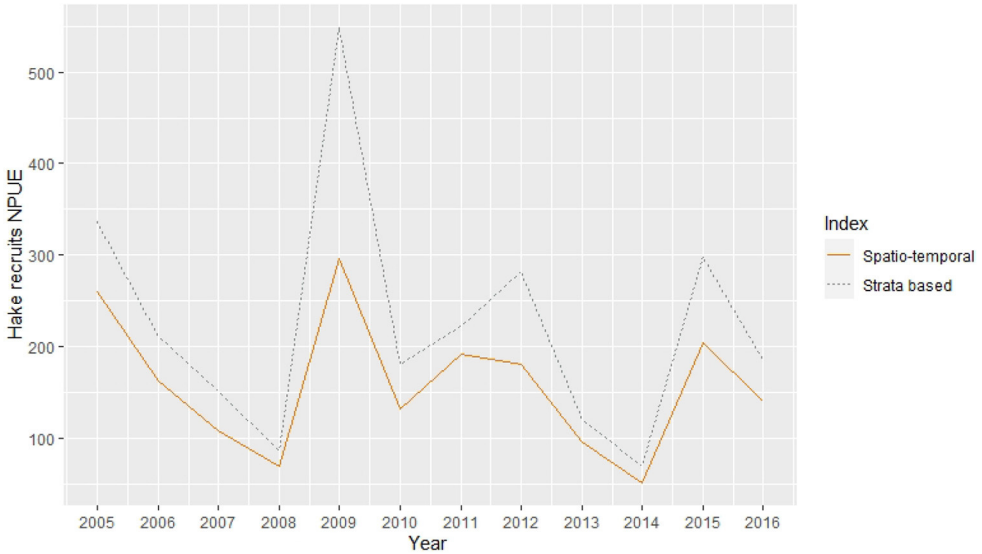

FIGURE 9 | Mean hake recruits abundance (num. recruits/30 min. trawl) indices along the study period. Dashed line represent the strata based index while solid line represent the spatio-temporal model predicted output index.

The spatio-temporal concentration of hake juveniles has been found to be related to mesoscale oceanographic processes (eddies), as previously described by Sánchez and Gil (2000). These processes have an important influence on the retention of hake recruits and zooplankton. Moreover, the concentration of juveniles could also be due to spatial aggregation based on size-dependent shoaling or trophic behavior, as has been demonstrated in other Merluccius species (Gordoa and Duarte, 1991). In a study by Sánchez and Serrano (2003) in the Cantabrian sea, the hydrographic scenario best explained by the environmental variables had a weak Navidad current and high upwelling index events, with depth found to be the most influential abiotic factor in determining the assemblages of fish species, such as hake. These authors pointed out that a bathymetric spatial pattern structure of fish communities remained relatively constant throughout the study period, especially when there was a lack of mesoscale activity over the shelf. For these reasons, we consider that bathymetry may not directly explain the distribution of hake recruits, however, it could be associated to hake recruit habitat preference bathymetric conditions, given that environmental variables, such as temperature, chlorophyll and light, or processes, such as species aggregations, are distributed and reflected in the gradient of depth. To better understand the main drivers on recruit aggregations, other oceanographic events (upwelling, currents, mesoscale eddies, among others) and biotic variables (i.e., primary production) should be taken into account in future models.

With respect to abundance predictions throughout the study period, we identified persistent hake recruit aggregation areas to be the one in front of Vigo, the Artabrian gulf (off La Coruña), and La Carretera, and intermittent areas to be the one in front of Santander, Bermeo, and Guetaria-Fuenterrabía, respectively. These results differ slightly from the nursery areas identified by Sánchez and Gil (2000) studied up to the year 1995, who found the persistent areas to be La Coruña, La Carretera, and an intermediate area between both called Ribadeo, and two small aggregations that only appeared in years with high annual class strength, Fuenterrabía and the area off Vigo. In addition, we also defined potential nursery areas with NPUE above the 90th percentile for the total average study period (2005-2016), where four contoured regions in the northwestern part of the Iberian Peninsula have been identified. Our results are very similar to the results obtained by Pennino et al. (2019) for the period 1997–2016. However, an important difference between both studies is that the predicted abundance maps for each year can help us to assess the recruit inter-annual spatial aggregation patterns which could be different from distant years within a large time period. Thus, regarding spatio-temporal management goals, a recent and stable set of years must be selected, rather than the whole study period, in order to identify potential nursery areas.

It should be noted that certain areas identified as persistent coincide with permanent spatial closure areas (La Coruña and La Carretera), whereas some of the intermittent areas coincide with temporary spatial closure areas (Bermeo, Guetaria, and Fuenterrabía) that have a lower bathymetric limit of 100 meter isobath (BOE, 2015). It is worth mentioning that the functional hake size analyzed in this study (<21 cm) only partially coincides with the size that fishing closures are focused on, since smaller individuals are not captured by commercial trawls. In the Mediterranean, the authors Colloca et al. (2015) evidenced that the main persistent areas of hake overlapped in a 15.3% with the areas subjected to some kind of fishery restriction. We found that the main FRA of La Coruña coincides in a 27.46% with our identified nursery area. As was pointed by Carlucci et al. (2009), the non-take zones for this species could

be positively influencing the main recruitment areas and a possible spillover may benefit the adults population. Thus, spatial management in order to increase the protection of these areas could be key in order to benefit the stock renewal of the species, specifically for years where the environment negatively affects them.

The results found in the present study provide important insights into hake nursery grounds along the time and demonstrate that they are stable, despite possible changes in external variables. Moreover, this information is important toward elaborating a spatially explicit management plan. Indeed, this study demonstrated that despite the high mobility and interannual variability in the peak of abundance locations, some areas consistently offer favorable nursery grounds for this species, thus making the task of protecting them easier.

By contrast, the resulting output index from our spatio-temporal model showed lower temporal variation in the mean abundance trend than in the strata-based index. The estimated mean abundance was lower for the whole study period, specifically for the years with considerably high recruit catch values. Recent studies with similar results have evidenced the advantages of including spatio-temporal variability and habitat covariates into abundance indices in order to calibrate stock assessment models. For example, Cao et al. (2017) pointed out that the resulting index from a spatio-temporal habitat model showed a similar trend to the classic strata-based index for the northern shrimp (*Pandalus borealis*) in Canadian waters. Despite this, the results from the assessment model showed a better goodness of fit, as well as better predicted abundance, for the spatio-temporal index input (Cao et al., 2017). In the study carried out by Shelton et al. (2014) of darkblotched rockfish (*Sebastes crameri*), the habitat model, including environmental covariates and spatial correlations, showed smoothed abundance changes over extreme values, whereas strata models with adjusted abundance were too sensitive for these events. Furthermore, changes in hake distribution among years can also bias the strata-based index as a abundance index for calibration purposes in stock assessment models. This indicates that spatio-temporal habitat model indices can give more precise and interpretable abundance estimates than classical design strata methods.

Given the above, we argue that our proposed model, which considerably reduces data uncertainty by including spatio-temporal and bathymetric effects, could be used as input data to calibrate length based assessment models, such as the GADGET (Taylor et al., 2007) and Stock Synthesis 3 (SS3) (Methot and Wetzel, 2013) models used by ICES. Results from B-HSTHMs could be used as a base to make catch recommendations to sustainable manage a population (ICES, 2018a) and could be applied to improve the quality of hake or other species abundance estimates included in stock assessments, thus contributing to increasing accuracy in scientific advice on catch recommendations.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. The dataset analyzed for this study can be found in the DATRAS https://www.ices.dk/data/data-portals/Pages/DATRAS.aspx.

AUTHOR CONTRIBUTIONS

FI, IPa, MP, SC, and DC designed the research. FI, IPa, MP, SC, DC, FS-R, and AF performed the research. FI, IPa, and MP analyzed the data. FV, AP, and IPr collected the data. All authors wrote the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.614675/full#supplementary-material

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Climate-Driven Range Shifts Are Rapid Yet Variable Among Recreationally Important Coastal-Pelagic Fishes

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Shifts in species distributions are occurring globally in response to climate change, but robust comparisons of redistribution rates among species are often prevented by methodological inconsistencies, challenging the identification of species that are most rapidly undergoing range shifts. In particular, comparable assessments of redistributions among harvested species are essential for identifying climate-driven changes in fishing opportunities and prioritising the development of management strategies. Here we utilise consistent datasets and methodologies to comparably analyse rates of climate-driven range shifts over 21 years for four recreationally important coastal-pelagic fishes (Australian bonito, Australian spotted mackerel, narrow-barred Spanish mackerel, and common dolphinfish) from the eastern Australian ocean warming hotspot. Latitudinal values corresponding to the poleward edge of species' core oceanographic habitats were extracted from species distribution models (SDMs). Rates of poleward shifts in core oceanographic habitats ranged between 148.7 (i.e., common dolphinfish) and 278.6 (i.e., narrow-barred Spanish mackerel) km per decade over the study period. However, rates of redistribution varied by approximately 130 km per decade among species, demonstrating that subtle differences in species' environmental responses can manifest in highly variable rates of climate-driven range shifts. These findings highlight the capacity for coastal-pelagic species to undergo rapid, yet variable, poleward range shifts, which have implications for ecosystem structure and the changing availability of key resources to fisheries.

Keywords: climate change, *Coryphaena hippurus*, range shift, *Sarda australis*, *Scomberomorus commerson*, *Scomberomorus munroi*, species distribution model, species redistribution

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INTRODUCTION

Shifts in species geographic distributions are an evident biological response to the environmental effects of climate change. In marine systems, species redistributions are occurring approximately an order of magnitude faster than in terrestrial systems (Chen et al., 2011; Poloczanska et al., 2013), in part due to marine ectotherms having a greater physiological vulnerability to environmental

warming (Pinsky et al., 2019). Determining which species are most likely to undergo climate-driven range shifts, and assessing the rates at which these changes are occurring, is essential for managing the consequences for ecosystems and human well-being (Pecl et al., 2017; Bonebrake et al., 2018). However, rates of redistribution among marine taxa are considerably variable (Pinsky et al., 2013; Poloczanska et al., 2016; Fredston-Hermann et al., 2020), challenging the capacity of scientists and managers to develop adaptation strategies that are applicable to broad groups of species (Fogarty et al., 2019).

Marine species associated with rapid redistributions commonly exhibit broad geographic distributions, high adult mobility, long pelagic larval durations, and generalist diets (Luiz et al., 2012; Feary et al., 2014; Sunday et al., 2015; Monaco et al., 2020). For example, adult mobility has been identified as a strong predictor of the rate of range expansion across diverse marine taxa (Sunday et al., 2015), and dietary generalism is known to facilitate the persistence of range extending species in novel environments over interannual time scales (Monaco et al., 2020). Coastal-pelagic fishes (i.e., species whose distributions encompass both coastal-shelf and open ocean habitats) display many of these characteristics (e.g., large latitudinal ranges and high adult mobility), indicating that these species are likely to have already undergone large spatial shifts to track their environmental habitat preferences in a warming ocean (Sunday et al., 2015; Briscoe et al., 2016). Rates of redistribution refers to the pace of latitudinal and/or longitudinal shifts in defined components of species ranges (e.g., leading or trailing edges) through time, which have been found to be relatively rapid for coastal-pelagic fishes when compared to nearshore species. For example, rates of recent poleward redistributions of coastal-pelagic fishes off eastern Australia [e.g., *Seriola lalandi*: 94.4 km per decade (Champion et al., 2018) and *Istiompax indica*: 88.2 km per decade (Hill et al., 2015)] markedly exceed average rates of range change for a suite of nearshore fishes from the same region (38 km per decade; Sunday et al., 2015). Environmental variability is also a strong predictor of range shifts among marine taxa, having been shown to be approximately six times more powerful than species functional traits for explaining variation in rates of redistribution in marine fishes (Pinsky et al., 2013). Subsequently, climate-driven range shifts in coastal-pelagic fishes from fast warming regions of the global ocean are expected to be among the most rapid biological responses to climate change (Hazen et al., 2013; Poloczanska et al., 2013), indicating the need to prioritise these species in quantitative range shift analyses to inform climate adaptation strategies.

Species distribution models (SDMs) have proven to be valuable tools for quantifying the spatial distribution of species as a function of environmental variables (Elith et al., 2010; Robinson et al., 2011). These models have been successfully used to quantify climate-driven range extensions and contractions in diverse marine taxa (Dell et al., 2015; Martínez et al., 2018; Champion et al., 2019). However, careful parameterisation of SDMs with consistent datasets and methodologies is required for generating comparable multi-species range shift analyses as methodological differences can greatly affect model results (Brodie et al., 2019; McHenry et al., 2019). When standardised methods are used across species, SDMs are valuable tools for identifying the relative effects of changing environmental conditions on the spatial distribution of biodiversity. Furthermore, spatial predictions from SDMs can be converted to indices that define specific areas of species' distributions, such as the effective area occupied (Thorson et al., 2016) and core (Hill et al., 2015) and range-edge habitats (Robinson et al., 2015; Champion et al., 2018). When spatial predictions are created at consistent timesteps (e.g., monthly), indices such as these can form appropriate response variables for analyses that quantify changes in species distributions through time.

Over the past six decades, ocean temperatures off the east coast of Australia have risen at a rate that is approximately four times faster than the global average (Ridgway, 2007; Hobday and Pecl, 2014). Ocean warming off eastern Australia is primarily driven by the strengthening of the East Australian Current (EAC) in response to increased wind stress over a broad region of the South Pacific (Cai et al., 2005; Sloyan and O'Kane, 2015). The extension of anomalously warm seawater to higher latitudes off eastern Australia (Holbrook and Bindoff, 1997; Hobday and Pecl, 2014) has been linked with range shifts in diverse marine taxa (Sunday et al., 2015; Malcolm and Scott, 2016), including multiple coastal-pelagic fishes (Hill et al., 2015; Champion et al., 2019).

Changes to the distributions of coastal-pelagic fishes off eastern Australia have important socio-ecological implications as species are commonly targeted by recreational fishers. For example, catches of coastal-pelagic fishes by recreational anglers off eastern Australia commonly exceed catches taken by the commercial sector (West et al., 2016) and recreational fishing enhancement projects (e.g., the deployment of fish aggregation devices and coastal artificial reefs) aim to assist recreational fishers targeting these species (Dempster, 2004; Smith et al., 2016). Furthermore, a recreational gamefish tagging program administered by the New South Wales Department of Primary Industries has tagged over 480,000 individuals since its inception in 1973 (NSW DPI, 2019), demonstrating considerable fishing effort by recreational anglers targeting coastal-pelagic species. While there is emerging evidence that range shifts in some coastal-pelagic fishes off eastern Australia are resulting in increased fishing opportunity for recreational anglers at higher latitudes (Champion et al., 2019), it remains uncertain whether multiple species are responding at similar rates.

The overarching objective of this study was to assess variation in predicted rates of climate-driven redistributions among multiple recreationally important fishes from a global ocean warming hotspot. Specifically, we aimed to (1) quantify the oceanographic habitat preferences for four coastal-pelagic fishes off eastern Australia using consistent data sources and methodologies, and (2) quantify and compare rates of climate-driven redistribution of core oceanographic habitat for these fishes over two decades. By addressing these aims, we demonstrate variation in the sensitivity of multiple coastal-pelagic fishes to climate change and highlight changing fishing opportunities off eastern Australia.

MATERIALS AND METHODS

Study Extent and Species

The spatial extent of this study encompassed the marine environment adjacent to eastern Australia (145–160°E; 15–45°S; **Figure 1**). Coastal-pelagic fishes from this region selected for habitat modelling and range shift analyses were based on the availability of species occurrence records within the New South Wales Department of Primary Industries gamefish tagging database (NSW DPI, 2019). This government administered citizen science database contains a large set of occurrence records for a suite of coastal-pelagic fishes, representing a valuable resource for the development of comparable habitat suitability models that can facilitate a robust multi-species range shift analysis. Occurrence records within this database were recorded by recreational anglers as part of a cooperative catch-and-release tagging program that spans a temporal range from 1973 to the present. However, data were initially restricted to 1998–2018 to match the availability of satellite−derived oceanographic variables. Data were further restricted to ensure spatial and temporal independence among species occurrence records (**Supplementary Figures 1–4**), which involved retaining species occurrences from a unique day and location, and retaining only those that were greater than 0.1° (∼11 km) apart, as per the methods applied by Brodie et al. (2015). A minimum of 300 unique occurrence records was used as the threshold for species inclusion within this study to (1) facilitate statistical modelling of non-linear relationships between species data and oceanographic covariates, while (2) allowing for robust *k*-fold model validation, which requires multiple models to be trained on subsets of the full dataset to evaluate the accuracy and skill of the optimal models. Based on this method of refinement, the study species selected were Australian bonito (*Sarda australis*; n = 314; hereafter "bonito"), Australian spotted mackerel (*Scomberomorus munroi*; n = 410; hereafter "spotted mackerel"), narrow-barred Spanish mackerel (*Scomberomorus commerson*; n = 889; hereafter "Spanish mackerel") and common dolphinfish (*Coryphaena hippurus*; n = 558; hereafter "dolphinfish"). These species represent four of the 28 (∼14%) coastal and pelagic fishes recorded within the gamefish tagging database (NSW DPI, 2019). To ensure that oceanographic habitat models and subsequent range shift analyses were comparable among species, 300 occurrence records were randomly sampled for each species from the resulting dataset and retained for model selection and evaluation (**Figure 1**).

In order to create a binomial response variable for quantifying species' oceanographic habitat preferences, pseudo-absence data were spatially and temporally randomised nearshore of the continental shelf-break (200-m isobath) throughout the study extent and period to characterise unsuitable habitat for each study species. A consistent dataset containing a total of 10,000 pseudo-absences was used for each species, based on Barbet-Massin et al. (2012), who recommend a large number (i.e., 10,000 or more) of randomly selected pseudo−absences for regression−type analyses for species distributions.

Oceanographic Variables

A suite of oceanographic variables known to influence the distributions of coastal-pelagic fishes (Hobday and Hartog, 2014) were downloaded from the Copernicus Marine Environment Monitoring Service[1] and matched to species occurrence and pseudo-absence data. These variables were sea surface temperature (SST; 0.05° spatial resolution), salinity (SAL; 0.25° spatial resolution), eddy kinetic energy (EKE; 0.25° spatial resolution), sea level anomaly (SLA; 0.25° spatial resolution) and chlorophyll *a* concentration (CHL; 0.04° spatial resolution). The native spatial and temporal resolutions of oceanographic variables were used when matching species occurrence and pseudo-absence data for developing habitat models (see **Supplementary Table 1**), and were bilinearly interpolated to a common 0.1° grid and aggregated to a monthly temporal resolution when making spatial predictions of habitat suitability. Collinearity among predictor variables was assessed using Spearman rank correlation coefficients and variance inflation factors (VIFs). When correlated ($r > 0.5$ or < -0.5) variables were identified, the predictor variable with the clearest ecological interpretation from covarying pairs was retained for model selection (Zuur et al., 2013). Sea surface temperature and salinity were negatively correlated ($r = -0.71$) resulting in the removal of salinity from the suite of potential oceanographic predictors prior to model fitting. Given that Spearman coefficients only describe pairwise correlations, variance inflation factors (VIFs) were used to assess the effect of collinearity among the remaining explanatory variables during model fitting. VIFs for all remaining predictors were less than 1.5, indicating that collinearity among these variables was unlikely to negatively affect model performance (Zuur et al., 2007). Full descriptions of oceanographic variables available for model selection are provided in **Supplementary Table 1**.

Oceanographic Habitat Modelling

Generalised additive mixed effects models (GAMMs) were used to describe oceanographic habitat suitability for all species. GAMMs used a logistic link function to relate binomially distributed response variables (i.e., species occurrence or pseudo-absence) to multiple oceanographic covariates. Year was included as a random intercept term in all models to control for intraclass correlations between data collected during the same year, which may have been temporally biased due to unmeasured variation in species catch per unit effort over the study period. Non-linear responses were modelled using penalised regression spline smoothers applied using generalized cross validation, which is recommended to optimise smooth functions and to avoid overfitting to the data (Zuur et al., 2009). However, smoothers were removed from predictor variables in favour of linear terms if their effective degrees of freedom were approximately equal to 1, indicating linearity with log-of-odds transformed binomial responses variables.

A backward model selection procedure was initially applied to identify all significant oceanographic predictors

[1]https://marine.copernicus.eu

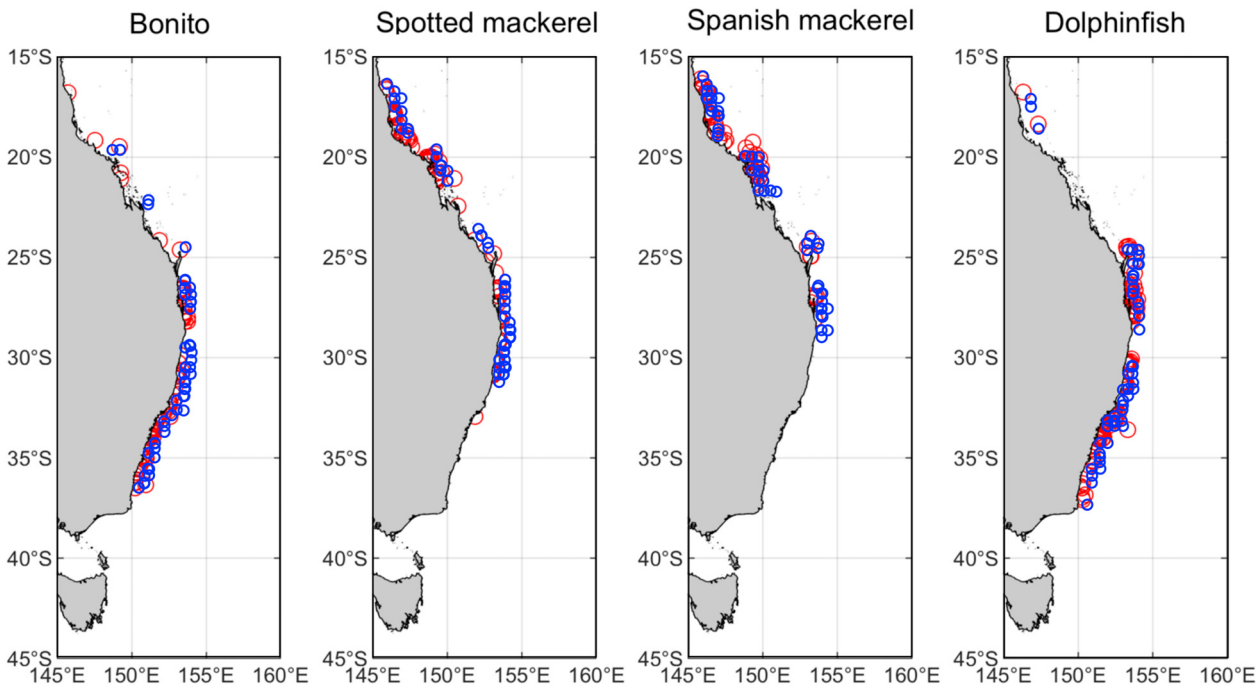

FIGURE 1 | Map of eastern Australia displaying the spatial extent of the study region and the distribution of random samples of 300 species occurrence records (red circles) used in model fitting and 50 independent occurrences (blue circles) used in model testing for bonito (*Sarda australis*), spotted mackerel (*Scomberomorus munroi*), Spanish mackerel (*Scomberomorus commerson*), and dolphinfish (*Coryphaena hippurus*).

TABLE 1 | Summary of full models for each species and nested alternatives assessed using an AIC informed model selection procedure on covariate combinations of decreasing complexity.

Iteration	Model	Variable dropped	ΔAIC	Mean AUC (± SD)	Mean TSS (±SD)
Bonito (*Sarda australis*)					
0	*s(SST) + EKE + s(SLA) + (1| Year)*	–	0	0.891 ± 0.018	0.752 ± 0.021
1	*s(SST) + s(EKE)+ (1| Year)*	SLA	23.62	0.846 ± 0.009	0.738 ± 0.012
2	*s(SST) + (1| Year)*	EKE	73.05	0.768 ± 0.008	0.676 ± 0.013
Spotted mackerel (*Scomberomorus munroi*)					
0	*s(SST) + s(CHL) + s(SLA)+ (1| Year)*	–	0	0.832 ± 0.008	0.636 ± 0.022
1	*s(SST) + s(CHL) + (1| Year)*	SLA	42.12	0.764 ± 0.007	0.511 ± 0.018
2	*s(SST) + (1| Year)*	CHL	160.87	0.711 ± 0.009	0.436 ± 0.019
Spanish mackerel (*Scomberomorus commerson*)					
0	*s(SST) + s(CHL) + s(SLA)+ (1| Year)*	–	0	0.741 ± 0.009	0.526 ± 0.022
1	*s(SST) + s(CHL) + (1| Year)*	SLA	57.83	0.692 ± 0.006	0.431 ± 0.019
2	*s(SST) + (1| Year)*	CHL	210.66	0.632 ± 0.008	0.419 ± 0.023
Dolphinfish (*Coryphaena hippurus*)					
0	*s(SST) + s(EKE) + s(CHL) + s(SLA)+ (1| Year)*	–	0	0.734 ± 0.011	0.599 ± 0.018
1	*s(SST) + s(EKE) + s(CHL) + (1| Year)*	SLA	50.12	0.701 ± 0.009	0.541 ± 0.019
2	*s(SST) + s(EKE) + (1| Year)*	CHL	103.44	0.665 ± 0.010	0.487 ± 0.011
3	*s(SST) + (1| Year)*	EKE	592.21	0.623 ± 0.011	0.444 ± 0.015

Smoothing factors are indicated by "s." Delta-AIC values denote differences in AICs between models relative to the most parsimonious model (i.e., ΔAIC = 0). Area Under the receiver-operating Curve (AUC) statistic and True Skill Statistic (TSS) are derived from sixfold model validation using an independent set of species occurrence records. SST, sea surface temperature; EKE, eddy kinetic energy; CHL, chlorophyll a concentration; SLA, sea level anomaly.

from the suite of non-correlated variables. Models were further reduced using a *p*-value informed backward stepwise selection procedure to produce a set of explanatory models for each species that contained nested covariate combinations of decreasing complexity (**Table 1**). The model in this set with the lowest Akaike information criterion (AIC) value was considered the most parsimonious model. Optimal GAMMs estimated species probability

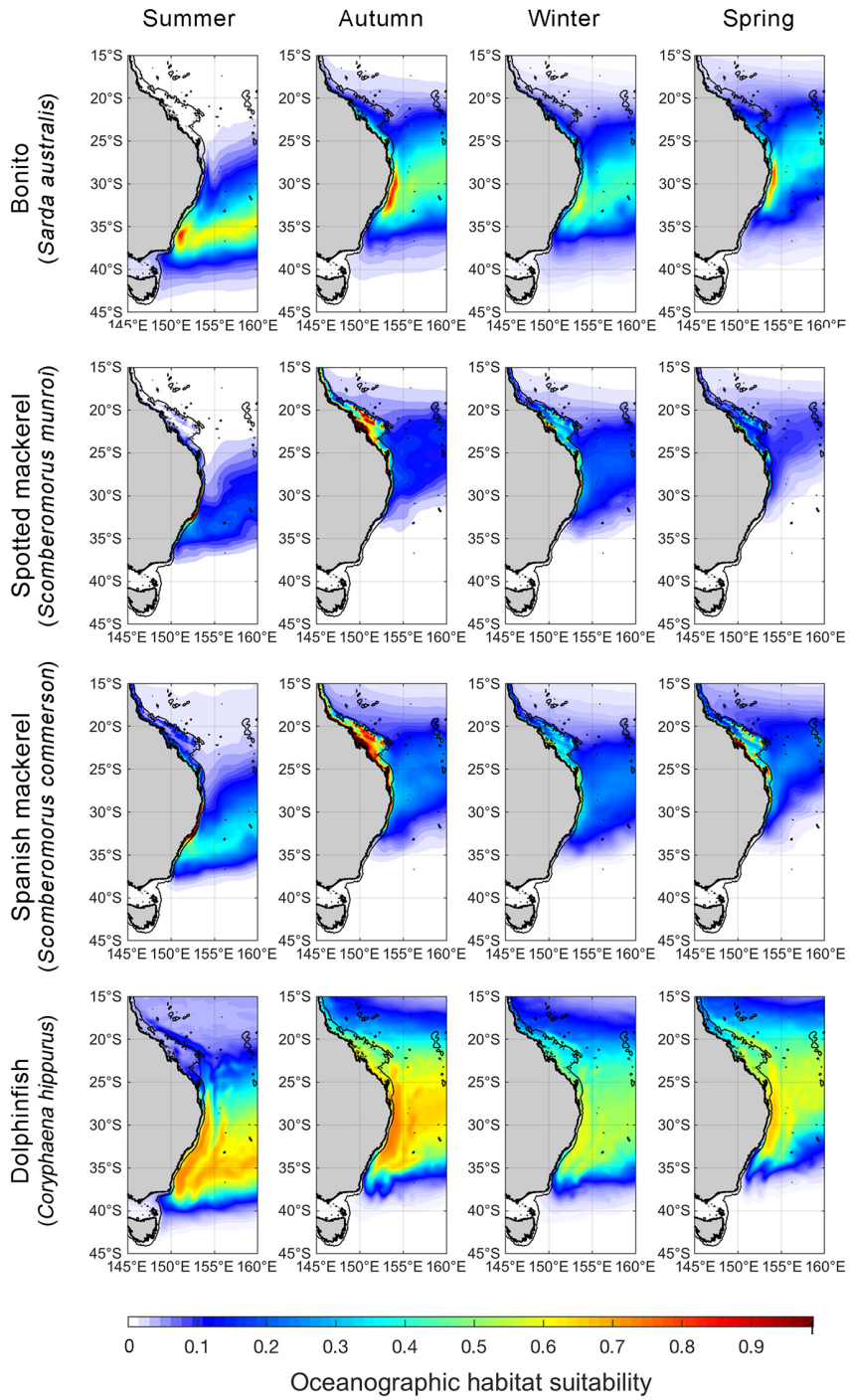

FIGURE 2 | Spatial predictions of seasonal oceanographic habitat suitability off eastern Australia. Monthly spatial predictions were averaged for the period encompassing January 1998–December 2018 and seasonally aggregated (Summer = December to February, Autumn = March–May, Winter = June–August, Spring = September–November). The black line offshore of the coastline denotes the continental shelf-break (i.e., 200-m isobath). We note that although spatial predictions of oceanographic habitat have been extrapolated beyond the continental shelf-break to improve visual communication in this figure, range shift analyses were only undertaken on oceanographic habitat nearshore of the continental boundary.

of occurrence, but given that absolute probabilities are dependent on the ratio of occurrence to absence data (Pearce and Boyce, 2006) and that pseudo-absences were randomly generated, probabilities were rescaled to an index of oceanographic habitat suitability ranging from 0 (unsuitable) to 1 (optimal).

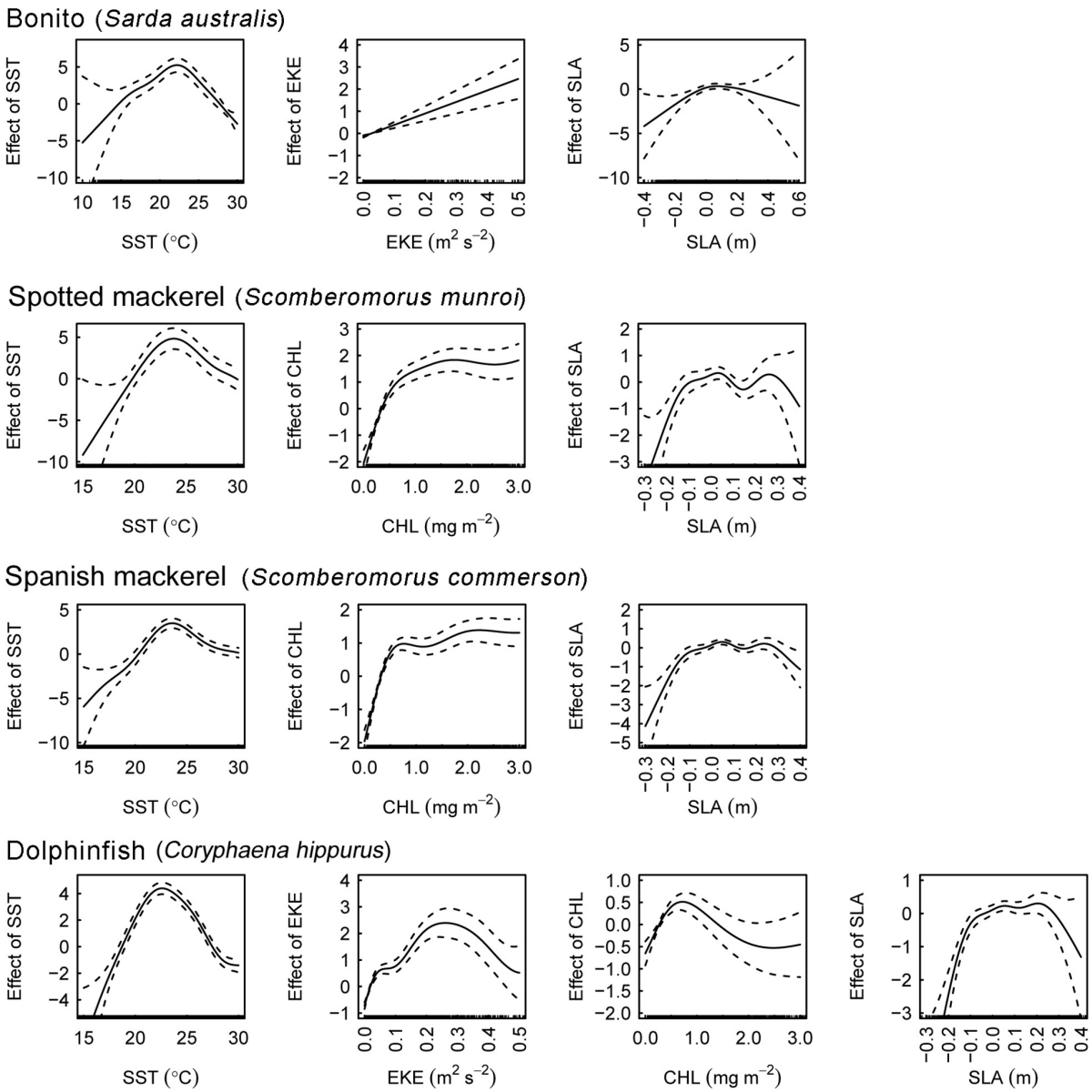

FIGURE 3 | Partial effects of covariates on the fitted values of the optimal bonito (*Sarda australis*), spotted mackerel (*Scomberomorus munroi*), Spanish mackerel (*Scomberomorus commerson*), and dolphinfish (*Coryphaena hippurus*) habitat suitability models. Dashed lines denote 95% confidence intervals. Rugs on x−axes indicate occurrence and pseudo−absence data for each covariate. SST, sea surface temperature; EKE, eddy kinetic energy; CHL, chlorophyll *a* concentration; SLA, sea level anomaly.

The accuracy and predictive skill of all models containing unique combinations of predictors were quantified using a *k*-fold validation approach that incorporated an independent testing dataset. To do so, the full dataset was randomly divided into six subsets ($k = 6$) that each contained 50 occurrence records and 2,000 pseudo-absences, and models for each species were trained on each subset of the data. Six-fold validation was used due to concerns that too few occurrence data would be available (i.e., < 50) for model fitting if the full dataset was partitioned into a greater number of folds. All models for each species were then tested against an independent set of species occurrence records ($n = 50$ per species; **Figure 1**) extracted from the Atlas of Living Australia database[2] and a unique set of 2000 pseudo-absences randomly sampled from the full dataset used in model fitting. These comparisons produced a set of confusion matrices for calculating two model accuracy indices, which were the mean area under the receiver operating characteristic curve (AUC) and mean true skill statistic (TSS). AUC values range from 0 to 1, where > 0.7 AUC < 0.8 indicates fair model performance, > 0.8 AUC < 0.9 indicates good performance

[2]https://www.ala.org.au

TABLE 2 | Summary of range shift analyses.

Species	Poleward redistribution of core oceanographic habitat (95% CI)	*p*-value	Intra-class correlation coefficients	
			factor: "month"	*factor: "ENSO state"*
Bonito (*Sarda australis*)	244.2 km per decade (195.3–293.2 km dec^{-1})	<0.001	0.715	0.081
Spotted mackerel (*Scomberomorus munroi*)	269.7 km per decade (219.0–320.4 km dec^{-1})	<0.001	0.682	<0.008*
Spanish mackerel (*Scomberomorus commerson*)	278.6 km per decade (223.6–333.7 km dec^{-1})	<0.001	0.631	0.033*
Dolphinfish (*Coryphaena hippurus*)	148.7 km per decade (102.4–195.1 km dec^{-1})	<0.001	0.745	0.010*

**Denotes factors excluded from the optimal linear mixed effects model due to negligibly low (<0.05) intraclass correlation coefficients.*

and > 0.9 AUC indicates excellent performance (Swets, 1988; Araújo et al., 2005). Alternatively, TSS ranges from -1 to 1, where 0 denotes the threshold between models with some predictive skill (model skill increases toward 1) and models that are no better than random (model skill declines toward –1) (Allouche et al., 2006).

Range Shift Analyses

Core oceanographic habitat for each species was quantified by comparing the spatial distribution of the independent species occurrence records used in model validation with day-specific predictions of modelled habitat. Values of oceanographic habitat suitability (created with 0.1° spatial resolution) matching the spatial and temporal location of independent occurrence records (n = 50 per species) were extracted and the mean of these values was considered to represent core oceanographic habitat for each species. This approach for identifying core habitat is a data-driven alternative to selecting arbitrary threshold values (e.g., 0.5) for discriminating between species' suitable and unsuitable environmental habitats, which commonly lack ecological basis (Liu et al., 2005; Champion et al., 2019). Defining species core habitats in this way is one option for developing comparable analyses of spatiotemporal change in species distributions, provided that (1) consistent methods are applied to quantify discrete areas of environmental habitat (e.g., core or range edge habitat), and (2) values are held constant at each time point that a spatial prediction of habitat suitability is generated.

Linear mixed effects models were used to quantify latitudinal changes in the poleward edge of core oceanographic habitats between January 1998 and December 2018. These models incorporated random terms to account for intra- and inter-annual climate variability on the latitudinal distribution of core oceanographic habitat throughout the study period. However, random effects were removed if these had low intraclass correlation coefficients (i.e., < 0.05), which indicates negligible collinearity among levels within these factors (Zuur et al., 2013). Initial range shift models fitted for all species took the form (in script notation):

$$Latitude = Year + (1 \mid Month) + (1|ENSO\ state)$$

where *Latitude* is the most poleward location corresponding to the distribution of each species' core oceanographic habitat nearshore of the continental shelf-break modelled as a function of time (*Year*), with *Month* and *ENSO state* included as random intercept terms to account for the effects of short- and long-term climate variability on the distributions of core oceanographic habitats. ENSO state is an index of El Niño Southern Oscillation that drives oceanographic variability off eastern Australia over interannual timescales. Rates of redistribution (km per decade) of core oceanographic habitats and associated 95% confidence intervals were derived from the fixed slope parameters of linear models fitted to data extracted from monthly predictions from January 1998 to December 2018. Residual plots were assessed visually to confirm that linear mixed effects models (i.e., range shift models) satisfied the assumptions of normality and homogeneity of variance.

Data pertaining to range shift analyses are available in the Zenodo repository[3]. Statistical analyses were undertaken using the R programming language (R Core Team, 2017): GAMMs were fitted using the "gamm4" package (Wood and Scheipl, 2013), spatial and temporal autocorrelation was assessed using the "gstat" package (Gräler et al., 2016), k−fold cross validation was undertaken using the "dismo" package (Hijmans et al., 2013) and linear mixed effects models were fitted using the "lme4" package (Bates et al., 2015). Oceanographic habitats and data were plotted in the MATLAB computing environment (ver. 9.8, The MathWorks, Inc.).

RESULTS

Oceanographic Habitat Models

Monthly spatial predictions of oceanographic habitat showed consistent patterns of seasonal variation among all species distributions, which underwent poleward advances during the Austral summer and autumn and equatorward retreats during winter and spring (**Figure 2**). Optimal models for all species contained the predictors SST and SLA, while CHL contributed to oceanographic habitat suitability for all species except bonito (**Table 1**). EKE was a significant predictor of the distributions

[3]https://doi.org/10.5281/zenodo.4475997

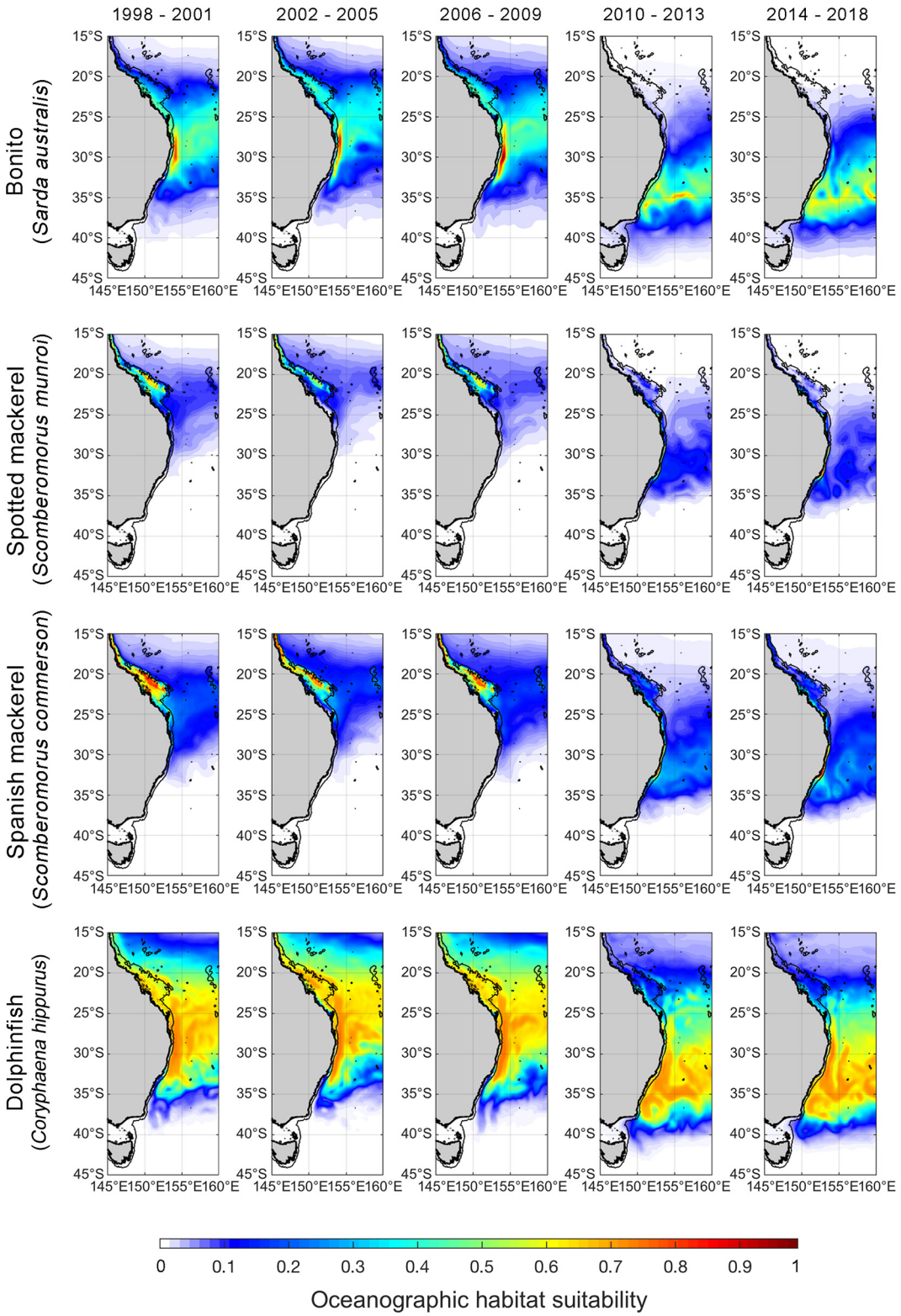

FIGURE 4 | Spatial predictions of Autumn oceanographic habitat suitability off eastern Australia from January 1998 to December 2018. Monthly predictions have been averaged into 4-year time bins to aid visualisation of temporal trends. The black line offshore of the coastline denotes the continental shelf-break (i.e., 200-m isobath). We note that although spatial predictions of oceanographic habitat have been extrapolated beyond the continental shelf-break to improve visual communication in this figure, range shift analyses were only undertaken on oceanographic habitat nearshore of the continental shelf boundary.

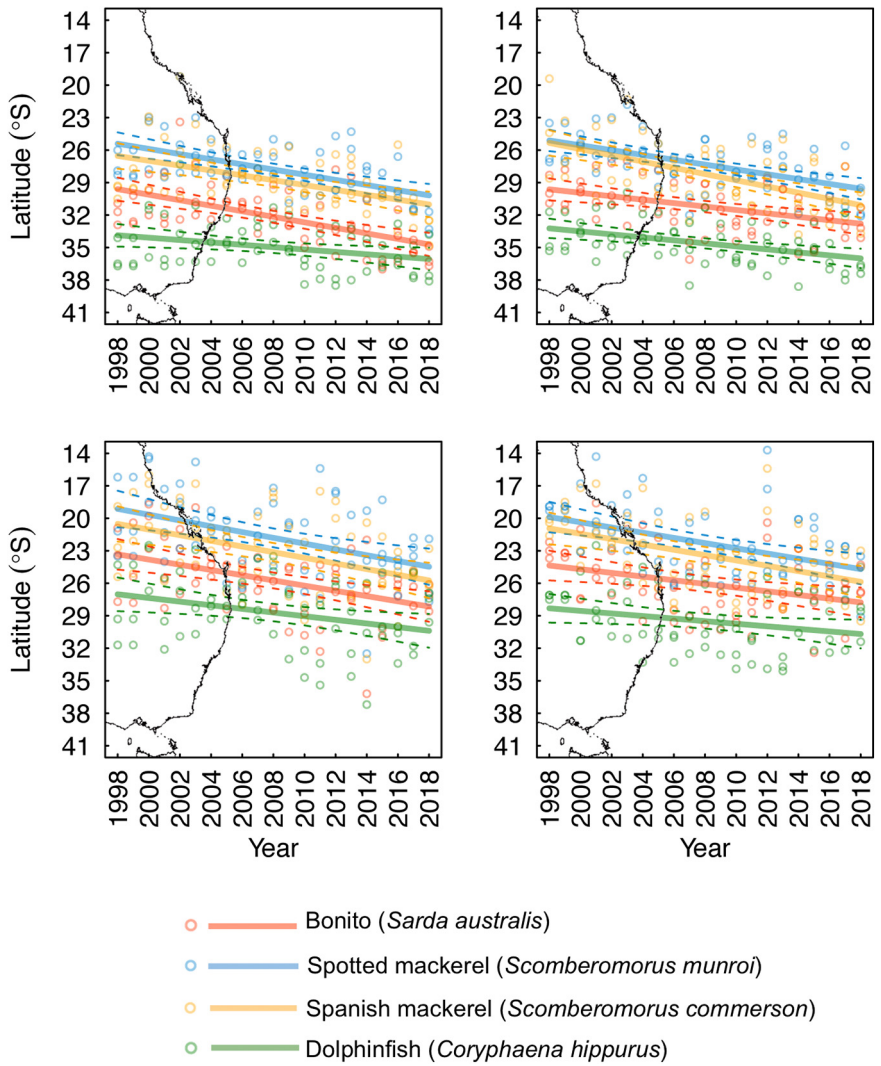

FIGURE 5 | Seasonally explicit latitudinal trends in monthly predictions of the poleward edge of species' core oceanographic habitats nearshore of the continental shelf-break (dashed lines denote 95% confidence intervals). The east Australian coastline has been underlaid to aid visual interpretation of the trends presented.

of bonito and dolphinfish, but not spotted or Spanish mackerel (**Supplementary Table 2**). Collectively, the distributions of all study species were found to be driven by simultaneous responses to multiple oceanographic variables, with some variables (e.g., SST and CHL) contributing to the oceanographic habitat quality of multiple species.

The effects of oceanographic variables on the occurrence of all species took both non-linear and linear forms (**Figure 3**). SST had a consistent, unimodal effect on oceanographic habitat suitably. Peaks in optimal thermal habitat occurred between 22.5 and 24.5°C for all species. Both spotted and Spanish mackerel models produced consistent responses to SST, CHL and SLA. SLA ranging between −0.1 and 0.3 m positively affected oceanographic habitat suitability for all species, with the effect of this variable on models becoming negative toward lower and higher values than these. All covariates in each optimal oceanographic habitat model were significant at alpha level = 0.001 (**Supplementary Table 2**).

Six−fold validation against an independent dataset not used in modelling fitting revealed that optimal models for each species had high predictive accuracy based on multiple indices of model performance (**Table 1**). Mean AUC and TSS values for all optimal models ranged between 0.734–0.891 and 0.526–0.752, respectively. Values within these ranges denote models with fair to good performance (Swets, 1988) and are considered reliable for conservation planning applications (Pearce and Ferrier, 2000), indicating that all optimal models produced accurate spatial predictions of species distributions for subsequent range shift analyses.

Range Shift Analyses

Habitat suitability values representative of species' core distributions were: bonito = 0.573, spotted mackerel = 0.451, Spanish mackerel = 0.408, dolphinfish = 0.568 (**Supplementary Figure 5**). The poleward edge of core oceanographic habitats for

all species were found to have undergone significant poleward shifts between 1998 and 2018 (**Table 2** and **Figure 4**). Linear mixed effects models revealed that core oceanographic habitats rapidly (i.e., > 100 km per decade) moved toward higher latitudes for all species over the study period (**Figure 5**). However, rates of redistribution varied by approximately 130 km per decade among coastal-pelagic fishes, with core habitat shifting most rapidly for Spanish mackerel (278.6 km per decade), followed by spotted mackerel (269.7 km per decade), bonito (244.2 km per decade) and dolphinfish (148.7 km per decade; **Table 2**).

Poleward shifts in core oceanographic habitat occurred over a relatively lower range of latitudes for both spotted and Spanish mackerel than range shifts identified for bonito and dolphinfish (**Figures 4**, **5**). The random "month" term was retained in all linear mixed effects models (**Table 2**), indicating that monthly variability in regional oceanography drove spatial variation in the distribution of core habitat for all species. However, the random "ENSO state" term was dropped from the dolphinfish and both spotted and Spanish mackerel models but retained in the bonito model (**Table 2**), indicating that the distribution of core habitat for bonito, but not any other species analysed, was marginally dependent on ENSO during the study period.

DISCUSSION

By developing comparable analyses of spatial shifts in the distribution of core habitats for four coastal-pelagic fishes from a warming western boundary current, we found evidence for rapid (i.e., up to ∼280 km per decade) recent poleward redistributions. These findings are consistent with climate-driven range shifts in over 30,000 species globally that show marine taxa moving to higher latitudes six times faster than their terrestrial counterparts (Lenoir et al., 2020) and support the results of previous research demonstrating rapid climate-driven redistributions in coastal-pelagic fishes (Hill et al., 2015). However, we found that rates of redistribution varied by approximately 130 km per decade among species, highlighting that subtle differences in species' environmental responses can manifest in highly variable rates of climate-driven range shifts.

Our analyses revealed that species' core oceanographic habitats have shifted poleward by between ∼312 and 585 km since 1998 in response to climate−driven changes in regional oceanography. This range exceeds rates of poleward redistribution predicted for yellowtail kingfish (*Seriola lalandi*; approximately 240 km since 1996) and black marlin (*Istiompax indica*; 140 km between 1999 and 2013) off eastern Australia quantified using correlative analyses comparable to those applied here (Hill et al., 2015; Champion et al., 2018). Taken together, these findings indicate that poleward range shifts in core oceanographic habitat for coastal-pelagic fishes off eastern Australia are generally exceeding 100 km per decade, with predictions for some species (e.g., bonito and both spotted and Spanish mackerel) in excess of 200 km per decade. Given the north-south orientation of Australia's east coast, poleward shifts of this magnitude may considerably alter the availability of resources to fisheries along the coast (e.g., Selden et al., 2020). Out-of-range observations logged by recreational anglers with the Range Extension Database and Mapping project (Redmap; Pecl et al., 2019) provide observational support for predicted shifts in coastal-pelagic fish distributions. For example, recreational catches of yellowtail kingfish off eastern Tasmania and dolphinfish off southern NSW have become increasingly reported via Redmap website and smartphone applications since the inception of this citizen science project in 2009 (Stuart-Smith et al., 2016; Fogarty et al., 2017). These catch records concur with predictions of increasing environmental suitability for these species off south-eastern Australia due to changing oceanographic conditions (Champion et al., 2018). Based on relative rates of poleward redistributions quantified using standardised methods, our results suggest that fishing opportunity off south-eastern Australia is likely to be most rapidly increasing for Spanish mackerel, followed by spotted mackerel, bonito and dolphinfish. While our analysis was developed to infer potential increases in fishing opportunity at higher latitudes, and thus quantified and compared shifts in the leading edge of oceanographic habitats, poleward shifts in the trailing edge of suitable habitat may manifest in reduced fishing opportunity at lower latitudes. For example, projected redistributions for truly pelagic fishes off eastern Australia have found that trailing edges of environmental habitat are likely to shift poleward more rapidly than leading edges in the future (Robinson et al., 2015), suggesting that losses in fishing opportunity at lower latitudes may outpace increases in opportunity at higher latitude. We acknowledge that our predictions of habitat suitability do not reflect species realised distributions directly due to their reliance on correlative relationships between species and available environmental conditions (Elith et al., 2010), which also do not incorporate the effects of biotic interactions on species distributions. Nevertheless, our findings illustrate how the redistribution of suitable oceanographic habitat for recreationally important fishes can be estimated using publicly available data to understand changes in fishing opportunity and inform fisheries adaptation.

The application of a consistent methodology and dataset for developing comparable range shift analyses was a crucial aspect of this study as methodological difference have been found to explain approximately 22% of variation in rates of climate-driven redistributions (Brown et al., 2016). For example, studies utilising continuous and consistent time series more accurately quantify rates of species redistributions than estimates based on infrequent data that may confound short-term variability with long-term trends (Brown et al., 2016; Fredston-Hermann et al., 2020). Therefore, our range shift estimates based on monthly predictions of species' core habitats over 21 years (i.e., n = 252 per species) are likely to be more robust to short-term oceanographic variability occurring during this period than, for example, analyses based on seasonal or annual data. Although redistribution analyses using infrequent measurements commonly produce estimates of change that exceed studies using continuous time series (Brown et al., 2016), our results markedly exceed previous rates quantified for nearshore and truly pelagic fishes off eastern Australia. For example, historical analyses

utilising observational data of 50 nearshore fishes identified an average rate of poleward redistribution of 38 km per decade (Sunday et al., 2015), while climate-driven redistributions for 16 pelagic fishes not analysed here averaged less than 50 km per decade (Hobday, 2010). While it is probable that rates of poleward redistributions in coastal-pelagic fishes are exceeding those of other marine fishes off eastern Australia, it is also possible that methodological differences between studies account for variation between our results and previously documented rates of redistribution. For example, our analyses incorporated species responses to multiple oceanographic variables analysed over a recent historical period, while previous research has utilised observational data (Sunday et al., 2012; Malcolm and Scott, 2016), correlative relationships with single environmental covariates (e.g., SST only; Hobday, 2010) and scenario-based projections of future ocean conditions (Robinson et al., 2015) to quantify rates of redistribution. Despite methodological difference preventing robust comparisons between our findings and previous research, results from our standardised analysis highlight that marine fishes from eastern Australia's are likely to be undergoing poleward shifts in distribution more rapidly than previously thought.

Robust estimates of species responses to environmental conditions underpin climate change vulnerability assessments (Pacifici et al., 2015; Foden et al., 2019) and the subsequent prioritisation of species within conservation and adaptation strategies (Watson et al., 2013). Trait-based, correlative and mechanistic analyses represent the three primary approaches supporting climate change vulnerability assessments of species (Foden et al., 2019). By using species distribution or habitat suitability models to compare rates of range change for four coastal-pelagic fishes, we demonstrate the utility of correlative analyses for discriminating between the sensitivity of species distributions to climate change. Despite all species assessed being likely to receive similar climate sensitivity scores within trait-based assessments (e.g., using the methods of Pecl et al., 2014), correlative analyses identified variation in species responses. For example, the distribution of Spanish mackerel was found to be most sensitive to the environmental effects of climate change off eastern Australia, followed by the distributions of spotted mackerel, bonito and dolphinfish. These results demonstrate the utility of correlative methods for identifying species that are most likely to attract increasing fishing effort in novel poleward environments under climate change, and for prioritising the development of climate-sensitive fisheries management strategies for marine fishes that are undergoing climate-driven redistributions.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because no animal collection was undertaken.

AUTHOR CONTRIBUTIONS

CC conceptualised the research question and designed the study approach with input from MC. CC and SB extracted and processed oceanographic data. CC undertook the statistical and spatial analyses with assistance from SB. CC, SB, and MC wrote the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.622299/full#supplementary-material

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BRIEF RESEARCH REPORT
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Innovative Aquaculture for the Poor to Adjust to Environmental Change in Coastal Bangladesh? Barriers and Options for Progress

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More so than wealthier, less nature-dependent social groups, the poor in tropical coastal regions suffer from adverse environmental change and need new income options. With high levels of saltwater intrusion into coastal lands, innovative brackish water aquaculture (BWA) including integrated multi-trophic aquaculture (IMTA) are crucial adaptation options to the expanding marine waters. This article examines how poor Bangladeshi coastal residents view BWA, and what is needed to make BWA a viable and sustainable livelihood for the coastal poor. In sites that are affected by major salinity intrusion, we used a semi-structured questionnaire to interview 120 households. We examine three questions: (1) What kind of aquaculture is currently being undertaken in brackish/saline/coastal waters? (2) Do poor coastal residents see BWA (and, by implication the hitherto fairly unknown IMTA) as a viable and sustainable livelihood? (3) What is needed to make BWA a feasible and promising livelihood in Bangladesh? Our results show both information and perception biases obstruct in particular coastal poor women and men from engaging with innovative BWA. Their knowledge on ecosystem-based aquaculture was scarce and their views of aquaculture were related mainly to previous experiences with shrimp monoculture and its polarizing socio-economic effects. We propose some strategic fields of action to develop innovative BWA that also benefits coastal Bangladesh's poorest people.

Keywords: pro-poor innovation, marine and coastal change, brackish water aquaculture, integrated multi-trophic aquaculture, climate adaptation

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INTRODUCTION

Poorer residents of tropical coastal regions are more dependent on nature and more vulnerable to environmental change than more affluent groups. The poorest coastal women and men are therefore also most in need of new opportunities to adapt their livelihoods (Cinner et al., 2018). Particularly coastal regions that are densely populated and heavily impacted by the expanding sea and related environmental changes require a transformation toward new socially and ecologically sustainable nature-dependent forms of production that ensure the livelihoods of the poorest (Berkhout, 2002; Chapin et al., 2009; O'Brien, 2011; Glavovic, 2013).

Coastal Bangladesh is among the regions on earth that are most affected by salinity intrusion with oceanic and other sources. Former agricultural lands transform to brackish or marine states while the millions of terrestrial livelihoods for the poor are lost. This calls for innovative ideas. Despite early work on innovative agricultural services by the landless in Bangladesh (Wood and Palmer-Jones, 1991), the benefits from new ideas and technologies have largely bypassed those initially endowed with least resources, both in agriculture and more recently in aquaculture (Röling, 2009; Hornidge et al., 2011; Ul-Hasan et al., 2011; Diana et al., 2013; Krause et al., 2015). The innovative co-development of production technologies with and for the poor therefore remains an important and still underexplored arena with few long-term achievements. The expanding ocean boundary and its polarizing socio-economic effects makes relevant research more urgent.

This article identifies barriers to the participation of poor and marginal coastal populations in innovative ecosystem-based brackish water aquaculture (BWA). We use a set of indicative early field research results and outline first steps toward the co-development of an innovative, ecosystem-based approach (integrated multi-trophic aquaculture—IMTA) to aquaculture in the brackish and marine areas of Bangladesh. At the moment, marine aquaculture is only incipient in Bangladesh, but as salinity advances into coastal lands, millions of farmers and rural laborers who are losing agriculture as their main income source require new options.

MATERIALS AND METHODS

Background

Bangladesh is the sixth most climate change vulnerable country on earth (Kreft et al., 2016). The shallow, funnel-shaped Bay of Bengal is subject to particularly fast salinity intrusion while, at the same time, Bangladesh's densely populated coastal regions sustain about one third of the country's at least 160 million people (Alexandratos and Bruinsma, 2012).

Poverty is pervasive in Bangladesh, particularly on the coast. According to the World Bank (2018), 13.8% of the population live below the poverty line in Bangladesh. The population is predominantly rural (almost 80%). Dependence on nature is a mainstay for the poorest who cultivate coastal lands and/or work with freshwater pond aquaculture, as small owners, and in the majority, as landless laborers. Flooding and river erosion are major challenges, particularly for the coastal Bangladeshis who also face freshwater shortages due to increases in sea level and salinity (Selim et al., 2018). The coastal districts (19 of 64 districts), are home to one-third of the national population, almost 50 million people, and are the most vulnerable and poorest areas in the country, highly exposed to natural disasters. Between 1970 and 2015, over 45 devastating cyclones swept across mostly the coastal regions causing immense harm to lives, property and coastal livelihoods in fisheries, forestry, and agriculture (Haque et al., 2016).

Coastal natural resources are also exposed to rapid environmental change. Salinity has advanced up to 100 km inland (Disaster Management Bureau (DMB), 2010), causing losses of agricultural terrain to the sea and productivity losses for paddy fields and freshwater ponds. To support millions of coastal poor people who depend on agriculture and freshwater aquaculture, and also to mitigate out-migration from coastal Bangladesh (Kartiki, 2011), coastal and marine production systems in the Bay of Bengal need to transform to provide livelihoods to 20 million Bangladeshis in line with the increasingly saline and insecure conditions in the coastal lands they live and work in.

Salinity-tolerant paddy varieties and raised horticulture are part of the needed transformation of coastal production (Pouliotte et al., 2009; Islam et al., 2016). However, low and falling available land per capita, due to growing population density and land losses from saltwater intrusion, indicate that BWA will also need to increase. Shrimp monoculture, the currently predominant form of BWA, is a major export sector and foreign exchange earner for Bangladesh (Department of Fisheries (DoF), 2017). Shrimp aquaculture is, however, associated with social and economic polarization and ecological problems and conflict; its expansion is likely to exacerbate coastal inequality and poverty (Paul and Vogl, 2011; Hossain et al., 2017).

New uses of the coastal environment, which are supported by appropriate institutional frameworks, are needed, These should respond to the increasingly saline conditions in the densely populated coastal lands and the resulting displacements of livelihoods for large numbers of poor coastal inhabitants. BWA is a necessarily important part of the adaptation to the ongoing landward expansion of saline conditions, and it will need to be environmentally and economically sound as well as accessible to the coastal poor.

IMTA aims for the integrated waste-free production of diverse aquatic goods (including food, feed, fertilizers or bioactive compounds). IMTA uses the waste of (fed) species as fertilizer, food or energy for other (extractive) species (Zhang and Kitawaza, 2016). We suggest that, with a context-appropriate co-design of IMTA production systems for Bangladesh, within a favorable institutional context (Zwaag and Chao, 2006; Ahmed and Glaser, 2016), IMTA has "plausible promise" (Hornidge et al., 2011; Largo et al., 2016) of providing sustainable new livelihoods for the salinity-affected coastal poor of Bangladesh.

A pro-poor development of IMTA for brackish or marine areas will require appropriate choices. This includes the choice of species and construction inputs, of production technologies and processes, of management techniques, and of how the development of value chains is undertaken. It is now consensus that classical one-way "technology transfer" models (Rogers, 2003) are developmentally ineffective and that to increase their own opportunity space for beneficial engagement, poor women and men need to be involved in developing appropriate approaches "as experts and experimenters" (Röling, 2009; Hornidge et al., 2011).

We propose that, in the context of the unavoidably expanding ocean boundary, and as part of an ecologically and socially responsible aquaculture (Diana et al., 2013) that aims for "inclusive innovation and development" (Heeks et al., 2014; Joffre et al., 2017), IMTA needs to be developed with socially and

economically marginal women and men in coastal regions. These groups have been further harmed by environmental change and need to be enabled to pursue forms of production and marketing of marine products with equitable resource access rights that improve their food and livelihood security (Kittinger et al., 2017).

Research Questions

This article assesses some contextual preconditions for poor residents in coastal Bangladesh who are exposed to an expanding sea and increasing salinity, to co-develop and to benefit innovative BWA, such as IMTA. We investigate the opportunity spaces in BWA with a focus on those who are typically least successful within conventional transfer of technology models, i.e., poor coastal women and men; we explore local knowledge on BWA and we discuss opportunities and challenges for (co)-developing aquaculture as a sustainable livelihood with and for the poor majority in coastal Bangladesh. This article addresses three interrelated questions:

1. What kind of aquaculture is being undertaken in brackish/saline/coastal waters?
2. Do poor coastal residents see BWA (and, by implication IMTA) as a viable and sustainable livelihood?
3. What are the opportunities and barriers for making BWA a possible and promising livelihood in particular for these groups?

Methods

Our field research was hosted by the Climate-Resilient Ecosystems and Livelihoods (CREL) project and done in four sites where CREL had operated since 2012 (**Figure 1**). In these sites, CREL focused on training women for three livelihood options (integrated aquaculture in freshwater ponds, homestead gardening and poultry raising) and carried out vulnerability assessment training for climate change and disaster risk reduction (Climate-Resilient Ecosystem and Livelihoods (CREL), 2016). CREL focused on salt-tolerant species and improved genetic varieties of such species (e.g., Tilapia) and provided training, mostly to women, on income generating skills (e.g., stitching/knitting for an international fair trade organization). Our field research team conducted 120 sampling interviews, notably with non-beneficiaries of the CREL project from eight villages in the four coastal CREL project sites (**Figure 1**). These interviewees had not received any intervention, e.g., poultry or aquaculture training from any NGO projects. In these study areas, around 2,000 non-beneficiaries were involved in aquaculture related activities. A sample of 120 respondents was considered to be representative based on expert judgment, though we acknowledge some limitations in their selection. We employed a semi-structured questionnaire to capture households' socio-economic status, level of education, access to land, means of employment and their knowledge and perception of climate change impacts and of opportunities and challenges with implementing BWA. Due to the extreme remoteness and lack of accommodation in the study sites, our fieldwork was part of a set of prearranged visits to CREL field sites. This reduced our options to randomize interviewee selection. Respondents were recruited opportunistically while walking through the villages and visiting tea stalls and shops. Data from questionnaire

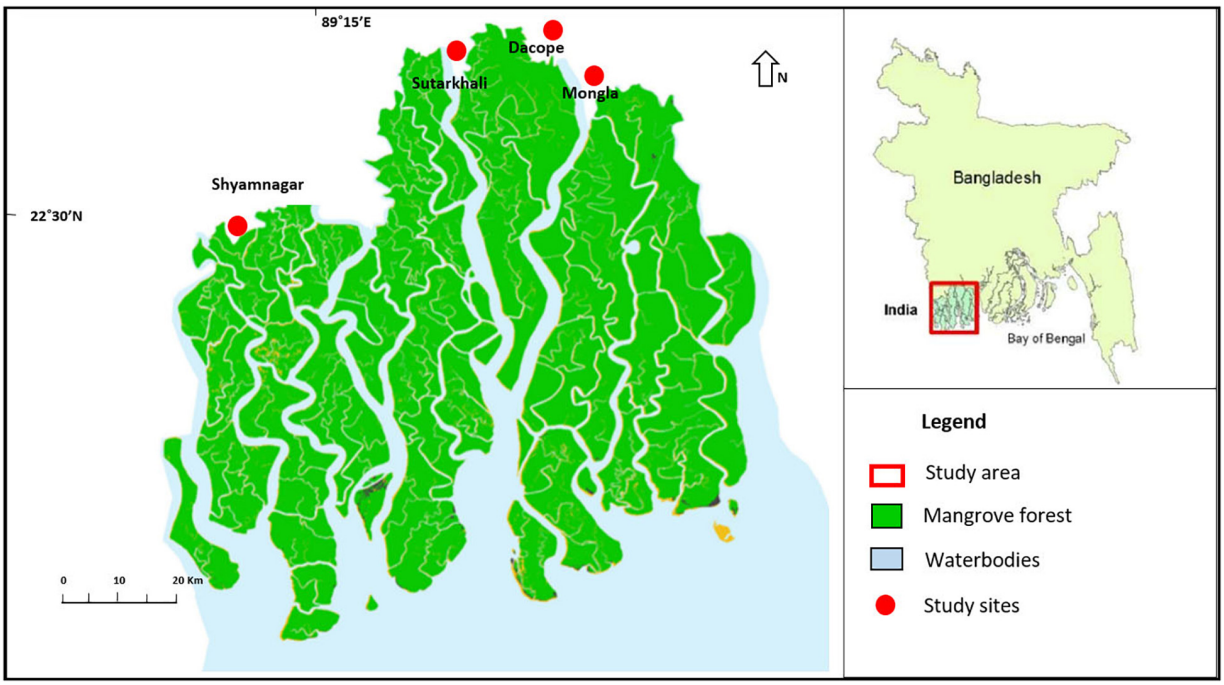

FIGURE 1 | Bay of Bengal and CREL research sites (red dots).

TABLE 1 | Distribution of positive attitudes toward BWA among socio-economic groups (no and % of respondents within category).

Is current BWA an option for sustainable livelihoods?	**No**	**Not sure/no reply**	**Yes**
Number of respondents	8% (*n* = 10)	60% (*n* = 72)	32% (*n* = 38)
Reasons for response	"it is increasing salinity in the water" "it reduces sources of pure drinking water" "salinity is not a problem there"		"shrimp and tilapia can be cultivated, less cost & time and good profit " "salinity increasing so it is needed now" "yes due to salinity, it is a way for us to still earn money" "Decrease in agriculture and fresh water fish cultivation" "creates jobs" "salinity is increasing, cannot have fresh water fish anymore"
Gender			
Female	9% (*n* = 4)	55% (*n* = 26)	36% (*n* = 17)
Male	5.5% (*n* = 4)	42.5% (*n* = 31)	52% (*n* = 38)
Land ownership			
Landowner	12% (*n* = 9)	54% (*n* = 42)	35% (*n* = 27)
Landless	2% (n = 1)	71% (*n* = 30)	26% (*n* = 11)
Income group			
Annual income BDT 0–20 k (poor)	7.4% (*n* = 2)	48% (*n* = 13)	44% (*n* = 12)
Annual income BDT 20–45 k (middle)	8.5% (*n* = 5)	49% (*n* = 29)	42% (*n* = 25)
Annual income BDT >45 k (high)	4% (*n* = 1)	39% (*n* = 11)	57% (n = 16)
Did not declare income	0% (n = 0)	67% n = 4	33% n = 2
Occupation			
Farmer/fishing	2% (*n* = 1)	67% (*n* = 29)	30% (*n* = 13)
Labor	29% (*n* = 7)	58% (*n* = 14)	13% (*n* = 3)
Rickshaw/van/bike puller	0 (*n* = 0)	40% (*n* = 4)	60% (*n* = 6)
Small business owner	0 (*n* = 0)	60% (*n* = 9)	40% (*n* = 6)
Other occupation	6% (*n* = 2)	44% (*n* = 16)	28% (*n* = 10)

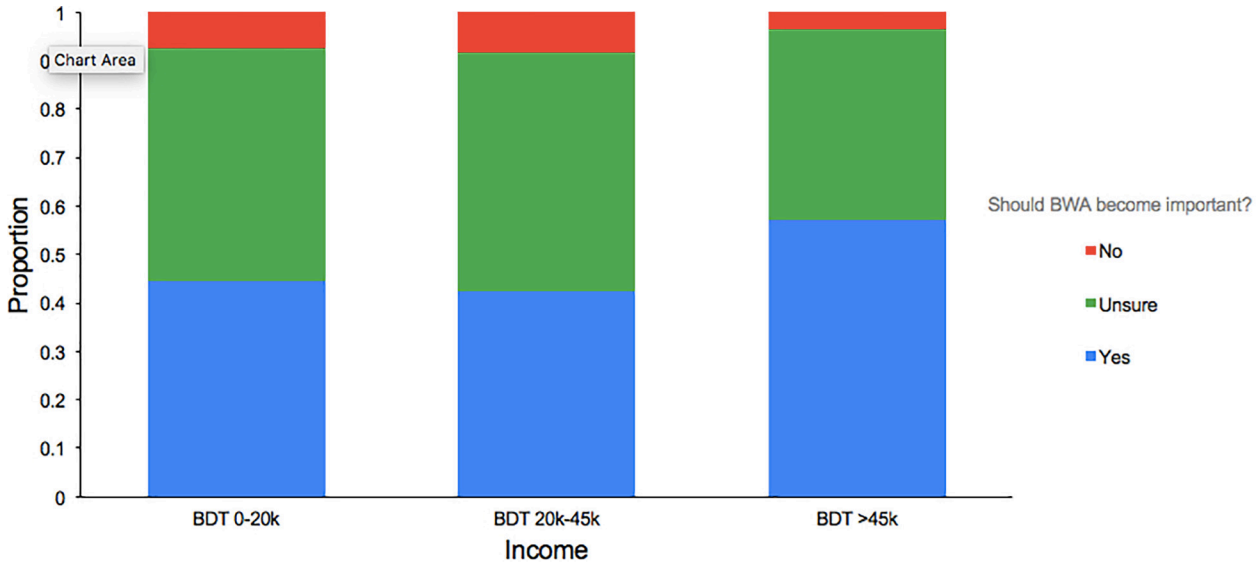

FIGURE 2 | Interest in brackish water aquaculture (BWA) among case study site respondents by self-reported annual household income [in Bangladesh Taka (∼100 Taka/Euro)].

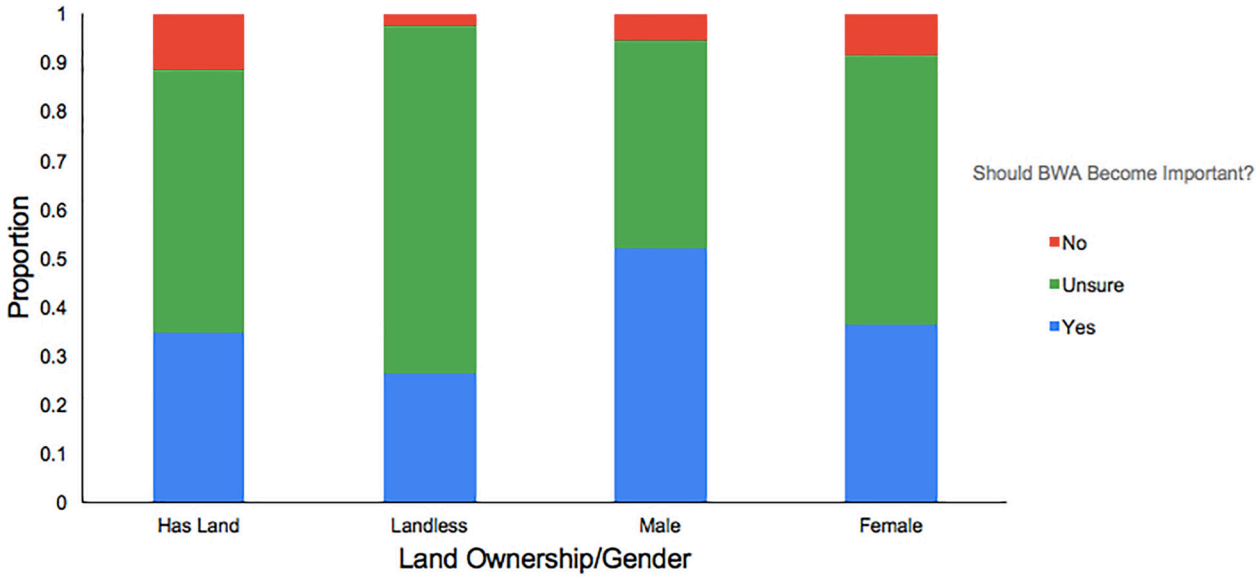

FIGURE 3 | Interest in brackish water aquaculture (BWA) by land ownership category and gender.

interviews were analyzed by using Microsoft Excel to produce descriptive statistics.

RESULTS

Respondents (73 men and 47 women aged between 18 and 65) were interviewed at eight villages (administrative subunits): Koyra, Dacope, Halna, Kaligonj, Mongla, Morelganj, Shatkhira, and **Figure 1** shows Shyamnagar. About 35% of interviewees owned no land at all (i.e., not even their homestead land). Among the 65% of respondents that owned land, the size of landholding ranged between 1 *Katha*[1] (0.03 acres) and 937.5 *Kathas* (28.13 acres), an average of 89 *Kathas* (2.67 acres).

Confirming relevant available literature (Disaster Management Bureau (DMB), 2010), salinity intrusion was mentioned by almost all interviewees (86%), and ranked as by

[1]*Katha* is a unit of area used in Bangladesh. The units are mainly standardized, e.g., 1 *Bigha* = 20 *Kathas* (Ministry of Land (MoL), 2016), however, they can vary significantly between district to district. Therefore, this study uses the local conversion of the coastal district Khulna with 1 *Katha* = 0.03 acre.

far the most deleterious coastal environmental change. We now turn to our three main research questions:

1. *What kind of integrated or other aquaculture is currently being undertaken in brackish/saline/coastal waters?*

BWA in our study sites features ponds with various combinations of aquatic species but focuses on *bagda* shrimp (*Penaeus monodon*) farming and mud crab fattening. The poorest people, mostly women and children, survive on shrimp fry collection from the wild, an illegal, low-income, and ecologically potentially unsustainable occupation (Selim et al., 2018).

2. *Do poor coastal individuals and households see current BWA as a viable and sustainable livelihood?*

Respondents' perceptions and knowledge on BWA related to shrimp farming in *ghers*[2] and saltwater tolerant tilapia. Only a third of respondents (34%, n = 38) thought that BWA was a sustainable livelihood option. About 65% (n = 72) were unsure and knew little about BWA (**Table 1**), and 8% (n = 10) thought that BWA was not a viable livelihood.

Disaggregated by our indicators of poverty (landownership, income level, and occupation—**Table 1**), we find indications of a gender bias:

- A higher percentage of female than male respondents were unsure or critical of BWA,
- 52% of men but only 36% of women saw chances for sustainable livelihoods based on BWA.

Figures 2, **3** distinguish perceptions of BWA as a means for sustainable adaptation to increasing salinity by income level, access to land and gender of respondents.

While there is no strong connection between income level and outlook on BWA, **Figure 2** shows that the lowest income group had the least positive and the highest income group the most positive views on BWA. Also, a higher percentage of men than women, and more landowners than landless respondents perceived BWA as of future importance (**Figure 3**).

3. *What is needed to make BWA a feasible and promising livelihood and what are the barriers?*

Our results (**Table 1**) indicate that:

- The outright rejection of BWA is a minority opinion: 12% of landowning but only 2% of landless respondents reported negative attitudes toward BWA.
- A majority of all three income groups report little knowledge on BWA but this was most pronounced among the landless, the two lower income groups, and among female respondents.
- The percentage of respondents that considered current BWA a sustainable income source is strikingly higher among respondents with the highest income level (57% of respondents with higher income, but only 44 and 42% with poor and middle income, respectively).
- Although farming and fishing are potential competitors to BWA, farmer and fisher respondents rarely dismissed the potentials of BWA (2% of respondents) but largely professed lack of knowledge on BWA (67%).
- Poor respondents from the service sector (rickshaw/van/bike pullers) have more positive views on the prospects of BWA (60%) than higher income service sector respondents of business/shopkeepers (40%).

Barriers to BWA and needed conditions for developing it which were most frequently mentioned all concerned assets and access: training in aquaculture (23% of respondents, n = 28), funds (20% of respondents, n = 24) and land/assets (19% of respondents, n = 23). Further mentioned needs were technology, NGO support, and business ideas.

DISCUSSION AND CONCLUSION

Where absolute poverty is high among large sections of the population and further impoverishment is under way, as in coastal Bangladesh, new production approaches such as IMTA for newly wet and saline environments, need to be environmentally sound, economically profitable, well governed, and produce healthy products for which there is demand (Barrington et al., 2010). However, beyond this, they also have a clear development task. Production and marketing need to be explicitly tailored for the economic, social, and cultural context and needs of the poorest victims of environmental change so as to enable these groups to realize significant benefits. In coastal Bangladesh, the poor, among them a majority of women, own little or no land but are as sharecropper/tenants or laborers nonetheless most dependent on the rapidly changing natural resource base while having little access to other promising income sources and services.

Need for Informed Knowledge Exchange

Despite its potentials for responding to salinity intrusion (Ahmed and Glaser, 2016), IMTA is, so far, neither known nor practiced in coastal Bangladesh. Therefore, we adopted the wider term BWA for this study. Between 20 and 60% of respondents reported interest in BWA (**Figures 2**, **3**). Higher income respondents had higher BWA acceptance levels and fewer reported information deficits than low-income (**Figure 2**) landless, and female respondents (**Figure 3**). Interviews also indicated that both the positive and the negative perceptions of BWA expressed by our wealthier study respondents were mostly associated with shrimp monoculture while there was little or no knowledge on ecosystem-based production. There is thus a clear need for information on modern IMTA and related options. The differences found across responses given by women vs. men should be investigated further. Although they are active in and are a target group for aquaculture development, female respondents reported lower levels of information and less positive attitudes

[2]The Bengali term *gher* combines aquaculture with a remnant of crop cultivation in the transitional land-ocean zone: A high protective dike is built around a rice field and a canal of several feet in depth excavated along the inner periphery of the rice field. The outer canals retains water during the dry season. During the rainy season, the entire water body is used to cultivate prawn and fish, while only the canal is used for fish during the dry season, with rice planted in the central plot.

about the potentials of BWA for providing sustainable livelihoods than male respondents (**Figure 3**).

Globally, considerable research has been conducted on the development of BWA, including IMTA (Gunning et al., 2016). In China, IMTA has been practiced for decades, and understanding of the dynamics between IMTA and the environment in Sanggou Bay can provide guidance to adaptively manage IMTA systems to ensure sustainability (Fang et al., 2016). The adoption of IMTA into tropical settings using local species of high market value can help sustainable farming in southern Cebu, Central Philippines (Largo et al., 2016). A successful trial of IMTA in the Sundarban region, India has been conducted (Biswas et al., 2019). These findings suggest that the development of IMTA in coastal Bangladesh is feasible if identified challenges are addressed.

Inequality and Pro-poor Development in Rural Coastal Regions

Negative perceptions can turn into self-fulfilling prophecies and undermine potential opportunities in aquaculture development as in other fields. Investigations of stakeholder perceptions of IMTA are rare in the literature and have so far focused on consumers in regions of the globe with high consumer power (Barrington et al., 2010). Our study looks at the producer side, in a context of pervasive and extreme poverty and finds that a higher proportion of wealthier respondents perceived opportunities associated with BWA[3] while lower income, landless and female respondents, although they displayed a good level of interest in BWA (**Figures 2**, **3**) clearly viewed the cards as stacked against them. The constraints and barriers to BWA that our respondents might be mostly asset-related, and associated with poverty.

Absolute landlessness was widespread with 35% of our respondents affected, while many of the landowning respondents in this study only had just enough land for homestead gardening and, at times, a small pond. In contrast, those with the largest landholdings in our study reported to own 28 acres, 900 times the amount of land that the smallest landowner reported. These and other stark inequalities within rural coastal communities in Southwestern Bangladesh need to be taken into account if the scope for benefiting from innovative aquaculture co-development is to be extended to the poorest women and men. Success in expanding the productive or marketing potentials of the poor has been documented in a few cases across the globe (Asian Development Bank (ADB), 2005; Pant et al., 2014).

Social and Governance Biases

Inequality and poverty embedded in asymmetrical relations of power and influence (Escobar, 2008; Peluso and Lund, 2012), set the scene for pervasive patron-client relations in Bangladesh, and also for gender relations. These limit the scope for the poor to engage in self-organized, and self-serving efforts at transformative innovation (Aminuzzaman and Sharmin, 2006). In the context of a project to enable the landless poor to become "sellers of irrigation water" Wood and Palmer-Jones (1991) speak of the "political weakness and status inferiority" of the rural poor. This is framed by a wickedly resilient governance context (Glaser et al., 2018), in which power dynamics and associated institutions consistently operate against the poor (Gereffi et al., 2005; Aminuzzaman, 2006; Lewis, 2011) and particularly against poor women. Efforts such as the co-development of pro-poor IMTA will need to take such persistent social and governance biases into account, for instance, by promoting institutions that support equal access for the poor to credit, inputs, and markets.

Outlook

The desirable long-term scenario for coastal Bangladesh is an eventually self-organizing transformation toward sustainable and equitable coastal resource use and livelihoods under the emerging wetter and more saline environmental conditions. So as not to exacerbate poverty and socio-economic inequalities, those sections of the population that are most affected by environmental change and least well-endowed to engage with innovations, need to be actively included in, and capacitated for innovation co-development. This study shows that lower income groups and women perceive fewer opportunities in BWA and (consider themselves to) have less knowledge on it. Options such as an innovative ecosystem-based IMTA may turn into promising drivers of sustainability-enhancing transformation, if carefully embedded in inclusive and empowering knowledge generation and exchange. A range of factors including governance, transparency and bureaucracy, inequality, gender bias, power and access to resources need to be explored to assess upcoming challenges and options. This study indicates socio-economic and gender biases in perceived prospects and capabilities. Further questions to be explored concern forms and dynamics of local (collective) self-organization, formal and informal institutional dynamics and, for different aquaculture products, the potentials of knowledge networking and coalition-building along local to global value chains. Attention also needs to be paid to why, despite its plausible promise (Ridler et al., 2007), IMTA has not yet become a transformative force anywhere on earth (Klinger and Naylor, 2012), except possibly in China (Fang et al., 2016).

Aquaculture development across the globe has been dominated by economic growth objectives rather than by the livelihood priorities of the coastal poor (High Level Panel of Experts (HLPE), 2014). The Intergovernmental High Level Panel of Experts on Food Security and the SDGs call for policies that support zero hunger/food security. Inclusive pro-poor innovation to support ecosystem-based aquaculture development that includes ownership by small-scale or collective producers, labor-intensive techniques, gender equality and a role for low-skilled labor to deliver here.

Emerging Fields of Action/Next Steps

Aquaculture is culturally appropriate in Bangladesh where environmental change is generating growing potential for BWA and IMTA. We propose three strategic fields of action to start

[3] IMTA being a locally unknown concept, BWA was employed as the wider known category in this study.

addressing the emerging options and challenges of inclusive, pro-poor BWA and IMTA development:

1. Diagnostic and scoping workshops in local coastal communities that deliver knowledge on IMTA options and identify important stakeholder or gender-specific opportunities, priorities, concerns and challenges. Inclusive approaches such as future visioning could facilitate the process of adapting co-development approaches to the needs of (poorer) coastal women and men.
2. A first pioneering set of facilitated IMTA experimentation groups to serve as temporary "safe spaces" in which interested poor coastal women and men can be supported in collaborating in the development of ecosystem based aquaculture innovation. The outcome of such an "experimental co-design phase" with IMTA field trials, in which groups of local poor people contribute their contextual and grounded knowledge but also need to be supported by natural and social scientists and local technical expertise, would aim to explicitly include group members' own priorities, for instance in the selection of species, of aquaculture sites, of construction materials, and in the development of input and credit access and marketing.
3. Finally, we propose a networked and institutionalized knowledge exchange between key stakeholders along the value chain from producer to consumer. This might include an regionally active but internationally networked "knowledge-building and contextualization platform" to promote and include the creative agency of poor women and men displaced by coastal environmental change.

Social innovations beyond technology will be needed to enable developmentally effective (i.e., pro-poor) and ecologically sustainable innovation. Low-external-input modes have been found to best benefit poor rural people. This stands in contrast to increasingly capital intensive aquaculture development modes so that options and trade-offs have to be identified and negotiated. In this, the poor need capacities and rights to actively participate in decisions to ensure their benefits. Vested income and/or gender-based power differentials are likely to require the establishment of countervailing power among marginal coastal residents if innovative ideas are to be co-developed equitably. With our field results and the ensuing suggested strategic fields of action, we have sketched out some first steps.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Liberal Arts Bangladesh. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

SS: conceptualization, field investigation, methodology, project administration, and writing. MG: conceptualization, methodology, data analysis, writing, editing, and review. FT: data analysis, visualization, editing and review. MR: data analysis and visualization. NA: writing, review, and editing. All authors contributed to the article and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.635281/full#supplementary-material

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Five Questions to Understand Epistemology and Its Influence on Integrative Marine Research

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Developing solutions to the complex and uncertain problems facing marine and coastal social-ecological ecosystems requires new forms of knowledge production and integration. While progress has been made both in terms of successfully producing integrated marine research and connecting that knowledge to decision-makers, a number of significant challenges remain that prevent the routine development and implementation of successful integrated research practice. Based on our own experiences as social researchers working within interdisciplinary research teams, we contend that one of the main barriers to successful integrative marine research relates to understanding, and where possible reconciling, the different epistemologies that unpin how knowledge is created or discovered in different disciplines. We therefore aim to provide an accessible introduction to the concept of epistemology, with a focus on its importance and influence to integrated marine research practice. Specifically, we present and discuss five questions of research design that relate to epistemology in integrative research practices: (1) What is the object of study we seek to create knowledge about; (2) how do we create knowledge; (3) who accepts knowledge as 'true' and how?; (4) how do we determine the epistemology underpinning marine science; and (5) what are the implications of epistemology for applied integrative marine science? We demonstrate the application of each question through a hypothetical case study of marine restoration, focusing on coral transplanting. Finally, we offer readers a simple heuristic to guide them, irrespective of career stage or discipline, to understand and account for epistemology when participating in integrative marine research practices.

Keywords: interdisciplinary studies, research philosophy, social science, methodology, epistemic communities

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INTRODUCTION

Coastal and marine ecosystems provide critical goods and services that underpin human well-being and prosperity (Barbier et al., 2011; Cracknell, 2019) and are considered part of the basic global life support system for more than 40% of the world's population (Seto, 2011; Neumann et al., 2015). Despite their importance to humanity, increased pressures (e.g. from climatic changes and coastal development) threaten the long-term persistence of these ecosystems and the goods and services they provide (Halpern et al., 2008). The scale and nature of contemporary challenges facing coastal and marine ecosystems are complex, unpredictable and uncertain (Nash et al., 2017, 2020). Thus,

identifying, developing and implementing solutions to navigate these challenges to ensure societal well-being and prosperity represent an equally significant challenge.

In response to these challenges, the community of scientists who study marine social-ecological systems are often seeking to support decision-making processes via the knowledge created within their research and practice (Cvitanovic et al., 2015). Traditionally, this knowledge has been confined to single academic disciplines, but more integrated approaches to knowledge production (e.g. interdisciplinary research) are recognised as necessary to deal with the complexity and unpredictability of social-ecological systems (Dick et al., 2016; Norström et al., 2020). In particular, recognition is increasing in relation to the value and importance of integrating social dimensions of marine conservation into research activities (Bennett, 2016; Bennett et al., 2019), and the ways in which marine social science can support this endeavour (McKinley et al., 2020).

Increased efforts are therefore being made throughout the marine research community to collaborate across disciplines to integrate knowledge systems. Progress is being made both in terms of successfully producing integrated marine research (e.g. Cinner et al., 2018; Barnes et al., 2019; Bodin et al., 2019) and also in connecting that knowledge to decision-makers to support evidence-informed decision-making processes (Cvitanovic and Hobday, 2018). Yet, a number of significant barriers and challenges remain that prevent the routine implementation of successful integrated research (e.g. Alexander et al., 2019). Building capacity to overcome these challenges is critical in enabling improved interdisciplinary marine research processes (e.g. Blythe and Cvitanovic, 2020).

'EPISTEMOLOGY' AS A BARRIER TO INTEGRATIVE RESEARCH

Based on our own experiences as social researchers working within interdisciplinary research teams, we contend that one of the main barriers to successful integrative research processes relates to reconciling the different *epistemologies* that unpin how knowledge is created (see also Elsawah et al., 2020). Epistemology is the branch of philosophy that asks: how do we know what we know? It is concerned with how we can ensure that knowledge is both adequate and legitimate (Maynard, 1994), by considering: (a) what constitutes a knowledge claim, including the assumptions that are made; (b) how knowledge is produced or acquired; and (c) how the extent of its applicability can be determined.

Epistemology is important in developing solutions to contemporary challenges facing complex socio-ecological systems where a range of disciplines and practices converge, with their own methods and assumptions regarding the adequacy and legitimacy of knowledge (e.g. Teel et al., 2018; Moon et al., 2019b). Yet, the concept of epistemology tends to be absent from the natural (including marine) science literature, arguably because the natural sciences tend to be underpinned by the dominant epistemology of (post) positivism (see also objectivism below) (Evely et al., 2008). With increased focus on the implementation of integrated research practices, it is necessary to improve awareness and understanding of epistemology more broadly throughout the marine conservation community, particularly where different epistemologies arise. In doing so, we can explore how these different epistemologies influence research and practice and identify more effective strategies for converging disciplines founded upon divergent assumptions.

AIMS AND PAPER STRUCTURE

To assist in overcoming these challenges, and in accordance with the aims of this Special Issue that focuses on promoting integrated research by marine early career researchers, we aim to provide an accessible introduction to the concept of epistemology, with a focus on its importance and influence to integrated marine research practice. We do so through by presenting five questions that researchers should consider. First (Question 1), we consider the role and importance of epistemology for achieving integrative marine research and the types of knowledge we create within marine sciences. We then (Question 2) consider the process of creating that knowledge, and the circumstances under which it can be 'justified' as a true belief. We then explore (Question 3) who it is that can accept knowledge as 'true', before (Question 4) offering a simple heuristic for identifying the epistemology of the marine research in which we engage and then finally what epistemology means for the application of integrated marine research and practice (Question 5).

To demonstrate how each of these considerations can apply in practice we use a hypothetical case study of marine restoration, and in particular, coral transplanting. Marine restoration approaches that aim to build reef resilience to the increasing threat of climate change (e.g. rising sea surface temperatures, ocean acidification, increased storm activity) are growing in diversity and popularity (West and Salm, 2003; van Oppen et al., 2015; McLeod et al., 2019). One of the more widely applied approaches is coral transplantation (Epstein et al., 2003; Rinkevich, 2005), which has been shown to be effective (when appropriately managed) at restoring coral cover, diversity and reef structural complexity at small scales (e.g. <100 m; Boström-Einarsson et al., 2020). This work involves either the direct transplantation of coral fragments onto the target reef or via a nursery where coral fragments grow to a suitable size before transplantation (i.e. coral gardening; Tunnicliffe, 1981; Bruno, 1998; Meesters et al., 2015). Despite this approach showing some success, it has been criticised because it has rarely been implemented at a spatial scale large enough to have a meaningful influence (Precht et al., 2005; Edwards and Gomez. 2007; Omori, 2011; Bayraktarov et al., 2016), focuses on short-term (e.g. coral survivorship) rather than long-term outcomes for coral reef communities (Hein et al., 2017) and does not mitigate the cause of declining reef condition (i.e. rising carbon dioxide emissions; Edwards and Gomez, 2007; Braverman, 2016). From an integrative research perspective, such work could also be criticised for its lack of attention to the

socio-political context in which any transplantation work takes place. For example, a transplant program might only focus on *what* success looks like, rather than *how* success is achieved. Successful transplanting might, for instance, require funding (e.g. investment from policy-makers), monitoring (e.g. commitment from citizen scientists) and community support (e.g. social license to operate).

Question 1: What Is the Object of Study We Seek to Create Knowledge About?

The first step in considering the role and importance of epistemology for achieving integrative marine research is to consider what it is that we seek to study in the marine sciences. The natural sciences focus on the biophysical dimensions of systems, where the object of study is usually physical (i.e. tangible, material). In a marine setting, objects could include substrate types (e.g. assessing changes in coral cover, Pisapia et al., 2019), marine organisms (e.g. to understand patterns of fish behaviour, Pratchett et al., 2014) or attributes such as wave energy (e.g. Fulton and Bellwood, 2005). The focus on physical objects stems from the aims of natural science to understand and describe natural phenomena, which is typically achieved through observation and experimentation focused on establishing a high level of validity and reliability in the knowledge (**Table 1** and **Figure 1**).

The social sciences focus on human dimensions of the system, which can include relationships with biophysical elements. Human dimensions can be physical and observable (e.g. a person's behaviour), and non-physical and non-observable (e.g. a person's beliefs). When looking at physical objects, a researcher from the social sciences might choose to conduct a large survey of a representative sample to make generalised observations about the population (e.g. levels of ocean literacy among school aged children and their implications for marine stewardship, Guest et al., 2015). When looking at non-physical objects, a researcher might be interested in understanding the worldviews and/or motivations of a small sample of people (e.g. a recreational fishing community, McNeill et al., 2019). A researcher could examine both physical and non-physical objects, for example, they might observe particular behaviours (i.e. physical), and then ask people to explain what motivated them to undertake those behaviours (i.e. non-physical) (e.g. observing the behaviours of scuba divers on a coral reef, and then seeking to understand what motivated certain behaviours such as making contact with the substrate).

An integrated object of study might be coral reef resilience, which could be considered an outcome (i.e. goal achievement, compared to an output which is an implementation behaviour, Moon et al., 2017). The research might look at social and ecological threats to a coral reef community, where coral transplants become one of a number of possible solutions. Aspects of the system that are examined might include physical, measurable parameters (e.g. coral transplant survivorship, coral cover) (Omori, 2011; Boström-Einarsson et al., 2020), as well as social and cultural factors that explain perceptions of different management interventions on reef user experience, stewardship and social resilience (Hein et al., 2017).

Question 2: How Do We Create Knowledge About the Objects of Study in the Marine Sciences?

The second step is to think about the process of creating that knowledge. It can be helpful to think, quite broadly, about knowledge as a 'justified, true belief' (see Parikh and Renero, 2017). That is, the way in which an individual/group 'knows' something is true. To understand this concept let us consider the beliefs of a coral ecologist working with coral transplants. Firstly, they might start with a belief that transplanting corals on to a reef is an effective approach for building reef resilience and adapting to the effects of climate change. Secondly, they might seek to justify this belief as true. They might start to take monthly photographs of transplanted corals and collect environmental data (e.g. daily water temperature) for a prolonged period of time (i.e. 3 to 5 years). Thirdly, they might seek to determine whether observed trends are unique to the coral reef they sample, or whether these trends have been observed at other coral reef transplantation sites. Here, they are seeking to create knowledge beyond their study location to determine the extent to which their belief applies. Epistemology then relates to the nature of the knowledge that (a group of) people create or discover. In the above example, epistemology relates to how the belief was generated (i.e. that coral transplanting is effective), the extent to which it corresponded to (a) reality (i.e. local observation), and what evidence, testimony or observation was used to justify the belief as true.

It is entirely possible, however, that two coral reef ecologists with access to the same data, could create knowledge in different ways. This possibility arises from the nature of the *beliefs* they hold, which they seek to justify as true (i.e. knowledge) (see Williamson, 2002). For example, one ecologist might have a belief, on the basis of decades of experience, observation and experimentation, that irrespective of changing climatic conditions, existing coral structure and species composition could be managed to build reef resilience to changing environmental conditions. Another ecologist might have a belief that such restoration efforts (including coral transplantation) would be an ineffective response to the coral reef crisis, also based on decades of scientific research, because rising ocean temperatures will continue to present increasing threats until at least 2050. Here, different actors are constructing their knowledge from both their objective *observations* of 'reality' and their subjective *reasoning*, with different outcomes for what we (seek to) learn. Armstrong (1973) points out that beliefs might be best viewed as maps by which we steer; in other words, beliefs are action-guiding, influencing what we seek to create knowledge about. What this brief example points to is that people can construct meaning of the same object or phenomenon in different ways on the basis of their cultural, historical and social perspectives, and interactions with human communities (e.g. their social network) (Crotty, 1998; Creswell and Creswell, 2017). It therefore becomes necessary to consider *how* different beliefs are justified (e.g. via reason, emotion, perception and language) and accepted as knowledge within an 'epistemic community' (Question 3).

TABLE 1 | Measures and definitions of research quality.

Quantitative data measures	Definition (Lincoln and Guba, 1985)	Qualitative data measures	Definition (Guba, 1981, pp. 79–80)
Reliability	Does the method, applied to the same units, consistently yield similar measurements over and over? (Reliability is a pre-cursor for validity – an unreliable measure cannot be valid)	Dependability	How can one determine whether the findings of an inquiry would be consistently repeated if the inquiry were replicated with the same (or similar) subjects (respondents) in the same (or similar) context?
Objectivity	Would multiple observers agree on the phenomenon of cause and effect?	Confirmability (where relevant)	How can one establish the degree to which the findings of an inquiry are a function solely of the subjects (respondents) and conditions of the inquiry and not of the biases, motivations, interests, perspectives and so on of the inquirer?
Internal validity	Can the variations in the outcome (dependent) variable be attired to controlled variation in an independent variable? Can we infer truth or falsity of cause and effect between two variables?	Credibility	How can one establish confidence in the 'truth' of the findings of a particular inquiry for the subjects (respondents) with which and the context in which the inquiry was carried out?
External validity/generalisability	To what extent can we infer that the causal relationship can be generalised across other persons, settings and times?	Transferability	How can one determine the degree to which the findings of a particular inquiry may have applicability in other contexts or with other subjects (respondents)?

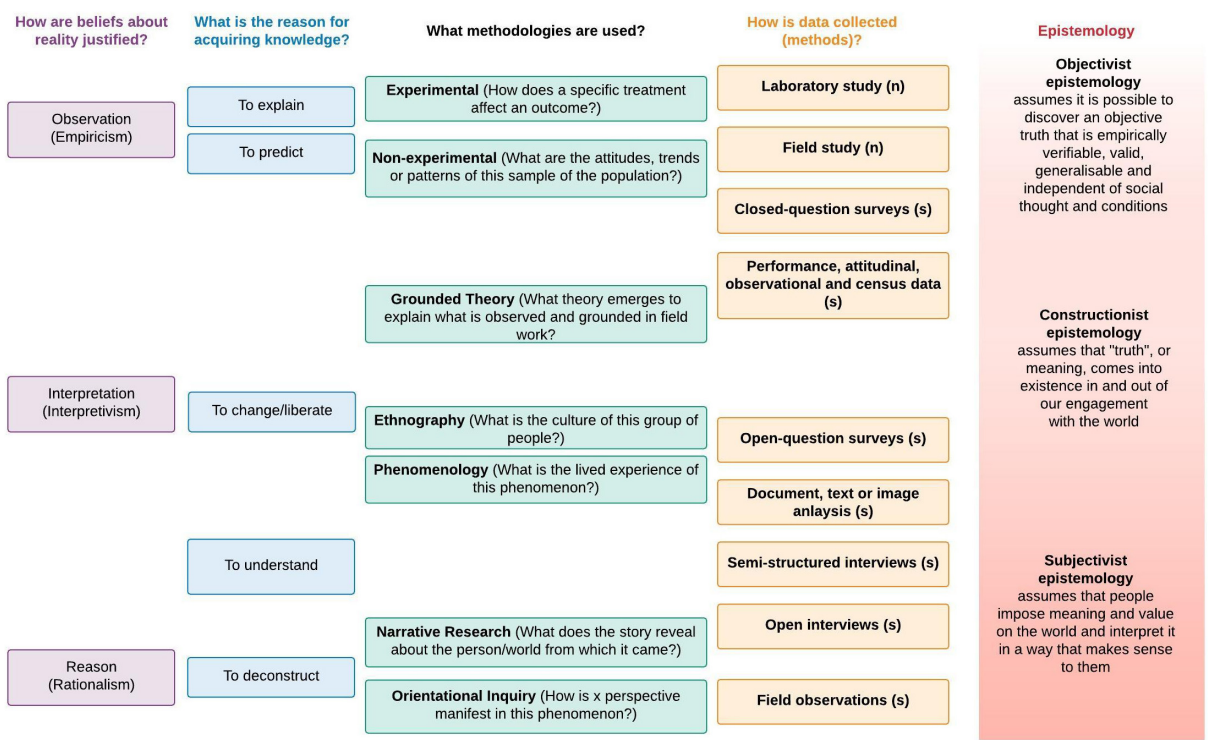

FIGURE 1 | A heuristic device (developed as one example of the diversity of ways that epistemology can be applied) to assist with understanding the epistemology of integrative marine science. By locating the aims of the research (reason for acquiring knowledge), the methodologies or methods used, or the ways in which beliefs are justified, it becomes possible to understand the assumptions underpinning the research (i.e. epistemology). 'n' denotes common methods in natural science; 's' denotes common methods in the social sciences.

Question 3: Who Accepts Knowledge as 'True' and How?

The third step in achieving integrative marine research is seeking to understand who accepts knowledge as 'true' and how they do so. Building on the above section, if knowledge takes on different forms (e.g. objective, constructed and subjective, **Figure 1**), then how do we decide what *is* knowledge? Generally speaking, for knowledge to be 'accepted' (i.e. justified, true beliefs), an epistemic community is required. An epistemic community is a group of people who are considered experts in a knowledge domain, for example, within a discipline (e.g. physics, ecology, anthropology, political science, sociology and law), industry

(e.g. aquaculture, beef, soy, inshore fisheries and diving tourism) or cultural group (e.g. religious and indigenous). The important role of epistemology here is asking us to be involved in an ongoing examination of 'what I know', 'how I know it' and 'how it corresponds (or not) with the knowledge of others'? (Patton, 2002). This last question is particularly important in integrated research, where different knowledge sets often collide.

For knowledge to be justified as true, the epistemic community evaluates the creation, generation or discovery of new knowledge, makes corrections where necessary and ensures that the knowledge meets certain criteria (Popper, 1963). Different epistemic communities use different criteria to evaluate knowledge. Much of the knowledge created in the natural sciences is evaluated according to criteria such as reliability, internal and external validity, objectivity and generalisability (see Moon et al., 2019b) (**Table 1**). These criteria are also important to social science research that generates quantitative data. Yet, because of the different objects of study, some social science research (particularly that which generates qualitative data) use different criteria to evaluate knowledge, which include dependability, credibility, confirmability and transferability, and relate, respectively, to the criteria used in the generation of quantitative data (**Table 1**). Sampling strategies, for example, are often different in the natural (e.g. representative) versus social (e.g. purposive) sciences because of the different aims (and objects of study) of research within these fields. Yet even with unique evaluation frameworks across disciplines to account for the differences in how knowledge is created and assessed, it will not always be the case that individuals will assess knowledge in the same way within those frameworks. Peer review, for instance, can often result in different reviewers providing very different critiques of the same body of work, where one might accept the findings of the research where another rejects them, even though they apply the same evaluative frameworks.

By recognising that (groups of) people create or discover and assess knowledge in a variety of ways, we can begin to open our minds to multiple ways of knowing, all of which can be validated in different ways within and across defined epistemic communities. Of course, it is not necessary to agree with how different epistemic communities validate and accept knowledge (or even develop their beliefs), just as they do not have to agree with how your epistemic community does so. Yet recognising other ways of knowing can assist with developing productive collaborations. This recognition can reduce confusion (e.g. 'But I have some scientific evidence – won't that change your mind?'), a lack of communication (e.g. 'You are ignoring the legitimacy of my knowledge [and that of my epistemic community] and so I cannot engage with you anymore') and conflict (e.g. 'We are completely opposed on this issue and so my only option is to exit from the process').

Question 4: How Do We Determine the Epistemology Underpinning Marine Science?

Epistemology is the bridge between thinking and reality – it is a theory of knowledge that allows us to determine whether we can create knowledge that corresponds with something that is 'real' (constructivism, **Figure 1**). The assumptions that are associated with epistemology, and thus underpin research, are critical to understand. We have provided a simple heuristic device to assist in understanding the epistemology of marine research and what it means in terms of research practice and outcomes (**Figure 1**, see also Moon and Blackman, 2014). The intention here is not to be comprehensive, but to provide a simple map of how to get a sense of where researchers' assumptions might lie in relation to how they have sought to create knowledge. The device offers three broad epistemologies: objectivism, constructionism and subjectivism (Crotty, 1998). It then points to how beliefs tend to be justified (i.e. observation, interpretation and reason), why knowledge is acquired, and the common methodologies and methods employed. By locating the nature of the research within the device, it becomes possible to start to consider the assumptions that have been made during knowledge creation or discovery, which can be further examined in the literature (e.g. Bohensky and Maru, 2011; Moon and Blackman, 2014; Teel et al., 2018; Martin, 2019; Mathevet and Marty, 2020).

Using this heuristic device, we can consider the epistemologies that underpin, for example, coral restoration research. Most commonly, this field of research fits with objectivist (or post-positivist), and to a lesser extent constructionist, epistemology (**Figure 1**). A review by Boström-Einarsson et al. (2020) found that of the 362 coral restoration case studies, most were focused on improving the restoration approach using empirical observational data (e.g. coral transplant growth and survival rates). For example, objectives of the Gomez et al. (2011) included an assessment of the survivorship and growth of *Montipora digitata* with respect to prevailing environmental conditions, density of transplantation and surface orientation (objectivist epistemology, which assumes it is possible to discover an objective truth that is empirically verifiable, valid, generalisable and independent of social thought and conditions, **Figure 1**).

In contrast, there are studies that seek to understand why some coral transplantation projects fail and others succeed using constructionist epistemology (that assumes 'truth' or meaning comes into existence in and out of our engagements with the world, **Figure 1**), by considering the social, cultural and economic landscape. For example, Hein et al. (2019) used targeted key-informant interviews where respondents were asked closed questions (e.g. how long have you been working in the location, what's your diver experience), scalar questions (e.g. rate attributes of local reefs in terms of coral and fish abundance) and open-ended questions (e.g. opinions on specific aspects of the restoration efforts) to assess the potential socio-ecological benefits (and limitations) of coral restoration (**Figure 1**). The aim of the work was to characterise stakeholder's perceptions of the benefits and limitations of reef restoration efforts. Participants recommended improved consideration of socio-cultural dimensions in goal setting (see above).

Integrated marine research can include multiple epistemologies. Moon and Browne (2021), for example, developed a sequential method, eliciting mental models from coral reef ecologists and managers in a way that provided an understanding and exploration of the diversity of knowledge of

complex carbonate coral reef systems. They then sought to find similarities between different knowledges to develop a shared model of the system to predict how these systems will respond to climatic change (objectivism). One of the benefits of this method was in supporting participants to see how they constructed their own knowledge of the system and how those constructions were similar or different to others, providing opportunities for exploration and discussion of knowledge assumptions.

Question 5: What Are the Implications of Epistemology for Applied Integrative Marine Science?

A number of benefits arise from understanding the role of epistemology in the application of integrated marine science (see **Table 2**). We briefly discuss two important ones here. Firstly, an understanding of epistemology can increase our awareness of the partiality of our knowledge, which can only ever be provisional, qualified and even uncertain due to the nature of research questions and designs that only focus on a part of the system (**Figure 1**). In recognising that we only know a part of the story, we can start to foster a greater sense of humility to the claims of authority in our research, and engage in more genuine approaches to integration among disciplines (Moon et al., 2019a). Yanow (2009) suggests that we can embrace humility through a reflective practice that moves from the language of certainty to one of inquiry, involving an interrogation of our self, our epistemological assumptions, and our ways of thinking and doing. For example, the majority of coral reef ecologists working on coral transplants measure success using coral growth and survivorship over 1 to 2 years (Boström-Einarsson et al., 2020). Although these metrics provide some insight into the success of the project at a small spatial and temporal scale, there has been limited focus in assessing the long-term implications (>5 years) at larger (ecosystem) scales (Boström-Einarsson et al., 2020) and within different social-ecological contexts. Improving knowledge on, for example, the reproductive output of transplanted fragments or measuring changes in structural complexity (Okubo and Onuma, 2015), would provide a more holistic assessment of the impact of coral transplantation for reef resilience and related ecosystem services (e.g. biodiversity and coastal protection). To improve the acceptability of the approach, inclusion of social, political, economic and cultural factors, as discussed above, will also be critical in determining what factors contribute to a higher chance of program success.

Secondly, an understanding of epistemology provides opportunities to consider power relations in research and practice. Academic knowledge is only one type of knowledge, yet it is often privileged above others, such as Indigenous, experiential and cultural knowledge. For example, Shackeroff and Campbell (2007, p. 346) argue that the legacy of colonialism has positioned Westerners as superior and non-Westerners as an inferior but necessary 'other', where 'traditional ecological knowledge' is considered to 'fill in some knowledge gaps, but cannot challenge Western knowledge'. Within marine conservation and restoration projects (including coral transplantation), the early involvement of stakeholders is considered crucial to their success (Bayraktarov et al., 2019). Despite the known value of these sources of knowledge, a review of four well-established (8 to 12 years) coral restoration projects in different regions of the world identified the lack of community

TABLE 2 | Questions to ask in understanding the epistemology of marine science.

Questions	Exploratory questions
1. What is the object of study?	• What is it that the researcher seeks to create knowledge about?
	• Why and how do they determine the object of study?
	• What is the object of study – is it tangible or intangible?
2. How do we create knowledge?	• What beliefs underpin the research?
	• How have the researchers sought to justify their beliefs as true?
3. Who accepts knowledge as 'true' and how?	• What methods of data collection have been used? How were they justified?
	• What sampling strategies were adopted? Why and what were the considerations made for ensuring reliability?
	• How did the researchers identify and reflect bias in designing and implementing the research?
	• Who determines whether the methods, results and truth claims are valid?
	• What criteria were used to assess the quality of the truth claims?
4. How do we determine the epistemology underpinning marine science?	• What assumptions about reality underpin the research?
	• What methodologies were used?
	• What methods were used?
	• What was the nature of data collected (e.g. qualitative and/or quantitative)
	• How was the data analysed and interpreted?
5. What are the implications of epistemology for applied integrative marine science?	• How was the transferability of the data determined?
	• In what ways could the data be applied (e.g. can it be generalised to the population or is it context or site-specific?)
	• How were different stakeholders engaged in the research process?
	• How were marginalised groups considered and engaged?

awareness, communication with the public and partnerships (e.g. local community groups) as limitations to project success (Hein et al., 2019). Acknowledging that different epistemic communities generate or hold credible and legitimate knowledge can aid in overcoming such power imbalances and ensure respectful and appropriate inclusion of different knowledge systems (Cornell et al., 2013). Certainly, it is also the case that we need to work more closely with indigenous people regarding their ontologies and worldviews to challenge Western academic knowledge (see Henry and Pene, 2001; Todd, 2016; Gewin, 2021).

CONCLUSION

Navigating the challenges facing marine social-ecological systems for ecosystem integrity and human well-being and prosperity necessitates the integration of the natural and social sciences (McKinley et al., 2020). While progress has been made in this regard, significant barriers to integrative marine research practice remain (e.g. Alexander et al., 2019). We argue that integrative research is not just about integrating different types of science but also about integrating different epistemologies. We have supported this proposition by drawing on our own personal experiences, as well as a hypothetical case study relating to marine restoration and coral reef transplanting, demonstrating the value of considering a range of practical questions in understanding the concept of epistemology, its implications for integrative marine research and practice, and the critical aspects that marine researchers should consider when embarking on integrated marine research endeavours. We also present a simple heuristic (**Figure 1**) to support this process, with exploratory questions for researchers to ask when working in integrative teams (**Table 2**). While further research is needed, particularly into the approaches or methods that could be used to enable different epistemologies (and indeed ontologies) to either integrate or work alongside each other, we hope that by sharing these perspectives and examples, drawing on the broader evidence base and developing a simple heuristic, that we have provided an accessible introduction to the concept of epistemology that can support marine researchers of all career stages embark on successful integrative research practices.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

KM and DB conceived of the idea of this manuscript. KM and CC wrote the manuscript with editorial contributions from all authors. NB provided case study content.

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frontiers in Marine Science

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Think of the Early Career Researchers! Saving the Oceans Through Collaborations

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Oceans are complex systems and problems preventing a sustainable future require complex solutions. This can be achieved through innovative blends of natural and social sciences, with input from stakeholders. There is growing expectation that early career researchers (ECR), especially conservationists, should be more than natural scientists. ECR are expected to have skills in several domains, not all important to the quality of their work. Scientific skills range from knowledge of complex statistics to programming, and experience in different scientific fields. It is not only impossible to master all such tasks in a lifetime, much less as an ECR, but most importantly, attempting to do so means an ECR cannot master any single skill. This is especially true for minorities, non-native English speakers, and those who must juggle doing science with little or no funding, while having other jobs and family commitments. ECR are also expected to participate in activities that, while important for conservation, do not necessarily improve their scientific skills. These are social skills and range from policy engagement to science communication. This can contribute to developing mental health issues as it hinders having a healthy work-life balance. This expectation of engaging in extracurricular activities can overwhelm people with social anxiety and other difficulties with social interactions (e.g., people in the autism spectrum). Through collaborations, we can effectively draw on the more specialized skills of various people. Building an inclusive scientific community for ECR, therefore, calls for seeing diversity of skills, thoughts, and personality traits as its strength.

Keywords: academia, autism, mental health, multidisciplinarity, science communication, ocean conservation

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INTRODUCTION

Consilience is the principle that knowledge from different disciplines converge to form a comprehensive understanding of a theory or field. With this in mind, we see ocean conservation as a multidisciplinary endeavor that requires unification of knowledge from different fields. These range from biology, ecology, and evolution, to engineering, statistics, and psychology, and together should work to identify conservation challenges oceans face and the best approaches

for developing and implementing effective solutions. Thus, although marine conservationists are trained in a wide range of topics, expert input from other fields are crucial to prevent unintended negative consequences.

One famous case of adverse consequences resulting from attempting to solve a complex issue without input from experts from all relevant fields is "The Ocean Cleanup" project. This is an international project aiming to build a large floating device to intercept plastic debris on the ocean surface[1]. Due to inadequate consultation with relevant experts, the environmental impact assessment was limited in their scope as well as conclusions (Zuijderwijk et al., 2014). The project was criticized by experts before, during, and after implementation[2][3], yet their concerns were dismissed[4], resulting in putting vulnerable marine animals at risk[5]. These unintended consequences could have been prevented by appropriate consultation, and collaboration, with relevant experts at earlier stages.

Throughout this manuscript, we will provide examples and context to argue that ocean conservationists should strive to build a collaborative, multidisciplinary environment instead of expecting conservationists to be themselves jacks-of-all-trades. The expectation that conservationists, especially early career researchers (ECR), should have expertise on a range of fields can affect researcher and the scientific endeavor. It is detrimental for the scientific endeavor because having a range of knowledge is not synonym with being an expert in those fields. And it is detrimental for researchers because the expectation that researchers, especially ECR, must do more than "just" science not only contributes to burnout and other mental health issues, but is also a form of hidden discrimination due to a myriad of factors we will address in the following sections.

We focus on ocean conservation due to the multidisciplinary nature of the task, however, the topics we will discuss throughout this manuscript also impact ECR and academics from other disciplines, scientific or otherwise.

Jack of All Trades, Master of None

There is growing expectation that ECR, especially those working in conservation, should be more than scientists seeking to understand the natural world. ECR are expected to have skills in several domains, many that are important to the quality of the scientific research they produce, while others are not. Required scientific skills range from fieldwork experience and knowledge of complex statistical analysis to programming and experience using a range of specific equipment or software. It is not only impossible for one individual to master all such tasks in a lifetime, much less as an ECR, but most importantly, attempting to do so means an ECR cannot master any single skill. This is especially true for minorities (e.g., non-native English speakers) and those who must juggle doing science with little or no funding, while having other jobs or family commitments (Hooker, 2020). Learning a new language, applying for funding, or attending other commitments, leave limited time to acquire new skills to increase career prospects.

We are certainly not arguing candidates who are not sufficiently qualified should be hired over a person with demonstrably more experience and knowledge. We are also not saying scientists should not seek to gain knowledge of fields outside of their area of expertise. We do argue that while knowledge about seemingly unrelated topics may be of significant value, becoming an expert is a life-long activity and expecting researchers to be themselves "multidisciplinary" (i.e., experts in a range of disciplines) can have detrimental consequences for the scientific endeavour as well as for researchers themselves.

SOCIAL SKILLS

> "*With me, though, there is no external sign that I am conversationally handicapped. So folks hear some conversational misstep and say, 'What an arrogant jerk!'*" – John Elder Robinson, 2008, Look Me in the Eye: My Life with Asperger's.

Science communication training courses focus on a range of topics such as writing scientific manuscripts, speaking to policy makers or the media, and engaging with the general public[6]. These activities require skills in social communication, which include skills in using language, changing language accordingly when changing audience, and being able to follow communication rules (e.g., taking turns to speak, making eye contact). Social communication skills develop naturally as we grow older and can be enhanced with training; however, some children (up to 7.5%; Ketelaars et al., 2009) suffer from social communication disorder, which are comorbid with other conditions such as autism and attention deficit/hyperactivity disorder.

People with social communication disorder have difficulties during social interactions and to communicate with others, as they have difficulties understanding social rules, such as when it is their turn to speak or how to continue with the topic of conversation. These difficulties, however, need not to be reflected in other activities such as writing a scientific manuscript, which is a form of communication, and a crucial one for scientists and ocean conservationists.

There is increased recognition of neurodiversity in academia and elsewhere; however, all scientists are encouraged or forced to engage in science communication *via* different channels, some even suggesting that science communication should be rewarded for career advancement[7]. This position ignores the difficulties neurodiverse people may face regarding social communication,

[1] https://theoceancleanup.com

[2] https://www.theatlantic.com/science/archive/2019/01/ocean-cleanup-project-could-destroy-neuston/580693/(accessed April 11, 2020).

[3] https://www.deepseanews.com/2019/02/the-ocean-cleanup-struggles-to-prove-it-will-not-harm-sea-life/(accessed April 11, 2020).

[4] https://theoceancleanup.com/updates/the-ocean-cleanup-and-the-neuston/ (accessed April 11, 2020).

[5] https://www.theguardian.com/environment/2019/oct/03/ocean-cleanup-device-successfully-collects-plastic-for-first-time (accessed April 11, 2020).

[6] https://www.unavco.org/education/professional-development/science-communication/science-communication.html (accessed October 16, 2020).

[7] https://watershednotes.ca/2020/01/29/how-should-we-reward-scientists-who-do-scicomm (accessed May 16, 2020).

and indirectly values social skills and charismatic individuals. Rewarding specific social skills constitute hidden discrimination of neurodiverse conservationists both for promotion as well as in hiring practices, affecting especially ECR who have not yet built a professional network.

Appropriate behavior and use of language are crucial to building a welcoming environment; however, charismatic individuals can be problematic too[8]. One of the most famous examples of how charismatic scientists can hinder scientific advancement is Prof. Neils Bohr. Bohr was a Danish Nobel laureate who made significant contributions to particle physics. However, he also believed that the weirdness of particles' behavior says nothing about reality. He was a highly influencial character who actively stopped scientists from working on understanding the reality behind particle physics, even to this day, due to his charming, enchanting personality (Becker, 2018).

In the following sections, we will discuss a series of conditions and factors that are often ignored in academia but can impair social communication skills, and the potential consequences of doing so. We intend to highlight academics suffer from these, but not to suggest they do so exclusively. We recognize these factors are many and wide, but expand on those we are more familiar with because of our personal experiences with them or those of people we know.

Autism Spectrum Disorder and Mental Health

> "The worst part of having a mental illness is that people expect you to behave as if you don't" - Joker (2019).

The two diagnostic criteria for autism spectrum disorder (ASD)[9] are social communication deficits and repetitive behaviors, including a spectrum of traits. Spectrum means not everyone diagnosed with ASD has the same traits or the same level of severity, and while some require constant support others can live independent lives (Lord et al., 2018). Typical traits include little or no eye contact, having strong interest in topics, objects, or people, strict routines, dislike of physical contact, difficulties understanding sarcasm, and reduced emotional empathy (Lord et al., 2018; Shah et al., 2019). Furthermore, many conditions are usually co-occurring with ASD, including gender dysphoria, depression, anxiety, and other mental illnesses (Baldwin and Costley, 2016; Heylens et al., 2018; Lord et al., 2018).

Reduced emotional empathy can also be present in non-ASD people due to suffering from alexithymia (Kinnaird et al., 2019), a condition by which a person cannot recognize their own emotions and usually describe them based on physical symptoms (e.g., stomach discomfort). Alexithymia is co-occurring with ASD in nearly 50% of ASD cases (compared to 5% in neurotypical people; Shah et al., 2019). Reduced empathy, in both autistic and non-autistic people, can lead to awkward moments or comments that can be interpreted as tactless or offensive. This may complicate working relationships, especially teamwork.

Early career researchers are in a more precarious conditions compared to senior scientists, not just regarding job security and opportunities for funding and collaborations, but also about their own knowledge and skills. Therefore, ECR with any of the conditions mentioned above will be specially impacted in an academic environment that expects them to master social communication skills to advance in their professional career. The pressure could discourage them from pursuing a scientific career but also lead to or worsen mental health issues of those already in academia.

The two most common mental health issues reported in academia are depression and anxiety (e.g., Sarokhani et al., 2013; Evans et al., 2018). The prevalence of anxiety and depression in graduate students is significantly higher than in the general population, with transgender and gender non-conforming students having the higher proportion (55 and 57%), followed by females (43 and 41%), and males (34 and 35%), respectively (Evans et al., 2018). On the other hand, those with a healthy work-life balance reported significantly lower levels of anxiety (24 vs. 56%) and depression (21 vs. 55%) (Evans et al., 2018). These issues may be present before or be unrelated to the academic environment (e.g., money and romantic relationship problems), but can be triggered or worsened in the usually stressful, unstable, and competitive environment (Furr et al., 2001; Gilbert et al., 2009). Further, Furr et al. (2001) found that the number of students who experience suicidal thoughts or attempt suicide might be significant, representing 9 and 1% respectively.

Other disorders and mental health issues academics may suffer include bipolar, personality, trauma-related, eating, and substance abuse disorders. Fear of stigmatization may lead academics to not disclose these conditions and thus not receive appropriate support. This is especially impactful for ECR who do not yet have a professional reputation and financial security to help them overcome the potential backlash of these conditions coming to light.

"If I Can Do It, Everyone Can". . . or Not

Some readers may think of famous science communicators with disabilities or speech impairments, such as Prof. Stephen Hawking, and think "well, if they could do it, everyone can!" However, not only he had financial and emotional support, he also had personality traits that helped him overcome the emotional turmoil that meant living with such physical disabilities. While the saying may be well-intended, in reality it ignores the many external and personal factors that might impact both mental health and productivity (Hooker, 2020). Advocates of the "everyone" should engage in science communication efforts rarely consider these, sudden or persistent, factors. Persistent factors include not being a native to the country they live in (e.g., marked cultural differences); lack of financial or emotional support from family members and/or friends; emotionally or physically abusive family members, love partners,

[8] https://animalecologyinfocus.com/2018/07/11/women-in-science-and-abuse-of-power/(accessed October 16, 2020).

[9] Note: some people prefer to be called *autistic person* while others prefer *person with autism*

and/or friends; no or limited funding or income. Moreover, researchers can also suffer from chronic conditions that may alienate them, including stutter, echolalia and other speech disorders, malformations, skin diseases, and trauma due to sexual abuse during childhood.

Unexpected circumstances that can lead to significant changes in everyday life include natural disasters and global emergencies such as economic crises and pandemics (e.g., COVID-19 crisis), political developments of the country of residence (e.g., authoritarian regimes, coup d'état). Other unforeseen scenarios include accidents, sexual assault, sudden death of loved ones, and friends or family members suffering from developmental or terminal illnesses. These circumstances not only can lead to post-traumatic stress disorder or trigger a relapse due to past traumas, but also impair social communication skills, crucial for building a professional network.

These factors impact ECR especially, as they lack a support network that can help them climb the professional ladder. Hence, realizing ocean conservation goals calls for a collaborative environment to draw on individuals' strengths.

COLLABORATION AND WHY IT MATTERS

Two key components of ocean conservation are science communication and education, and thus it is increasingly expected that scientists engage in these activities on social media, and *via* blogs or other forums. Conservationists are offered science communication courses for non-experts, which typically last a few days to a week, and where attendees are trained in a different set of skills for this purpose. As discussed in previous sections, such basic training is likely not suitable for individuals with social communication difficulties, especially those with difficulties in understanding communication rules.

There is a large body of evidence showing that communication (both how the message is conveyed and interpreted) is a complex process affected by a myriad of factors. Two influential books on this topic are *Nudge: Improving Decisions About Health, Wealth, and Happiness* (Thaler and Sunstein, 2009) and *Thinking fast, and slow* (Kahneman, 2011). Broadly speaking, there is always a stimulus the audience has been exposed to (e.g., room color) that influences message perception (Kahneman, 2011). This is known as priming. And there is always a structure in the message, known as framing, influencing message perception. For example, doctors are more likely to recommend an operation if 90% of patients survive than if 10% die, despite the numbers being the same (Tversky and Kahneman, 1981). Learning how to frame and prime a message is crucial, yet not an easy task, as there are endless factors that cannot be controlled affecting communication with an audience, including education level, beliefs, confirmation bias, last song they listened to, when was the last time they ate, how spicy the last meal was, how long they have been awake for, previous experience with the topic, and a long etc. (Thaler and Sunstein, 2009; Kahneman, 2011).

It is understood that, in topics such as psychology, legislation, and statistics, expertise is not acquired *via* basic training. We argue the same holds true for science communication. This is especially important given many researchers have difficulties in social communication, such as those with ASD, which are attending university in higher numbers (MacLeod and Green, 2009) due to an increase in support and better understanding of the topic (Robertson and Ne'eman, 2008). In light of this, we argue that, to achieve the best possible results, we should engage in multidisciplinary collaborations also when it comes to communicating with non-expert audiences (e.g., policy makers), instead of seeking to train all scientists (Cooke et al., 2017). Multidisciplinary collaborations are the backbone of science (Esteban et al., 2014; Parsons et al., 2015; Scans III, 2017; Carlén et al., 2018).

While many scientists are skilled at science communication, they like it, and are effective at it, we argue that, given the factors discussed above, not all conservationists (especially ECR) should be expected to do it as some suggest (Cooke et al., 2017). Not everyone has communication skills or can benefit from a basic course, therefore they should not be forced to do so. It can be stressful or lead to anxiety and impact their professional career, especially if science communication efforts are to be rewarded, which effectively punishes those who cannot engage.

Further, attempting science communication with basic training can lead to unexpected consequences. For example, in 2014, a group of scientists reported that a methane compound could be used to target mitochondria in cancer cells (Le Trionnaire et al., 2014). Despite the efforts of the press office, journalists reported that smelling flatulence could cure cancer and recommended the practice[10]. While such an extreme case is not expected to happen in the context of ocean conservation, there is plenty of opportunities for scientific findings to be misinterpreted (López-Escardó et al., 2018)[11].

Established scientists and conservationists may have extensive experience in communication attempts *via* publications, grant applications, and other forums, giving them the opportunity to identify their strengths (e.g., conveying their ideas at scientific gatherings after substantial rehearsal) and weaknesses (e.g., improvising). ECR however, have not yet had these opportunities and exposing them to interactions with a non-expert audience when they have difficulties doing so can affect their career prospects (e.g., inappropriate engagement in social media) and how the public perceives science. "Any" message is not better than no message at all.

CONCLUSION

There is an increasing demand in the field of ocean conservation to implement changes to accommodate a pressing need

[10]https://www.theguardian.com/science/brain-flapping/2014/jul/14/silent-not-deadly-how-farts-cure-diseases (accessed November 6, 2020).

[11]https://www.ibe.upf-csic.es/news/-/asset_publisher/PXTgqZXxlocA/content/id/213934032/maximized#.X6Wji9BKgmI (accessed November 6, 2020).

to communicate science to the general public, but there is also a need to accommodate new scientists and ocean conservationists who can make invaluable contributions to scientific advancements, regardless of their social and communications skills. While training in a range of fields (i.e., multidisciplinary training) is crucial to gain a general understanding of the many factors impacting ocean conservation, it is not, and should not be, an alternative to seeking expert input from other fields. Instead, we should foster collaboration with existing experts in all fields related to conservation, including experts in national and international legislation, as well as those related to behavioral change, such as psychology, evolutionary behavioral sciences, and science communication.

Throughout this manuscript we have highlighted many factors affecting conservationists, especially ECR, which are regularly ignored, and the ways they can contribute to developing mental health issues. We have shown that the expectation of engaging in extracurricular activities can have negative consequences for researchers, especially those with social communication difficulties. "Walk in my shoes" type of workshops for conservationists of all backgrounds could be crucial for raising awareness of the factors discussed in this manuscript. Simultaneously, ECR with communication difficulties could benefit from attending workshops early in their career to identify their strengths, weaknesses, and interests in relation to social communication, in a judgment-free environment. Through collaborations, we can effectively draw on the more specialized skills of various people. Building an inclusive scientific community for ECR, therefore, calls for seeing diversity of skills, thoughts, and personality traits as its strength.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

MC conceived the idea. MC and LS-P drafted the manuscript and aided in finalizing it. Both authors contributed to the article and approved the submitted version.

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Scenario-Based Approaches to Change Management in Fisheries Can Address Challenges With Scale and Support the Implementation of an Ecosystem Approach to Fisheries Management

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The Ecosystem Approach to Fisheries (EAF) management, recognising complexity, aims for the holistic, sustainable management of fisheries to promote healthy marine ecosystems and sustainable livelihoods. Effective implementation of the EAF has been problematic as we continue to grapple with issues of scale, knowledge integration and meaningful stakeholder engagement. Scenario-planning approaches in marine social ecological systems (SES) can address some of these challenges. Using systems-thinking, scenario-planning presents the opportunity to address challenges simultaneously at different scales of interaction by addressing the needs at smaller and larger decision-making scales. We here present a prototype scenario-based approach in which we used structured decision-making tools (SDMTs) in an iterative and interactive research process with marginalised stakeholders in a small-scale fishery in South Africa's southern Cape. Using this approach presented an opportunity for fishers to consider pathways for future responses to change while enhancing personal and local adaptive capacity. At the same time, these marginalised fishers were provided with an important opportunity to freely air their views while engaging with tools new to them. The process did not only benefit fishers, but also provided valuable insights into how they view and experience their marine SES. The use of these tools has provided a means to integrate different knowledge streams, identifying ways in which challenges presented by scale in SES is better addressed. As a next step in the prototype development, expansion to more diverse stakeholders in the biogeographical region relevant for this fishery is recommended. We highlight how this approach can contribute to multi-level governance. When considering EAF implementation, we highlight how engaging marginalised stakeholders need not mean losing the reproducible, transparent processes required for modern management. Lastly, we discuss how multi-scalar flow of information could improve the implementation of an EAF in a developing society, such as that of South Africa.

Keywords: ecosystem approach to fisheries management, scenario-planning, fishing communities, scale, marine social-ecological systems

INTRODUCTION

Fisheries, complex adaptive marine social-ecological systems (SESs), already beset by inherent complexity, are becoming increasingly uncertain due to escalating anthropogenic pressures on a global scale (e.g., Tegner and Dayton, 2000; Jackson et al., 2001; Scheffer et al., 2005; Halpern et al., 2008; Hoegh-Guldberg and Bruno, 2010; Poloczanska et al., 2013). This makes it more difficult for those who depend on fisheries for livelihoods and manage fishing activities to make proactive, informed decisions at various temporal scales (e.g., Berkes, 2003; Garcia and Cochrane, 2005; Jentoft and Chuenpagdee, 2013; Link et al., 2017; Jarre et al., 2018).

Recognising the complexity of marine SESs has given rise to research that seeks to incorporate approaches to management which take wider, system-based views (e.g., Garcia et al., 2003; Garcia and Charles, 2007; Ommer and Team, 2007; Haapasaari et al., 2012). Such approaches seek to cross disciplinary lines, perceptions, forms of knowledge and scales (Degnbol and McCay, 2007; Garcia and Charles, 2007, 2008; Ommer and Team, 2007). The ecosystem approach to fisheries management (EAF) - a widely adopted, inclusive management approach - strives to promote long-term sustainability in fisheries through management interventions that are bottom-up, systematic and participatory (FAO, 2003; Garcia et al., 2003). The question that arises is: are there inclusive methods that can be applied at the smallest scales of operation of a fishery, which can at the same time also inform large-scale decision-making to promote management approaches such as an EAF?

To address this central question, we should consider reframing approaches used in fisheries management and research to explore new (or different) methods and approaches. To this end, several authors advocate for the use of scenario-planning in marine SES to address challenges with the effects of long-term system change, uncertainty and complexity (e.g., Jarre et al., 2013; Daw et al., 2015; Maury et al., 2017). Scenario planning commonly takes place in global assessments such as the IPCC assessments of climate changes and the IPBES ecosystem assessments (e.g., IPCC, 2014; IPBES, 2016). Scenario-based approaches provide us with an opportunity not only to reframe some of the challenges (problems) encountered in marine SES but also offer an alternative to forecasting dynamically to consider future impacts and consequence of change. In South Africa, large scale scenario planning exercises, based on transformative scenario planning (TSP), include the Mont Fleur scenarios (charting the course or post-Apartheid development – see Kahane, 1992) and the Vumalena land reform scenarios[1], although these are all largely terrestrial.

Scenarios are an appropriate method for dealing with uncertainty within the entire SES. Uncertainties in SESs are generally difficult to quantify as some key drivers are unpredictable and change typically is non-linear and complex; human response actions to forecasts tend to be reflexive, and the system may change faster than the forecasting models can be recalibrated particularly in turbulent periods of transition (e.g., Walker et al., 2002). At smaller scales - of the individual, group of fishers or town – it is a useful tool for capacity building and social learning (Quay, 2010). As such, these approaches present the opportunity to address challenges simultaneously at different scales of interaction (e.g., Berkes, 2006; Cash et al., 2006) by addressing the need of the individual and/or household while informing larger scale policy processes such as the EAF. While scenarios based on forecasts for South African fisheries have been conducted (e.g., long-term adaptation scenarios for South Africa (DEA, 2013), participatory scenario planning approaches together with fishers have not been introduced or initiated as a decision-making or change-management tool, nor has participatory scenario planning been employed to inform governance or the implementation of an EAF at the national scale. We therefore embarked on a case study to assess the feasibility.

This paper focuses on the overarching scenario-based[2] approach used in the case study. We draw on results published independently (Gammage, 2019; Gammage et al., 2019; Gammage and Jarre, 2020; Gammage et al., in review[3]) to outline the philosophical approach taken in developing this interdisciplinary approach, operationalised in a developing context in support of improving the human dimension of EAF implementation in South Africa's southern Cape linefishery. We proceed with a brief overview of some concepts that are pertinent to the approach. We describe the over-arching methodology and results of the underlying case study (as published) before presenting a reflection on the process in relation to challenges with scale in managing human activities in the southern Cape linefisheries. We discuss the contribution made toward promoting the EAF implementation in South Africa, together with recommendations for future research.

THE NEED OF COHESIVE APPROACHES TO ADDRESS MULTIPLE OBJECTIVES IN MARINE SES

Global Policy Frameworks for Sustainable Fisheries Management in Small-Scale Fisheries

Adopting SES perspectives is integral to ecosystem-based management approaches, offering the opportunity to better integrate natural and human-social system components in pursuit of sustainability. Globally, the need for sustainable

[1]https://www.landreformfutures.org/

[2]The scenario-based approach outlined here, follows the principles of a transformative scenario planning (TSP) approach (see Kahane, 2012a,b; Kahane and Van Der Heijden, 2012). A participatory scenario planning approach, backcasting techniques are used to create normative scenarios which explore possible futures. These scenarios are exploratory and speculative (Wiebe et al., 2018) and are designed for all participants (or actors in the system) to work cooperatively and creatively to get a complex problem untangled and moved forward (Kahane, 2012a,b).

[3]Gammage, L. C., Jarre, A., and Mather, C. (in review). Failing to plan is planning to fail – lessons learnt from embarking on a scenario-based approach to change in a small-scale fishery. Submitt. *Ecol. Soc.*

futures and oceans are highlighted by the adoption of multi-national policy frameworks such as Agenda 2030[4] for sustainable development which recognises the need for systems thinking to address modern societal problems (UN, 2015). The importance of fisheries is highlighted by 'SDG 14 – Life below water' although fisheries make important contributions to the attainment of other SDGs. By implication, achieving the main goals of Agenda 2030 for all fishers and communities is a requirement (FAO, 2018).

The Food and Agriculture Organisation of the United Nations (FAO) provides the 'umbrella' policy goals that can facilitate integrative and innovative approaches for global fisheries management. The Code of Conduct for Responsible Fisheries (CCRF)[5] (FAO, 1995), is becoming increasingly relevant as global fish consumption increases (FAO, 2018). Developed as a compliment to the CCRF, the small-scale fishery (SSF) guidelines (FAO, 2015) provide a policy framework for the attainment of sustainability of SSFs. Not legally binding, instruments such as the SSF guidelines provide context and frameworks for achieving the SDGs. With greater emphasis on the role that fisheries play as sources of livelihoods, places where cultural values are expressed and as a buffer for shocks for poor communities; further development of the understanding of SSFs is required to support the commitments to SSF development and SDGs (FAO, 2015, 2018).

Ecosystem Approach to Fisheries Management (EAF)

The recognition and emphasis placed on the social (human) dimension in marine SESs are reflected in an ecosystem approach to fisheries management (EAF). The EAF[6], built on the principles of Sustainable Development, is a broader framework which aims for inclusive and sustainable management, accounting for the impacts that other sectors have on fisheries and *vice versa* (FAO, 2003). EAF was formally recognised as a fisheries management goal by the Reykjavik Conference on Responsible Fisheries Management in the Marine Ecosystem in 2001. The commitment to the EAF was restated at the 2002 World Summit on Sustainable Development (WSSD) by signatories, which included South Africa, to the Johannesburg declaration (WSSD, 2002). Despite the publication of the 'Guidelines for the implementation of the EAF' and the FAO recommending steps for the implementation and development of an EAF management plan (FAO, 2003; Garcia and Cochrane, 2005), the successful implementation of EAF has been challenging (also see Cochrane et al., 2015).

Moving toward more inclusive approaches such as the EAF requires multiple stakeholders, disciplines and objectives that see fisheries as SESs (Cochrane and Garcia, 2009; Berkes, 2012; Ommer et al., 2012) along with management structures that match scales, complexity, and interdependencies of SESs (Ommer et al., 2012). However, current approaches for implementing an EAF tend to be used in a way that expands traditional management paradigms rather than changing them. This evolutionary approach to implementing EAF is inadequate in dealing effectively with fisheries' multiplicity of issues and complexities, suggesting a more revolutionary approach is required (Berkes, 2012).

EAF Implementation in the Southern Benguela

In South Africa, the Marine Living Resources Act (No. 18 of 1998, MLRA) espouses the concept of an EAF, although significant gaps and weaknesses exist. Although progress has been made in understanding the ecological context, it has proven to be more difficult and complex to integrate social components (Shannon et al., 2010; Sowman et al., 2011). While some progress has been made toward the implementation of an EAF, especially in the country's larger industrialised fisheries, more sound and comprehensive policy and legal frameworks continue to be required for long-term fisheries governance in South Africa's fishing sectors (Cochrane et al., 2015).

Noteworthy progress toward implementing an EAF in South Africa include the agreement on sets of comprehensive management objectives through ecological risk assessments (ERAs) (Shannon et al., 2006; Nel et al., 2007; Petersen et al., 2010), further development of the ERA methodology to measure progress toward achieving the objectives (Paterson and Petersen, 2010), spatial approaches (Sink et al., 2011) and methodology to evaluate effects of different management strategies in system contexts (Shannon et al., 2010, 2020; Watermeyer et al., 2016; Weller et al., 2016; Cooper and Jarre, 2017a,b; Ortega-Cisneros et al., 2018).

Some progress has been made in the human dimensions of an EAF, with South Africa's southern Benguela ranking in the middle globally (Bundy et al., 2016). Research into the human dimension of the marine SES often places the focus on fishing communities, focussing (amongst others) on research into the human and political-economic dimensions of sustainable fishing, specifically in SSFs (e.g., Isaacs, 2012, 2013), assessments on the socio-ecological vulnerability and development of adaptation strategies to climate change in the Benguela Current Large Marine Ecosystem (BCLME) (e.g., Sowman and Cardoso, 2010; Sowman and Raemaekers, 2018; Sowman, 2020), social-ecological indicators for SSFs and drivers of poverty in fishing communities (e.g., Hara, 2014) and governance approaches in relation to high-value species such as abalone and lobster (e.g., Raemaekers, 2009). The impact of marine protected areas on some coastal communities is

[4] Agenda 2030 pursues the goal of achieving a just and sustainable world where the fulfilment of human potential contributes to shared prosperity (UN, 2015; CEB, 2017). The Sustainable Development Goals (SDGs) affirm the commitment of placing equality and non-discrimination at the centre of Agenda 2030.

[5] The Code of Conduct for Responsible Fisheries (CCRF) is a framework for the implementation of the principles of sustainable development in fisheries (FAO, 1995).

[6] Built on the principles of Sustainable Development, the EAF "strives to balance diverse societal objectives, by taking into account of the knowledge and uncertainties of biotic, abiotic and human components of ecosystems and other interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries" (Garcia et al., 2003) and specifically emphasises stakeholder engagement in management (FAO, 2003; Garcia et al., 2003; Wilson, 2006).

being researched (e.g., Sunde and Isaacs, 2008; Sowman et al., 2011; Muhl, 2019), and various newer studies enhance our understanding of the history of, and social dynamics in western Cape fishing communities under global change (e.g., Isaacs, 2013; Norton, 2013; Visser, 2015; Duggan, 2018; Duggan et al., 2020). The working conditions of compliance inspectors in SSF were researched by Norton (2014) and findings were synthesised in an assessment tool for the governance dimension of the EAF in South Africa (Norton and Jarre, 2019).

RAPID PROTOTYPING OF THE SCENARIO-BASED APPROACH USING A CASE-STUDY

The Southern Cape Linefishery System

The southern Cape line fishery operates in the coastal waters in the inshore area of the central Agulhas bank (**Figure 1**). Part of the southern Benguela, one of four sub-(eco)systems of the Benguela Current Large Marine Ecosystem (BCLME) (Hutchings et al., 2009; BCC, 2013), the Agulhas Bank subsystem overlaps with one of the climate change hotspots identified by Hobday and Pecl (2014). Various natural and anthropogenic drivers result in various multi-scalar spatial and temporal changes (Jarre et al., 2013, 2015; Blamey et al., 2015), making it challenging to establish the exact nature of the drivers of change and their interactions (Moloney et al., 2013). Long-term effects of anthropogenic climate change are inevitable and will add to inherent complexity, challenging both fishery resources and resource users (Jarre et al., 2013; Gammage et al., 2017a,b).

The South African (hand-)linefishery is a boat-based, multi-user, multi-area and multi-species fishery that conducts mostly day trips ranging from six to eight hours. The primary target species of the fishery is silver kob (*Argyrosomus inodorus*) (Blamey et al., 2015; Griffiths, 2000), other species targeted in the absence of kob include silvers/carpenter (*Argyrozona argyrozona*), redfish (like red roman, *Chrysoblephus laticeps*) and various species of shark. In recent years, increasing resource scarcity, variability in physical systems and policy uncertainty has plagued this fishery (Gammage, 2015; Gammage et al., 2017a). The crew component – small-scale fishers who act as crew in the commercial linefishery – are the focus of this study. This group of fishers, marginalised under South African Apartheid laws, remain designated as 'previously disadvantaged'. Generally, these fishers are poor, not well (formally) educated and highly vulnerable to change (Gammage et al., 2017a, 2019; Martins et al., 2019). Due to their perceived inability to participate meaningfully in formal decision-making processes, they often remain excluded (also see Isaacs, 2006; Sowman, 2006; Sowman et al., 2014). They live in rural, semi-rural and peri-urban areas (**Figure 1**) with direct and indirect access to the ocean (Gammage et al., 2017a).

In South Africa small-scale fisheries are managed through the Small-Scale Fisheries Policy (Act No. 474 of 2012) (DAFF, 2012). Adopting a people-centred approach to management, and recognising the important role played in poverty alleviation, the SSFP seeks to address sustainable development, empowerment, and inequality for small-scale fishers (Sowman et al., 2014). The implementation of this policy (alongside the commercial handline fishing rights) has, however, been plagued with delays, with government being unable to successfully implement across South Africa since promulgation in 2012. Hamstrung by the non-allocation of long-term fishing-rights, challenges associated to policy and regulation remain 'top of mind' (Gammage et al., 2017a, 2019; Gammage and Jarre, 2020).

In addition to the regulatory challenges, the southern Cape linefishery is experiencing challenges with resources scarcity, increasing variability in physical systems and policy uncertainty (Gammage et al., 2017b, 2019; Martins et al., 2019). For fishers to secure sustainable livelihoods in future, these communities will need to respond to change more proactively, engaging in activities that are based on informed decisions (Gammage, 2015; Gammage et al., 2017b).

Using Structured Decision-Making Tools (SDMTs) to Include Marginalized Fishers Into Management Discourses

We used systems-thinking[7] to implement a prototype scenario planning approach developed with small-scale fishers who operate in South Africa's southern Cape linefishery. After establishing the drivers[8] of change from the fishers' perspectives using qualitative (see Gammage, 2015; Gammage et al., 2017a) and quantitative (see Gammage et al., 2019) survey methods, we used structured decision-making tools (SDMTs, specifically causal mapping and Bayesian belief networks for problem structuring) to contribute to a more complete system description, thereby adding to the knowledge base on drivers of change (Gammage and Jarre, 2020). As the next step, scenario stories were generated in an interactive and iterative process (Gammage, 2019; Gammage et al., in review). The overall approach provides a prototype which can be expanded to include more diverse stakeholders from various decision-making scales (**Figure 2**).

Firstly, we describe the broad findings of each component of the overarching approach (**Figure 2**) as they relate to the SDMTs outcomes (product). Detailed methods and results for each component have been published elsewhere (Gammage et al., 2019; Gammage, 2019; Gammage and Jarre, 2020; Gammage et al., in review). The process-related results are provided in section "Addressing Challenges Associated With Scale" as a reflection on challenges associated with scale as they relate to this case study. Details of the overarching methodology

[7] Arnold and Wade (2015: 675) define systems thinking as "a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects. These skills work together as a system."

[8] The terms 'stressor' and 'driver of change' were often used synonymously throughout this research. The term 'stressor' was specifically used in the interactions with the fishers as the meaning was universally understood. For the purposes of this research the terms stressors and drivers of change are "broadly defined to include a wide range of factors, including micro-and macro level social and environmental changes. . ..of which impacts can manifest at individual household and community level as gradual or sudden shocks. . ." (Bunce et al., 2010, 409).

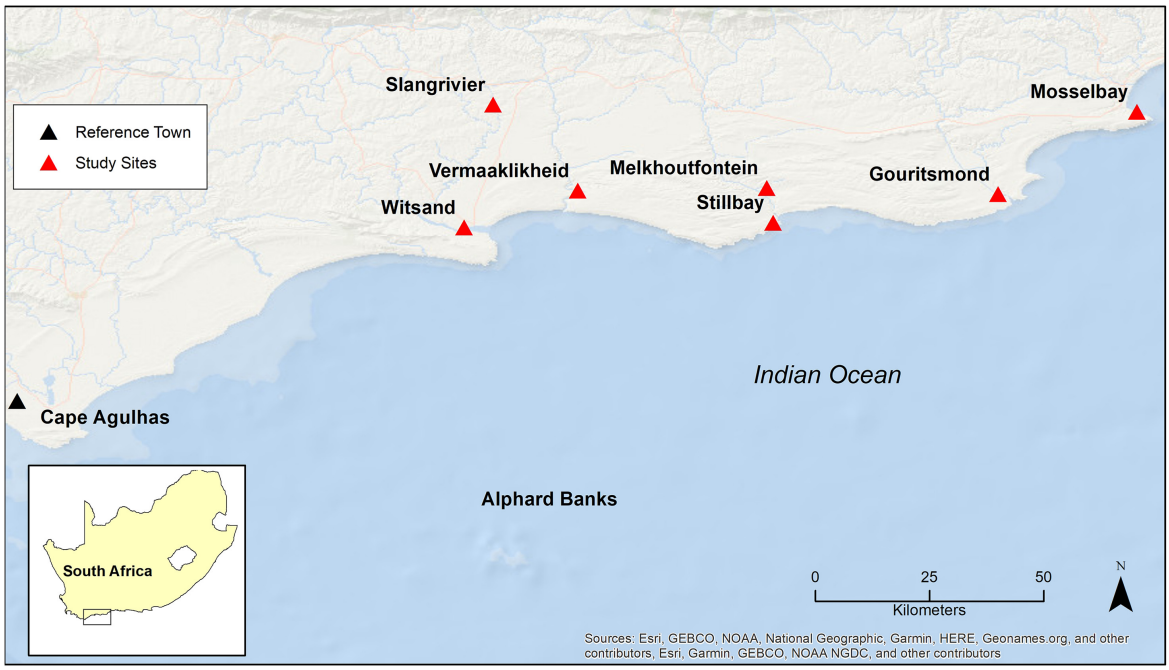

FIGURE 1 | Map of the research area. Mossel Bay - large urban centre situated on the coast; Bitouville - situated next to Gouritsmond at the Gourits River mouth; Melkhoutfontein - situated approximately 8 km from Still Bay on the coast, Vermaaklikheid - 7 km from the coast as the crow flies, but fishers often travel 47 km by road to launch in Still Bay; Slangrivier - situated 26 km inland as the crow flies, fishers travel 38 km by road to Witsand where boats are launched into the Breede River mouth.

of the approach and the data sources used are provided in **Supplementary Appendix A**.

Component 1: Stressors That Lead to Change

This component, which forms the basis for scenario-based approach is based on previous research in the southern Cape linefishery (Gammage et al., 2017a, 2019; Martins et al., 2019). Based on this independently published research, we outline salient findings to provide context. These authors describe stressors (drivers of change) in the linefishery system. Gammage et al. (2017a) identified a thematic framework of these drivers (**Figure 3**), dividing them into major stressors (mentioned by 80% and above of participants), mid-range stressors (50% and above, but less than 80%) and minor stressors, (mentioned by less than 50% of participants). Major stressors comprised policy and regulation, climate variation and other fishing sectors; mid-range stressors comprise policy enforcement, economics (capital), "political" issues and socio-economic issues, and minor stressors comprise the geography of the area, infrastructure, social factors, and lack of knowledge. This research has shown that although these stressors are consistent throughout the research area, the poorer fishing communities tend to cope and react rather than proactively adapt, impacting adaptive capacity (Gammage et al., 2017b).

Gammage et al. (2019) argued that the lack of internal variation in responses makes a case for area-specific management in this fishery, echoing findings by Blamey et al. (2015) who argue that spatialised management approaches of the linefish stock at the scale of the southern Cape biogeographic region would be more appropriate than the current practice. At the same time, taking a more inclusive view of the linefishery system also highlighted the complexity and associated uncertainty of the interactions of, and between, these stressors. The same complexity and uncertainty made it difficult for fishers to apply risk-adverse decision-making strategies. In this case, determining principal drivers of change was a first crucial step in this scenario-based approach.

Component 2: Causal Mapping to Structure Complexity

A set of causal maps, implemented across the research area, built on the thematic framework and was further refined by an iterative participatory process with fishers (Gammage and Jarre, 2020). Here we present a broad overview of the findings. The resulting, final causal map, constructed from inputs from all towns in the research area, are shown in **Figure 4** (also refer to Gammage and Jarre (2020) for more detail on the map). These maps highlight feedback loops and indirect interactions not immediately apparent from the previous, qualitative research (Gammage et al., 2017a). These causal maps helped fishers form a more complete picture of their fishery, including direct and indirect relationships between stressors and highlighting system complexity.

The successful implementation of the tool demonstrated the usefulness in showing complexity, together with the ability to easily integrate perspectives and knowledge from various sources

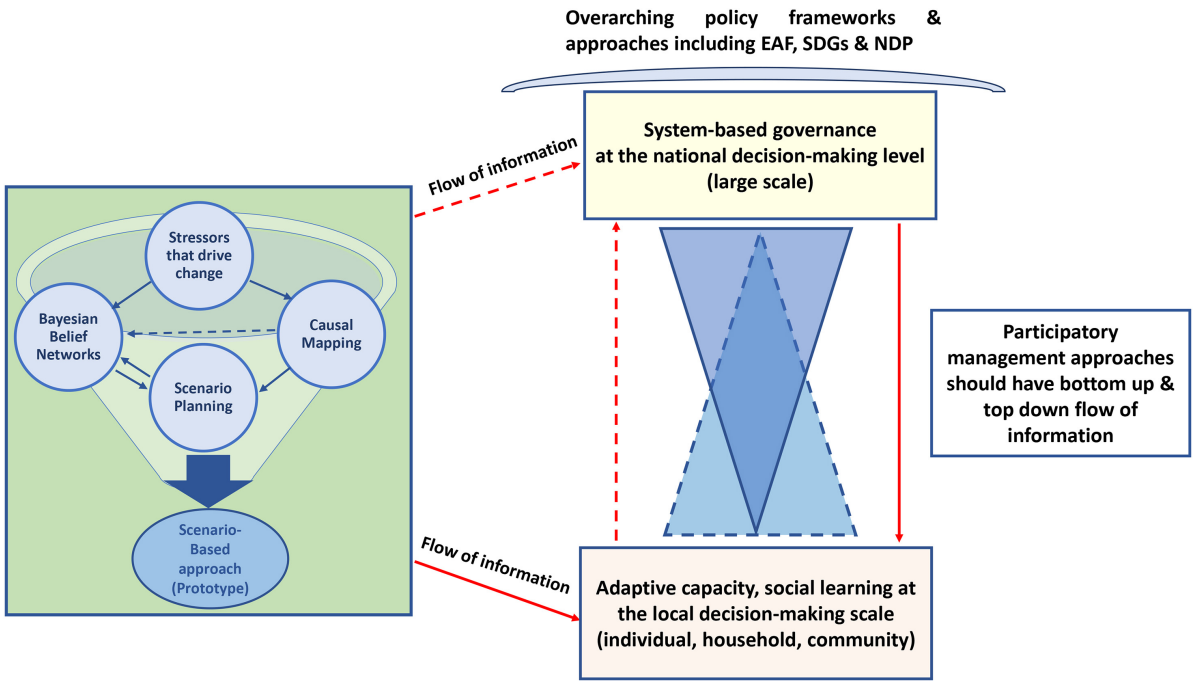

FIGURE 2 | Overall framing of the research. From left to right - this prototype scenario-based approach to management employs various decision-making tools to generate both quantitative and qualitative knowledge. For this case study (shown by the solid red lines which are 'flow of information'), the knowledge generated through the implementation of the tools contributes to capacity building (enhancing adaptive capacity) and more informed decision-making by the individual/household or community at the smaller scales of operation. While top-down interactions (scaling down) are functional in the current management paradigm (shown by the inverted triangle), practical mechanisms to facilitate bottom-up interactions are ill-defined or non-existent. The implementation of the approach identifies a method that facilitates the multi-directional flow of information (shown by broken lines) in the pursuit of the implementation of an EAF together with other over-arching policy goals such as Agenda 2030.

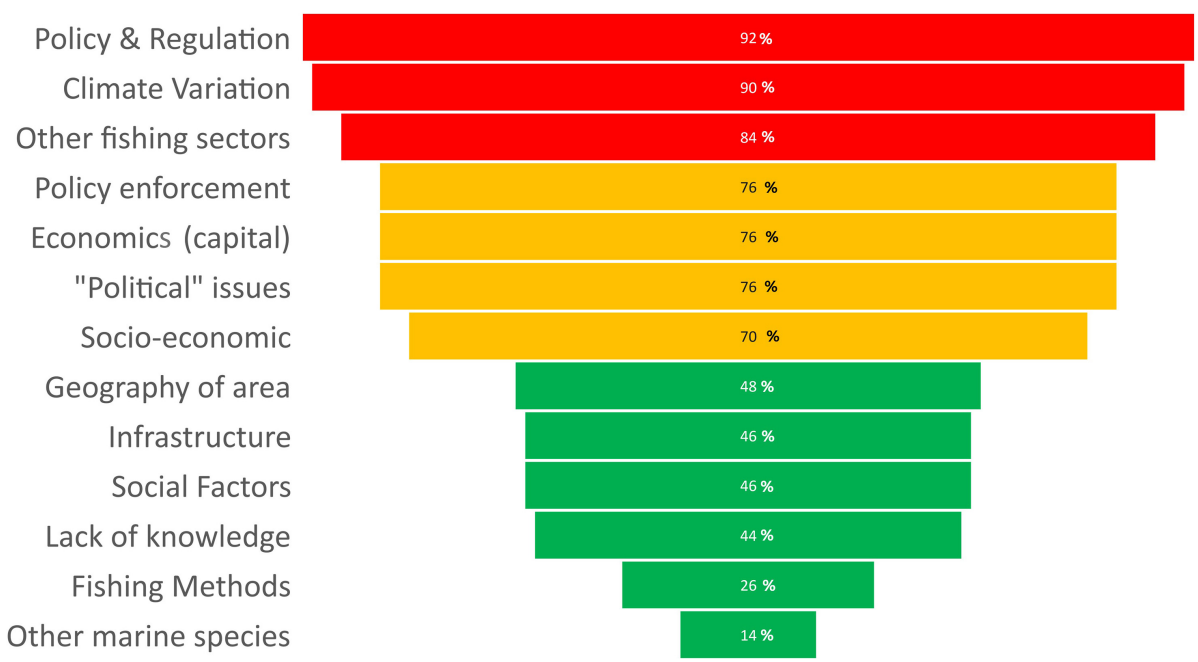

FIGURE 3 | Stressors identified be previous research carried out by Gammage et al. (2017a) and Gammage et al. (2019). The numbers are shown as percentages (%). The red colour depicts major stressors, the yellow – mid range stressors whilst the green shows the minor stressors.

(Gammage and Jarre, 2020). When considering challenges with scale, the parity in results depicting stressors with results from previous research suggested that geographic scale should not be considered above contextual (or conceptual) scale (also see Gibson et al., 2000) in management and decision-making contexts. For the southern Cape linefishery, this implies that management decisions should rather be made at an appropriate ecosystem scale (biogeographic region) (also see Blamey et al., 2015) as opposed to the currently defined linefish management zones.

Component 3: Bayesian Belief Networks to Capture Different Views on Relative Impact of Main Drivers

A prototype Bayesian Belief network[9] (BBN) (**Figure 5**) was constructed through a workshopping process that took place in the town of Melkhoutfontein (see Gammage and Jarre, 2020).

Insights into the drivers resulting from the construction process are consistent with those from previous research and the causal mapping. Sensitivity analyses of the BBN confirmed the high uncertainty in the system, across the various stressors relating to principal drivers (see Gammage and Jarre, 2020). Importantly, the BBNs presented the opportunity to combine different knowledge streams and data, whilst capturing the uncertainties that have arisen from discrepancies in individual views. Furthermore, through the iterative construction process, important space for dialogue was created where 'top of mind' concerns which often dominated the discourse, were addressed in a constructive forward-thinking setting. The importance of the findings in this context is that the tool, though abstract, was implementable with a group of disenfranchised fishers who would not normally be involved in such a development process. This prototype BBN is not yet suitable to inform decision-making, its value lies in the process around its construction. It created an important space for participants to engage with each other on difficult topics through mutual learning. The process demonstrates the value of continued engagement with fishers and other stakeholders to create enabling conditions such as spaces for active dialogue and learning (Gammage and Jarre, 2020) – a requirement for active participation of all stakeholders in a decision-making context.

The implementation of both the causal maps and the BBN have provided insights into how human dimensions of marine SES can be better integrated into an EAF in South Africa, by offering a possible methodological blueprint for future multi-stakeholder processes at larger scales of operation, while at the same time promoting mutual learning and capacity building at the local scale. The use of these tools allowed for the reframing of questions on familiar topics, thereby moving conversations beyond the superficial, standard responses toward a more positive forward-thinking and solution-driven space (Gammage and Jarre, 2020).

[9]"Bayesian Belief Networks (BBNs) are models that provide graphic and probabilistic representations of the relationships that exist amongst the variables within a parameterized system (Smith et al., 2018). The term BBN refers to an acyclic directed graph of probability distributions (Nicholson and Flores, 2011; Johnson and Mengersen, 2012)" – Gammage and Jarre, 2020:5

Component 4: Developing Stories of Multiple Future Scenarios

Scenario stories, using information gained from the same workshopping process used to derive the BBNs, were constructed for the town of Melkhoutfontein. The details of this component are being published independently (see Gammage, 2019 and Gammage et al., in review). Here we present a brief overview of the research and findings.

Centred on two key driving forces (KDFs) identified by participants – 'Access to capital' and 'Access to Marine resources (Rights)', the final stories were complemented by two more KDFs identified through the BBN sensitivity analysis – 'Climate change' and Fish availability,' which were subsequently used as a basis to build four scenarios for the town in 30 years' time. **Figure 6** presents an artistic depiction of these stories. The first story, 'Nothing much has changed,' closely follows the present conditions in the town. The second story, 'We will get there eventually,' is based on a possible future where fishers do have access to marine resources, but they lack access to funds, curtailing their options and resulting in quite subtle differences between this and the first story. The last two – more positive - stories, 'The going is good' and 'The future is bright,' result from more positive politico-economic scenarios. Interestingly and significantly, the participants did not imagine futures where the individual's riches were foregrounded, but rather built futures where the increased money in the town is used to improve the town for everyone in the community, e.g., through increased employment opportunities in small businesses, through the development of a business district, improvement of public amenities and infrastructure and the development of tourism (Gammage, 2019; Gammage et al., in review).

In their current form these scenario stories - developed at a small scale and with a homogenous group of stakeholders - are most valuable to the fishers of Melkhoutfontein. This is due to the mutual learning that took place, the knowledge co-creation and the development of a systems view. As with the SDMTs, the process created the space to reflect on interactions in the marine SES and the implications of changes on the possibilities of the future under certain conditions, sometimes forcing fishers to contrast and consider more diverse issues at scale. From our results, there is no doubt that scenario planning can provide opportunities to address some of the challenges associated with multi-scalar governance in marine SESs. The promotion of learning and capacity building is not only valuable at the level of the individual or community, but also an important step in eventually building the capacity for disenfranchised stakeholders to meaningfully engage in larger scale scenario-planning processes (Gammage, 2019; Gammage et al., in review).

Addressing Challenges Associated With Scale

In implementing the overall approach, important insights have been gained related to the process and how this can be improved upon, specifically on the role of scale in the management of this fishery. As a start, it is important to define the flow of information between the various decision-making scales in the linefishery

FIGURE 4 | Causal map showing direct and indirect drivers of change (stressors) in the southern Cape linefishery as compiled in collaboration with fishers. In this map the different colours represent different themes of drivers of change (stressors) – Red boxes: key stressors, Turquoise: Biophysical, Yellow: Biophysical (other fisheries), Light blue: Social networks, Green: Social and Economic; Purple: Regulation/management and White: seas state. Pink arrows are positive interactions, blue show negative interactions, orange arrows show interactions which are neither positive or negative. Dashed (broken) lines are indirect interactions – Black dash: Non- directional indirect interaction/stressor, Blue dash: Dampening (–) indirect interaction/stressor and Pink dash: Amplifying (+) indirect interaction/stressor (from Gammage and Jarre, 2020).

governance structure. To successfully implement collaborative system-based approaches such as EAF, multi-level and cross-scale governance require information and knowledge that is not only 'top-down' but also 'bottom-up'. **Figure 7A** shows the current management paradigm in the South African context. Although bottom-up management practices may be espoused in legislation such as the MLRA, the mechanism to affect practices from the bottom up is not defined nor effective (shown by the broken line); management remains top-down with local scale interaction not being considered at the policy decision-making scale (Sowman, 2011). Importantly, the SSFP makes explicit provision for the co-management of small-scale fisheries, although the same is not true for other fishing sectors. When considering the interaction between national and multinational (**Figure 7B**), the bottom-up interaction is more effective as South Africa is afforded the opportunity to give input as participant in and signatory of multi-national/international fora and agreements, such as the EAF.

For the southern Cape, a bottom-up management approach would imply an uptake of fishers' knowledge at the policy-making scale together with more meaningful sharing of information and interactions between the small-scale, commercial handline and inshore trawl fisheries, which operate in the same area (Gammage, 2019). Competing interests at various levels of decision-making exist - for example, local perspectives on biodiversity tend to focus on livelihoods (Gammage et al., 2019; Gammage and Jarre, 2020), the national level may focus on tourism development and the international level on global biodiversity conservation. Importantly, these competing interests also exist between different fishery sectors. All these perspectives are unique and valid and need to be incorporated into overarching governance and decision-making structures.

Through the implementation of the SDMTs within the context of our approach, it became clear that the approach presented an opportunity for more direct engagement with problems of scale, due to the potential it holds for the facilitation of dialogue at various levels of the decision-making structure. Applied in the approach pursued here, the tools present a means to engage more directly with problems of scale by facilitating dialogue at and between various levels of the decision-making structure. Even when carried out at this small scale, it was not only useful for capacity building but also provided valuable insights that would be valuable at larger scales. **Figure 8** shows how such a multi-scalar decision-making process using scenario approaches could work in the South African context. Here we suggest how approaches such as this one (the tools or methods), can facilitate both 'top-down' and 'bottom-up' flow of information within

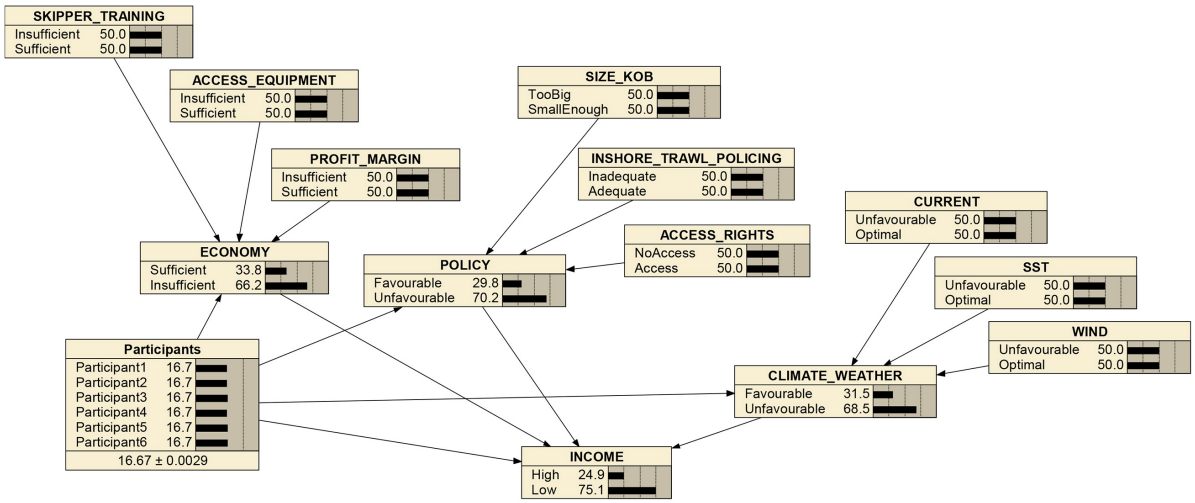

FIGURE 5 | This prototype Bayesian Belief network (BBN) represents six individual networks combined into one through the addition of the auxiliary node "participants" (each with a weighting of 16,7%). The outcome node for this network is "Income" and refers to the 'Ability to earn a sustainable fishery-derived" income. At the next level of the network are the "Climate-Weather," "Economy" and "Policy" nodes. Each of these nodes have three contributing factors which have no inputs in this particular model, and the states are thus set as being 50/50. Each node in the network has a dichotomous state indicating a favourable/unfavourable outcome expressed as a percentage (%) (from Gammage and Jarre, 2020).

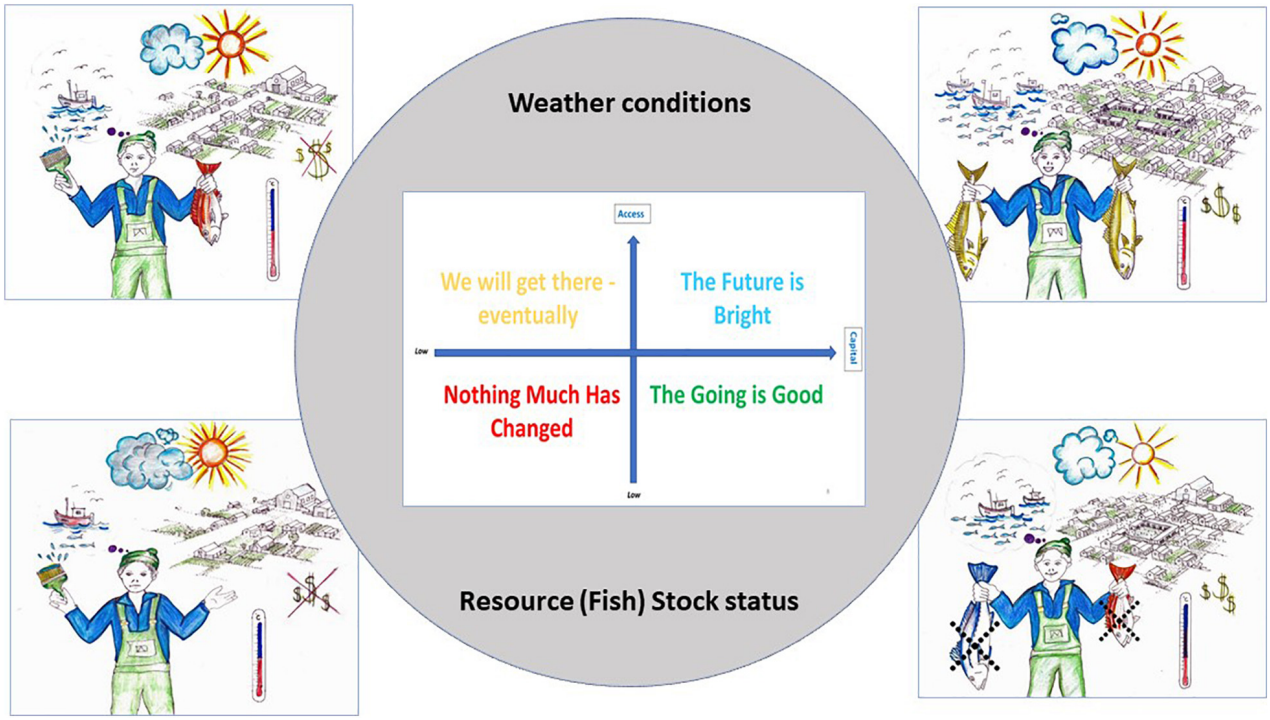

FIGURE 6 | Representation of the four scenario stories were designed around two Key driving forces (KDFs) defined by participants – access to (fishing) resources and access to (financial) capital. The context of two additional KDFs – resources (fish) availability and climate variation, were integrated with the fishers' stories into four distinct stories – "Nothing much has changed," "We well get there, eventually," "The future is bright" and "The going is good" (adapted from Gammage, 2019).

and between various decision-making (or governance) scales, where policy processes are not linear, but iterative. By facilitating bottom-up flow of information, the small-scale 'situation on the ground' can inform policy decisions to ensure best-fit policies at the national level that take all stakeholders and their needs into account. National assessments and policies would in turn inform the country's inputs to international fora and policy frameworks. These multi-and international policy frameworks must at the

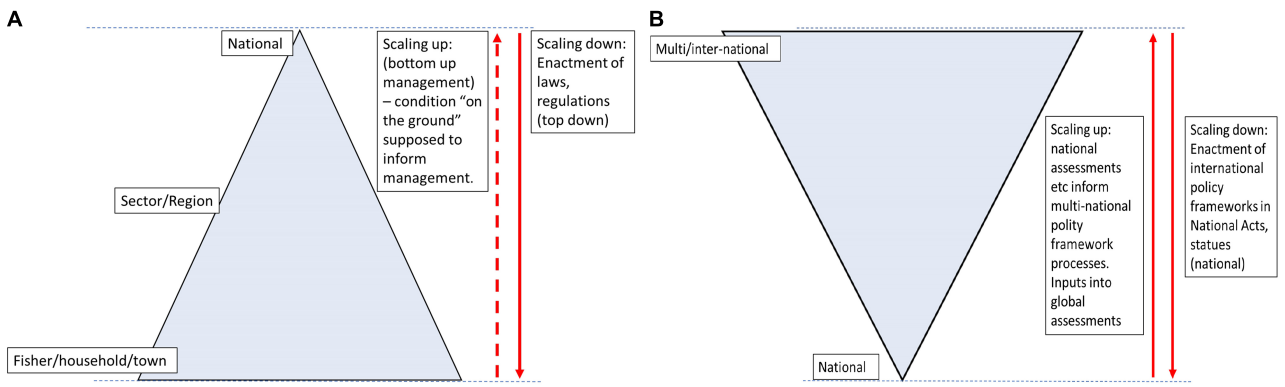

FIGURE 7 | Current pathways for scaling processes in the South African fisheries policy landscape. Fisheries management in South Africa is typically 'top-down' **(A)** With local scale interactions often not considered in policy-making decisions (indicated by broken line). Inter-, multinational policy frameworks and commitments **(B)** Are enacted in the government's national policies/acts. Conversely; national assessments, concerns are integrated into the inter-multinational policy frameworks and assessments by engagement in a process which formulate such frameworks and assessments (such as IPCC, IPBES, SDGs).

same time be enacted in the country's national legislation, which in turn must be enacted regionally and locally through the implementation of appropriate regulations and incentives. This two-way flow is essential for the needs and goals at the smallest scale of operation to be represented adequately.

By using SDMTs in these approaches, it not only becomes possible to integrate diverse knowledge streams from stakeholders across the SES, but also to facilitate communication and flow of information between various management scales. For multi-scalar processes, this is demonstrated by the ability to build local adaptive capacity, through learning, at the scale of the individual or town while at the same time engaging in processes that can inform larger-scale decision making (see Gammage, 2019; Gammage and Jarre, 2020; Gammage et al., in review).

DISCUSSION

This scenario-based approach is an example of how existing methods can be used in novel ways to address some of the challenges raised by changing marine SESs. Viewed holistically, the implementation of this approach highlights issues of complexity and scale of decision-making in the southern Cape linefishery, specifically within the context of the promotion implementation of an EAF in South Africa.

Complexity, Uncertainty and Managing Human Activities in the Southern Cape Linefishery

For the fishers of the southern Cape, it could be argued that what matters is not how fishers respond (adapt, react, cope), but instead how they are capacitated to respond to changes and drivers of change in proactive ways that are appropriate (in time and scale) for the situation. The scenario stories underscore the realistic (and attainable) ambitions participants hold for developments over the next generation. Notably, one of the highlights was that they do not limit their focus on the individual/household response but consider the community (town) as a whole – which is in keeping with the findings of previous research where change response strategies were identified per town (Gammage et al., 2017b). The Coasts Under Stress project (Ommer and Team, 2007) had similar findings in Canada. The importance of the community and its well-being recognised by fishers in this study for the ability to achieve sustainable livelihoods and well-being has important implications for management objectives, which should target at the level of the community.

The challenge presented by issues of scale is a key characteristic of the complexity of the human-environmental system, especially where multi-level decision-making is required. Governance issues in the Anthropocene are often multilevel and cut across jurisdictional scales while linking decision-makers both horizontally and vertically (Berkes, 2017). A governance approach will be more effective when the scale of ecological processes is well matched within the human social institutions that are charged with managing in the human-environmental interactions (Leslie et al., 2015).

In the case of South African fisheries, sectoral management enforces a mismatch between the scales of the ecosystem and that of the management structures. This is demonstrated by the delineation of management zones in the South African linefishery (DAFF, 2013) and the linefish stock composition on the western Agulhas bank (Blamey et al., 2015). To ensure better alignment between management and ecological scales, Blamey et al. (2015) show how management zone delineation could be adjusted to better suit the fish assemblages (ecological) units of scale. For the southern Cape line fishers, a better alignment between ecological and management scales would benefit both the natural subsystem of the SES and the fishers operating in the revised regions because it would provide a (1) meaningful boundary on the set of stakeholders to be included in management decisions and (2) provide them with an appropriate space in the decision space. Such a shift in approach could

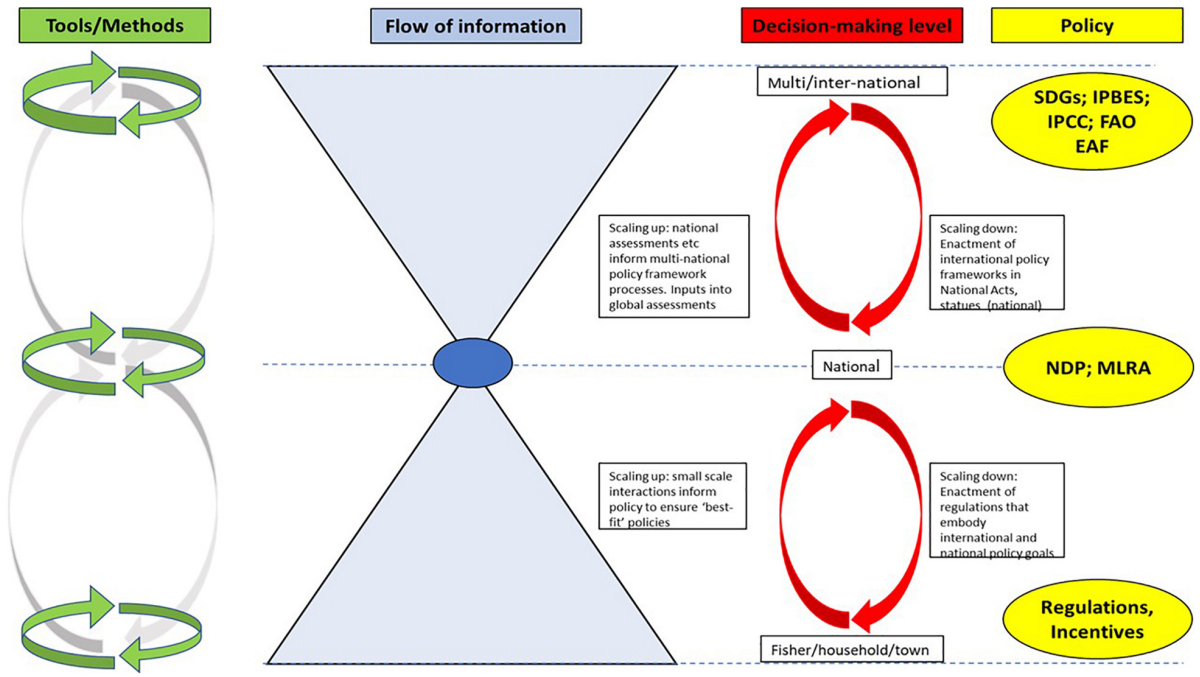

FIGURE 8 | Schematic representation of the potential pathways for scaling within the South African decision-making context. International policy positions and international undertakings are enacted in national policy and legislation. For effective EAF management, actions at the small-scale must inform legislation at the national level and will ultimately shape and inform inputs made to multi-national and international evaluations and policy positions (directly or indirectly). There is thus a need for simultaneous 'top-down' and 'bottom-up' governance processes – these are not linear, but rather iterative and take place within a decision-making level and between various decision-making levels. By making use of multi-stakeholder approaches such as this overarching scenario-based approach, it becomes possible to facilitate these iterative and interactive processes, there by facilitating better flow of information across scales. Scenario processes and the use of structured decision-making tools will be more effective if used in a governance approach which considers and integrates processes at various scales.

result in the reduction of friction within the fishery, by allowing for trust to be built between various stakeholders (Duggan, 2018).

Implications for the Implementation of an Ecosystem Approach to Fisheries Management in South Africa and Scope for Future Work

While rooted in the human dimensions of SES and keeping a focus on stakeholder engagement, this case study has explored tools which can be practically implemented to achieve a balance between social, economic and ecological objectives, as needed for a successful EAF. The research, which is reproducible, transparent and adhering to principles of democracy and ecosystem justice[10] (Brunk and Dunham, 2000) opens a new view on the human dimensions of the southern Cape linefishery (Gammage and Jarre, 2020) and describes a methodology which can be applied in ecologically meaningful regions and across fishery sectors in South Africa.

For any EAF implementation to succeed, various perspectives need to be integrated into the decision-making process at various scales. Paterson et al. (2010) highlight the need for a transdisciplinary approach where real-world problems are used to develop solutions in partnerships with multiple stakeholders. They identify a common vision, exemplified by the development of an EAF and the means to facilitate useful interactions using SDMTs, as the two most important requirements for the development of sustainable research partnerships. SDMTs do not only help stakeholders make sense of their SES, but also guide managers in uncertain and complex systems. Through participating in processes where such tools are developed in support of an EAF, a common focus for all stakeholders can be fostered. Additionally, through the implementation of such approaches, it is also possible to address barriers to the successful implementation of an EAF. Importantly, through the development and implementation of scenario-based approaches, we are also able to address different system needs at various scale simultaneously which may be a crucial step forward in appropriately addressing the challenges associated to practically dealing with challenges presented by scale mismatches in SES.

Considering these requirements, the scenario-based approach presented here provides a means to conduct the type of transdisciplinary research required in the development and implementation of an EAF in South Africa. This research has shown that SDMTs can work in communities where participants/fishers have little formal education. Here we show that to engage stakeholders there is no need to lose structure altogether. With structure crucial to the practical aspects of

[10]Ecosystem justice is "the ethically acceptable relationship among all competing and complementary interests of an ecosystem 'community'" (Brunk and Dunham, 2000:294).

fisheries management to ensure repeatability and transparency, this finding shows that by using SDMTs in processes where the required groundwork, capacity building and resourcing take place, it is possible to integrate vulnerable, marginalised stakeholders into formal decision-making processes directly and effectively, as required by the EAF (Garcia et al., 2003).

This paper presents an approach which will need to be developed more widely and comprehensively to make a meaningful decision-making contribution. As a start, this would entail scaling up to cover a larger geographical scale. For the southern Cape linefishery this would entail engaging with all fishery sectors who target linefish in the area between Cape Infanta and Cape St Francis. Crucial to the success of such a process is the painstaking work of laying the appropriate basis to ensure that all stakeholders are engaged in a co-initiating (or convening phase). Kahane (2012a,b) describes the requirements of this first phase of the process in detail while also highlighting the importance of the phase for the overall success of the process.

Initiating the scenario-planning process will be challenging given the South African fisheries management context. Although the State is central to management, it is considered weak (Norton, 2014; Jarre et al., 2018). To convene a process that can have meaningful inputs at various decision-making scales, it will be important to at least have a champion within the State who would be willing to participate in such a process. Institutions such as NGOs who have close links to the target communities will also be crucial to the co-initiating phase, as discussed above. Importantly, much time and effort will have to be spent by the research and facilitation team to identify and approach key individuals from the State and other institutions who will be willing to learn from each other, remain engaged in a long-term project and who can facilitate collaboration with various communities of fishers. It does not mean it cannot be done.

Given the inductive nature of the research, it remains important that some flexibility is built into the research design. Although the prototype process has been based on the principles of a TSP, there is space to integrate other types of scenarios into the process. There is also a need to ensure that the tools used for structured decision-support are appropriate, bearing in mind that there are more tools that can be developed. While the tools were mostly used successfully in this research, these tools may not be suitable for all contexts and would require testing (prototyping) in different contexts to ensure wide applicability. As the robustness of the process depends on diverse stakeholders giving diverse opinions on often sensitive matters, an experienced facilitator (or facilitation team) remains key to the eventual success of the planning process. Importantly, the need to implement the process in a slow-and-careful manner which ensures that all participants are prepared to actively engage with the process, together with the time and resources to ensure a properly facilitated process with diverse stakeholders, remains key to the successful implementation of the approach. These findings underline the simultaneous focus on product and process highlighted by McGregor (2015) in her research with stakeholders in the large, highly capitalised SA small pelagic fishery (also see McGregor et al., 2016).

For linefishers, the creation of enabling conditions, where policy and decision-makers (which include fishers as direct resource users) at various levels actively engage on issues affecting the marine SES, is key to effectively implementing an EAF, moving fisheries and dependent coastal communities closer to attaining sustainable futures. Specifically, this research shows that by engaging in capacity building on the ground, disadvantaged communities can actively be empowered to participate in more complex, multi-stakeholder planning processes. Their inputs could thus inform policy processes in a bottom-up approach, as opposed to the current top-down approach. While bottom-up management mechanisms do not currently function well in South Africa, the approach demonstrates the potential to facilitate a two-directional flow of information between scales.

CONCLUSION

Complexity and uncertainty in marine SESs hamper effective decision-making at all scales. Traditional forecasting approaches will likely not overcome the limitations posed by various uncertainties in models, thereby hampering decisions toward mitigation and adaptation (Quay, 2010). This contribution argues that scenario-based approaches present a practical, scalable methodology that can facilitate learning, capacity building and decision-making with the ultimate aim of improving the implementation of an EAF. Importantly, through the use of SDMTs, crucial local system insights have been documented, enhancing our understanding of local system interactions.

The benefit of oceans to people is undeniable and well described. Complexity and uncertainty in marine SES require a change in thinking in how we perceive, study, manage and govern. Considering that the earth system seems to be nearing critical tipping points faster than previously expected, it becomes evident that this paradigm shift cannot take the traditional 'slow and steady' trajectory generally favoured by researchers and decision-makers alike. Importantly, this change in thinking calls for research that moves beyond the traditional framings and discourses that place the focus on what we know, toward approaches where there is a focus on increasing the capacity of stakeholders to make sustainable decisions within rapidly changing complex adaptive systems with an eye on actively planning for the future.

The research presented in this paper has shown that modelling approaches such as SDMTs can be carried out with disenfranchised stakeholders, even if they have not previously been exposed to such methods. Through the implementation of an interactive and iterative process, the process has resulted in the promotion of capacity building at the scale of the individual, household and community of fishers. Importantly, meaningful scenarios have been developed with the small-scale fishers in Melkhoutfontein. Reflecting on the development and implementation process has allowed for the discussion of multiple stakeholder settings and the value of the approach in addressing issues across multiple scales in SESs.

By building on this essential knowledge of the local SES, the next implementation step will be to scale up the scenario-planning process to an appropriate ecological scale. To facilitate the necessary learning and capacity building required for valuable interactions, the research shows that it is crucial to lay the appropriate basis for multiple stakeholder meetings, with all the effort that needs to go into it. Only then is it meaningful to embark on a full-blown, multiple stakeholder planning process.

Through the implementation of tools and approaches that aim to promote the holistic implementation of an EAF (such as this one used here), it may become possible to improve decision-making at all scales, by promoting adaptive capacity of the person, household and community while enabling improved governance at the larger scale. Ultimately, better decision-making does not only promote social justice for fishers, but also ecosystem justice, both of which are crucial not only for the implementation of an EAF, but more generally, for long-term system sustainability.

DATA AVAILABILITY STATEMENT

The datasets generated for this study cannot be made publicly available due to restrictions from ethics requirements and agreements with research participants. Requests to access the datasets should be directed to LG, louise.gammage@uct.ac.za.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Cape Town – Faculty of Science Research Ethics Committee (FSREC 03 – 2016). The participants provided informed consent to participate in this study, in writing.

AUTHOR CONTRIBUTIONS

LG conceptualised the research, carried out the fieldwork, and authored the manuscript which formed part of her Ph.D. research. AJ was the primary supervisor of the research. All authors contributed to the article and approved the submission.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.600150/full#supplementary-material

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Coastal Research Seen Through an Early Career Lens—A Perspective on Barriers to Interdisciplinarity in Norway

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The value of interdisciplinarity for solving complex coastal problems is widely recognized. Many early career researchers (ECRs) therefore actively seek this type of collaboration through choice or necessity, for professional development or project funding. However, establishing and conducting interdisciplinary research collaborations as an ECR has many challenges. Here, we identify these challenges through the lens of ECRs working in different disciplines on a common ecosystem, the Norwegian Skagerrak coast. The most densely populated coastline in Norway, the Skagerrak coast, is experiencing a multitude of anthropogenic stressors including fishing, aquaculture, eutrophication, climate change, land runoff, development, and invasive species. The Skagerrak coastline has also been the focus of environmental science research for decades, much of which aims to inform management of these stressors. The region provides a fantastic opportunity for interdisciplinary collaboration, both within and beyond the environmental sciences. This perspective article identifies the barriers ECRs in Norway face in establishing interdisciplinary and collaborative research to inform management of coastal ecosystems, along with their root causes. We believe our discussion will be of broad interest to all research institutions who employ or educate ECRs (in Norway and worldwide), and to those who develop funding mechanisms for ECRs and interdisciplinary research.

Keywords: early career researchers, interdisciplinarity, marine science and technology, Norway, ocean, Skagerrak

INTRODUCTION

In a time when global anthropogenic impacts on ecosystems call for urgent solutions, interdisciplinary collaboration can push the boundaries of marine research to enable innovative knowledge building and provide resource managers and policymakers with tools to secure a productive and healthy ocean (Ledford, 2015). As such, more than ever before, researchers are expected to think and work across disciplines to solve pressing challenges (Ledford, 2015;

Rylance, 2015; Andrews et al., 2020). Across the globe, interdisciplinary institutes and think tanks push innovation by facilitating knowledge exchange (Ledford, 2015; Vienni Baptista et al., 2019; Mäkinen et al., 2020). The European Union framework program Horizon 2020 has heavily promoted interdisciplinary research, even so far as stating that it is the "key to future scientific breakthroughs," and awarded grants accordingly (Science Europe, 2012).

Early Career Researchers (ECRs) have an essential role within academic research, as driving forces that push science forward with research-focused workloads, fresh ideas, and enthusiasm (Friesenhahn and Beaudry, 2014; Andrews et al., 2020). Despite the documented benefits of interdisciplinarity, ECRs face many barriers to working successfully across disciplines (**Table 1**). The structure of academia is one such barrier, with field-specific funding calls, discipline-specific jargon, and short-term contracts, making interdisciplinary collaborations particularly challenging for ECRs (Brewer, 1999; Bromham et al., 2016; Andrews et al., 2020). This perspective article provides an overview of the barriers faced by ECRs within a recently established interdisciplinary research center in southern Norway, and their causes. To our knowledge, it is the first of its kind to focus on interdisciplinary coastal research in Norway and adds to the limited information on the topic in Scandinavia (**Table 1** and see also **Supplementary Material**: Literature search).

With Norway being a maritime nation, the Norwegian government's long-term plan for research and higher education has a particular focus on research-based innovation and industry-oriented research, with the ocean being one of the priority areas (Norwegian Ministry of Education and Research, 2019). Investment in technology and research infrastructure is highlighted as crucial to promoting sustainable development and to increasing the value of industries in ocean and coastal areas. Norway's continued investment in this sector is reflected by the country having the world's highest proportion of marine scientists per capita (UNESCO-IOC, 2020). Norway could be used as an example by other countries of how to begin removing barriers for ECRs.

The aim of this article is to (1) identify barriers to interdisciplinary research faced by ECRs who work on a common ecosystem in Norway and (2) consider the root causes of these barriers. By sharing our perspective, we hope to draw attention to practices that need to be reviewed for more effective interdisciplinary research by ECRs in Norway and worldwide, leading to better informed management of coastal ecosystems during this time of global change. A background description of the Norwegian Centre for Coastal Research and the development of this manuscript can be found in the **Supplementary Material** (**Supplementary Material**: Background of This Study).

COMMON BARRIERS TO ECR INTERDISCIPLINARITY

To identify barriers to their research and their causes, the authors participated in individual and small-group work during winter and spring 2019/2020, then discussed these during a 3 days virtual workshop held in April 2020 (for details, see **Supplementary Material**: Background of this study). Three major themes emerged with regard to barriers, related to (1) short-term employment, (2) knowledge sharing via networks and partnerships, and (3) data-associated limitations (**Figure 1**). Within these themes, barriers were related to three main types of causes: (A) practical limitations hindering ECR research, (B) structural limitations inherent to the local research environment, and (C) systemic limitations inherent to the current scientific, political, and societal situation in which research occurs (later referred to as "practical," "structural," and "systemic" causes, **Figure 1**).

This perspective is in agreement with previous work reporting that main barriers limiting ECRs' capacity for interdisciplinary research are not only of scientific origin but rather due to the working environment and conditions (Andrews et al., 2020; Brasier et al., 2020). A review of recent literature summarized in **Table 1** suggests many diverse barriers to successful interdisciplinary collaborations for early career researchers. Since most of the barriers and their causes were raised by several researchers independently, we determined that these challenges occur across subdisciplines and will continue to hinder the progress of future ECRs unless they are addressed directly. As such, we outline below the identified barriers and causes. We acknowledge that our perspectives are biased toward our experiences in natural sciences and of being an ECR in Norway. Norway has comparatively favorable working conditions, specifically in relation to salary and gender equality at the ECR stage in our general field than many other countries. Furthermore, in Norway flatter structures are more common than in many other countries, which enables ECRs to engage with senior researchers and management staff more easily, as well as provide constructive criticism in regard to the work environment with less fear of repercussions. We discussed solutions, but given that we do not know the practicalities or secondary consequences of these, we have not made specific recommendations. Instead, we include our suggestions as a starting point for further discussion both briefly within the text and in more detail in **Supplementary Material** (**Supplementary Material**: Potential Solutions to Causes and Prevention of Barriers). In addition, solutions to the barriers identified in literature have been added to **Table 1**.

Barrier 1: Temporary and Short-Term Contracts

An overarching topic of our discussions related to temporary contracts and time limitations of short-term employment, which are not conducive to interdisciplinarity when considering the time investment needed to explore and establish collaborative research. There were several challenges associated with this barrier, such as pressure to publish; balancing time required to learn about the research environment, acquire skills, and conduct research; and job insecurity. The high competition for limited postdoc and permanent positions may not foster

TABLE 1 | Summarized barriers to successful interdisciplinary research from an early career perspective and suggested solutions, from literature published since 2015.

Barriers to ECR interdisciplinarity	Proposed solutions
Poor research networks (e.g., due to relocation, institutional structures; Pannell et al., 2019; Fork et al., 2020)	• Bolster research networks through collaborative program structure and mentorship (Fork et al., 2020) • Create ECR-focused spaces (e.g., regular ECR events, online communities, databases of ECR research, connect ECRs with complementary projects, funding for ECRs to attend encounters*; Pannell et al., 2019; Fork et al., 2020)
Short duration of ECR positions, research time constraints (Bridle et al., 2013; Kelly et al., 2019; Pannell et al., 2019; Brasier et al., 2020; Fork et al., 2020)	• Longer-term contracts, career development, and workshops on how to attract funding with salary support (Brasier et al., 2020) • Access to established interdisciplinary networks (Brasier et al., 2020)
Ineffective support: supervisory or institutional (Killion et al., 2018; Kelly et al., 2019; Andrews et al., 2020; Blythe and Cvitanovic, 2020; Fork et al., 2020)	• Active support within integrative research communities (e.g., formalize mentorship, provide training, interdisciplinary courses, organize encounters*, network building, provide seed funding, and follow-up activities; Lyall and Meagher, 2012; Bridle, 2018; Jaeger-Erben et al., 2018; Gibson et al., 2019; Pannell et al., 2019; Andrews et al., 2020) • Establish good channels of communication (e.g., provide early feedback on nascent ideas, alert to imminent funding opportunities, dialog-led management; Gibson et al., 2019) • Promote junior research group leaders, give the rank of junior professor (increases credibility with partners; Jaeger-Erben et al., 2018; Gibson et al., 2019)
Stress due to career uncertainty, including short-term employment contract (Bridle et al., 2013; Hein et al., 2018; Gibson et al., 2019; Andrews et al., 2020; Brasier et al., 2020; Fork et al., 2020)	• Enable development of transferable skills useful across a wide range of potential careers (Brasier et al., 2020; Fork et al., 2020) • Provide and normalize use of mental health support (Andrews et al., 2020) • Promote sustainable working collaborations, counseling support, time, and funding for student support roles (Brasier et al., 2020)
Traditional measure of success not appropriate for interdisciplinary work (manuscripts and citations, whereas interdisciplinary outputs are geared toward more real-world outcomes; Bridle et al., 2013; Hein et al., 2018; Jaeger-Erben et al., 2018; Martinez et al., 2018; Gibson et al., 2019; Pannell et al., 2019; Andrews et al., 2020; Blythe and Cvitanovic, 2020; Brasier et al., 2020)	• Acknowledge, support, and develop ways to measure alternative outputs (e.g., collaborations, cooperative learning, policy engagement, science communication outputs; Bridle et al., 2013; Pannell et al., 2019; Brasier et al., 2020) • Integrate interdisciplinarity into research groups (e.g., graduate programs, training opportunities, develop interdisciplinary agendas; Haider et al., 2018; Martinez et al., 2018) • Encourage recognition for interdisciplinarity from senior colleagues (Hein et al., 2018)
Lack of funding/lack of access to funding (Hein et al., 2018; Pannell et al., 2019; Blythe and Cvitanovic, 2020; Bradley et al., 2020)	• Funding models to encourage interdisciplinary collaboration (e.g., to attend encounters*, seed funding, travel advances; Bridle, 2018; Hein et al., 2018; Gibson et al., 2019; Pannell et al., 2019; Bradley et al., 2020) • Active, practical support from institutions, funding bodies, and mentors (Pannell et al., 2019)
Limitations of hierarchical structures (Pannell et al., 2019; Brasier et al., 2020; Nash et al., 2020)	• Promote ECR into leadership positions (Gibson et al., 2019; Pannell et al., 2019) • Facilitate supportive dialog between senior collaborators/researchers and ECRs (Gibson et al., 2019) • Enforce codes of conduct to prevent harassment (Brasier et al., 2020)
Competition between ECRs (Pannell et al., 2019; Brasier et al., 2020)	• Facilitate knowledge and progress sharing between projects (Pannell et al., 2019) • Create interdisciplinary work environments (Brasier et al., 2020)
Data issues (e.g., sharing, obtaining, accessing, managing; Drakou et al., 2017; Durden et al., 2017; Pannell et al., 2019)	• Create tools, infrastructure, and standards for data and data sharing (Drakou et al., 2017; Pannell et al., 2019; Wilson et al., 2021)
Difficulties associated with integrating divergent academic disciplines (e.g., different terminology, measurement scales; Palmer et al., 2016; Drakou et al., 2017; Hein et al., 2018; Hossain et al., 2018; Jaeger-Erben et al., 2018; McDonald et al., 2018; Gibson et al., 2019; Kelly et al., 2019; Pannell et al., 2019; Brasier et al., 2020; Wilson et al., 2021)	• Provide training and opportunities to practice (e.g., communication, team skills, disciplinary bias and reflexivity, relationship building; Hein et al., 2018; Hossain et al., 2018; Wilson et al., 2021) • Facilitate interaction and development of relationships (e.g., encounters*; Palmer et al., 2016; Wilson et al., 2021) • Invest in interdisciplinary infrastructure (e.g., journals, educational programs, connectivity between disciplines; Drakou et al., 2017; McDonald et al., 2018)
Managing work–life balance (Jaeger-Erben et al., 2018; Andrews et al., 2020; Brasier et al., 2020)	• Provide and normalize use of mental health support (Andrews et al., 2020) • Provide career development opportunities and support (Haider et al., 2018) • Outline expectations and limitations (Jaeger-Erben et al., 2018)
Complexity of initiating interdisciplinary work (e.g., steep learning curve, perform multiple roles; Bridle et al., 2013; Jaeger-Erben et al., 2018; Alexander et al., 2019; Gibson et al., 2019; Andrews et al., 2020)	• Integrate interdisciplinarity into research groups (e.g., graduate programs, training opportunities; Andrews et al., 2020) • Provide guidance, training (e.g., in building networks, strategizing, time negotiation; Jaeger-Erben et al., 2018; Alexander et al., 2019) • Provide and fund opportunities for networking across disciplines (e.g., encounters*; Bridle et al., 2013)
Individual skill requirements (Drakou et al., 2017; Durden et al., 2017; Cvitanovic et al., 2018; Elliott et al., 2018; Bohleber et al., 2020; Nash et al., 2020)	• Use professional development opportunities (e.g., mentor programs, skill development for interdisciplinarity, self-reflexivity, managing complexity and uncertainty, participation in interdisciplinary projects; Drakou et al., 2017; Cvitanovic et al., 2018; Elliott et al., 2018; Haider et al., 2018; Nash et al., 2020)

(Continued)

TABLE 1 | Continued

Barriers to ECR interdisciplinarity	Proposed solutions
	• Maintain open communication to set and manage expectations (data, roles, outcomes, skill gaps; Durden et al., 2017; Nash et al., 2020) • Participate in ECR networks to build broad skillset (Bohleber et al., 2020)
Lack of access to networks (e.g., interdisciplinary, outside of academia; Killion et al., 2018)	• Provide networking and training opportunities (e.g., encounters*; Bridle, 2018; Killion et al., 2018) • Improve integration of stakeholders in the research process and community (Killion et al., 2018)
Lack of exposure to other disciplines (e.g., knowledge frameworks; Palmer et al., 2016; Hein et al., 2018; Killion et al., 2018; Gibson et al., 2019)	• Provide training in communication, different knowledge frameworks, collaboration, and team skills (Palmer et al., 2016; Hein et al., 2018; Killion et al., 2018) • Promote leaders to guide and facilitate teamwork (Palmer et al., 2016)
Difficulty of interdisciplinary publication (journal preference, reviewer expertise; Bridle et al., 2013; Drakou et al., 2017; Hein et al., 2018; Hossain et al., 2018; Gibson et al., 2019)	• Creation of interdisciplinary journals (Drakou et al., 2017)
Geographical distance between collaborators (Rekers and Hansen, 2015)	• Spatial co-location of interdisciplinary centers (Rekers and Hansen, 2015)
Dominance of traditional (single-discipline) structure within academia (Lyall and Meagher, 2012; Hein et al., 2018)	• Expand networking opportunities (e.g., organize encounters* and provide training; Hein et al., 2018)
Lack of interaction or tensions between collaborators (Palmer et al., 2016; Blythe and Cvitanovic, 2020)	• Enable interpersonal and professional interactions, incorporate mechanisms that ensure engagement from multiple perspectives (Palmer et al., 2016; Blythe et al., 2017) • Outline different knowledge framings and encourage plurality (Blythe et al., 2017)
Different definitions of interdisciplinary (Gibson et al., 2019; Blythe and Cvitanovic, 2020)	
Early stage of career—still getting established in academia (Jaeger-Erben et al., 2018)	• Outline expectations including scope and limitation (Jaeger-Erben et al., 2018) • Training including: (1) soft skills (moderation, science communication), (2) best-practice using example cases, (3) peer–peer learning (Jaeger-Erben et al., 2018) • Provide experienced mentors (Jaeger-Erben et al., 2018)
Language (Brasier et al., 2020)	• Language training and support, translate summaries, encourage non-English events (Brasier et al., 2020)
Discrimination (Brasier et al., 2020)	• Zero tolerance policies for discrimination (Brasier et al., 2020) • Diverse research groups (Brasier et al., 2020) • Encourage reporting of harassment and other abuses (Brasier et al., 2020)

Encounters, referring to events designed to connect and encourage interdisciplinary networks and collaborative working. For details on how literature search was conducted, see **Supplementary Material: Literature Search.*

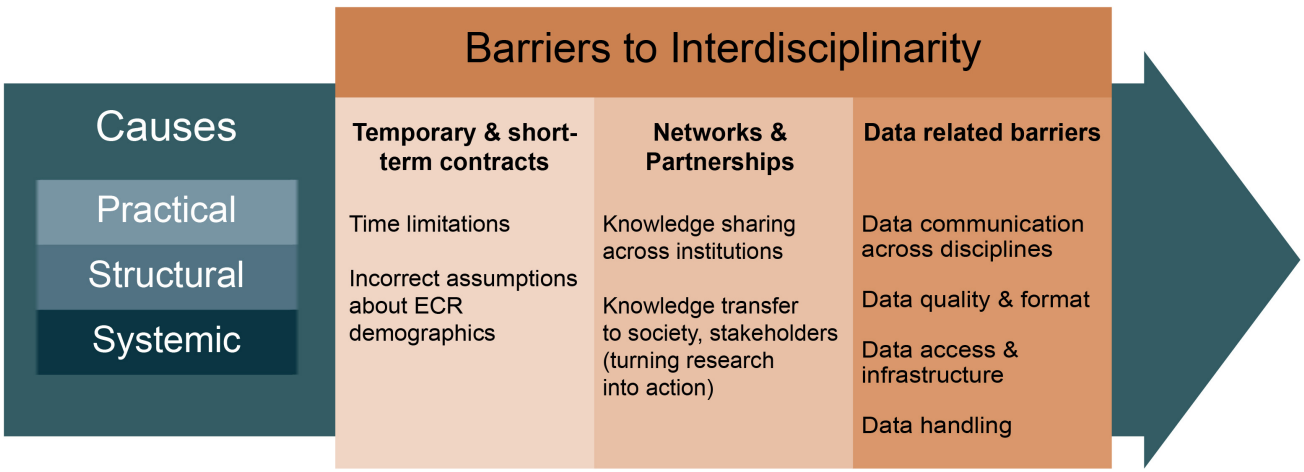

FIGURE 1 | Practical, structural, and systemic causes contributed to barriers to interdisciplinary research across the three overarching themes (bold text) and the specific examples (regular text) identified by ECRs in marine science.

a collaborative working environment, as ECRs may feel they are in competition with their colleagues for limited resources. Time is a limiting factor for ECRs where, as a consequence, mental health and well-being suffer (Gewin, 2012; Woolston, 2018; Bosanquet et al., 2020; **Table 1**) with clinical symptoms such as depression and anxiety up to six times higher in graduate students compared to the general population (Evans et al., 2018). The problematic nature of short-term contracts for ECRs has

become especially visible during the ongoing pandemic (Pardo et al., 2020). However, these problems were also identified by ECRs prior to COVID-19 and will not disappear post COVID-19 if long-term solutions are not created on all levels (**Figure 1** and **Supplementary Table 1**). Furthermore, there is a growing body of literature related to career uncertainty in general and the associated economic and personal costs (Garwood, 2014; Bozzon et al., 2017; Chesters et al., 2019; **Table 1**). Underlying practical, structural, and systemic causes were identified, as detailed below.

Practical Causes

Practical reasons that short-term contracts are a barrier to ECRs establishing successful interdisciplinary projects include lengthy processes, such as finding potential collaborators and developing project plans that suit all partners; designing and trialing new experimental methods, which often have unpredictable results and timeframes; and seasonal limitations on field sampling or laboratory experiments.

Structural Causes

Time limitations due to fixed-term contracts may also become a barrier for several practical reasons. Many tasks ECRs have to complete during their short-term employment may be mandatory or prescribed by their local research environment (i.e., following of internal routines and procedures). As specific examples, such time-demanding tasks may be (1) mandatory legislative approval for data collection or animal welfare approval for practical work, mandatory safety, lab, and method training. Although recognized as highly important, these tasks may be overly time consuming if proper guidance is not provided immediately. (2) ECRs depend on cyclical and highly competitive funding opportunities to cover field and lab expenses—funding opportunities which may have months between initial application, decision, and receipt of grant money. (3) Furthermore, interdisciplinarity requires working outside of an ECR zone-of-knowledge, whereby completing tasks and learning new methods may require additional time (Andrews et al., 2020). Lastly, (4) while learning native language is not a requirement for international staff on temporary contracts in most institutions in Norway, much of the communication between colleagues is conducted in the native speech. Such informal discussions are generally a great source for learning about colleagues' work and opportunities to collaborate. Language courses are often only provided to permanent staff and, where available to temporary employees, are often at extra costs (time and money). Free language classes may sometimes be available at affiliated universities; however, those may not be frequent enough to provide the practice required to adequately engage in conversation until the end of the temporary contracts and are often not at the appropriate level to enable work-related conversation (Mentzoni et al., 2016).

Systemic Causes

ECRs are typically expected to move during their academic career in order to expand their research and network horizon, i.e., take temporary positions (Bridle et al., 2013; Brasier et al., 2020; Fork et al., 2020). This funding and employment system appears to be driven by several assumptions, in particular the ECRs' ability to relocate, i.e., the traditional view of ECRs as young, able, single, or with a stay-at-home spouse who is willing and able to relocate, and not as parents or carers for vulnerable relatives, or unable to relocate for other reasons (Jaeger-Erben et al., 2018; Andrews et al., 2020; Brasier et al., 2020). However, this assumption is exclusionary to the majority of our ECR authors who do not fit that demographic. There may also be an assumption that forced relocation to a new research environment, e.g., as a postdoctoral researcher in another country, is more valuable than long-term employment within one location. Yet, shorter research visits and exchanges with partner sites, instead of contractual relocation, can be an efficient option for knowledge transfer in both directions and on various levels (on a national, institutional, and individual level). In addition, while new knowledge and new studies could be conducted at the partner site, ongoing research and networks at the already established "home institute" could be maintained and continued, making investment in interdisciplinary partnerships more likely.

Barrier 2: Networks and Partnerships (Knowledge Sharing Across Institutions)

Sharing of methods, data, and knowledge among disciplines is essential to pushing scientific frontiers forward. Barriers to interdisciplinarity identified by ECRs included access to appropriate networks, establishing successful collaborations, and overcoming communication barriers between disciplines (**Supplementary Table 2** and **Table 1**). ECRs may largely depend on input from collaborators, supervisors, and senior academics, which may not fully acknowledge the needs of the ECRs or provide the required guidance. The problem is asymmetric, as for ECRs future employment may depend on successful interdisciplinary research experience while the project may not be pivotal for the careers of the senior researchers involved. Reluctance in sharing methods, data, and knowledge between individuals, research groups, disciplines, or even research generations was found to be a barrier to successful collaborations for ECRs.

Practical Causes

We identified several practical causes, such as the lack of holistic perspectives in the planning of data collection and experimentation, the difficulties in communication and open data sharing between disciplines and new partner institutions, the traditional divisions among sciences and the different types of knowledge produced, and lack of resources or technical limitations.

Structural Causes

Engagement with stakeholders, practitioners, and local authorities, as well as the broader society is a prerequisite for turning research into action and to overcoming real-time coastal challenges in a long-lasting way. However, a lack of such established networks within research centers may prevent ECRs

from connecting with relevant contacts and implementing their research. Interdisciplinary research institutes may be able to help ECRs overcome those structural barriers by actively promoting encounters between ECRs and already established networks (Bridle et al., 2013; MacLeod, 2018).

Systemic Causes

Time and funding may be too limited to contact, exchange, and develop novel methods in collaboration with partners during an ECR contract. Although the general attitude toward sharing has largely improved over the past decade, sharing methods across disciplines and with new contacts can still be challenging. Often, collaborators may not be willing to share, contribute, or exchange expertise with new members, as ECRs will be less "known" compared to more senior researchers within collaborator networks and so may be less trusted with data. As a result, ECRs may not have access to new methods before they are published. Publication of novel, interdisciplinary methods may be more time demanding than traditional methods as reviewers or editors may be more skeptical or perceive themselves as less qualified to review the manuscript.

Barrier 3: Data-Related Barriers

Reliable data is an integral part of research and remains so for interdisciplinary collaboration. Data acquisition, cleaning, normalization, and integration across interdisciplinary areas are an inherent part of ECR work. Technical advancements can provide significant assistance by simplifying the data acquisition process. The barriers we identify affect ECRs' research in terms of quality, quantity, and efficiency (**Table 1**). Resolving data-related issues will not only improve the ECRs efficiency but also help the interdisciplinary research centers by ensuring their position at the forefront of research and help equip the next generation of interdisciplinary scientists to handle the rapidly increasing amount of data available (**Supplementary Table 3**). We identified four broad barriers related to data:

(A) Data communication. Communication barriers hinder the smooth sharing and coordination of data between different disciplines. Challenges arise in dissemination and publication of research activities that integrate the expertise of many domains, such as marine biology, chemistry, ecotoxicology, computer science, including reporting of results, and technical language.

(B) Data quality and format. All the ECR participants experienced challenges in integrating data for interdisciplinary research, despite having access to the datasets they needed.

(C) Data access and infrastructure—ECRs may not be in possession of their data, instead relying on institutes, senior researchers, and collaborative companies to access their databases and platforms. In some cases, ECRs may rely on the willingness of different project stakeholders for data access and later feel indebted to them (e.g., eternal inclusion on project ideas, papers). Furthermore, in our experience, database management is not the primary priority of project stakeholders, and often only few people know the nature of data (e.g., metadata). To meet the international standards of high impact work, addressing these issues is inherently crucial to ECRs' work.

(D) Data handling. Traditionally, data acquisition was a manual process, especially within biology. "Big data" has become a mainstay of research due to advancement in technology, particularly sensors and remote observations, and exponential growth in internet capabilities and various open and online data platforms for visualization and analytics. The use of such datasets and platforms requires big data skills as well as knowledge of data security. ECRs therefore need to update and maintain these skill sets but are seldom provided with training opportunities to do so.

Practical Causes

With regard to data communication barriers (A), data collection and storage are often not designed for collaborators in different subfields to understand and use, and ECRs often lack sufficient knowledge about other topics and tools to share data in ways meaningful outside their own disciplines. Data quality and format (B) became a barrier for ECRs working with inherited data where, despite substantial efforts in the past to standardize and clean datasets by different researchers, data inconsistencies could not be eliminated. Furthermore, legacy data from senior researchers or online databases inherit errors that new recipients are unaware of. Regarding data access and infrastructure (C), the lack of transparent and replicable routines for data management and storage often prevents the use of existing data. Practical causes of barriers related to data handling (D) include a lack of common framework in open and online data platforms that enable interdisciplinary usage of data. Finally, in some overlap with the temporary and short-term contract barriers, time constraints for ECRs are an overarching practical cause of the interdisciplinary data-related barriers above. For example, reliable and relevant data acquisition often relies on manual sampling, a time-consuming, often seasonally limited process, and data cleaning, management, and handling take time to master when considerations must be made for use by other disciplines.

Structural Causes

(A) The discipline-specific organization of universities inhibits interdisciplinary discussions and development of a common language between disciplines. (B) Past data cleansing efforts are not being circulated and shared in professional circles (Ma et al., 2018), and the absence of institutional frameworks for data collection and format leads to inconsistent entries or data exclusion. (C) There is a lack of integrative open and online data platforms, and decisions are yet to be made regarding who should be responsible for dealing with such challenges: individual researchers, ECRs, research centers, external companies handling external servers, universities, or governments (Durden et al., 2017). Therefore, ECRs need the specific support from project stakeholders and universities to establish networks with big data and data security specialists. (D) There is a lack of recognition of the importance of developing skill sets for handling big data across disciplines and lack of institutional capacity available to train ECRs. Large-scale data science initiatives can help to maximize the use of interdisciplinary data for both individual researchers and the research community as a whole by providing

concepts, analytical tools, and training materials (e.g., the Big Data to Knowledge initiative of the National Institutes of Health for biomedical big data; Margolis et al., 2014). Such initiatives will likely disproportionately improve ECRs' data-related challenges.

Systemic Causes

(A) Traditional division of academic disciplines continues to hinder smooth communication of data and interdisciplinary results. For example, professional societies and publication outlets are often organized by a specialist topic and may not promote interdisciplinary content or have trained interdisciplinary editors and reviewers, who can translate the languages of different disciplines and uphold the quality of interdisciplinary research (McLeish and Strang, 2016). (B) We noted a lack of research funding and human resources invested in continuous monitoring programs and long-term data collection. (C) The conflicts of interests between the scientific community, universities, institutes, researchers, and project stakeholders hinder the data acquisition process of ECRs, for example through access to potential data sources. (D) The lack of a common data framework established by international regulatory bodies.

CONCLUDING THOUGHTS

Interdisciplinary research centers are well-positioned to both lead work to solve complex ocean challenges and to share knowledge through collaborations between public, private, academic, and community groups. We encourage researchers tackling global environmental challenges to increase collaboration across fields but also across career stages. In particular, we encourage more senior researchers and institutes to include and support ECRs in their long-term funding planning, their research networks, and their active research to help overcome the above-described barriers (**Supplementary Tables 1–3**).

Finally, as ECRs in Norway, we recognize our privilege in earning a salary through our research that enables us to live comfortably without the necessity of a second job, and with a reasonable level of job security for the duration of our contracts. These conditions contribute to a better work environment than is the case for many ECRs globally. It is likely that ECRs at other research centers, within and outside of Norway, will experience additional barriers and may differ in terms of priorities (for limitations of this study, see **Supplementary Material**: Limitations of this study). In sum, we consider that the barriers highlighted in this article are likely to be close to baseline that is applicable to ECRs around the world (**Table 1**). We suggest that shorter research visits and exchanges with partner sites could be explored to replace contractual relocation during temporary and short-term contracts (Barrier 1). This will continue to encourage knowledge transfer as well as enable ECRs to establish successful interdisciplinary projects at a "home institute." Creation of interdisciplinary strategies and infrastructure for collaboration by institutions could enable knowledge sharing both within and between institutions, improve access to methods within the research community, and facilitate networking opportunities for ECRs (Barrier 2). Improved data management standards and associated training at all career stages will reduce data-related barriers to interdisciplinary research for ECRs and all levels of a research organization (Barrier 3). We hope our perspective will help to improve the work and working conditions for ECRs in interdisciplinary settings and ultimately improve the search for solutions to complex ocean challenges.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

AD and AM conceived, designed, and organized the workshops and the resulting perspective together and wrote a first draft of this manuscript with main help from JP, as well as inputs from all co-authors via the workshop events and on an initial outline. All authors critically revised the text.

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SUPPLEMENTARY MATERIAL

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Entering Negotiations: Early-Career Perspectives on the UN Conference of Parties and the Unfolding Climate Crisis

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As the pressure to address the climate crisis builds, scientists must walk the line between research and activism. This was apparent at the 2019 United Nations (UN) Framework Convention on Climate Change – Conference of the Parties (UNFCCC – COP), the largest annual meeting to address the climate crisis via supranational policymaking. COP has convened annually since 1995 in effort to establish international agreements for the reduction of greenhouse gas emissions, and in 2015, was the launch pad for the UN Paris Climate Agreement (PCA). Here, we present our collective perspective as early-career researchers on COP, an institution that we believe plays a critical role in the future of our oceans. Given the current pledges from signatories to the PCA, Earth is expected to warm ∼3°C by 2100, with the majority of anthropogenic heat content stored throughout the ocean. For this reason, among others, we feel it is crucial for ocean scientists to have a baseline understanding of the negotiations unfolding at COP and within the UNFCCC. We also provide evidence that certain features/structures of COP formalize colonial hierarchies, marginalize certain groups, and threaten to perpetuate the drivers of the environmental crises we all face. Thus, we urge that the future of such gatherings include purposeful and self-reflective acts of restructuring the space they occupy, the solutions they advocate, and the ways in which power is distributed amongst participants. We balance our critique with examples of how this has already been successful at COP, particularly with respect to organizing around ocean-climate issues.

Keywords: conservation, climate change, United Nations, climate justice, climate policy, ocean-climate action

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INTRODUCTION

Describing climate change as a "crisis" is not hyperbole (IPCC, 2014, 2018, 2019). In addition to higher mean temperatures, climate change means more frequent exposure to extreme weather events (IPCC, 2014, 2018); a greater likelihood of heatwaves, both terrestrial and marine (Frölicher and Laufkötter, 2018); desertification in some areas, inundation and drowning in others

(Hirabayashi et al., 2013; Burrell et al., 2020). Climate change is likely to alter the form and function of nearly every system on Earth (IPCC, 2014, 2018), and it is imperative that all people collaborate to abate the emissions trapping excess heat in our atmosphere. For this reason, supranational dialog and consensus building such as that of the United Nations (UN) Framework Convention on Climate Change (UNFCCC) has a valuable role to play.

Convened in 1994, the UNFCCC aims to "prevent dangerous anthropogenic interference with Earth's climate system,"[1] in coordination with other UN departments and affiliate agencies working to accomplish relevant climate and humanitarian goals (e.g., the "2030 Agenda for Sustainable Development"). The UNFCCC holds an annual state-of-the-science and climate policy conference known colloquially as "COP" (i.e., the Conference of the Parties; est. 1995). At COP21 (Paris, France; 2015), the UN Paris Climate Agreement (PCA) was signed into international law (UNFCCC, 2015). The PCA is a multinational environmental treaty designed to limit anthropogenic warming to 2°C above the pre-industrial average through country-specific pledges to decarbonize known as "NDCs" (Nationally Determined Contributions). Countries are expected to re-up their NDCs at the next COP (COP26) in Glasgow, Scotland – which, as they are currently written, are likely to result in 2.9–3.4°C warming by 2100 (IPCC, 2018). The majority of anthropogenic heat content is or will be stored in the marine environment (IPCC, 2019), yet, it was not until Paris that negotiators with the UNFCCC began to substantively integrate the ocean into plans for climate action (Gallo et al., 2017). For these reasons, we feel it is critical for ocean scientists to have a baseline understanding of the negotiations currently unfolding at COP.

Since 2015, COP gatherings have largely focused on codifying the Paris Rulebook, which tells countries precisely how they should work together to respond to this existential threat. Major technical decisions are negotiated in advance by the UNFCCC's Subsidiary Bodies (listed in **Table 1**) during intersessional and pre-COP meetings (which function much like COP but with fewer Observers). COP on the other hand is a highly visible forum for the final stages of negotiations, during which voting representatives from every one of the Framework's 197 Parties must reach consensus to advance any particular outcome.

Six authors of this piece attended COP25 in Madrid, Spain (2019) as graduate student researchers at Scripps Institution of Oceanography with the University of California delegation. Many of us have additional experience from COPs 22 (Marrakesh, Morocco), 23 (Bonn, Germany), and 24 (Katowice, Poland). Our perspectives are informed by our professional experience and education in Earth, Ocean, and Atmospheric Science, framed by our own identities as individuals who are young, multi-ethnic, mostly women, graduate degree-holding, and multinational. We view the COP process as a critical vehicle for global dialog and emphatically support unified action to reduce harm associated with the climate crisis. However, as relative newcomers to the UNFCCC process, we've experienced a felt-disconnect between the strategies to reduce greenhouse gas emissions embraced within the formal COP negotiations and the more holistic, justice-centered approaches advocated for outside of those chambers (Goodman, 2019) (**Figure 1**). In an effort to lower the barriers to entering and understanding the COP process, we describe some of the lessons we've learned and present a list of key terms to help orient readers to the intricacies of the Conference itself and the Framework under which it's come to be (**Table 1**).

At COP we've witnessed two related issues which we view as obstacles to just international climate policy: the perpetuation of structural/institutional barriers to equitable inclusion of diverse constituents in decision-making; and a pronounced focus on market-based climate solutions, while largely skirting issues related to resource consumption. We explore these ideas in sections ""Setting the Stage" – Consensus of the Powerful" through "The Push for Representation at COP and Within the UNFCCC" of this article, while attempting to balance our critique with examples of COP actors working to solve many of the issues we've observed. In sections "The Push for Representation at COP and Within the UNFCCC" and "Power to the People Sees Direct Ocean 'wins,'" we highlight aspects of COP that we feel are worthy praise and outline how collective action and organizing have effectively paved the way for supranational ocean-climate action.

"SETTING THE STAGE" – CONSENSUS OF THE POWERFUL

Conference of the Parties itself is a massive enterprise, hosting tens of thousands of attendees in convention centers that stretch for multiple city blocks. Policymaking occurs in restricted-access areas of the convention hall between UN negotiators. An extensive, vibrant, Civil Society Zone is open to members of the press and representatives of observer organizations, which are entities that have been approved to attend (e.g., NGOs, IGOs, and industry representatives). Many of the observer organizations have self-organized around shared interests or perspectives to form cooperative constituency organizations. Nine constituencies are officially recognized by the UNFCCC (**Table 1**), including the Research and Independent NGOs constituency (RINGO) which hosted our participation.

The strength of COP is that, as an international body, it has a mandate to address transnational impacts of climate change mitigation and adaptation. Requiring consensus among PCA Parties enhances this positive characteristic, however, post-colonial political boundaries ensure that many communities remain politically disenfranchised when it comes to voting (e.g., Sealy-Higgins, 2017). For example, the *de facto* reliance on recognized nation states as Parties to the PCA is poorly aligned with the sentiments expressed in the UN Declaration on the Rights of Indigenous People (The United Nations General Assembly, 2007). Groups who have and continue to benefit most from the extraction and consumption of material goods (and high emissions) appear to have the greatest representation across negotiations, exacerbated by the fact that a country's

[1] http://unfccc.int/about-us/about-the-secretariat

TABLE 1 | Definitions and reference materials for (i) Acronyms, (ii) Participants, (iii) Key terms, (iv) Relevant texts and entities invoked throughout the text.

	Definition and/or brief explanation	Historical context and general references
(i) Acronyms		
UN	United Nations	The UN was founded in 1945, after the Second World War. As an organization, it work to maintain international peace and security, develop friendly relations among nations, and to promote social progress, better living standards, and human rights To learn more, visit: https://www.un.org/en/
UNFCCC	United Nations Framework Convention on Climate Change It is also known, simply, as the "Convention." Its objectives are outlined in the section "Introduction" of this article	In 1992, countries joined an international treaty, the UNFCCC, as a framework for international cooperation to combat climate change and cope with its impacts To learn more, visit: https://unfccc.int
IPCC	The Intergovernmental Panel on Climate Change An independent scientific body under the UN tasked with assessing/summarizing the science related to climate change. It provides regular scientific assessments on climate change, future risks, adaptation, and mitigation	The IPCC was established in 1988, to provide policymakers with regular scientific assessments on the current state of knowledge about climate change Visit: https://www.ipcc.ch
PCA	(UN) Paris Climate Agreement, or simply "The Paris Agreement" The PCA is a landmark agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future. It brings all nations to undertake ambitious efforts to combat climate change and adapt to its effects	The language of the PCA was negotiated during COP 21 and adopted by consensus on December 12th, 2015. As of March 2021, 191 out of 197 UNFCCC Parties have formally adopted the PCA To learn more, visit: https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement
NDCs	Nationally Determined Contributions NDCs refer to countries' commitments pledged under the PCA in an effort to reduce emissions and adapt to climate change at a national level	The concept derives from the Intended Nationally Determined Contributions (INDC), which were reductions in greenhouse gas emissions pledged under the UNFCCC. In 2015, with the adoption of the PCA, INDCs became the NDCs for those countries that have ratified the PCA To learn more, visit: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/nationally-determined-contributions-ndcs
COP	(UNFCCC) Conference of the Parties The COP is the supreme decision-making body of the UNFCCC and is made up of all States that are Parties to the Convention. One of the key tasks is to review the national communications and emission inventories by the Parties	The COP has met every year since 1995, excluding 2020, to review the implementation of the UNFCCC. At COP3 (1997), the Kyoto Protocol was adopted. Eighteen years later, the PCA was adopted at COP21 (2015) To learn more, visit: https://unfccc.int/process/bodies/supreme-bodies/conference-of-the-parties-cop
SBSTA	(UNFCCC) Subsidiary Body for Scientific and Technological Advice The SBSTA's area of work includes synthesizing the impacts, vulnerability and adaptation capabilities of countries to climate change, while also promoting the transfer of IPCC scientific knowledge, development and transfer of environmentally-sound technologies, and preparing/reviewing greenhouse gas emission inventories	Established at the first COP (1995; Berlin, Germany), the SBSTA is mandated by Article 9 of the UNFCCC To learn more, visit: https://unfccc.int/process/bodies/subsidiary-bodies/sbsta
SBI	(UNFCCC) Subsidiary Body on Implementation The SBI works at the heart of all implementation issues under the Convention, the Kyoto Protocol, and the PCA. The SBI agenda to implement treaties and instruments are based on transparency, mitigation, adaptation, finance, technology and capacity-building	Established at the first COP (1995; Berlin, Germany), the SBI is mandated by Article 10 of the UNFCCC To learn more, visit: https://unfccc.int/process/bodies/subsidiary-bodies/sbi
LDCs	"Least Developed Countries" In the UN context, this nomer is applied to 47 low-income countries confronting severe structural impediments to sustainable development, highly vulnerable to economic and environmental shock. They have the lowest indicators of socioeconomic development and the lowest Human Development Index	The concept originated in the late 1960s, and was adopted by the UN in 1971 To learn more, visit: https://www.un.org/development/desa/dpad/least-developed-country-category.html
SIDS	"Small Island Developing States" This nomer applies to 38 member States (countries), whose islands are located in the Caribbean Sea and the Atlantic, Indian and Pacific Oceans	The SIDS were recognized as a distinct group of developing countries in June 1992, at the UN Conference on Environment and Development. The SIDS have demonstrated tremendous leadership in raising ambition to reduce greenhouse gas emissions to limit global warming below 1.5°C To learn more, visit: https://sustainabledevelopment.un.org/sids/partnershipframework

(Continued)

TABLE 1 | Continued

	Definition and/or brief explanation	Historical context and general references
LCIP	"Local Communities and Indigenous Peoples" A term used by the United Nations to describe local and Indigenous communities, whose perspectives have, historically, been underrepresented in UNFCCC negotiations. We use the term relative to the LCIP Platform and Facilitative Working Group discussed in section "The Push for Representation at Cop and Within the UNFCCC"	To learn more about this term relative the LCIP Platform and Facilitative Working Group, visit: https://unfccc.int/LCIPP
(ii) Participants		
Parties	Countries, territories and supranational entities that are signatories of the UNFCCC	To learn more, visit: https://unfccc.int/process/parties-non-party-stakeholders/parties-convention-and-observer-states
Party Groupings*	Party Groupings (e.g., SIDs or LDCs) allow Party negotiators to form political alliances along similar sociopolitical, economic, and historical axes. These blocs can dramatically alter the cadence, tone, and success of COP negotiations	To learn more about officially-recognized Party Groupings, visit: https://www.carbonbrief.org/interactive-the-negotiating-alliances-at-the-paris-climate-conference
Delegations	Each Party to the Convention and the Kyoto Protocol are represented at sessions of the Convention by a national delegation. Delegations consist of one or more officials (delegates) empowered to represent and negotiate on behalf of their country's (or constituents') best interests	Contact information for all 193 Member States (name of their Ambassador, officials and staff members), is listed in the last "Blue Book," released in September 2020. To download the latest, visit: https://bluebook.unmeetings.org/ To learn more about delegations, visit: https://www.un.org/en/sections/resources-different-audiences/delegates/index.html
Negotiators	These are representatives of Party delegations that have access to the high-level negotiation processes and meetings. Some negotiators *vote* on behalf of their Party	To learn more about COP negotiators, visit: https://www.un.org/en/model-united-nations/fundamentals-negotiation
Constituencies	Loose groups of NGOs with diverse but broadly clustered interests or perspectives. At this point in time, Constituencies do not have the power to vote but can "intervene" in COP negotiations We discuss the importance of Constituencies within the main body of this text	Groups that communicate systematically with the Secretariat and the Parties. They are currently nine formally-recognized constituencies: BINGO (Business and Industry NGOs) ENGO (Environmental NGOs) Farmers (Farmers and agricultural NGOs) IPO (Indigenous Peoples Organizations) LGMA (Local Government and Municipal Authorities) RINGO (Research and Independent NGOs), TUNGO (Trade Union NGOs) WGC (Women and Gender Constituency), and YOUNGO (Youth NGOs) See https://unfccc.int/process-and-meetings/parties-non-party-stakeholders/non-party-stakeholders/information-by-category-of-observer/admitted-ngos#eq-2
Observers	Refers to a diverse range of non-governmental organizations (NGOs), intergovernmental organizations (IGOs), industry representatives, relevant to the UN System and its Specialized Agencies. These groups have the status of "non-party stakeholders," meaning that they do not have the power to vote and may be barred from certain closed sessions or negotiations. For example, we attended as Observers hosted by the RINGO constituency	To learn more about Observers, visit: https://unfccc.int/process-and-meetings/parties-non-party-stakeholders/non-party-stakeholders/overview
(iii) Key Terms		
Equality (in context)	To ensure that all individuals have equal opportunities to make the most of their lives and talents. In the COP context, equality means that all Parties to the PCA have the right to vote or veto during the high-level negotiation process	See below
Equity (in context)	The fair treatment, access, opportunity, and advancement for all people. In the COP context, equity means that all Parties would have the same power and leverage during the high-level negotiation process	The first meanings of "equity" in English were a direct translation from the original Old French *equité*, a word whose Latin root means "even," "just," and "equal" To learn more about the difference between "equity" and "equality," we suggest reading: https://independentsector.org/resource/why-diversity-equity-and-inclusion-matter/
[Climate] Reparations	Here, reparations are best understood within the context of "loss and damage," articulated by Article 8 of the PCA. The term "loss and damage" is used by the UNFCCC to refer to the harms caused by climate change. The appropriate reparations/compensation for these harms is especially sought after and supported by vulnerable and "developing" countries, e.g., LDCs. However, some "developed" countries have resisted the inclusion of reparations and compensation as policy mechanisms to right climate wrongs	During the draft of the UNFCCC, in 1991, the Alliance of Small Island States (AOSIS) proposed the creation of an international insurance pool to "compensate the most vulnerable small islands and low-lying coastal developing countries for loss and damage arising from sea level rise." Countries most responsible for global emissions and higher GDPs would offer a larger contribution to this pool of funding. The proposal was rejected when the UNFCCC was adopted in 1992, without mention of loss or damages to it. The concepts of "loss and damage" and "reparations" were vividly debated during COP25 To learn more, we suggest reading *The Case for Climate Reparations* by Táíwò and Cibralic (2020)
Threat multiplier	Climate change intersects with other factors to contribute to negative security problems. Climate change is currently impeding and will continue to impede living standards in many countries, causing widespread political instability and a greater likelihood of conflict (e.g., the Syrian civil war)	The 2007 CNA Military Advisory Board (MAB) report on climate security introduced this term to recognize that there is a link between climate change and security: https://www.cna.org/CNA_files/pdf/National%20Security%20and%20the%20Threat%20of%20Climate%20Change.pdf See also: https://journals.ametsoc.org/wcas/article/6/3/331/970
Environmental refugees	People who have been forced to leave their traditional homelands, temporarily or permanently, because of environmental disruption that jeopardizes their existence and/or seriously infringes upon the quality of their lives	Defined by UNEP researcher Essam El-Hinnawi in 1985. See: https://www.kcet.org/shows/earth-focus/1-billion-people-may-become-climate-refugees-by-2050
Hegemony	Hegemony refers to the social, political, economic, and ecological dominance exerted by a dominant group or groups	Depending on the context, the term "hegemony" frequently connotes cultural imperialism as well as the eradication/erasure of non-dominant thinking, practices, and ways of life

(Continued)

TABLE 1 | Continued

	Definition and/or brief explanation	Historical context and general references
"Degrowth"	"Degrowth" as described by Hickel (2020) refers to the "planned reduction of energy and resource use designed to bring the economy back into balance with the living world in a way that reduces inequality and improves human well-being." It is *not* synonymous with "recession"	There is a growing body of literature surrounding the idea of "degrowth," including critique of the term itself. See article by Hickel (2020) for a summary and clarification of this term/movement. Additionally, please see work by Rodríguez-Labajos et al. (2019) for a thoughtful critique of "degrowth" and its relationship to environmental justice movements in territories affected by a long-standing history of colonialism and imperialism, experiencing differential economic and social change
Frontline communities*	Communities that are the first to be and are acutely affected by climate change. These communities are often composed of people of color or people from low-income communities	To learn more, visit: https://ecotrust.org/centering-frontline-communities/
(iv) Relevant Texts and Entities		
The Paris Rulebook	Detailed rules and procedures to implement the PCA Sometimes referred to, simply, as "the Rulebook"	Adopted in 2018 To download a *Brief Guide to the Paris Agreement and 'Rulebook'*, visit: https://www.c2es.org/site/assets/uploads/2019/06/paris-agreement-and-rulebook-guide.pdf
Article 6 (of the PCA)	Part of the PCA informally referred to as the "market article." It provides a framework for general cooperation in the implementation of the PCA and NDCs. Currently, Article 6 lacks precise provisions to create a framework that will enable the creation of an international carbon market	To review Article 8, consult the PCA available at: https://unfccc.int/process/the-paris-agreement/status-of-ratification#:$\sim$:text=191%20Parties%20out%20of%20197,the%20Paris%20Agreement%20was%20achieved
Article 8 (of the PCA)	Article 8 of the PCA describes the provision for climate "loss and damages." This article is not yet finalized and is seen as highly contentious in some circles	To review Article 8, consult the PCA available at: https://unfccc.int/process/the-paris-agreement/status-of-ratification#:$\sim$:text=191%20Parties%20out%20of%20197,the%20Paris%20Agreement%20was%20achieved We also recommended this as further reading: https://www.tandfonline.com/doi/full/10.1080/14693062.2020.1778885
The Green Climate Fund (GCF)	The world's largest fund to help "developing" countries to reduce their greenhouse gas emissions and enhance their ability to respond to climate change We touch on the pros and cons to the GCF Fund in section "Understanding How Proposed Climate "Solutions" May Perpetuate Crises" of this article	Set up by the UNFCCC in 2010, the GCF is intended to play a critical role in achieving the Paris Agreement. It was designed to support the goal of keeping average global temperatures well below + 2°C by providing funds for improvements to low-carbon infrastructure in "developing" countries To learn more about the GCF, visit: https://www.greenclimate.fund/about
Fridays for Future	This is an international movement of youth activists (mostly pre-college students) who forgo Friday classes to participate in demonstrations to demand action from politicians. Fridays for Future demands climate action in accordance with the 1.5°C target among other key climate goals We mention the important role that Fridays for Future has played in altering COP negotiations in section "The Push for Representation at Cop and Within the UNFCCC"	This movement originated in August, 2018, after Greta Thunberg, a youth activist, sat in front of the Swedish parliament to protest against the lack of action on the climate change crisis. Since then, it's grown into an international phenomenon, helping to unite youth organizers from all around the world To learn more about Fridays for Future, their demands, and organizing, visit: https://fridaysforfuture.org/
Local Communities and Indigenous Peoples Platform (LCIPP)	This platform, which we introduce in section "The Push for Representation at Cop and Within the UNFCCC," was established with the purpose of sharing knowledge, exchange experiences and enhancing the engagement of local communities and Indigenous peoples within the UNFCCC process	Established during COP 23 in Bonn in accordance with the Paris Agreement and Decision 1/CP.21, the LCIPP explicitly states that the rights of local communities and Indigenous peoples need be respected, promoted and considered when taking action to address climate change To learn more about work from the LCIPP, visit: https://unfccc.int/LCIPP
UN Convention on Biological Diversity (CBD)	The (UN) CBD is a multilateral treaty, with three main goals: the conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of benefits arising from genetic sources We touch on the role of the CBD in section "The Push for Representation at Cop and Within the UNFCCC."	The CBD was inspired by the world community's growing commitment to sustainable development. It opened for signatures on June, 1992, at the UN conference on Environment and Development (a.k.a. the Rio "Earth Summit"), and entered into effect on December 29, 1993 Visit: https://www.cbd.int
Friends of Ocean Action	A coalition of over 50 ocean leaders who are fast-tracking solutions to the most pressing challenges facing the ocean. Its members come from business, civil society, international organizations, science and technology sectors We touch on the importance of this coalition in section "Conclusion" of this article	To learn more about Friends of Ocean Action, visit: https://www.weforum.org/friends-of-ocean-action/who-we-are
Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES)*	The intergovernmental body that assesses the state of biodiversity and of the ecosystem services it provides to society, in response to requests from decision makers. In some respects, IPBES generates and synthesizes knowledge surrounding the status of global biodiversity and ecosystem services similarly to how the IPCC does for climate change	In June, 2010, States at a meeting on biodiversity and ecosystem services, adopted a document that stated, "an intergovernmental science-policy platform for biodiversity and ecosystem services should be established." In April, 2012, States established IPBES as "an independent intergovernmental body," with its Secretariat located in Bonn, Germany To learn more, visit: https://ipbes.net
International Indigenous Peoples' Forum on Climate Change (IIPFCC)*	Representative members of Indigenous peoples who attend COPs and SBSTA/SBI meetings. IIPFCC's mandate is to come into agreement specifically on what Indigenous peoples will negotiate for in specific UNFCCC arenas	The IIPFCC was established in 2008 as the formal space of constituents for the negotiating body of Indigenous peoples in the UNFCCC To learn more about the IPFCC, visit: http://www.iipfcc.org/

Terms or phrases marked with an asterisk (*) are not explicitly referred to in the article but are still relevant. We encourage readers to utilize this as an "orientation guide" for understanding the rather complex organizational and intellectual networks within which COP is embedded.

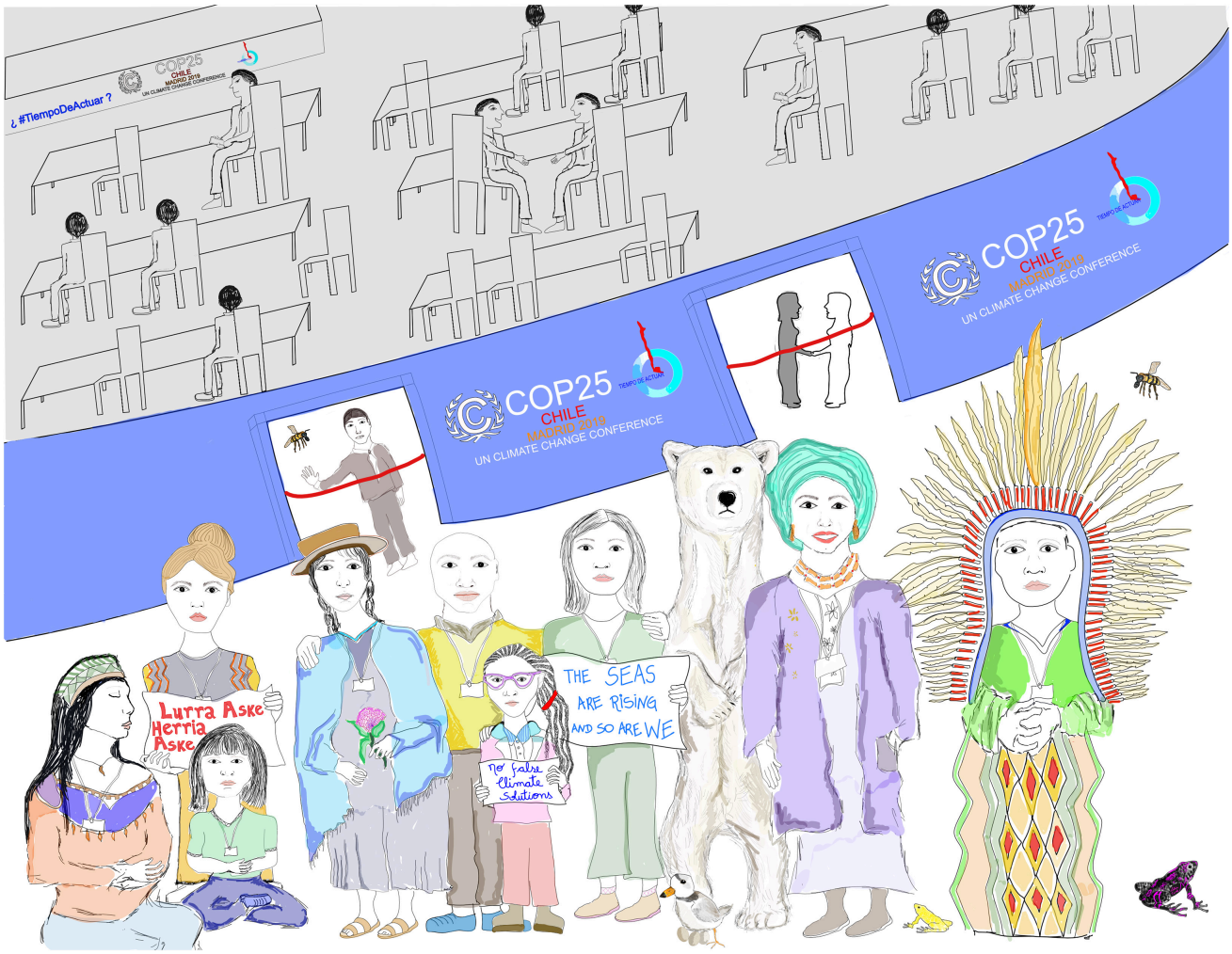

FIGURE 1 | The two realities of the Conference of Parties 25 (COP 25) inside the Baker Hall at Feria de Madrid, Spain. In the main plenary room, high-level negotiations/meetings are held. Outside, Observers gather to make their voices heard, including representatives from Indigenous communities, youth organizations, the Women and Gender Constituency among many others. COP participants frequently wear clothes or hold up signs that reflect their identity and core values. Animals are also depicted here since they are indirectly represented at COP by various observer organizations. Original artwork by author Leticia Cavole.

Party does not necessarily represent the interests of all its constituents/communities.

Despite the egalitarian objective of the UN to maintain international peace, we have observed that COP functions a bit like a microcosm of the world we live in, where the worldviews of some have been notoriously excluded or are systemically undervalued borne from intersecting forms of oppression, such as racism, sexism, ageism, homophobia, transphobia, and religious discrimination among others (e.g., see Soumaré, 2021). Communities (and countries) that have been excluded from and/or explicitly targeted by dominant socioeconomic structures may have a seat at the table, but at this time, must use that platform to request alliance, compassion, and financial support for adaptation, loss and damages (e.g., Sealy-Higgins, 2017; see PCA Article 8). This highlights the distinction between equality and equity, and demonstrates why the equality offered by consensus may be insufficient to provoke meaningful change and reparations for climate damage already done.

UNDERSTANDING HOW PROPOSED CLIMATE "SOLUTIONS" MAY PERPETUATE CRISES

To achieve a "good life for all within planetary boundaries," it is essential that we reduce the level of resources associated with a high standard of living (O'Neill et al., 2018). This includes a more equitable per capita consumption of resources (Giljum et al., 2009) as well as protections for communities and ecosystems that have been historically exploited. This knowledge permeates the negotiations at COP, however, it is not politically popular to discuss the fact that economic growth – while a primary need in many parts of

the world (Rodríguez-Labajos et al., 2019; Hickel, 2020) – is counterbalanced by a need for "degrowth" (**Table 1**) in places where resource consumption is disproportionately high (Rodríguez-Labajos et al., 2019; Hickel, 2020). For reasons we suspect are related to the financial interests of a minority of wealthy/powerful people, lobbies, and Parties (who have no intention of advocating for decreased material consumption or "degrowth"), market-driven and technocratic solutions to climate change are heavily favored in COP negotiations overall (Bachram, 2004; Fernandes and Girard, 2011; Sealey-Huggins, 2017). We feel that it is important to contextualize these proposals and their actual potential to mitigate climate change.

Regarding market-driven solutions, the lynchpin of COP25 was in deciding the outcomes of specific subpoints in PCA – Article 6 (**Table 1**), dealing with the regulation of carbon-trading markets. These schemas (e.g., carbon offsets) are highly contentious, present a false substitute for decarbonization, and have been criticized as a modern-day extension of colonialism and imperialism (Bachram, 2004; Sealey-Huggins, 2017). Another utilization of "the market" within the UNFCCC that we find to be more appropriate is the Green Climate Fund (GCF), which is intended to redistribute monies from high-emission countries to low-emission countries that are least responsible for climate change but also highly vulnerable to its effects (Táíwò and Cibralic, 2020). While the GCF increasingly relies of private sector financial mechanisms and has, unfortunately, achieved $< 10\%$ of its 2020 $100 billion goal (Táíwò and Cibralic, 2020), we feel that the ideas behind the project, such as monetary redistribution and reparations, are worthy of full consideration at COP.

Under the umbrella of technocratic climate solutions is the push for a "green energy revolution." This movement bears potential for deep decarbonization but is not without its own set of problems. Renewable energy technologies require the raw materials for batteries used in grid storage and electric vehicles, i.e., rare earths and other precious metals. In the span of just 10 years (2018–2028), demand for lithium-ion batteries is forecasted to grow seven-fold (Bibienne et al., 2020), with just a few "developed" countries driving $\sim 90\%$ of the import-market in international trade (Sun et al., 2017). Similar to preceding generations of energy revolution, the current loci of extraction are often Indigenous or colonized lands (Estes, 2018; Whyte, 2020). Lithium is often sourced from the Andean highlands of South America, using a highly destructive process of extraction that threatens access to water and land among local and Indigenous communities. On the other side of the Atlantic Ocean, in Central Africa (mainly in the Democratic Republic of the Congo), people mine for the metallic supplements to lithium batteries (e.g., cobalt) (Banza Lubaba Nkulu et al., 2018). The byproducts of this extraction are toxic (e.g., uranium), jeopardizing the health and wellbeing of people who work in these oft-mismanaged mines as well as the function of local riparian/forest ecosystems (Banza Lubaba Nkulu et al., 2018).

While it may not be immediately obvious, the push for "green" energy is of particular relevance to those who study the ocean. Conflicts and environmental concerns around terrestrial mining may move exploration and exploitation for precious metals offshore via deep-seabed mining, where the impacts of human activity are not well understood and the regulations of mining yet to be defined (Levin et al., 2020). The ornate tapestry of life we've observed in the deep sea represents hundreds of years' worth of development, and huge gaps in information plus challenges in data collection and monitoring exist for deep-sea and midwater environments (Drazen et al., 2020; Levin et al., 2020). This makes it difficult to establish an environmental baseline or to even understand what constitutes serious impacts to these ecosystems (Mengerink et al., 2000; Levin et al., 2016, 2020; Drazen et al., 2020).

Similar to terrestrial mining, seabed mining threatens "non-human" life as well as the communities of people whose culture and subsistence are dependent on healthy oceans (Levin et al., 2016, 2020). These were themes explored during COP25 at the Moana Blue Pacific Pavilion, sponsored by Fiji in combination with other Pacific Island nations. Without political measures to empower Local Communities and Indigenous Peoples ("LCIPs"), the market-driven extraction of metals for green-energy technologies, whether on or off shore, threatens to create populations of environmental refugees, migrating from homelands damaged in the name of climate "solutions" (Isenberg, 2010; Brito-Millan et al., 2019).

Resource extraction driven by the push to mitigate climate change is a territory-crosscutting vulnerability which threatens to perpetuate the environmental crises we face. Instead, we should work thoughtfully to address what we view as one of the root causes of climate change: rapid, inefficient, and *highly* inequitable consumption of resources (O'Neill et al., 2018; Hickel, 2020). As a "threat multiplier" (Huntjens and Nachbar, 2015), climate change will affect everyone, but for some, it's a matter of home or homelessness, "a matter of life or death" (Head of State Hilda Heine of the Republic of Marshall Islands comm., September 2016) (**Figure 2**). To this end, climate "solutions" should be carefully considered and scrutinized based on their social and ecological impacts, including violations to sovereignty and health. We, as authors of this piece but also beneficiaries of tremendous privilege, feel united in a desire to sacrifice material excess and political hegemony for the health and longevity of the planet and each other. We assert that this trade-off is valid, not naive, and should be part of political climate negotiations at the largest scale.

THE PUSH FOR REPRESENTATION AT COP AND WITHIN THE UNFCCC

Despite an ongoing push to represent alternative perspectives within the UNFCCC, COP participants who do not conform to the zeitgeist of proposed climate solutions are frequently marginalized. At COP25, for example, 200 + Observers were temporarily banned from the convention center after staging a sit-in demonstration advocating increased attention to climate justice, and solutions *beyond* carbon markets (McGrath, 2019). This demonstration came on the heels of an earlier protest staged by the organization Fridays for Future (**Table 1**), where youth

FIGURE 2 | Linocut by author Simona Clausnitzer that depicts the lived experience of hurricanes, in particular Hurricane María. The image can be interpreted literally, as a hurricane and its numerous impacts, or more symbolically: watching ourselves twist in a storm system of inequities that caused people living in Puerto Rico to be without power for as much as 328 days following María, largely due to a lack of support from the United States' federal government. As severe weather events worsen in frequency and intensity, it is crucial to have meaningful justice-oriented climate legislation, much of which is being developed at COP.

activists occupied the center stage of the negotiation chamber to demand climate justice in accordance with the IPCC's Special Report on 1.5°C Warming (2018). No doubt, the organizers of these protests will continue to make their voices heard at COP26, and in our opinion, they are successfully altering the tone of climate negotiations.

During the final plenary of the convention, 2 min were allocated to the constituency group for Indigenous Peoples' Organizations (IPOs). IPOs had pushed fruitlessly for negotiators to elaborate on the protection of human rights and Indigenous peoples' rights within the PCA – Article 6, arguing that carbon market approaches directly harm Indigenous communities (Webb and Wentz, 2018). When the time came for the plenary, the President delivering the address attempted to omit their statement, asking instead that they upload it to the website due to a two-day delay in closing the negotiations. In contrast to this act and the history of Indigenous exclusion within the UNFCCC (Sherpa, 2019), negotiators formally constituted the Facilitative Working Group of the LCIP Platform (LCIPP) at COP25. The LCIPP is composed of 14 members: one Party representative from each of the UN's five regional groups; one Party representative from a Small Island Developing State (SIDS); one Party representative from a "Least Developed Country" (LDC); and seven IPO representatives. The core functions of this working group are to: (1) protect and apply traditional knowledge, (2) build capacity for UNFCCC LCIP engagement, and (3) to facilitate strong climate change policy that respects LCIP rights.

Similar efforts to build political representation and power for other historically marginalized groups exist within the UNFCCC, including the Women and Gender Constituency. A UN Environmental Program report (2020) makes clear that climate change has gendered impacts on society, stemming from patriarchal social conditions under which women and girls have less control over resources, wealth, and power – and are exposed to disproportionately high levels of physical and sexual violence resulting from climate instability (Nellemann et al., 2012; UNDP, 2020). Yet, just one-third to two-fifths of UNFCCC leadership roles, Party, or subsidiary delegations, are occupied by women (Greene, 2019; UNFCCC WEDO, 2020). Furthermore, the intersectionality (Crenshaw, 1989) of gender discrimination with (for example) race, ethnicity, socioeconomic status, or disability may heighten vulnerabilities (Nellemann et al., 2012; Vinyeta et al., 2015; UNDP, 2020), especially among groups of people who do not see their experiences reflected by Party representatives.

The political outcomes of COP negotiations also have major impacts on Earth's flora and fauna (IPBES, 2019;

Duarte et al., 2020), but the PCA fails to operationalize their inherent rights to exist and thrive. Countries such as Bolivia have lobbied hard to codify these rights at COP (see PCA Introduction – item 13) and in parallel proceedings (e.g., The World People's Conference on Climate Change and the Rights of Mother Earth, 2010); but it's been difficult to garner political support for the "rights of nature" (see Republic of Ecuador, 2008) as a matter of international law. In this respect, the Rulebook does a poor job at honoring nature's intrinsic value as well as the lives and cultural practices of people for whom human and "non-human" life is spiritually intertwined (McCauley, 2006; Whyte, 2020). It also undervalues the many impending climate consequences associated with mass extinction and biosphere collapse (Anderson-Teixeira et al., 2013; IPBES, 2019). Technically, the UN's Convention on Biodiversity (CBD) is tasked with stemming the contemporaneous crisis of biodiversity loss, but their work is increasingly recognized as inextricably tied to UNFCCC negotiations. And, in a somewhat hopeful turn of events, the Presidency of COP26 will center "Nature" as one of its five "Presidential Campaigns."

As we've described, the politics of climate change adaptation and mitigation have the potential to exploit and amplify pre-existing and intersecting social vulnerabilities. Moreover, a wide breadth of social-ecological knowledge/perspectives will be required to tackle the complex governance challenges and biogeochemical consequences associated with climate change (e.g., IPBES, 2019). For these reasons, equitable representation of historically marginalized groups is paramount in political arenas such as COP, and we propose that the pre-existing infrastructure for official constituencies be leveraged to enfranchise communities that are not well-represented by Parties.

Constituency groups already have enhanced representative power at COP, including access to the Floor in the form of interventions and facilitated exchange with the UNFCCC Secretariat. Their current status as "non-party organizations," however, means that they cannot vote on nor veto official Rulebook language. Constituencies do not represent a single country or territory, rather, they encompass politically cross-cutting groups with common interests, perspectives, and struggles. Thus, developing mechanisms to give constituencies official Party status could bring voting representation for explicitly marginalized groups into the negotiation chambers with enhanced power to advocate for the communities they represent.

We recognize, however, that representation (even within leadership positions) may be insufficient to counteract foundational legacies of exclusion; that formal representation is often met with pressure to conform; and that negotiators are people, and no one person can "fix" everything. Thus, without *systemic* accountability practices, the dominant culture may continue to control chambers of power. Additional mechanisms/metrics should be developed to track progress toward meaningful inclusion of diverse perspectives and to promote organizational practices that counteract the long-held influence of power, money, and political hegemony. We contend that these mechanisms must address the multifaceted effects of hierarchy by ensuring inclusion and actively combating prejudice (e.g., practicing anti-racism) within the organization.

POWER TO THE PEOPLE SEES DIRECT OCEAN "WINS"

Culminating at COP25, we've seen how the political organization of communities from historically marginalized groups can fundamentally change the outcome of negotiations, whereby Fiji and its many allies through the "Friends of the Ocean" coalition (**Table 1**) secured attention for ocean-climate action in future UNFCCC negotiations. Specifically, the coalition laid the groundwork for future SBSTA discussions related to ocean-climate action and ocean-based solutions (Decision 1/CP.25)[2]. This represents an important step because, until COP21, the ocean had been largely excluded from negotiations altogether; this oversight is at odds with the incredible role that the ocean plays in regulating Earth's climate as well as the numerous manifestations of climate change in the marine environment (IPCC, 2019).

In the COPs following COP23 (spearheaded by Fiji), we noticed increases in Indigenous representation and a concerted focus on the ocean-climate nexus. We also observed an increase in both the span and depth of conversations centered on SIDS, the unequal effects of climate change, and the key role that local and Indigenous knowledge/leadership plays in successfully implementing the PCA. This gave way to the ideas behind the LCIPP Facilitative Working Group, and beginning in January 2018, Parties adopted a new facilitative dialog publicly introduced by COP23's President and Fijian Prime Minister (Frank Bainimarama).

This traditional dialog, known as the *Talanoa* dialog, is a solutions-oriented style of decision-making which places emphasis on collective action. It involves storytelling and skill-sharing to build trust and improve negotiations through empathy (Informal Note by COP Presidencies). We support Parties fully integrating and convening through the *Talanoa* or similar dialogs, emphasizing inclusivity and transparency to enact decisions both *for* and *by* all. Moreover, leadership emanating from LCIPs, SIDs, and Pacific Islander communities on issues related to the ocean exemplifies why alternate epistemologies must be integrated into UNFCCC negotiations.

CONCLUSION

Despite the sheer magnitude of the climate crisis, we believe that a better world is possible, and that purposeful restructuring of the UNFCCC/COP process will aid in our shared goal to abate emissions and overcome the negative effects of warming. We have seen how increased representation from diverse constituents and delegations at COP has successfully shifted the narrative on climate change, generating increased attention to intersectional climate justice as well as political interest in our coasts, islands,

[2]https://unfccc.int/documents/210471

and oceans. In writing this piece, we directly address our fellow early-career researchers who find themselves driven to push for climate action beyond their role in science, and hope that our experiences motivate an increased attention to the global climate negotiations that will undoubtedly shape the future of our lives and the oceans we love.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

EH conceived the initial idea for this manuscript and EMF organized its execution. DFD, EMF, EH, RS, and TCO worked to develop the original content for the manuscript. EMF and EH contributed the first drafts of the manuscript. LMC, SC, DFD, EMF, EH, TCO, and RS helped to contribute with the subsequent framing, writing, and revisions. EMF, EH, and SC served as the main editors for the manuscript. LMC, DFD, TCO, and EMF prepared the table. LMC and SC contributed to the original artwork to this manuscript. All authors contributed to the article and approved the submitted version.

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frontiers in Marine Science

METHODS
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A Dynamic Stress-Scape Framework to Evaluate Potential Effects of Multiple Environmental Stressors on Gulf of Alaska Juvenile Pacific Cod

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Quantifying the spatial and temporal footprint of multiple environmental stressors on marine fisheries is imperative to understanding the effects of changing ocean conditions on living marine resources. Pacific Cod *(Gadus macrocephalus)*, an important marine species in the Gulf of Alaska ecosystem, has declined dramatically in recent years, likely in response to extreme environmental variability in the Gulf of Alaska related to anomalous marine heatwave conditions in 2014–2016 and 2019. Here, we evaluate the effects of two potential environmental stressors, temperature variability and ocean acidification, on the growth of juvenile Pacific Cod in the Gulf of Alaska using a novel machine-learning framework called "stress-scapes," which applies the fundamentals of dynamic seascape classification to both environmental and biological data. Stress-scapes apply a probabilistic self-organizing map (prSOM) machine learning algorithm and Hierarchical Agglomerative Clustering (HAC) analysis to produce distinct, dynamic patches of the ocean that share similar environmental variability and Pacific Cod growth characteristics, preserve the topology of the underlying data, and are robust to non-linear biological patterns. We then compare stress-scape output classes to Pacific Cod growth rates in the field using otolith increment analysis. Our work successfully resolved five dynamic stress-scapes in the coastal Gulf of Alaska ecosystem from 2010 to 2016. We utilized stress-scapes to compare conditions during the 2014–2016 marine heatwave to cooler years immediately prior and found that the stress-scapes captured distinct heatwave and non-heatwave classes, which highlighted high juvenile Pacific Cod growth and anomalous environmental conditions during heatwave conditions. Dominant stress-scapes underestimated juvenile Pacific Cod growth across all study years when compared to otolith-derived field growth rates, highlighting the potential for selective mortality or biological parameters currently missing in the stress-scape model as well as differences in potential growth predicted by the stress-scape and realized growth observed in the field. A sensitivity analysis of the stress-scape classification

result shows that including growth rate data in stress-scape classification adjusts the training of the prSOM, enabling it to distinguish between regions where elevated sea surface temperature is negatively impacting growth rates. Classifications that rely solely on environmental data fail to distinguish these regions. With their incorporation of environmental and non-linear physiological variables across a wide spatio-temporal scale, stress-scapes show promise as an emerging methodology for evaluating the response of marine fisheries to changing ocean conditions in any dynamic marine system where sufficient data are available.

Keywords: stress-scapes, Gulf of Alaska, machine learning, visualization, Pacific cod, multiple environmental stressors

INTRODUCTION

Environmental variability and associated trends induced by climate change can create unique and potentially stressful conditions for marine fisheries that fluctuate through space and time. Increasing water temperatures and ocean acidification related to changing ocean conditions have the potential to negatively impact individual fish – through direct and indirect effects – which can potentially impact fisheries by way of fishable biomass, annual stock productivity, and spatial shifts in the population outside of the traditional fishing areas (Holsman et al., 2020; Laurel and Rogers, 2020). The Gulf of Alaska Pacific Cod (*Gadus macrocephalus)* fishery is one example of a commercial fishery that is highly susceptible to changing ocean conditions. In recent years, Pacific Cod abundance has declined dramatically in the Gulf of Alaska (GOA) ecosystem, leading to a fisheries disaster declaration in 2018 and a closure of the federal fishery in 2020 (Barbeaux et al., 2020). Quantifying the spatial and temporal footprint of modern environmental stressors on GOA Pacific Cod is crucial for ensuring the accuracy of plans and forecasts for this valuable fishery.

Decadal and long-term patterns influence the GOA's thermal variability due to warm-phase shifts of climatic phenomena and background warming related to climate change. The GOA has also experienced two anomalous marine heatwave events in the past decade. Between late 2013 and 2016, a marine heatwave occurred in the GOA that exceeded the magnitude and duration of any other heatwave on record in the region. This heatwave event led to temperature anomalies greater than 2.5°C (Bond et al., 2015; Di Lorenzo and Mantua, 2016) and unprecedented shifts in the region's biological communities, including increases in harmful algal blooms, reductions in fishery recruitment, and mass mortality of marine mammals and seabirds (Leising et al., 2015; Piatt et al., 2020; Suryan et al., 2021). In the summer of 2019, the GOA was impacted by another marine heatwave, leading to similarly extreme temperature anomalies (Amaya et al., 2020). The increasing frequency and intensity of marine heatwaves in the coming years are likely to coincide with challenges to marine fisheries' long-term health (Oliver et al., 2018; Cornwall, 2019).

In addition to thermal variability, there are several sources of environmental variability that co-occur in the GOA and which have the potential to overlap, compound, or negate one another in ways that are still not fully understood (Bopp et al., 2013). Ocean acidification is one such potential stressor and refers to the gradual increase in hydrogen ions and consumption of carbonate ions in marine systems in response to elevated levels of anthropogenic carbon dioxide entering the ecosystem (e.g., Feely et al., 2004; Evans et al., 2014). The GOA, with the naturally lower concentrations of carbonate ions characteristic of high latitude marine habitats, is at higher risk for the effects of ocean acidification as additional losses of carbonate ions can lead to proportionally larger changes in seawater chemistry than would be expected in lower latitude systems (Fabry et al., 2009; Mathis et al., 2011). Additionally, the GOA and Kodiak Island regions are known to have higher seasonal variability in natural surface pCO_2 levels (seasonal amplitudes of as much as 309.8 and 279.4 μatm, respectively) when compared to open ocean environments due to upwelling conditions (Chen and Hu, 2019). Some interactions between sea surface temperature and the carbonate system are known – for example, carbon dioxide becomes less soluble in water as water temperature increases – but the full effects are not yet known in the context of physiological stress to living marine resources (Mathis et al., 2015).

Recent declines in Pacific Cod stocks are likely connected to changing thermal conditions in the GOA. Pacific Cod is a stenothermic species with peak hatch success occurring in 4–5.5°C water (Laurel and Rogers, 2020) and optimal juvenile growth occurring below 13°C in nursery habitats (Hurst et al., 2010). It is likely that Pacific Cod, like other stenothermic species, exhibit stage-specific responses to warming, with potential for thermal bottlenecks between different life stages (Dahlke et al., 2020; Rogers et al., 2020). Early life stages may be particularly sensitive to changes in temperature due to higher metabolic rates in the embryonic, larval, and juvenile stages (e.g., Finn et al., 2002: Werner, 2002). Elevated temperatures in the GOA are associated with high larval mortality of Pacific Cod (Doyle and Mier, 2016) and a larger size at nursery entry. During the 2014–2016 and the 2019 marine heatwaves, it is hypothesized that a loss of suitable spawning habitat during heatwave conditions contributed to declines in Pacific Cod hatch success and consequent older life stages (Laurel and Rogers, 2020).

Pacific Cod also appear to be moderately impacted by ocean acidification in the GOA. Elevated levels of carbon dioxide in the water column during the first two weeks of the larval duration are associated with suppressed growth, although this trend has been shown to reverse as larvae grow (Hurst et al., 2019). By

the juvenile stage, effects of elevated carbon dioxide levels on growth largely disappear (Hurst et al., 2012). It is hypothesized that fishes are better able to withstand the effects of ocean acidification than calcifying marine invertebrates due to their high metabolism and ability to regulate their inter/intracellular acid-base balance (e.g., Melzner et al., 2009). However, elevated levels of carbon dioxide could lead to several indirect impacts on fishes including behavioral changes (e.g., Williams et al., 2019); changes in the biochemical structure of prey (e.g., Cripps et al., 2016); and changes in the abundance of calcifying marine invertebrate prey (e.g., Lischka et al., 2011). Many of the direct and indirect impacts of ocean acidification on cod and other marine finfish species are unknown, and the modest impacts of ocean acidification observed in the laboratory may indeed be "significant" when compounded by other environmental stressors or realized over longer time scales. Here, we do not account for potential interaction between temperature and ocean acidification as further studies are needed to better understand the interactive effects of these two variables on Pacific Cod early life stages.

Quantifying and visualizing environmental conditions in space and time can be beneficial in understanding when and where the Pacific Cod fishery may be most influenced by changing ocean conditions in the GOA. By viewing the ocean as a dynamic mosaic of physical and biogeochemical seascapes, researchers, managers, and other end-users can efficiently communicate information about environmental conditions in the ocean through space and time. This approach is known as dynamic seascape classification (Kavanaugh et al., 2014). Recent advances have allowed for the dynamic classification of ocean regions based on multiple biophysical interactions observable by satellite remote sensing or marine ecosystem models (e.g., Kavanaugh et al., 2018). These dynamic classifications have been used to predict biogeochemical processes (Kavanaugh et al., 2014), phytoplankton structure and function (Kavanaugh et al., 2015; Montes et al., 2020), and individual species occurrences (Breece et al., 2016). The seascape ecology framework has potential utility for quantifying biological and human responses to known environmental stressors, including elevated temperature and ocean pCO2. By applying a dynamic seascape framework in marine resource management contexts, Klajbor (2020) established possible novel relationships between dynamic ocean management principles and socioeconomic vulnerability in fishing communities.

Large, biophysical time series like those used in a seascape ecology approach have been classified in space and time simultaneously using a probabilistic self-organizing map (prSOM) machine learning algorithm (Kavanaugh et al., 2014, 2016, 2018). The prSOM combines two statistical algorithms, K-Means and expectation-maximization, and a machine learning algorithm called the Self-Organizing Map (Kohonen, 1990; Richardson et al., 2003) to approximate the multivariate distribution of data as a mixture of Gaussians and uniform distributions (Anouar et al., 1998; Lebbah et al., 2015). The prSOM algorithm has utility in capturing biological metrics, such as Pacific Cod growth, in addition to environmental metrics because it is robust to non-linear relationships between variables and is topology-preserving. Also, the prSOM algorithm does not rely on data being identically distributed or independent (i.i.d). This feature is critical for classifying complex, potentially non-linear interactions like those found in data from spatio-temporal time series, which are not independent because the current year's classification almost always depends on previous months, years, and nearby regions.

Here, we introduce "stress-scapes" as a novel machine learning framework to understand juvenile Pacific Cod's response to potential environmental stressors across the GOA ecosystem. Juvenile Pacific Cod was selected for this project due to the availability of information and data related to the effects of temperature and ocean acidification on early life stages. While there remain many unknown biological responses to these stressors, both alone and in their potential interactive effects, we incorporate the most recent available data on this critical species for this proof-of-concept study. Stress-scapes incorporate remotely sensed sea surface temperature (SST) data, pCO_2 data, and estimated juvenile Pacific Cod specific growth rate (SGR) into a prSOM algorithm to identify ocean conditions that may be stressful to juvenile Pacific Cod across a broad spatial and temporal scale. The juvenile Pacific Cod stress-scape presented in this study is not intended as a comprehensive reconstruction of Pacific Cod growth history in response to environmental variability in the GOA, but rather as a novel framework to visualize and classify potential environmental stress on the species across space and time. In this way, the stress-scape framework is distinct from an Individual-Based Model (IBM), which is a biophysical model that describes fish growth, recruitment, and mortality as dependent on environmental factors (Hinckley et al., 1996; Hermann and Moore, 2009; Koenigstein et al., 2016). IBMs are often coupled with Regional Ocean Modeling Systems (ROMS) and dispersal models to capture environmental conditions at depth and track the movement of fish in early life stages through their environment (e.g., Stockhausen et al., 2019). An IBM for Pacific Cod has already been developed for the GOA ecosystem (Hinckley et al., 2019).

In our case study, we develop weekly stress-scapes from 2010 to 2016, including marine heatwave conditions in 2014–2016, using existing juvenile Pacific Cod laboratory growth models and remotely sensed environmental data. These stress-scapes are then evaluated spatiotemporally to determine how well they capture changing conditions both seasonally and interannually, including during the marine heatwave event. We then evaluate the sensitivity of the stress-scape model to the Pacific Cod SGR input variable to determine the importance of this variable in influencing the model's classification. Finally, we compare the stress-scape model output to otolith-derived growth data from juvenile Pacific Cod collected from Kodiak Island, AK to comment on the success of the model in capturing processes occurring in the field.

MATERIALS AND METHODS

Environmental Data

Sea surface temperature and sea-surface carbonate chemistry data (pCO_2) were collated for the GOA ecosystem between the

years 2010–2016 (see **Supplementary Material: Appendix A** for spatial extent of environmental data). Environmental data were selected from publicly available modeled, *in situ*, and remotely sensed products. The data's temporal range was selected to include dates before, during, and after the 2014–2016 marine heatwave event. Sea surface temperature data were subset from the National Oceanic and Atmospheric Administration (NOAA) Optimum Reynolds Interpolation SST V2 product provided by the OAR/ESRL PSL, Boulder, Colorado, United States (Reynolds et al., 2002). The product is developed using a combination of *in situ* and remotely sensed data, producing weekly means on a one-degree grid. Associated variance related to each point was also downloaded and used to calculate total error related to the stress-scape classification. Sea-surface carbonate chemistry data were subset from the NOAA National Center for Environmental Information CSIR-ML6 v2019a Global Sea-Surface pCO2 product. A smoothed mean monthly pCO_2 product was selected from their ensemble mean product that is calculated using a combination of 6 machine learning techniques. The smoothed product differs from their raw product, as a $3 \times 3 \times 3$ convolution is applied to the data through time, latitude, and longitude (Gregor et al., 2019). Mean monthly values ranged from 262.6 to 469.4 μatm in the study domain.

Only the environmental data from the known spatial and temporal ranges of Pacific Cod were included in the subsequent machine learning training and stress-scape visualization, ensuring that the selected data and resulting stress-scapes were relevant to juvenile Pacific Cod distribution. Age-0 juvenile Pacific Cod are distributed in shallow, nearshore habitats, typically <30 m depth during their first summer (Laurel et al., 2007, 2009). We used a bathymetric data subset from the General Bathymetric Chart of the Oceans 2020 Gridded Global Bathymetry product (GEBCO Bathymetric Compilation Group 2020, 2020) for 30 m and 100 m isobaths to compare habitat size across both depth distributions. Due to the small size of the habitat at <30 m depth, we selected 100 m depth as the cutoff for the juvenile habitat, acknowledging that this represents a broader habitat range than would be expected for a typical age-0 juvenile Pacific Cod during their first summer and subsequently may bias our interpretation toward cooler temperatures than would be experienced *in situ* (e.g., Laurel et al., 2012). We used a year-round temporal range for the juveniles in the nursery habitat to represent both the first summer in the nursery and overwintering in the nursery. The study's spatial domain only includes the GOA, so any data that our filter included from the Bering Sea were excluded from the training of the prSOM model. Additionally, there were 5 points where the pCO_2 or SST were not available (**Supplementary Material: Appendix B**); rather than attempt to interpolate the data where it was not possible due to missing data, the value of each pixel was set to NaN.

To account for seasonal variance the monthly z-scores were computed for each grid point across the GOA for each of the relevant variables:

$$z_{ij}(\theta, \phi, t) = \frac{x_{ij}(\theta, \phi, t) - \mu_j(\cdot, \cdot, \cdot)}{\sigma_j(\cdot, \cdot, \cdot)}$$

where j is the variable index, i is the observation index and the represents an average value across the entire GOA through time. The spatio-temporal z-scores were used to train the prSOM to compute stress-scape classes across the GOA from 2010 to 2016 (Gregor et al., 2019); hence, the stress-scape classes represent regions that similarly deviate from the spatio-temporal mean.

Juvenile Pacific Cod Growth Data

Juvenile Pacific Cod temperature-dependent growth data were obtained from two existing experimental studies: Laurel et al. (2016) and Hurst et al. (2010). These studies were all conducted in the laboratory using age-0 juveniles collected from the GOA population. Similar growth data related to variable pCO_2 are currently unavailable for age-0 juvenile Pacific Cod [although see Hurst et al. (2019) for earlier life stage responses]. As a proxy, we used the pCO_2 growth response of age-0 juvenile Walleye Pollock (*Gadus chalcogrammus)* based on experimental work from Hurst et al. (2012). While response to ocean acidification is variable among marine finfish, Walleye Pollock are congeners of Pacific Cod and share a similar growth response at the age-0 juvenile stage (Laurel et al., 2016).

A weight-based growth model was used instead of a length-based growth model throughout this stress-scape analysis to better align with potential future bioenergetic applications of the stress-scape to fish bioenergetics. Therefore, a specific growth rate (SGR) model was used to approximate the percent change of fish wet weight over time. SGR were calculated from the formula:

$$SGR = 100\left(e^g - 1\right)$$

where g is the instantaneous growth coefficient obtained from the equation:

$$g = \frac{lnWW_2 - lnWW_1}{t_2 - t_1}$$

where WW_1 is the wet weight of the fish at the beginning of the experiment at time t_1, and WW_2 is the wet weight of the fish at the conclusion of the experiment at time t_2.

A temperature-dependent growth model was developed using a general linear model with SGR as the independent variable and a quadratic temperature term as the dependent variable (Simple Linear Regression; $R^2_{adj} = 0.636$; $P < 0.0001$). Uncertainty in the model was evaluated using 95% confidence intervals and 95% prediction intervals.

Juvenile Pacific Cod growth response to ocean acidification was divided into two potential outcomes: growth under "low" pCO_2 conditions (<1,000 μatm) and growth under "high" pCO_2 conditions (>1,000 μatm). These two classifications represent growth at ambient to moderate pCO_2 concentrations ("low"), and growth at high to very high pCO_2 concentrations ("high"), because juvenile Pacific Cod growth only begins to change as pCO_2 concentrations become very high (e.g., Walleye Pollock; Hurst et al., 2012). Growth under low pCO_2 conditions was unchanged from the temperature-dependent growth curve and was represented by the equation:

$$SGR = 0.059 + 0.290Temp - 0.013Temp^2$$

Growth curves under high pCO_2 conditions were calculated from the percent decrease in growth (−2.3%) observed in Hurst et al. (2012). Specific growth rates from the temperature-dependent growth curves were then depressed to reflect the

percent change in growth that would be expected under elevated pCO_2 conditions. Growth under high pCO_2 conditions was represented by the equation:

$$SGR = 0.061 + 0.297Temp - 0.013Temp^2$$

Classification of Stress-Scapes

Stress-scapes were classified using remotely sensed observations of SST; partial pressure of CO_2 (pCO_2) as an indicator of the carbonate system; and the specific growth rate (SGR) of juvenile Pacific Cod. The prSOM approximates the multivariate distribution of SST, pCO_2 and SGR through space and time. The prSOM was configured with 225 neurons in a 15 × 15 neuron map. Previous efforts in the North Pacific found that this configuration resulted in sufficiently large number of data points (e.g., >500) per node (Kavanaugh et al., 2014). The prSOM algorithm executed 50 epochs in order to give the prSOM enough time to converge. We applied Hierarchical Agglomerative Clustering (HAC) to the 225 neurons grouping them into five individual stress-scapes (e.g., Saraceno et al., 2006; Hales et al., 2012; Kavanaugh et al., 2018).

The SST, pCO_2, and SGR maps of the GOA were interpolated using bilinear interpolation from 14 × 40 grid points to a 780 × 2340 image to classify stress-scape class boundaries in the remotely sensed data. The interpolated image was copied to the Graphics Processing Unit (GPU) memory and classified according to the trained neurons' weight vectors and variances by identifying the stress-scape class most likely to generate each interpolated value in the GOA. Our unique prSOM implementation classified the GOA in parallel using the GPU. Parallel classification is an important distinction because many visualization methods rely on processing done on the Central Processing Unit (CPU), but the amount of data we needed to classify made classification on the CPU impractical. Any consumer-grade GPU released in the past decade can classify the entire GOA in a small number of clock cycles (∼1–100 clock cycles) by taking advantage of massively parallel processing. In contrast, even with a parallel CPU implementation, the number of clock cycles will range from 300,000 to 1.7 million clock cycles on most modern processors. There are 365 time slices, so the classification must be done 365 times; hence the speedup is substantial.

We selected 5 stress-scape classes from the HAC using the Gap Statistic (Tibshirani et al., 2001) which suggested 5 classes with 2 well separated classes and 3 less separated classes. Choosing an optimal number of stress-scapes is difficult as there is no single metric that can select an ideal number of clusters with certainty, and often, the statistically significant number of clusters does not agree with domain expert analysis. For our implementation, we compared results from three different methods of clustering evaluation: the elbow method, the silhouette method, and the Gap Statistic (see **Supplementary Material: Appendix C**). The elbow method works by estimating the amount of variance in the data explained by the clusters, an optimal number of clusters is chosen by identifying the point in the graph where an increase in the number of clusters does not provide additional explanation of the variance. The silhouette method works by estimating the quality of each cluster and then reporting the average quality over all the clusters for increasing number of clusters. An optimal number of clusters can be determined from the silhouette method by choosing a number K for which the quality of the clusters is greater than the quality of the K-1 and K + 1 clusters. The Gap Statistic works by computing the HAC algorithm for an increasing number of clusters. For each number of clusters, from 1 to 10, we computed the inter-cluster sum of square error, the average quality of the clusters, and the gap statistic using the clustGap() function in R.

In order to evaluate the effects of anomalous heatwave conditions on the stress-scape classification results, classification results from 2010 to 2013 were compared to classifications during a known anomaly, the marine heatwave event of 2014–2016, to more normal ocean conditions preceding the heatwave. In comparing the classification results, we identified a dominant stress-scape and examined the qualities of the dominant stress-scape using a decision tree and a table to records the frequency and the environmental characteristics of the stress-scapes. Further details describing our implementation of the prSOM are provided in **Supplementary Material: Appendix C**.

Sensitivity Analysis

We trained a second, bivariate prSOM to compare the results of the stress-scape to a classification that did not include juvenile Pacific Cod SGR. This bivariate classification allowed us to evaluate the sensitivity of the trivariate stress-scape framework to the additional information gained by including the juvenile Pacific Cod SGR variable in the training process. To account for the reduced variance in the bivariate prSOM, we used the Gap Statistic to estimate 4 classes in the bivariate prSOM. We applied Hierarchical Agglomerative clustering until the 225 neurons were merged into 4 distinct stress-scape classes. We focused our comparison efforts on the coastal regions near Kodiak Island.

Pacific Cod Field Growth

Otolith structural analysis of juvenile Pacific Cod collected from Kodiak Island nurseries is being completed as part of a related study (Thalmann et al., unpublished data). Therefore, after developing the lab-based model for juvenile Pacific Cod SGR, training the prSOM algorithm, and generating the mosaic of stress-scapes across the coastal GOA, we estimated otolith-based SGR from these field-collected juveniles to compare with our stress-scape classifications of growth observed in nearshore Kodiak Island nursery habitat. This comparison aimed not to provide a comprehensive analysis of otolith data but rather to identify a relationship between temporal patterns in the otolith-based growth rates and temporal patterns in the stress-scapes. Juvenile Pacific Cod were collected in annual summer beach seine surveys on Kodiak Island in 2010 and 2012–2016 through the NOAA Alaska Fisheries Science Center Fisheries Behavioral Ecology program. Samples were not available in 2011. Pacific Cod were collected from two shallow (<30 m) embayments along the northeastern coast of Kodiak Island during successive days in July each year. Fish were captured using a demersal beach seine (36 m bag with 5-mm mesh; 1 m × 2.25 m wings with 13-mm mesh), sorted to species, counted, and measured (total

length, mm). Samples were then frozen (−20°C) and returned to Hatfield Marine Science Center in Newport, OR for post-processing. During post-processing, standard length (mm) and wet weight (g) were measured, and otoliths were removed for analysis (**Table 1**).

Otolith structural analysis was used to generate growth estimates for field-collected juveniles collected at Kodiak Island. Otoliths are calcium carbonate structures in the inner ear of teleost fishes that can be used to determine age and growth of an individual (Pannella, 1971; Campana and Thorrold, 2001). Otolith size and body size are highly correlated in Pacific Cod (DiMaria et al., 2010; Miller et al., 2016), and daily formation of otolith increments has been validated for Pacific Cod at 10°C up to 120 days post-hatch (Narimatsij et al., 2007). Sagittal otoliths were mounted on glass slides using thermoplastic resin and polished to expose the core in the transverse plane using Wetordry paper (800–2000 grit), Buehler lapping film (3–30 micron grit), and alumina slurry (0.3 micron). Polished otoliths were imaged at 100× and 400× magnification using a Leica DM1000 compound microscope and a Levenhuk M1000 digital camera. Final otolith radius and otolith radius from 8 and 16 days prior to capture were quantified using increment analysis. Daily increments for these two 8-day growth periods (representing three weeks of nursery residence at the same 8-day resolution as the stress-scape model) were counted and measured using ImagePro Premier software. Each otolith was interpreted three times with greater than 80% similarity in mean increment width between reads, and reads were averaged in order to compare otolith-generated estimates of growth to the stress-scape.

First, we estimated fish length and mass at 8-d and 16-d prior to capture based on otolith increment analysis, and then estimated growth in length and mass over these two 8-d periods for comparison with the 8-d prSOM output. Otolith radius measurements and fish standard length were log-transformed to meet parametric assumptions, and a log-linear model with otolith radius, year, and their interaction as independent variables and standard length as a dependent variable was developed (Multiple Linear Regression; R^2_{adj}. = 0.85; $P < 0.0001$; **Supplementary Material: Appendix D**). Using this relationship, we developed a proportional back-calculation model to estimate fish size 8- and 16-d prior to capture using the measured otolith radius from 8- and 16-d prior to capture (Francis, 1990; Campana and Jones, 1992). Length-based growth of juvenile Pacific Cod in mm per day was examined for each year and compared to a mm/d laboratory growth model obtained from the same studies (Hurst et al., 2010; Laurel et al., 2016) as the laboratory SGR model used in the stress-scape analysis.

To estimate juvenile wet weight 8- and 16-d prior to capture, we developed a second log-linear model with standard length and year as independent variables and wet weight as a dependent variable (Multiple Linear Regression; R^2_{adj}. = 0.96; $P < 0.0001$; **Supplementary Material: Appendix D**). Wet weight from 8- and 16-d prior to capture was then determined using a second proportional back-calculation model using estimated standard length from 8- and 16-d prior to capture. Juvenile Pacific Cod SGR in the field was calculated in the same manner as the laboratory SGR model described above from Hurst et al. (2010) and Laurel et al. (2016). We utilized weight-based SGR calculated from otoliths rather than length-based growth estimates for comparison to the stress-scape.

To compare otolith-generated SGR estimates from the 8- and 16- day periods prior to capture with the stress-scape, we determined the dominant stress-scape class for coastal Kodiak Island at an 8-day resolution in July for each year between 2010 and 2016. Mean SGR from the dominant stress-scape class was then compared to otolith-generated SGR for that year using a paired *t*-test. Otolith-generated growth estimates for each year were additionally compared to the temperature-dependent laboratory growth model using a paired *t*-test. We also compared otolith-derived growth rates in heatwave conditions in 2014–2016 to more normal conditions in 2010–2013 using a 1-way analysis of variance.

RESULTS

Stress-Scape Analysis

Utilizing the prSOM and HAC, we resolved 5 unique stress-scapes across the GOA that quantified the spatio-temporal footprint of changing ocean conditions and the modeled specific growth rate (SGR) of juvenile Pacific Cod. **Table 2** describes the means and standard deviations for the SST, pCO_2, and SGR values of each of the resolved classes. Stress-scape classes were determined and distinguished semantically through a decision-tree of z-scores for each input variable, including the characteristics of each decision mode, which effectively describes

TABLE 1 | Annual sample sizes, average fish size, mean July ocean temperature, mean July pCO2 levels, and ocean conditions for juvenile Pacific Cod captured annually in July 2010 and 2012–2016 from Kodiak Island, AK.

Year	Sample size (n)	Fish size (SL; mm)	July temperature (°C)	July pCO_2 (μatm)	Ocean conditions
2010	23	43.35 ± 0.82	10.07 ± 0.15	288.31	Normal
2012	17	41.47 ± 1.17	10.04 ± 0.32	291.00	Normal
2013	19	50.00 ± 1.43	11.64 ± 0.40	295.02	Normal
2014	19	51.79 ± 1.53	12.52 ± 0.23	287.90	Heatwave
2015	9	47.67 ± 1.29	11.69 ± 0.21	300.08	Heatwave
2016	20	62.40 ± 1.16	12.85 ± 0.25	313.57	Heatwave

Samples were not collected in 2011. All samples were collected through the NOAA Alaska Fisheries Science Center (AFSC) as part of the Fisheries Behavioral Ecology Program.

TABLE 2 | Mean values for each of the 5 resolved stress-scapes.

	SST (°C)		SGR $\left(\% \frac{WW}{Day}\right)$		pCO_2 (μatm)		Count	Color
	Mean	Std	Mean	Std	Mean	Std		
Class 1	10.42	2.48	1.4	0.16	359.4	33.66	2895	
Class 2	6.25	2.38	1.04	0.28	340.3	39.99	1856	
Class 3	9.34	2.62	1.34	0.19	346.9	37.12	1515	
Class 4	6.36	2.14	1.06	0.24	370.4	38.18	2403	
Class 5	7.85	2.25	1.22	0.23	339.1	36.41	1331	

Means and standard deviations are included for SST, SGR measured in percent wet weight per day (%WW/day), and pCO_2 concentration values along with a count of the number of remotely sensed data points belonging to each class and their corresponding classification color. The stress-scapes were classified based on the provided environmental data and the decision tree outlined in ***Figure 1****.*

how the classes were sorted (**Figure 1**). Stress-scape classes 2, 3, 4, and 5 (maroon, green, orange, and yellow) were distinguished by their respective growth rate input variables when they were decided by node 5. This highlights the non-linear relationship between SST and SGR. Class 1 (blue) was primarily distinguished by differences in SST and pCO_2.

The stress-scape analysis identified distinct classes that corresponded to heatwave conditions in 2014–2016 compared to more normal ocean conditions in 2010–2013 for both coastal Kodiak Island (**Figure 2**) and the larger GOA coastal ecosystem (**Figure 3**). Animated versions of these figures with corresponding ribbon plots that show how the stress-scapes shift and progress through time can be found in **Supplementary Material: Appendix E**, **Supplementary Videos 1, 2**. At both the Kodiak and regional scales, seasonal and interannual patterns emerge in the incidence of each of the classes. Classes 2 and 5 contract over time, supplanted by expansions (in space and time) of classes 1 and 4. Class 2 is the low SST class that seems to be replaced by high pCO_2 in class 4. Class 5, the pre-heatwave late spring-early summer class, is replaced by class 3, characterized by high SST, during heatwave years. Class 3 starts appearing earlier and persisting each year during the heatwave.

In July, stress-scape class 5 (yellow) dominated the areas around Kodiak Island in 2010 and 2012, whereas stress-scape class 3 (green) expands both around Kodiak and within the greater GOA area during heatwave conditions in 2014, 2015, and 2016. In 2013, stress-scape class 3 and stress-scape class 5 were both present throughout the coastal GOA. Stress-scape class 3 was characterized by above average temperatures (10.42 ± 2.48°C), higher pCO_2, concentrations (359.4 ± 33.66 μatm), and high juvenile Pacific Cod SGR (1.40 ± 0.16% Wet weight/day). In contrast, stress-scape class 5 was characterized by near average temperatures (7.85 ± 2.25°C), lower pCO_2 concentrations (339.1 ± 36.41 μatm), and near average SGR (1.22 ± 0.23% Wet weight/day).

Sensitivity Analysis

The bivariate prSOM, trained on SST and pCO_2 but excluding SGR, resolved four stress-scape classes for the coastal GOA. **Table 3** describes the means and standard deviations for the SST and pCO_2 values of each of the resolved classes used for the sensitivity analysis. By excluding the SGR variable, the dominant stress-scape for coastal Kodiak Island was reclassified to a new stress-scape class 1 (blue), which identifies a mean SST of 10.42 ± 2.48°C and mean pCO2 concentration of 359.4 ± 33.66 μatm across all years of analysis. Stress-scape class 1 of the bivariate model corresponds to stress-scape class 3 of the trivariate-model. **Figure 4** shows the dominant yearly classes for the bivariate prSOM sensitivity analysis near coastal Kodiak Island during the first week of July 2010 and 2012–2016 and should be evaluated using **Table 3**. Stress-scape class 1 is distinguished from the other three classes with its higher-than-average SST and near average pCO_2 concentrations. The bivariate prSOM groups the two higher temperature classes of the trivariate dynamic stress-scape together because it lacks the SGR variable necessary for distinguishing between these classes. In addition, the bivariate prSOM is unable to distinguish between heatwave conditions and more normal ocean conditions in the GOA, with stress-scape class 1 dominant across all six years of the analysis.

Juvenile Nursery Growth

The dynamic stress-scape underestimated the observed juvenile Pacific Cod SGR in its classification schema for coastal Kodiak Island by 39–187% across all six years of the analysis (**Figure 5**). Mean July SGR from the dominant stress-scape for coastal Kodiak Island differed significantly from otolith-derived SGR for both the last 8 days of growth and the penultimate 8 days of growth (paired t-test; last 8 days: $t_5 = 6.72$; $P = 0.0011$; penultimate 8 days: $t_5 = 6.94$; $P = 0.0009$). Otolith-derived SGR were between 10 and 105% higher than the laboratory growth model across all six years for both the last 8 days of growth and the penultimate 8 days of growth (paired t-test; last 8 days: $t_5 = 4.69$; $P = 0.0053$; penultimate 8 days: $t_5 = 5.39$; $P = 0.0029$). In contrast, otolith-derived mm/d growth were between 13% and 79% lower than the laboratory growth model for both the last 8 days of growth and the penultimate 8 days of growth (paired t-test; last 8 days: $t_5 = 6.54$; $P = 0.0012$; penultimate 8 days: $t_5 = 5.71$; $P = 0.0023$). Across all years, field estimated growth rates were similar between heatwave conditions in 2014–2016 compared to more normal ocean conditions in 2010–2013 (1-way ANOVA; $F_{1,102} = 0.75$; $P = 0.39$), highlighting the difference in potential SGR predicted by the prSOM and the realized SGR observed in the field during heatwave conditions.

DISCUSSION

The application of seascape ecology methods to the evaluation of potential environmental stressors across a wide spatio-temporal scale on juvenile GOA Pacific Cod represents a new approach to visualize and synthesize the effects of extreme environmental variability on marine fisheries. Five dynamic stress-scapes were resolved from 2010 to 2016 that correspond to unique environmental conditions and growth responses of juvenile Pacific Cod. Stress-scape identity and spatial extent changed as a function of time, capturing unique

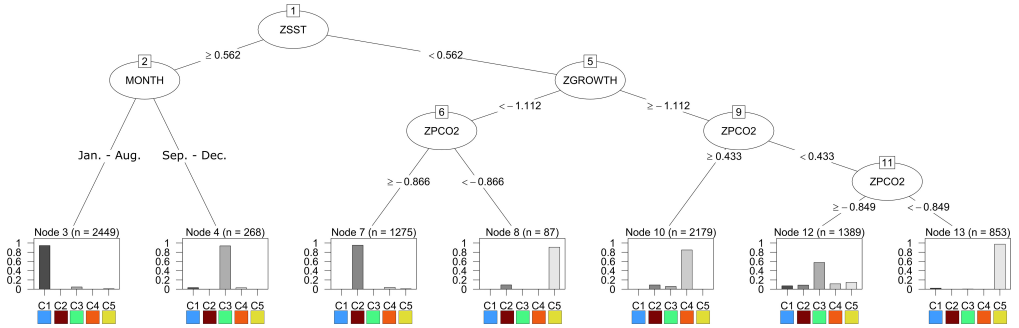

FIGURE 1 | The results of the decision tree trained on the output of stress-scape classification using 5-stress-scapes and 4 variables: SST z-score (ZSST), juvenile Pacific Cod SGR z-score (ZGROWTH) measured in percent wet weight per day (%WW/day), pCO_2 concentration (μatm) z-score (ZPCO2), and the month of the remotely sensed observation (MONTH). Each node of the decision tree represents a decision about the variable labeling the vertex and is labeled with a number. The root node represents a decision about the monthly z-score of SST. If the pixel's SST is greater than.562 standard deviations above the mean SST value across the entire GOA from 2010 to 2016, the left branch is taken; otherwise, the right branch is taken. Note that by including SGR (ZGROWTH) as a classification variable we can make biologically relevant interpretations of the stress-scape classes that are classified by the right branch of node 1. The bar graph provides the percent of each class that is classified by each leaf node of the tree.

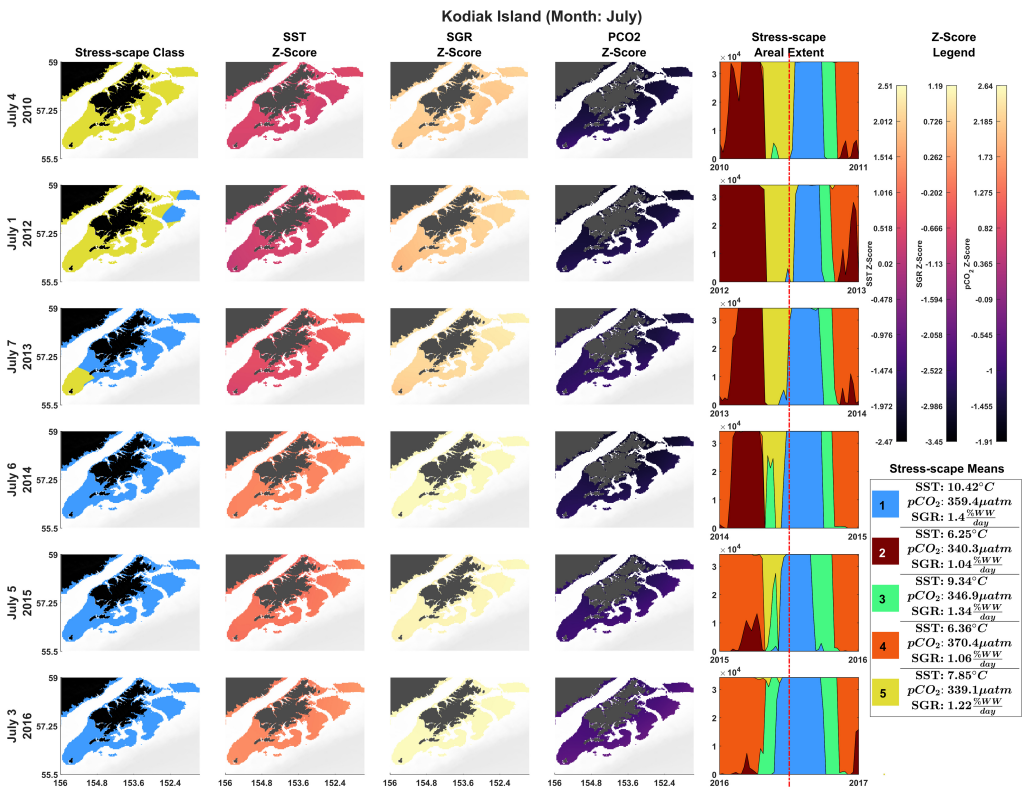

FIGURE 2 | Dominant yearly stress-scape classes for coastal Kodiak Island during the first week of July 2010 and 2012–2016. Heatwave conditions are present in 2014–2016. Column 1 highlights the dominant stress-scape classes for coastal Kodiak Island. Column 2 is the z-score for SST; Column 3 is the z-score for SGR, and Column 4 is the z-score for pCO_2. The red line marks the time shown in the figure across all years. Dark purple z-scores are below average and yellow z-scores are above average for that variable. An animated version of this figure can be found in **Supplementary Material: Appendix E** and **Supplementary Video 1**.

conditions and responses during the 2014–2016 marine heatwave compared to the previous cooler conditions. Stress-scapes captured non-linear biological responses to the environment: when SGR was included as a variable (in addition to SST and pCO_2) there was a single stress-scape that dominated during heatwave years that did not dominate prior to heatwave years. This dominant stress-scape corresponds to observed elevated growth rates from the otolith data from Kodiak Island. Even though SGR is a function of SST, including fish growth as a variable in the stress-scape captures patterns of

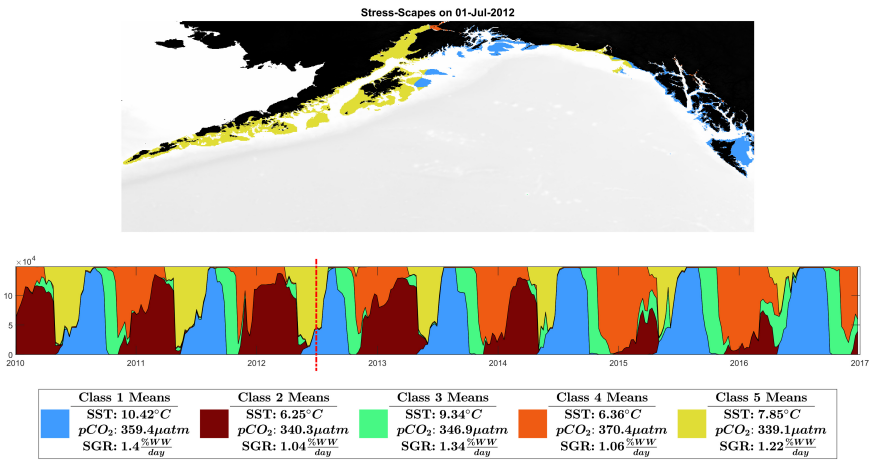

FIGURE 3 | Ribbon plot showing total Stress-scape class area per time slice. Each column represents a single slice through time of the entire GOA. A stress-scape dominates in time if it persists along the x-axis. For example, in 2016, stress-scape class 1 was spatiotemporally dominant. From 2014 to 2016 stress-scape classes 1 and 4 dominate for a longer period than in 2010–2013. Classes 1 and 4 are coincident with the anomalous elevated growth rates seen in the otoliths data. A seasonal and interannual pattern emerges in the incidence of each of the classes: The spatiotemporal footprint of classes 2 and 5 contract over time, supplanted and are replaced by expansions of classes 1 and 4. Class 2, a low SST class, that seems to be replaced by high pCO_2 class 4. Class 5, the pre-heatwave summer class, is replaced by the high SST class 3, which starts appearing earlier and persisting each year during the heatwave. This ribbon plot can be viewed as a video alongside a map of the GOA in **Supplementary Material: Appendix E** and **Supplementary Videos 1, 2**.

growth that are comparable to those derived from otoliths *in situ*.

Output from the stress-scape visualization indicated that juvenile Pacific Cod experienced moderately higher potential growth during heatwave years compared to more normal environmental conditions. Accelerated growth is a common bioenergetic response of teleost fishes to warmer ocean conditions, with increased temperatures contributing to increased metabolism and faster growth as long as caloric and oxygen requirements are adequately met, until an upper limit above which growth will begin to decline (e.g., Beauchamp, 2009; Thalmann et al., 2020). These results suggest that warmer temperatures during the juvenile life stage led to faster growth than would be expected during normal ocean conditions. However, in contrast with these observed potential growth rates, Pacific Cod abundance was anomalously low in the GOA during marine heatwave conditions. Pacific Cod, like many stenothermic fish species, are likely to experience life stage-specific thermal bottlenecks, especially in the embryonic and adult spawner stages where the fish may be particularly vulnerable to environmental variability (Dahlke et al., 2020). It has been shown that Pacific Cod hatch success is strongly correlated with temperature, with hatch success most optimal at temperatures between 3 and 6°C (Laurel and Rogers, 2020). During the 2014–2016 marine heatwave, optimal spawning habitat was restricted to shallower regions and earlier times of the year, and this decline in suitable spawning habitat may have led to widespread reductions in reproductive output. Those individuals that survived the thermal bottleneck at the embryonic life stage may have experienced higher growth rates during the larval and juvenile life stages in warmer conditions, especially if prey was available and "matched" in time and space (Laurel et al., 2021). Additionally, juvenile Pacific Cod collected in Kodiak nurseries were two to four months old by July and the product of selective mortality. In poor survival years, such as 2015, slower growing or smaller fish can experience higher rates of mortality, leaving only the faster growing fish in the population (Litvak and Leggett, 1992; Sogard, 1997). Thus, the results from the stress-scape visualization likely do not capture the full impact of the 2014–2016 marine heatwave on Pacific Cod simply because it captures only a snapshot of the entire Pacific Cod life history, but the approach highlights the spatial and temporal extent of anomalous and potentially stressful conditions. With the addition of information on prey quantity and quality and pCO_2 and temperature data throughout the water column, a more comprehensive exploration of the effects of the heatwave throughout the life history of Pacific Cod, and potentially other species, would be possible.

TABLE 3 | Mean values for each of the 4 resolved stress-scapes that were classified to test the significance of the growth rate variable.

	SST (°C)		pCO_2 (μatm)		Count	Color
	Mean	Std	Mean	Std		
Class 1	11.41	1.84	316.0	19.02	3836	
Class 2	6.32	1.34	296.3	16.79	557	
Class 3	6.50	1.96	396.4	17.25	3939	
Class 4	5.93	1.93	350.7	16.79	1668	

Means and standard deviations are included for SST and pCO_2 concentrations as well as the number of remotely sensed data belonging to each class (count) and corresponding classification color for each of the 4 resolved classes for the bivariate prSOM sensitivity analysis.

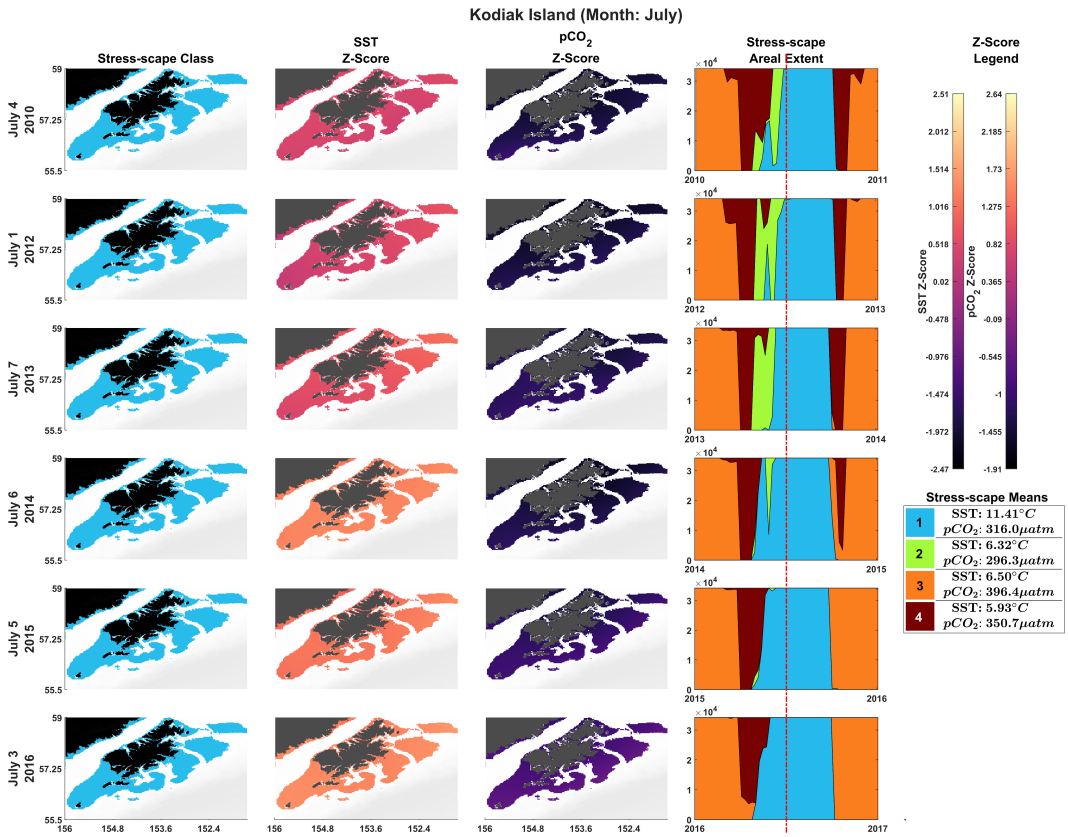

FIGURE 4 | Dominant yearly classes for the bivariate prSOM sensitivity analysis near coastal Kodiak Island during the first week of July 2010 and 2012–2016. Normal ocean conditions are present in 2010–2013, and heatwave conditions are present in 2014–2016. Column 1 highlights the dominant stress-scape classes for coastal Kodiak Island. Column 2 is the z-score for SST, and Column 3 is the z-score for pCO_2. The final column gives the areal extent of each stress-scape class. The red line indicates the time slice of the areal extent (see **Supplementary Material: Appendix E** and **Supplementary Videos 1, 2**).

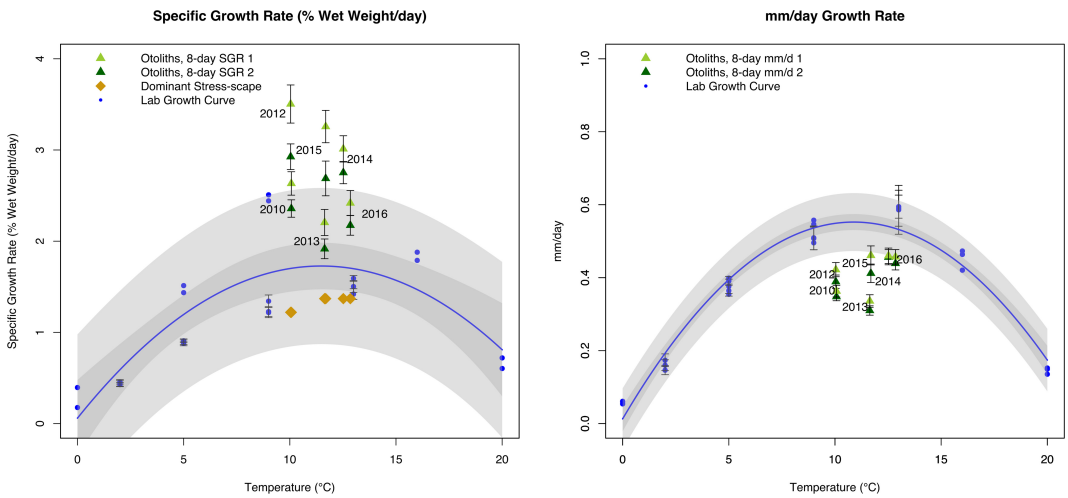

FIGURE 5 | Comparison of juvenile Pacific Cod SGR **(left panel**;% wet weight/day) and mm/day growth rate (**right panel)** from individuals collected from Kodiak Island, AK in July 2010 and 2012–2016. Final 8 days of otolith growth prior to capture are represented by dark green triangles, and penultimate 8 days of otolith growth are represented by light green triangles. Laboratory models are represented by the blue growth curve and blue circles. Specific growth rate from the dominant stress-scapes in July near Kodiak Island are represented by gold diamonds. Error bars represent standard error. Gray polygons represent confidence and prediction intervals of the laboratory growth model.

Otolith-derived SGR rates for field-collected juvenile Pacific Cod were between 39 and 187% higher than those predicted by the dominant stress-scape class for coastal Kodiak Island across most years of the analysis. This pattern highlights a potential underestimation of the stress-scape machine learning algorithm in predicting juvenile Pacific Cod growth in the field. The most parsimonious explanation for this result is that the temperature data used in the model did not accurately reflect shallow nursery conditions that often exceed 15°C in summer around Kodiak Island (Laurel et al., 2012). However, the laboratory model for SGR underestimated otolith-derived SGR across most years, while the laboratory model for mm/d growth overestimated otolith-derived growth. Growth in mass and growth in length are related but can reflect differences in energy allocation. For example, there is some evidence that seasonality can influence fish growth in the field, with fish adding more length earlier in the season when conditions are favorable for feeding, and then adding more mass later in the season to better prepare for winter conditions (e.g., Hurst and Conover, 2003; Hurst, 2007). Field growth may also exceed laboratory-based growth models due to a number of *in situ* processes, including higher food quality in the field (e.g., Mazur et al., 2007), favorable conditions in nearshore nursery habitat (e.g., Beck et al., 2001; Hinckley et al., 2019), and the effects of seasonality on growth rates, with juveniles feeding more vigorously in summer months to prepare for winter (e.g., Schwalme and Chouinard, 1999). In 2014, 2015, and 2012, two heatwave influenced years and a cool ocean year, respectively, juvenile Pacific Cod exhibited SGR in the field that were modestly higher than predicted from the laboratory temperature-dependent growth rate model. We note that the 2012 cohort of Pacific Cod was the strongest on record in the GOA since 1977, and growth was likely elevated in response to particularly favorable ocean conditions in that year and the production of multiple cohorts of juveniles (Hinckley et al., 2019). In the unfavorable ocean conditions occurring during the marine heatwave event in 2014 and 2015, only the fastest growing individuals were likely to survive to the juvenile life history stage, inflating the observed growth response of the survivors (e.g., Ricker, 1969; Litvak and Leggett, 1992; Moss et al., 2005). The variability between observed growth rates in the field and classified growth rates in the stress-scape suggests that future iterations of the stress-scape may benefit from added parameters related to selective mortality, foraging conditions, and additional environmental parameters related to ocean conditions.

In this analysis, we assume that the effects of temperature and pCO_2 on Pacific Cod growth are additive. We do not account for potential interaction between these two environmental variables as further studies are needed to elucidate the interactive effects between warming and ocean acidification on the growth of Pacific Cod early life stages. We acknowledge that the potential for interactive effects between temperature and pCO_2 on juvenile Pacific Cod growth may increase uncertainty in stress-scape classification and contribute to the deviation between Pacific Cod growth observed in the field compared to growth classified by the stress-scape. In general, early life stages of marine organisms tend to exhibit an increased sensitivity to the effects of ocean acidification in the presence of elevated water temperatures due to a heightened stress response (Harvey et al., 2013; Kroeker et al., 2013, 2014). However, fishes tend to be less sensitive than marine invertebrates to increased carbon dioxide in the water column even in the face of elevated temperature conditions due to their increased metabolism (e.g., Enzor et al., 2017), highly developed acid/base regulatory systems (e.g., Melzner et al., 2009), and potential for energy reallocation (e.g., Laubenstein et al., 2018). Studies examining the effects of elevated carbon dioxide concentrations on the early life stages of Alaskan gadids (including Walleye Pollock, a congener of Pacific Cod that shares a similar growth response at the juvenile stage), show limited impacts to growth response (Hurst et al., 2012, 2019). Therefore, we expect interactive effects of temperature and ocean acidification on SGR are likely minimal for juvenile Pacific Cod.

While previous dynamic classifications of the ocean include lower trophic level responses to environmental forcing (e.g., chl-a or carbon; Kavanaugh et al., 2014, 2018), the incorporation of fish physiology represents a notable revision and test of non-linear responses of higher trophic levels. Furthermore, our sensitivity analyses suggests that exclusion of biological responses results in an overly simple classification model. The bivariate prSOM (without growth rate) exhibited fewer output stress-scape classes compared to the full model and grouped several output classes together. In addition, the bivariate prSOM was unable to distinguish between heatwave conditions in 2014–2016 and more normal conditions in 2010–2013, with the dominant class remaining the same across all six years. Due to the quadratic relationship of Pacific Cod growth to ocean temperature (Hurst et al., 2010; Laurel et al., 2016), output classes in the full dynamic stress-scape model were able to successfully distinguish between similar growth rates that occurred in response to two different temperature ranges by classifying them into two separate output classes (classes 1 & 2). By including the biologically relevant growth response into the stress-scape, we could distinguish temperatures that were high enough to negatively impact growth rate from temperatures that were conducive to ideal growth. The utility of dynamic stress-scapes in capturing non-linear growth patterns could be expanded to include more complex biological patterns as indicators of changing ocean conditions, such as those associated with prey quality and quantity (e.g., Daly et al., 2017), predation (e.g., Fennie et al., 2020), or metabolic rate (e.g., Chung et al., 2019).

Machine learning models show promise in classifying marine heatwave events because they can generalize to regions of the ocean where there is limited data by being trained on more data-rich regions with similar conditions and then using the model to detect heatwave conditions. While there are several recent, well-received approaches to classifying marine heatwave events (e.g., Hobday et al., 2016, 2018; Oliver et al., 2018), many of these approaches exclude biological response in their classification schema for marine heatwaves. Our dynamic stress-scape classification of the GOA, which uses sea-surface measurements, successfully distinguished between marine heatwave conditions in 2014–2016 and more historically normal

ocean conditions in 2010–2013. In general, stress-scape classes that corresponded to heatwave conditions exhibited higher SST, moderate pCO_2 concentrations, and elevated juvenile Pacific Cod SGR. Stress-scapes that corresponded to more normal ocean conditions exhibited moderate SST, lower pCO_2 concentrations, and moderate SGR. Dynamic stress-scapes effectively present the biological footprint of remotely sensed oceanographic data by characterizing spatio-temporal changes in the modeled SGR of juvenile Pacific Cod. The stress-scape framework shows promise in for merging spatio-temporal data and biological models to understand how heatwave conditions across a wide spatial and temporal range might affect living marine resources.

Our methods are not without limitations. The prSOM algorithm was chosen for this analysis because its topology preserving nature and its sensitivity to non-linear data. However, the prSOM implementation does not use k-fold cross validation to avoid overfitting, which would improve the classification results. Future efforts would include t-distributed stochastic neighbor embedding (t-SNE; Maatan and Hinton, 2008), which provides a well-defined "optimal solution," lends itself to visualization of higher dimensional data (e.g., >3) and thus inclusion of additional in juvenile Pacific Cod fitness variables. Additionally, HAC can have issues when the geometry of the data is not flat (as is the case with the relationship between sea-surface temperature and growth rate). The DBSCAN (Ester et al., 1996) and OPTICS (Ankerst et al., 1999) algorithms could replace Hierarchical Agglomerative Clustering and be used in conjunction with a prSOM or t-SNE machine learning algorithm to provide a better stress-scape classification that distinguishes regions where the temperature is warm enough to constrain growth from regions where the temperature is conducive to optimal growth. Our visual results are a preliminary effort to introduce a visual system. In future work we will consider incorporating immersive visualization techniques for visual exploration of the ocean and coordinated multi-view visualization on the different types and sources of data for decision making. Efforts to expand on visualization within the fisheries community suggest interest in developing fast, scalable and explorative tools for fisheries scientists to understand the relationship between ocean variables, marine resources, and the algorithms used to process data from these two domains (Hermann and Moore, 2009).

Finally, our temperature-dependent growth model does not incorporate factors like prey quality, prey quantity, ocean currents, or ocean conditions at depth. Individual Based Modeling (IBM) and Regional Ocean Modeling Systems (ROMS) incorporate many of these factors and can be used to generate a spatial footprint of fish dispersal (Stockhausen et al., 2019). Information on the dominant dispersal pathways of Pacific Cod early life stages from an IBM/ROMS model could be paired with the stress-scapes by developing the duration of residence in each stress-scape. On a related note, IBM/ROMS models could be used to improve the data sampling used to train the prSOM. Currently, remotely sensed data are sampled uniformly at random at each epoch, where a different random sample is used at each iteration, but the distribution is uniform. The IBM/ROMS models could be used to estimate the probability of a juvenile Pacific Cod encountering potentially stressful conditions at each ocean pixel. This distribution could be used to inform the sampling method at each epoch of the prSOM so that the training data is more likely to represent the environmental context of the juvenile Pacific Cod. Our stress-scape framework is not intended as a substitute for an IBM, and it does not offer a comprehensive reconstruction of juvenile Pacific Cod growth history in the GOA (but see Hinckley et al. (2019) for an IBM currently in place for GOA Pacific Cod). Rather, the stress-scape represents a new way to visualize changes in both environmental conditions and Pacific Cod growing conditions before and during a marine heatwave event. Pacific Cod otoliths are used in the context of this study to support and serve as a point of comparison to the stress-scape classification of SST, pCO_2, and laboratory-derived juvenile Pacific Cod SGR.

In summary, stress-scapes offer three new and novel features relevant to the fields of marine resource management, ocean ecology and fisheries science. First, stress-scapes are based on both remotely sensed data and models that approximate biological response to remotely sensed environmental data. Second, machine learning models can generalize to regions of ocean where there is limited data by being trained on data that share similar conditions. Third, stress-scapes use machine learning algorithms that train on spatially relevant data, in this case based on temperature-growth models to approximate the growth rate of juvenile Pacific Cod. This produces an output that is potentially relevant for management in multiple fields and at multiple spatial and temporal scales. Environmentally, the stress-scapes are useful metrics that can benefit ecosystem-based and dynamic approaches to management of marine resources (Kavanaugh et al., 2016). From a management perspective, the biological relevance of the stress-scapes can be used to trace or even forecast potentially stressful conditions for a focus species. Downstream effects on socioeconomic conditions of resource users could also be identified by aligning the occurrence and longevity of stress-scape classes in space and time with economic indicators and extraction data. The process is extremely flexible and can handle large amounts of many types of time series data, furthering its utility.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because the field work was conducted solely by NOAA's Alaska Fisheries Science Center Laboratory in Newport, Oregon. Animal tissue, in this case otoliths, was provided to OSU several years after collection. This research was carried out in accordance

with all applicable institutional and national guidelines at the time that the study was conducted; all work followed American Fisheries Society policies on the Guidelines for Use of Fishes in Research (https://fisheries.org/docs/policy_useoffishes.pdf) and AVMA (American Veterinary Medical Association) Guidelines on Euthanasia (olaw.nih.gov/sites/default/files/Euthanasia2007.pdf). There was no formal ethics review of this study because NOAA National Marine Fisheries Service does not have an Institutional Animal Care and Use Committee (IACUC) or an ethics approval processes for research on fishes and, at the time of these collection (2010–2016), OSU was not involved in the research.

AUTHOR CONTRIBUTIONS

All authors conceived of and designed the project. JB, HT, and WK executed the research, analyzed the data, and wrote the manuscript with feedback from YZ, JM, BL, and MK. JB led the prSOM implementation, execution, analysis, and interpretation with input from YZ and MK. HT and BL compiled Pacific Cod growth data for incorporation into the prSOM. WK compiled environmental data for incorporation into the prSOM with assistance from MK. HT and JM completed otolith analyses and interpretation. BL provided fish samples.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.656088/full#supplementary-material

Supplementary Video 1 is located here: https://figshare.com/articles/media/14356751 and **Supplementary Video 2** is located here: https://figshare.com/articles/media/14356793.

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Climate Projections for the Southern Ocean Reveal Impacts in the Marine Microbial Communities Following Increases in Sea Surface Temperature

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Anthropogenic global warming can have strong impacts on marine ecosystems, especially on climate-sensitive regions such as the Southern Ocean (SO). As key drivers of biogeochemical cycles, pelagic microbial communities are likely to respond to increases in sea surface temperature (SST). Thus, it is critical to understand how SST may change in future scenarios and how these changes will affect the composition and structure of microbial communities. By using a suite of Earth System Models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6), machine learning, and 16S rRNA sequencing data, we investigated the long-term changes as projected by CMIP6 simulations in SST throughout the twenty first century and the microbial diversity responses in the SO. Four Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) were considered to assess the SO surface sensitivity to a warming climate. The SST changes across SSPs were ≈0.3, ≈0.7, ≈1.25, and ≈1.6^{o}C between 2015 and 2100, respectively, and the high emissions scenarios projected a much sooner emergence of the human-induced temperature change throughout the SO. The impacts on Antarctic marine diversity of bacteria and archaea are expected to be significant and persistent by the late twenty first century, especially within the higher end of the range of future forcing pathways.

Keywords: Southern Ocean (Antarctica), climate change, microbial diversity, CMIP6, time of emergence, machine learning

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INTRODUCTION

Throughout the second half of the twentieth century, most of the Earth's energy imbalance has been stored in the ocean, primarily at the surface (Ishii and Kimoto, 2009; Lyman et al., 2010; Trenberth, 2010; Abraham et al., 2013), and more recently reaching deeper layers (Bilbao et al., 2019). The resulting increase in ocean heat content has been reported to be largely due to anthropogenic forcing (Barnett et al., 2005; Gleckler et al., 2012; Pierce et al., 2012; Bilbao et al., 2019). These human-induced changes have already spread to about half (20–55%) of the world oceans (Silvy et al., 2020), and the largest heat gain has occurred in the Southern Ocean (Roemmich et al., 2015; Trenberth et al., 2016). However, the ice-insulated regions of the SO protect its sea surface waters

from climate forcing (Gille, 2008, 2002; Fahrbach et al., 2011; Tonelli et al., 2019). As a result, heat and carbon uptake happens mostly through the formation and subduction of water masses (Heuzé et al., 2013; Sallée et al., 2013), and the earliest detection of the anthropogenic warming fingerprint in the SO occurs in the ocean interior rather than in surface waters (Silvy et al., 2020).

Despite the ability of the ice-insulated regions of the SO to delay the warming trends throughout the global ocean due to the local circulation and the interaction with sea ice and ice shelves (Fahrbach et al., 2011; Tonelli et al., 2019), warmer surface waters lead to increased sea ice melting, loss of ice mass, and increased surface water flux (Rignot et al., 2008), ultimately leading to a slowdown of bottom water formation and the stalling of the CO_2 sink in the SO (Lovenduski et al., 2008; Lenton et al., 2009; Purkey and Johnson, 2012). In particular, the surroundings of the Antarctic Peninsula and the western Weddell Sea have been exposed to intense warming and sea ice melting (Fan et al., 2014).

Climate change affects the growth, reproduction, and survival of aquatic organisms (Kroeker et al., 2010; McFeeters and Frost, 2011; Weydmann et al., 2012; Cripps et al., 2014). The increase in ocean temperature will likely affect the structure and dynamics of microbial community, but since microorganisms show large population sizes and relatively fast reproduction, they might be capable of adapting to global environmental changes through phenotypic plasticity and adaptive evolution (Collins et al., 2014; Hellweger et al., 2014; Doblin and van Sebille, 2016; Verde et al., 2016; Cavan et al., 2019). Microorganisms' responses to climate change have strong implications for an environmentally sustainable future (Cavicchioli et al., 2019), but our understanding of how they respond to climate warming remains limited.

Although the effect of climate change on microbial functioning is still poorly understood, we know that marine phytoplankton performs half of the global photosynthetic CO_2 fixation and half of the oxygen production, and they can have a fast response to climate variations (Arrigo, 2005; Teeling and Glöckner, 2012; Buttigieg et al., 2018). Heterotrophic and chemolithotrophic microorganisms are also important drivers of ocean biogeochemical cycles and constitute the foundations of many marine ecosystems, acting as an essential part of the functioning of trophic levels (Arrigo, 2005; Teeling and Glöckner, 2012; Buttigieg et al., 2018). The SO has shown high and dynamic microbial diversity, with the community composition strongly influenced by temperature (Signori et al., 2014, 2018; Cavicchioli, 2015). Given that temperature increase is expected to modify microbial diversity and distribution with cascading effects at higher trophic levels, predicting how the microbial diversity and community composition will respond to climate change has become an important challenge (Thomas et al., 2012; Toseland et al., 2013; Cavicchioli et al., 2019).

The main tools to investigate projections of global climate change are state-of-the-art climate models designed to estimate the progression of Earth's climate system in the twenty first century (21C; Eyring et al., 2016). These complex models, however, are not able to represent the marine microbial structure. It is, therefore, critical to make use of new methodologies combined with real data to assess the impacts of climate change on these sensitive pelagic microbiomes. Machine learning (ML) techniques enable the analysis of high-dimensional data, linking prediction and computational intelligence methods based on *in situ* measured data, which can be used to elucidate relationships between microorganisms and environmental factors, such as temperature (Yu and Liu, 2003; Bishop, 2006; Qu et al., 2019; Thompson et al., 2019). ML algorithms like random forest (RF) and neural networks were reported to be one of the most effective tools for analyzing microbiome data, with high accuracy in a range of 16S rRNA sequencing data (Liu et al., 2011; Larsen et al., 2012; Statnikov et al., 2013; Pasolli et al., 2016).

Here, we investigate the long-term sea surface temperature (SST) changes throughout the 21C, as simulated by CMIP6 projections (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), as well as the response of microbial diversity and composition in the northwestern Antarctic Peninsula (NWAP) and the northwestern Weddell Sea (NWWS) using an RF model available from Python toolkit SciKit-Learn ML libraries.

MATERIALS AND METHODS

Climate and Earth System Models

The World Climate Research Program coordinates the development of Climate and Earth System Models (ESM) by major modeling centers under the scope of the Coupled Model Intercomparison Project, now in its sixth phase (CMIP6; Eyring et al., 2016). CMIP6 models simulate the climate under different scenarios of future anthropogenic activity (Shared Socioeconomic Pathways–SSP) within the scope of an endorsed CMIP6 project named ScenarioMIP (O'Neill et al., 2016). These SSPs are built upon the same radiative forcing range previously used in CMIP5 (Taylor et al., 2012) described as Representative Concentration Pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), and named after a possible range of radiative forcing values in the year 2100: 2.6, 4.5, 7.0, and 8.5 W/m^2, respectively (Meinshausen et al., 2011). The tier 1 SSPs are SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (O'Neill et al., 2016).

The SSP narrative[1] illustrates possible anthropogenic drivers of climate change over the 21C (departing from the historical runs), ranging from sustainable to fossil-fueled development (Riahi et al., 2017):

- SSP1–Sustainability–Taking the Green Road: Low challenges to mitigation and adaptation;
- SSP2–Middle of the Road: Medium challenges to mitigation and adaptation;
- SSP3–Regional Rivalry–A Rocky Road: High challenges to mitigation and adaptation;
- SSP4–Inequality–A Road Divided: Low challenges to mitigation, high challenges to adaptation;
- SSP5–Fossil-fueled Development–Taking the Highway: High challenges to mitigation, low challenges to adaptation.

[1]For a comprehensive description of the SSPs the reader is referred to Riahi et al. (2017).

Sea Surface Temperature Data

To quantify the projected changes in surface temperature over the Southern Ocean (SO), we computed the area-weighted SST annual means between 60°S and 80°S across four future scenarios, ranging from the more sustainable scenarios (SSP1-2.6 and SSP2-4.5) to high emissions trajectories (SSP3-7.0 and SSP5-8.5). The SST data were retrieved from the Earth System Grid Federation (ESGF[2]) CMIP6 archive (variable name "tos"; native grid "gn"). Monthly mean outputs from 18 ESM (**Table 1**) were available at the time of writing for the preindustrial control experiment (piControl) and four ScenarioMIP 21C projections: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. CMIP6 models are usually run multiple times for each experiment. Here, one single run was used for each model (usually the variant named "r1i1p1f1").

For consistency, the SST outputs from each model were firstly interpolated onto the same regular 360° × 180° grid using bilinear filtering with the same land-ocean mask, excluding the marginal seas and interior lakes like the Mediterranean Sea, Red Sea, Arabian Gulf, Black Sea, Caspian Sea, Baltic Sea, and Hudson Bay. The first-year annual mean (2015) is subtracted from each time series yielding the actual SST change over each SSP scenario projection. Although it has been suggested that model drift is negligible when considering multimodel means (Gupta et al., 2013), SST data were de-drifted based on each model piControl run to remove trends potentially caused by model equilibrium adjustment rather than by external forcing as in Ferrero et al. (2021).

Microbial Diversity Data

Microbial community datasets were obtained by our group from previously published studies (Signori et al., 2018; de Ferreira, 2019) under the Brazilian Antarctic Program, and comprised a total of 105 samples from surface waters (∼5 m depth) collected in the NWAP and NWWS. Sampling strategy and sample processing are detailed in Signori et al. (2018) and de Ferreira (2019). Briefly, approximately 3 L of seawater samples were filtered onto 0.22 μm-membrane Sterivex^{TM} filters using a peristaltic pump onboard the Brazilian polar vessel Almirante Maximiano (Signori et al., 2018) or at Comandante Ferraz Brazilian Antarctic Station (King George Island, Antarctica; de Ferreira, 2019). After filtration, samples were frozen at −20 or −80°C for molecular analysis. DNA extraction of SterivexTM filters was performed using the DNEasy Power Water Kit (Qiagen, Hilden, Germany), following manufacturing protocols, or according to specifications available in Signori et al. (2018). Total extracted DNA was then sequenced using an Illumina Miseq paired-end system 2 × 250 bp reads configuration, with the primers 515F (5′-GTGCCAGCMGCCGCGGTAA-3′) and 806R (5′-GGACTACHVGGGTWTCTAAT-3′; Caporaso et al., 2012), targeting the V4 region of the 16S rRNA gene for both Bacteria and Archaea. Reads are available in the NCBI database under the Bioproject IDs PRJNA383940 and PRJNA665033. The description of samples, coordinates, environmental temperatures, and NCBI Bioproject IDs are available in **Supplementary Table 1**.

We obtained a total of 8,538,820 reads distributed among the 105 water samples, which 5,968,201 were quality filtered and then analyzed with QIIME2 (Quantitative Insights into Microbial Ecology) and its plugins (Bolyen et al., 2019). Based on the quality scores observed using qiime demux summarize and the interactive quality plot, the forward reads were truncated at position 270, and the reverse reads at 200, using the q2-dada2-denoise script. This script uses DADA2 software to obtain a set of observed amplicon sequence variants (ASVs), as described by Callahan et al. (2016). Taxonomy was assigned through feature-classifier classify-sklearn using SILVA database v.132 with a confidence threshold of 0.7. Alpha diversity indices (Chao1 and Shannon) were calculated using the Phyloseq (McMurdie and Holmes, 2012) and vegan (Oksanen et al., 2020) packages in R (R Core Team, 2019). Shannon index is calculated based on the proportion of ASVs relative to the total number of ASVs and then multiplied by the natural logarithm of this proportion (Shannon, 1948), accounting for both the abundance and evenness of the ASVs. A map with the sampling regions is provided in **Supplementary Figure 1**.

TABLE 1 | List of models used in this study.

Model #	Model name	Model center	Model #	Model name	Model center
1	ACCESS-ESM1-5	CSIRO	10	GFDL-CM4	NOAA-GFDL
2	BCC-CSM2-MR	BCC	11	IPSL-CM6A-LR	IPSL
3	CAMS-CSM1-0	CAMS	12	MCM-UA-1-0	UA
4	CanESM5	CCCma	13	MIROC6	MIROC
5	CESM2	NCAR	14	MIROC-ES2L	MIROC
6	CESM2-WACCM	NCAR	15	MPI-ESM1-2-HR	DKRZ MPI
7	CNRM-CM6-1	CNRM-CERFACS	16	MRI-ESM2-0	MRI
8	CNRM-ESM2-1	CNRM-CERFACS	17	NESM3	NUIST
9	EC-Earth3-Veg	EC-Earth-Consortium	18	UKESM1-0-LL	MOHC

Expansions of institution acronyms are available at https://wcrp-cmip.github.io/CMIP6_CVs/docs/CMIP6_institution_id.html.

Time of Emergence

The Time of Emergence (ToE) is defined as the time at which the signal of a forced response emerges from the noise of internal variability (Hawkins and Sutton, 2012), thus providing an indicator of the human-induced climate change for several climate variables (Chadwick et al., 2019). The ToE was computed for each model separately as the year when the SST time series at each grid point exceeds two standard deviations of the monthly mean SST from the piControl experiment, similar to previous studies (Hawkins and Sutton, 2012; Bordbar et al., 2015; Lyu et al., 2020; Ferrero et al., 2021). The results were averaged to obtain the 18-model mean ToE for each SSP future projection.

[2]For a comprehensive description of the SSPs the reader is referred to Riahi et al. (2017).

Machine Learning Predictions

The RF model used to predict microbial diversity and composition responding to SST in the NWAP and the NWWS consists of a supervised machine learning algorithm available from Python toolkit SciKit-Learn (Pedregosa et al., 2011). This ML model is a classifier that combines multiple decision trees, trains each one on a slightly different set of observations, and its final prediction accords to the voting on each decision tree (Svetnik et al., 2003; Chen et al., 2018).

The RF model was firstly trained with Chao1 and Shannon indices and observed SST from oceanographic stations in the NWAP and the NWWS. From a total of 105 samples, 80% were used to train the model (84 samples) and the remaining 20% (21 samples) were used to test it.

In practical terms, each sample provides one value of observed SST, one Chao1 index, and one Shannon index. These variables are sorted by temperature values ranging from −1.6 to 2.3°C interval. The RF model is trained separately for each index multiple times using the same SST input as the classifier for both indices, which represent the ML targets. To avoid overfitting, the dataset is randomly partitioned into subsets of 84 samples for training, while 21 samples are kept for testing. Once validated for both indices, the model is used to predict the spatial distribution of Chao1 and Shannon using area-weighted SST annual means outputs from the projected future scenarios. It should be noted that, from a centennial-scale climate change perspective, the entire study area is subject to roughly the same warming trends within each SSP, therefore, the long-term SST time series used in RF predictions differ only across SSPs.

A similar approach was used to perform the composition analysis, where the participation percentage of each microbial taxon identified within the sample community and the associated SST observation were used to train the RF model. The projected SST annual means for each SSP were used to predict the composition percentage of each taxon and the results were merged to provide a temporal evolution of the microbial community composition. All RF trained models reached the score range of 0.87–0.93, suggesting good accuracy.

RESULTS AND DISCUSSION

Consistent with Bracegirdle et al. (2020), warming trends are projected to happen across all future climate scenarios, where higher human industrial activity leads to higher surface temperatures. The approximate SST change across these scenarios is ≈0.3, ≈0.7, ≈1.25, and ≈1.6°C between 2015 and 2100 (**Figure 1**). Variation within these scenarios increases throughout the second half of the 21C, particularly for the high forcing scenarios, mostly due to uncertainties arising from internal variability, model structural differences, and radiative forcing (Ferrero et al., 2021).

Our SSP1-2.6 simulations project mild warming in the SO (**Figure 1**). Significant increases in SST are not expected to happen in the northwestern Antarctic Peninsula (NWAP) coast before 2080 nor until the end of the century in the northwestern Weddell Sea (NWWS; **Figure 2A**). This is particularly relevant to reassure the Weddell Sea (WS) ability to cushion the offshore warming signal advected by the Weddell Gyre (Ryan et al., 2016) due to the local dynamics and cryosphere-related processes (Fahrbach et al., 2011; Tonelli et al., 2019).

The "Middle of the Road" outcome from SSP2-4.5 simulations indicates a slightly sooner emergence of the climate change signal across the NWAP, which is projected to take place during the 2060 decade (**Figure 2B**). Again, the NWWS is able to postpone the anthropogenic warming until the last decade of the 21C, with the inner WS still showing areas within the range of internal variability (≈65°S).

Due to greater environmental pressure, the results of SSP3-7.0 and SSP5-8.5 yielded even earlier ToE around the NWAP

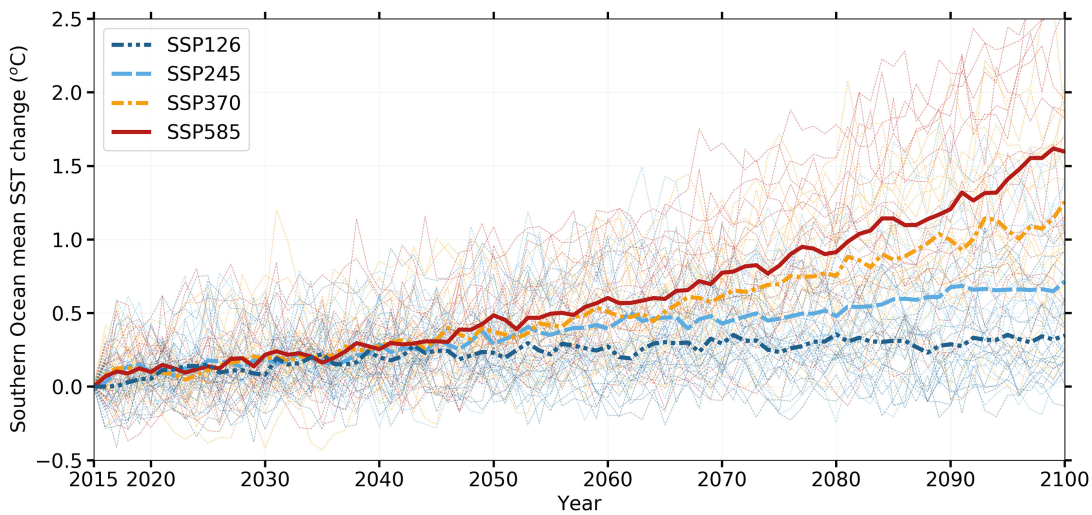

FIGURE 1 | Absolute sea surface temperature (SST) change in the Southern Ocean (annual means of the area-weighted SST between 60°S and 80°S) relative to 2015 for future scenarios. Thin dashed lines indicate individual ensemble members and solid lines indicate ensemble means for each SSP projection.

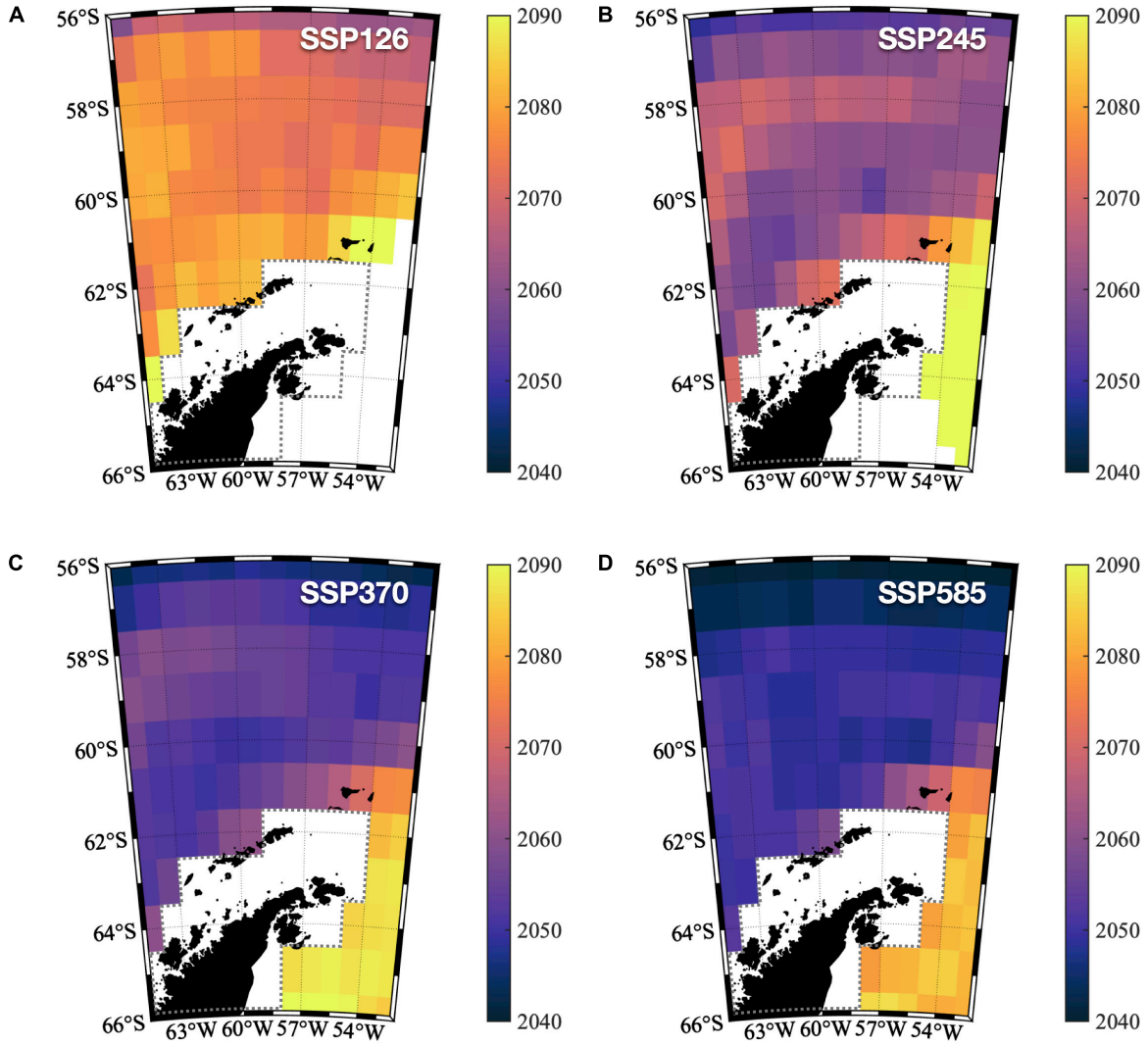

FIGURE 2 | Sea surface temperature Time of Emergence around the Northwestern Antarctic Peninsula and the Northwestern Weddell Sea: the decade when the SST time-series at each grid point exceeds the range of internal variability (defined by two standard deviations of the monthly mean SST simulated in the piControl experiment). The illustrated time of emergence (ToE) corresponds to the averaged ToE from all 18 models. **(A)** SSP126. **(B)** SSP245. **(C)** SSP370. **(D)** SSP585.

sea surface (**Figures 2C,D**). Close to coastal areas, rising SST exceeds the internal variability envelope in the early 2050 decade in these high forcing scenarios. And although the NWWS still exhibits a much later ToE compared to the NWAP, the human-induced warming is projected to reach the inner WS by the end of the 2070 decade based on SSP5-8.5 simulations. To assess the spatial variability of ToE, we have computed the horizontal anomalies with the mean ToE for each SSP (**Supplementary Figure 2**). This corroborates the understanding that the higher the anthropogenic footprint, the sooner the human-induced warming will emerge in the regions adjacent to the Antarctic Peninsula. Moreover, **Supplementary Figure 2** highlights that this warming signal is expected to emerge much sooner across the NWAP compared to the NWWS. The more intensive and faster warming in the NWAP is caused by the Antarctic Circumpolar Current carrying well-mixed warmer waters much closer to the continent, which is consistent with studies that investigated the ocean and ice shelf dynamics along the West Antarctica Peninsula (Jacobs et al., 2011; Hellmer et al., 2012; Paolo et al., 2015; Zhang et al., 2016; Smith et al., 2020).

Our machine learning models indicate a decrease in both microbial communities' richness and diversity within all climate projections, with higher emissions causing a more significant decrease in both indices, particularly under the most critical scenario SSP5-8.5 (**Figure 3**). Therefore, microbial communities might be highly impacted by increasing temperatures, corroborating the observed trend for phytoplankton (Thomas et al., 2012) and prokaryotic communities from a mesocosm experiment in the Baltic Sea (Lindh et al., 2013). Also, SSP1-2.6 and SSP5-8.5 yielded contrasting predictions for microbial composition (**Figure 4**). Whilst the low emission scenario projected small changes in the relative abundance of

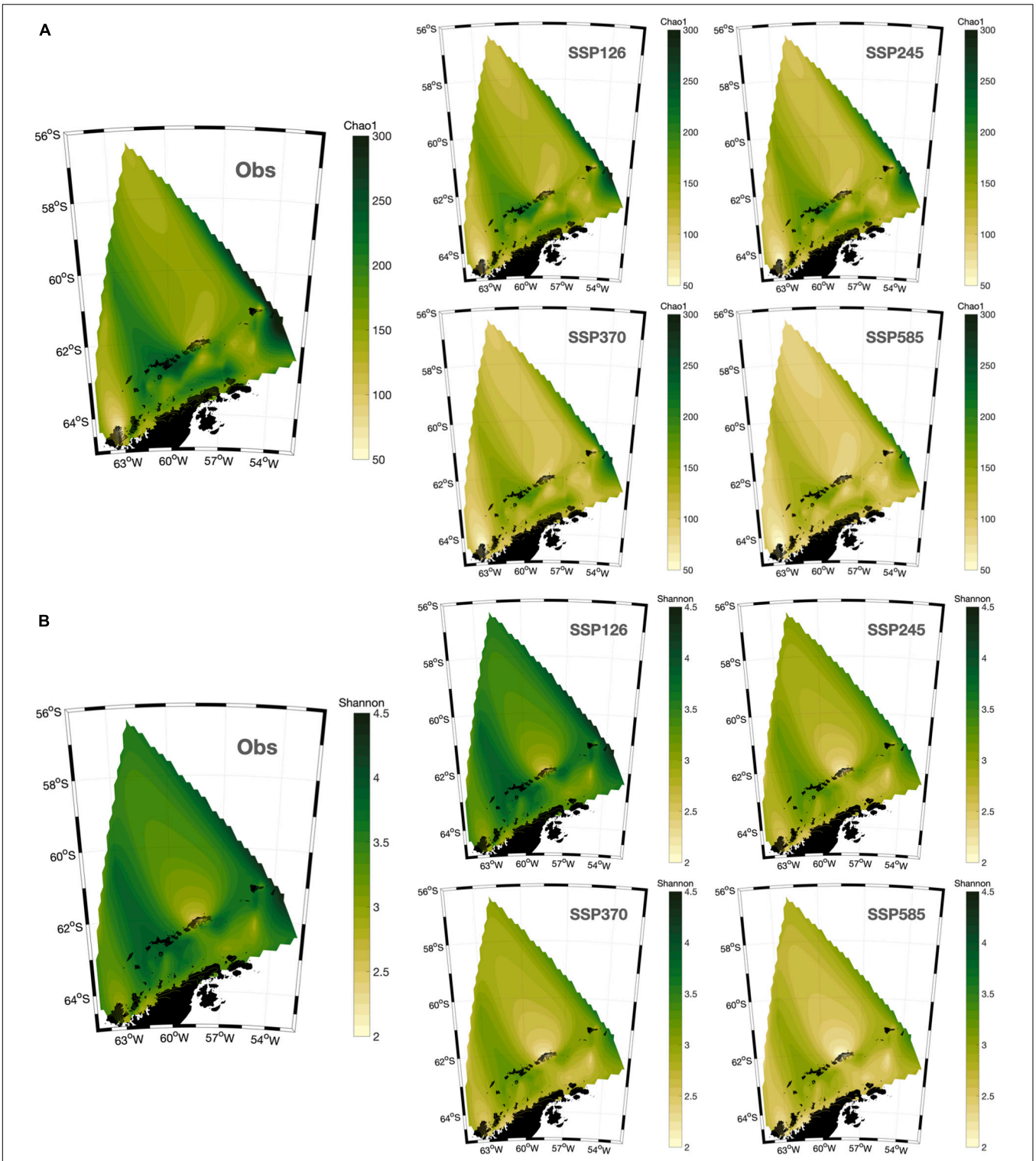

FIGURE 3 | Spatial distribution of observed (Obs) and machine learning projected (SSPs) microbial alpha diversity indices Chao1 **(A)** and Shannon **(B)** around the Northwestern Antarctic Peninsula.

microorganisms, the three scenarios with the highest increase in temperature, including the "middle of the road" scenario, show changes in microbial communities' structure, including the loss of diversity and decrease in microbial taxa that are important contributors to the biogeochemical processes and ecosystem functioning in the NWAP and NWWS. In

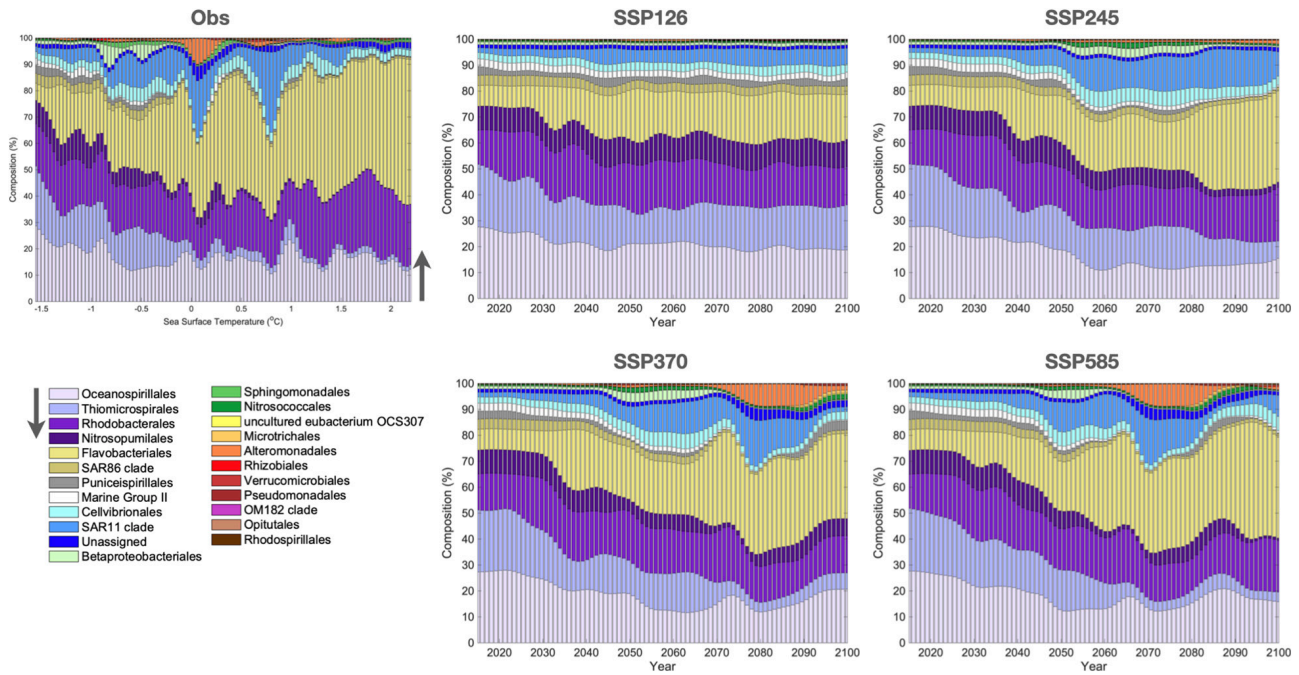

FIGURE 4 | Histogram representing the microbial composition (%) at the order level for the observations sorted by SST (*Obs*). The *SSPs* histograms are sorted by years of projection (as in **Figure 1**) to illustrate the temporal evolution of the bacterial and archaeal community composition. Only taxa with relative abundance above 1% are presented.

general, the heterotrophic Flavobacteriales are projected to have higher relative abundances, while the sulfur-oxidizing Thiomicrospirales, the ammonia-oxidizing Archaea within Nitrosopumilales, and the planktonic euryarchaeotal Marine Group II have reduced relative abundance. These orders are composed of several species with important roles in the functioning of pelagic ecosystems, including the sulfur, nitrogen, and carbon cycles, and are currently described as abundant taxa in the SO (Signori et al., 2014; Zhang et al., 2015; Liu et al., 2019). For instance, Nitrosopumilales members are important contributors to nitrogen remineralization and carbon fixation, and are often the most abundant taxa in cold waters, including the euphotic and aphotic zones of the SO (Signori et al., 2014; Cheung et al., 2019).

The implications of a decrease in ammonia oxidation in the pelagic ecosystems are still unclear, but some modeling studies have indicated that it might affect nutrient stoichiometry, denitrification, marine productivity, and the biological carbon pump (Beman et al., 2011; Kitidis et al., 2011). Members of the Marine Group II have not yet been cultured and their lifestyles are still not well known. The information obtained through the reconstruction of genomes from metagenomic data showed a photoheterotrophic lifestyle inferred by the presence of proteorhodopsin genes (Pereira et al., 2019). Some studies have suggested that photoheterotrophy contributes to biomass accumulation in oligotrophic waters, and a loss in this metabolism would potentially affect nutrients uptake by the pelagic communities (Evans et al., 2015). Furthermore, a decrease in Thiomicrospirales populations would affect the oxidation of sulfur compounds, which has been described as an important process that contributes to protecting marine ecosystems from sulfide toxicity in coastal areas (Hu et al., 2018). However, the importance of sulfur oxidation in the functioning of the SO ecosystem is still unknown.

Microbes respond to changes in light, temperature, metabolites, and other environmental factors, making them good candidates for monitoring both short- and long-term ecological variations (Hanson et al., 2012; Zinger et al., 2014; Brum et al., 2015; Turner et al., 2016; Baker-Austin and Oliver, 2018; Buttigieg et al., 2018). Climate change affects interactions between species and forces them to adapt, migrate, and even be replaced by others (Hoffmann and Sgrò, 2011; Hutchins and Fu, 2017). Understanding how well microorganisms are adapted to environmental factors, such as temperature, and predicting how well they will respond to warming is essential to elucidate ecological adaptation of these organisms (Cavicchioli, 2016).

In this work, we were able to project future changes of microbial community structure and a diversity decrease for NWAP and NWWS, according to the SSP climate change scenarios. The ML prediction showed a trend of decreasing important bacterial and archaeal taxa involved with crucial biogeochemical processes, such as Nitrosopumilales, Marine Group II, and Thiomicrospirales, and an increase of heterotrophic groups, such as Flavobacteriales. In other words, regardless of when the forced signal emerges from the internal variability, temperature changes are seen to modulate the dynamics of the Southern Ocean marine microbial community.

CONCLUSION

This investigation delivers an assessment of 21C projected changes in SST over the SO in the four Tier-1 CMIP6 ScenarioMIP scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. A multimodel mean of 18 ESMs projects approximate warming across these scenarios of ≈0.3, ≈0.7, ≈1.25, and ≈1.6°C, respectively, between 2015 and 2100. ToE analyses suggest delayed warming across the NWAP in the lower socioeconomic pressure scenarios, i.e., SSP1-2.6 and SSP2-4.5, compared to projections based on high forcing pathways (SSP3-7.0 and SSP5-8.5).

In response to SSP scenarios, our predicted results showed that the impacts of high latitude climate change on pelagic microbial communities vary across future projections and mainly indicate a loss of bacterial and archaeal diversity in surface waters. However, it should be noted that even though the use of machine learning is growing in microbial ecology studies, it remains a predictive tool whose interpretation needs to be done carefully (Lucas, 2020). To our knowledge, this is the first study to predict the effect of long-term climate changes of SST on microbial diversity in the SO. In addition, our results show a trend of decreasing important bacterial and archaeal taxa involved with crucial biogeochemical processes, such as Nitrosopumilales, Marine Group II, and Thiomicrospirales, and an increase of heterotrophic groups, such as Flavobacteriales. We suggest that these microorganisms can be applied as potential models in future marine studies, to validate our prediction and to create new hypotheses regarding the response of these microbial taxa under the increasing temperatures predicted by the SSP scenarios.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

We apply Time of Emergence analysis and machine learning models (ML), and 16S rRNA sequencing data, to investigate the long-term changes in the SST throughout the twenty first century in the Southern Ocean (SO), as projected by CMIP6 Earth System Models simulations (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), and the microbial diversity responses to increasing temperature in the northwestern Antarctic Peninsula. The high emissions scenarios projected a much sooner emergence of the human-induced temperature change throughout the SO. Based on ML predictions, the impacts on Antarctic marine diversity of bacteria and archaea are expected to be significant and persistent by the late twenty first century, especially within the higher end of the range of future forcing pathways. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.636226/full#supplementary-material

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Positive Social-Ecological Feedbacks in Community-Based Conservation

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Marine area-based conservation measures including no-take zones (areas with no fishing allowed) are often designed through lengthy processes that aim to optimize for ecological and social objectives. Their (semi) permanence generates high stakes in what seems like a one-shot game. In this paper, we theoretically and empirically explore a model of short-term area-based conservation that prioritizes adaptive co-management: temporary areas closed to fishing, designed by the fishers they affect, approved by the government, and adapted every 5 years. In this model, no-take zones are adapted through learning and trust-building between fishers and government fisheries scientists. We use integrated social-ecological theory and a case study of a network of such fisheries closures ("fishing refugia") in northwest Mexico to hypothesize a feedback loop between trust, design, and ecological outcomes. We argue that, with temporary and adaptive area-based management, social and ecological outcomes can be mutually reinforcing as long as initial designs are ecologically "good enough" and supported in the social-ecological context. This type of adaptive management also has the potential to adapt to climate change and other social-ecological changes. This feedback loop also predicts the dangerous possibility that low trust among stakeholders may lead to poor design, lack of ecological benefits, eroding confidence in the tool's capacity, shrinking size, and even lower likelihood of social-ecological benefits. In our case, however, this did not occur, despite poor ecological design of some areas, likely due to buffering by social network effects and alternative benefits. We discuss both the potential and the danger of temporary area-based conservation measures as a learning tool for adaptive co-management and commoning.

Keywords: commons, fisheries, no-take zones, Mexico, social-ecological systems, adaptive co-management, OECM, marine protected area

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INTRODUCTION

Area-based fisheries closures, or "no-take" zones, constitute a cornerstone of twenty-first century marine conservation and management (Campbell and Gray, 2019; Cabral et al., 2020). The popularity of no-take zones largely stands on ecological evidence of increased biodiversity and biomass where fishing is banned or limited (Halpern et al., 2009, 2010; Gill et al., 2017; Jones et al., 2018). A key finding from this literature is that older, more permanent area-based fisheries closures have better ecological outcomes (Edgar et al., 2014). Because permanent areas are one-shot games, there is pressure to perfect their initial design (Margules and Pressey, 2000). However, competing social and ecological objectives and evidence complicate attempts to optimize initial design (De Santo, 2013). No-take marine protected areas (MPAs) in particular frequently focus on ecological objectives first and social considerations second (De Santo, 2013; Campbell and Gray, 2019; Visconti et al., 2019). As a result, MPAs on average have increased fish biomass within their boundaries (Gill et al., 2017) while simultaneously leading to negative human well-being outcomes a third of the time (Ban et al., 2019). The design of MPAs by experts prioritizing ecological criteria may be perceived as illegitimate by the stakeholders whose compliance is most critical to the MPA's success (Jentoft et al., 2012). That can lead to the alienation and marginalization of local resource users, low compliance rates, and ecological failure of the MPA in the long run (Fabinyi et al., 2015; Basurto et al., 2016). Alternate no-take management models, such as Other Effective Area-based Conservation Measures (OECMs) (Garcia et al., 2019), can offer less resistance from local communities while still potentially generating ecological benefits (Gell and Roberts, 2002). In either case, ecological success depends on initial design, creating high stakes when implementing no-take zones for conservation and management.

Tension between ecological and social objectives for no-take zones manifests as conflicts related to design characteristics such as the duration, location, and in particular the size, of no-take areas (Beattie et al., 2002; Ban et al., 2013; Gruby and Basurto, 2014; Krueck et al., 2018). Large size is associated with greater ecological benefits like high recovery rates of fish biomass, enhanced spillover of adults and larvae to adjacent areas, and protection of highly mobile species (Claudet et al., 2008; Vandeperre et al., 2011). However, large areas present governance challenges, being hard to establish when multiple actors operate within their border, and also hard to monitor and enforce (Gruby et al., 2017; Campbell and Gray, 2019). Additionally, large permanent areas may struggle to adapt in response to climate change (Mills et al., 2015; Hopkins et al., 2016), an urgent concern recently raised during the 1st Global Planning Meeting of the UN Decade of Ocean Sciences for Sustainable Development (UNESCO, 2019). Similarly, ecological evidence suggests that MPAs are most successful when distant from human impacts, for example when isolated by deep water or sand (Edgar et al., 2014) or distant from fishing communities (Advani et al., 2015). On the other hand, social scientists have questioned the long-term efficacy of remote MPAs (Jones and De Santo, 2016) with evidence that MPAs near fishing villages are easier to monitor, and can have higher compliance (Pollnac et al., 2001; McClanahan et al., 2006), highlighting the importance of local support for their long-term sustainability (Basurto et al., 2016).

Acknowledging that social and ecological objectives are not separable but are interlinked (Ostrom, 2009; Persha et al., 2011), an emerging approach is the implementation of adaptive area-based conservation tools (Quintana and Basurto, 2020), which apply key principles of adaptive management for social-ecological systems: monitoring, assessment, learning, and iterative re-design (Armitage et al., 2010). This approach to area-based conservation prioritizes the decision-making process with fishers at the center, building opportunities for collective action (Gruby and Basurto, 2014; Quintana and Basurto, 2020). As such, it is an approach that values the process as much as the outcome, challenging the need to achieve the "right" design before establishing MPAs or other spatial management tools (Possingham et al., 2006; Giakoumi et al., 2018; Jantke et al., 2018). Examples include voluntary, temporary fisheries closures such as those in the South Pacific, Indian Ocean, Latin America, and the Caribbean (Cohen et al., 2013; Jupiter et al., 2017; Moreno et al., 2017; Villaseñor-Derbez et al., 2019). These temporary closures are spatially-explicit areas agreed to by local fishers where fishing is limited or prohibited for a specified period of time, after which they must be re-negotiated (McClanahan et al., 2006; Daw et al., 2011). Being inherently temporary creates an iterative process of learning and trust-building, a key facet of adaptive co-management, which also makes these potential tools for adaptation to climate change (Armitage et al., 2008; Plummer et al., 2012). These temporary fishing closures can further serve as an opportunity for resource users and regional governments to practice making collective decisions about (co-)management of coastal resources more broadly (Gelcich et al., 2006; Lozano and Heinen, 2016) and become biosphere stewards (Plummer et al., 2020). Such areas respond to calls to reconceptualize area-based conservation and management tools as "policy experiments" with opportunities for adaptation (Fox et al., 2012). They also have the potential to broaden participation beyond traditional experts, support development objectives, and adapt to climate change (Karr et al., 2017; Bennett et al., 2018; Flannery et al., 2018).

Where they produce ecological benefits, temporary closures can build trust, strengthen collective action, and support long-term sustainable resource harvest (Govan, 2009; Turner et al., 2016), especially where cooperation among fishers is supported by non-governmental organizations (NGOs) (Eraso et al., 2010; Basurto et al., 2016). However, where ecological benefits do not materialize, due to poor placement, short duration, or widespread non-compliance, fisheries closures may instead erode trust (Giakoumi et al., 2018; Scyphers et al., 2019). The competing design recommendations (size, duration, etc.) discussed above generate trade-offs that stakeholders must navigate. Temporary fisheries closures may thus entail a risky learning process because of positive feedback loops in the social-ecological system between trust, governance, and ecological outcomes, amplifying success or failure (see **Box 1** and **Figure 1**). The success or failure of such closures has implications for global efforts to expand ocean protection to 30% of the ocean's surface (IUCN, 2016), as the failure of one no-take approach can lower confidence in another.

BOX 1 | Theoretical feedback loop for temporary no-take zones designed by fishers.

The conceptual model below integrates social and ecological theory about area-based conservation measures (Fox et al., 2012; Gill et al., 2017; Mascia et al., 2017) within the frameworks of collective action (Ostrom, 2009; Partelow, 2018) and adaptive co-management (Olsson et al., 2004; Armitage et al., 2010). Based on this scholarship, we propose a theoretical feedback loop for adaptable no-take zones (areas where fishing is banned) designed by the users they affect. This conceptual model is likely relevant to other sustainable management tools.

In this simplified model, the level of initial *trust* in the no-take zone's potential (defined as confidence that it will have positive outcomes) determines initial *design* (number, location, size, etc.) (Charles and Wilson, 2009; del Mar Mancha-Cisneros et al., 2018). Empirically, this initial trust often depends on factors like historical relationship with government, non-governmental organizations (NGOs) and/or scientists (Kusumawati and Huang, 2015; Basurto et al., 2016; Ordoñez-Gauger et al., 2018), predicted compliance rates (i.e., reputational history of fishers affecting their likelihood of mutual restraint) (Ostrom and Ahn, 2009), and expected or potential ecological benefits (Bennett and Dearden, 2014; Hargreaves-Allen et al., 2017; McNeill et al., 2018). Depending on initial design (Halpern, 2003; Lester et al., 2009), and mediated by socio-ecological factors like habitat quality and compliance (Marin-Monroy et al., 2020), the no-take zone may (or may not) lead to ecological changes like increased biomass of target species (Edgar et al., 2014; Gill et al., 2017). This in turn may or may not be perceived by the fishers (Bergseth et al., 2015). The fishers then evaluate these perceived results to update their trust in the no-take zone, which starts the next iterative cycle with a collective action process and new area design (McNeill et al., 2018).

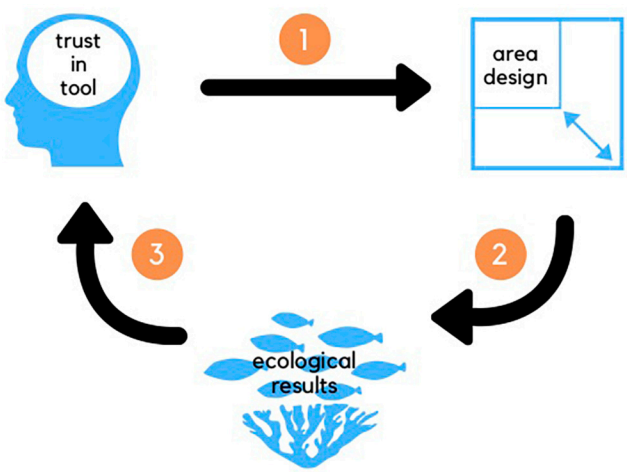


Diagram of simplified feedback loop between individual fishers' trust in the probable efficacy of a no-take area tool, the design they collectively agree upon, and the resultant ecological changes. Arrows generally represent positive feedbacks, but are mediated by numbered processes on the right, which affect the strength and direction of the feedback. Numbers above match processes on the right.

Link 1: Decision-making processes involving collective action such as leadership, social organization, and previous experience in collective action mediate how individual trust is reflected in collectively agreed-upon no-take zone design (Ostrom et al., 1994; Osmond et al., 2010).

Link 2: Social-ecological processes like compliance, species mobility, and spillover mediate the effect of design on ecological outcomes of the no-take zone (Fox et al., 2012; Edgar et al., 2014; Gill et al., 2017; Mizrahi et al., 2019).

Link 3: Assessment, perception, and valuation processes like fishing in adjacent areas, observing changes inside the no-take zone (e.g., underwater surveys), and perceived monitoring and enforcement mediate how ecological results are detected and evaluated to update individual trust in the next timestep (McClanahan et al., 2005).

FIGURE 1 | A diagram of the simplified feedback loop and the three Links that make up the conceptual model.

Model predictions: This simple model provides a potential mechanism for both an "upwards spiral" of increasing trust, improving design, and increasing ecological benefits, as well as a "downwards spiral" of evaporating trust, deteriorating design, and negligible ecological benefits. For example, the model predicts that when the system starts with low initial trust in the no-take zone's potential, it leads to a low-risk design (e.g., small size or protection of unproductive sites) and thus insignificant ecological results. The lack of results further reduces trust in the no-take zone's likely efficacy, which reduces fishers' willingness to close productive areas, and further decreases the likelihood of ecological benefits ("downwards spiral"). Conversely, high initial trust leads to a better no-take zone design that produces significant and detectable ecological results, leading to greater trust in the no-take zone's future potential. This leads to improving no-take zone design until the perceived costs (e.g., loss of fishing area) outweigh the benefits ("upwards spiral"). If such a feedback loop were to be widespread in adaptive no-take zones, the thresholds between these two outcomes in any particular context, as well as the mechanisms to reinforce or break out of the feedback loops, would be of great interest to conservation practitioners as well as scholars.

In this paper, we explore feedback loops for area-based no-take zones that prioritize adaptation and learning rather than optimized initial design. We first describe a conceptual model and discuss its utility in explaining empirical outcomes from temporary no-take zones aimed at rebuilding fisheries called fishing refugia (in Spanish, Zonas de Refugio Pesquero) in the Gulf of California, Mexico. In this region, a network of fishing refugia was established in 2012 with a 5-year duration, with the legal goal of rebuilding fisheries (DOF, 2012). When these expired in 2017, local fishers redesigned and renewed them, resulting in an increase in the number (+1) and size of the largest fishing refugia (550% growth) while the smaller areas were unchanged (DOF, 2017). We chose this case because of the authors' long-term experience (5–20 + years) in the study region and access to fine-scale and temporally overlapping social and ecological data (2009–2017). We examine the following research questions:

Can social-ecological feedback loops explain diverging outcomes in adaptive, temporary no-take zones designed by fishers? Is there empirical support for these feedback loops?

We depart from a theoretical conceptualization of how these dynamics would work, explained in detail in **Box 1**. We present

the conceptual model first for logical flow of the paper, but note that this model emerged both deductively and inductively, through iterative conversations about theory and this case. Since the model emerged (in part) from the case, we do not use the case to "test" the model's validity; instead we use the model to explore and critically evaluate possible mechanisms explaining patterns we found empirically. Specifically, we discuss the social and ecological feedback loops that may have caused a divergent pattern wherein the largest area was expanded and smaller areas were unchanged. We contribute to a growing body of work that combines models and empirical evidence to understand social-ecological dynamics within small-scale fisheries and marine conservation governance (Lindkvist et al., 2017; Okamoto et al., 2020; Wijermans et al., 2020).

MATERIALS AND METHODS

Case Study: Fishing Refugia of the Corredor, Baja California Sur, Mexico

Mexico's fishing refugia are area-based tools—either limited take or no-take zones—intended to protect or rebuild fisheries (DOF, 2014). Most are temporary (CONAPESCA, 2019). Unlike traditional protected areas governed by Mexico's Ministry of the Environment (SEMARNAT), which many fishers—for example in the northwest of Mexico—mistrust, fishing refugia are governed by Mexico's Fisheries Commission (Comisión Nacional de Acuacultura y Pesca, hereafter "CONAPESCA") which provides subsidies and fishing permits to fishers. CONAPESCA has implemented area-based fisheries closures like fishing refugia since 1975 (De Anda-Montañez et al., 2013), but fishing refugia were not established as an official fisheries management tool until 2007, when they were included in the General Law of Sustainable Fishing and Aquaculture with "the primary purpose of conserving and contributing, natural or artificially, to the development of fishing resources by protecting their reproduction, growth or recruitment areas, as well as preserving and protecting the environment that surrounds them" (DOF, 2007).

In 2010, after a series of meetings convened by civil society organizations and academic scientists, CONAPESCA opened an invitation to Mexico's fishers to initiate a process of fisheries management that included proposals to establish fishing refugia completely closed to fishing. The first effort to attend this call happened in the San Cosme to Punta Coyote Corredor region (the "Corredor") in the state of Baja California Sur, with technical support from the Sociedad de Historia Natural Niparajá (hereafter Niparajá), a civil society organization dedicated to regional conservation (Niparajá is led by one of the coauthors of this paper, AHW). After a process spanning several years, on November 16, 2012, Mexico's first network of no-take fishing refugia was established in the Corredor (DOF, 2012). Since 2012, 41 fishing refugia have been established across Mexico, covering 20,185 km^2 in the coastal waters of four states (CONAPESCA, 2017). Most to date have been designed and proposed by small-scale fishers, who decide on the location, size, and duration (typically 5 years at a time with the option of renewal). Almost all fishing refugia are strict no-take (including the first ones, established in the Corredor, which this paper discusses), although some of the refugia allow for limited take. Refugia are poorly enforced by CONAPESCA in practice, leaving much of the monitoring and enforcement to vigilantes, fisher organizations (e.g., cooperatives), or their civil society partners.

Mexico's first fishing refugia were established in the Corredor because of the confluence of declining fisheries and support from Niparajá. The Corredor is on the coast of the Gulf of California, which produces up to 71% of Mexico's total fisheries by volume (OECD, 2006). There is evidence of decline in the health of exploited ecosystems and the status of fish populations throughout the Gulf of California (Sala et al., 2004; Saenz-Arroyo et al., 2005; Giron-Nava et al., 2019), including the Corredor region, which has 13 permanent fishing towns, 659 residents, and 104 fishing vessels (Niparajá, 2016). Most livelihoods in the Corredor depend on fishing, with some ranching and tourism. Fishers in the region fish from 6 to 8-m "pangas" (fiberglass boats with an outboard motor) typically on day-trips although some set up fishing camps on nearby islands. Fishers have multispecies finfish permits, and primarily target snappers (especially red snapper, *Lutjanus peru*), groupers, jacks, and triggerfish; they are relatively homogeneous in terms of gear, with 93% of fishers using hook and line, although some (30%) also use targeted gillnets, especially for sharks and rays (Niparajá et al., 2009). Since 2009, Niparajá has led data collection efforts in the Corredor, including socioeconomic surveys in 2009 and 2016, annual underwater ecological monitoring data from 2012 to present, and fish catch monitoring data from 2012 to present, which we use in this paper.

Ecological Data

From 2012 to 2017, Niparajá implemented an ecological monitoring plan to track the ecosystem changes within and outside the network of fishing refugia established in 2012, partly with the involvement of fishers from the Corredor. For this monitoring, Niparajá trained nine fishers from the Corredor who joined their scientific team as "Buzos Monitores" (monitoring divers) in annual expeditions (mostly in October) to at least one site inside each fishing refugia and one comparable control site outside the refugia (Quintana et al., 2020). To perform the surveys, divers deployed a 30 m transect and registered all fish and invertebrates encountered in a 2 × 2-m box (4 m^2) over 20–30 min following the transect tape. Divers recorded the species, size and number of individuals observed. Given the fisheries objectives of the fishing refugia, we focused our analysis on the eight species of primary commercial importance that include: leopard grouper (*Mycteroperca rosacea*), creole fish (*Paranthias colonus*), trigger fish (*Balistes polylepis*), yellow snapper (*Lutjanus argentiventris*), cenizo snapper (*Lutjanus novemfasciatus*), mulato snapper (*Hoplopagrus guentherii*), jacks (*Caranx* sp.), and parrotfish (*Scarus* sp.). The selection of these eight primary commercial species provided one line of evidence to evaluate the refugia's progress toward its legal goal of curbing fisheries decline.

For each of the fishing refugia within rocky reefs (excluding the ones in estuaries given their role as nursery grounds), we estimated the total density in number of individuals per

square meter and the total biomass in tons per hectare, from 2012 to 2017. We calculated biomass from length estimates recorded during monitoring, scaled by species-specific length-weight ratios. These values were estimated for both the protected area and their respective control areas. We also estimated the average rate of change in biomass for each fishing refugia as the slope of a linear model between the year and the average annual biomass. These results were then compared to the total area of each fishing refugia to test the relationship between size and rate of recovery.

Social Data

The social outcomes discussed below are primarily based on a survey of 95 fishers that Niparajá and Duke University conducted in 2016, comprising over half of all 173 active commercial fishers in the Corredor (Niparajá, 2016). The surveys typically lasted from 1 to 3 h and covered diverse topics related to socioeconomics and fishing, including household economy, fishing behavior, and attitudes toward the fishing refugia. The survey questions used in this paper are extracted and listed in **Supplementary Material 4**. A team of trained enumerators conducted this survey through interviews using pen and paper in every town in the Corredor from June to December 2016. Participation was voluntary with no financial incentive. Spatial distribution of respondents is tabulated in **Supplementary Material 3**. Given the constraints of surveying fishers in rural towns, sampling was a mix of purposive, random, and opportunistic to achieve a minimum sample size of at least 50% of active fishers from each town. Half of respondents for the 2016 survey were selected purposively based on their participation in a 2009 survey (n = 86) also conducted by Niparajá, which aimed to survey 1/3 of boat captains about fishing behavior and socioeconomic status. This survey preceded the fishing refugia and aimed to assess interest in the tool, as well as general attitudes about fishing. The rest of the respondents for the 2016 survey were randomly selected from a list of names. However, since only active fishers were surveyed, and fishers frequently spend time away from their communities (either in nearby cities or at fishing camps), response rates are hard to estimate. No fishers declined to be interviewed, although some stalled and then could not be found later. When targeted fishers could not be found or were no longer active fishers, fishers from their nearest kin or fishing crew were interviewed. Ultimately, about half of active fishers were interviewed.

These outcomes are analyzed and contextualized using qualitative data about perceptions of the fishing refugia from 6 months of in-depth fieldwork including observation, journaling, and informal and semi-structured interviews (n = 68) with stakeholders involved in implementing and evaluating them, as well as document analysis of legal documents and white papers. Interviews sought to understand how fishers perceived the fishing refugia, covering topics such as fishers' knowledge; the Buzos Monitores fisher-monitoring program; adaptive management and evaluation; property rights and responsibilities; and fisheries change. For interviews, following IRB approval (Duke University permit 2018-0130) AQ spent approximately 180 days from 2016 to 2018 in the field, recording and transcribing 54 semi-structured interviews with fishers, their families, government fisheries agency staff, university scientists, and Niparajá staff. A further 14 interviews were not audio-recorded but information was recorded in detailed notes. A.Q. coded transcriptions and conducted thematic analysis iterative with writing. The quotations presented below were selected from the 68 interviews because they most succinctly and articulately represented the variation of attitudes and perceptions that emerged in these interviews. These quotations were translated from Spanish, with minor edits to maintain original sentiment and intent, and for clarity. Respondents' names are hidden to protect anonymity.

RESULTS

> *"For the past 20 years, fishing has been disappearing. So Niparajá came and invited us to make fishing refugia. The people [here] did not really agree, because we did not know how the refugia would function. We did not know how the refugia would end up. And so we in the community started to talk, amongst ourselves, about whether it would be good. Some said yes, some said no. Well, you don't lose anything by trying it for 5 years, by testing to see if it would work. So we agreed and signed the paperwork with Niparajá. And so we didn't fish there that year, and the second year. By the third year, we went to see: and there were many fish. Many, many, many fish. It was working."*
>
> (Interview with fisher from Agua Verde, 11/13/17)

Link 1: Effect of Initial Trust on MPA Size Mediated by Collective Decision Process

The fishers of the 13 towns of El Corredor ultimately designed 11 fishing refugia of highly variable size, the most salient design characteristic, ranging from 0.4 to 5.9 km^2 (DOF, 2012; **Table 1**). Individually, El Corredor fishers had variable trust in the probable efficacy of the fishing refugia. When Niparajá first presented the idea of fishing refugia to the fishers of El Corredor, they had mixed reactions. For example, an early supporter from the largest town of Agua Verde described the initial reaction to fishing refugia as follows: "To us in the community, it was like a light bulb: this is good, [the fishing refugia] will be like a natural nursery for fish reproduction" (interview with fisher, 11/14/17). A more skeptical fisher, also from Agua Verde, told us, "I don't see [the fishing refugia] as a place to discharge fish to the whole area where we fish; it is impossible" (interview with fisher, 12/8/17). Nothing like a fishing refugia (i.e., a legal area-based fisheries closure) had ever been established in the Corredor, where illegal fishing was already widespread in various forms. Technically, about half of the Corredor fishers lacked permits and thus operated outside the margins of legal fishing despite generations of fishing in the area (Niparajá et al., 2009). Far more problematic from the perspective of El Corredor fishers were illegal and semi-legal fishers from "outside" (especially, the town of Ensenada Blanca to the north, the city of La Paz to the south, and the states of Sonora and Sinaloa across the Gulf of California), who were perceived as responsible for fisheries

decline through the use of "damaging" gear like spearfishing, gillnets, and shrimp trawling. Finally, as a largely inaccessible region with low population density, no paved roads, and little coverage by cellular phone service, El Corredor was largely ignored by government officials, including fisheries officers. As such, there was also little trust in the official fisheries agency or its ability to enforce regulations.

While there was variation in individual fishers' trust in the fishing refugia's potential overall, focus groups conducted by Niparajá in 2009 revealed collective patterns among the 13 towns, published in a report called "Conociendo El Corredor" (Niparajá et al., 2009). Fishers from about half the towns (Agua Verde, Los Dolores, Ensenada de Cortes, San Evaristo, and El Pardito) proposed the solution of temporary area closures (such as refugia) (**Table 1**). Only fishers from Agua Verde proposed solutions like "establish well-defined catch sizes and limits" and "fishers should only catch species that their permits allow" indicating support for and trust in official regulations.

The reasons for town-level differences in initial trust in the fishing refugia was likely influenced by a number of endogenous variables like historical relationship to government, relationship to Niparajá, and road accessibility (**Table 1**). For example, in Agua Verde prior to 2009, a Niparajá staff member had built a permanent house and resided there for over a year, and government presence included a permanent paid government representative and government-funded schooling from pre-kindergarten through middle school.

The decision-making process mediated how initial individual trust level translated into the design of the fishing refugia in 2012. Because refugia are voluntary, they were negotiated and debated amongst the fishers between November 2009 and May 2010. In the northern Corredor (Agua Verde and Tembabiche), where towns are large and spread apart, there is very little overlap of fishing areas (**Table 1**; **Supplementary Material 1**), and towns decided individually on which areas to establish as fishing refugia. These towns are also characterized by the presence of fishing cooperatives, which establish a formal mechanism for leadership to reach consensus. On the other hand, in the southern Corredor (all other towns), fishing zones overlap substantially and respondents from many towns reported a lack of incentives to care for fisheries resources in 2009 (Niparajá et al., 2009) (**Table 1**), as such, proposals from one town were often rejected by another. Ultimately, refugia were only established when a majority of fishers from each affected town agreed. **Supplementary Table 3** lists all fishing refugia established in 2012, and which towns negotiated and agreed to each one's establishment.

The outcome given heterogeneous individual trust and a heterogeneous decision-making process, with greater presence of

TABLE 1 | Comparison of fishing towns in El Corredor in terms of total population, number of commercial fishers, relationship to government prior to 2009, relationship with Niparajá prior to 2009, accessibility through roads, lack of incentives to take care of fishing areas, conflicts with other fishers due to fishing areas overlap, and whether or not they proposed an area closure.

Town (population)	# Fishers	Relationship to government pre-2009	Relationship to Niparajá pre-2009	In focus groups in 2009, fishers identified the following issues:		
				Lack of incentives to protect resources*	Overlap of fishing areas*	Interest in establishing closures*
Agua Verde (278)	60	Paid government representative and multiple funded schools	Niparajá built a house for staff member, who lived there for 1.5 years. Also is a common place for fishers meetings.			×
Tembabiche (80)	18	Paid government representative				
Los Dolores (6)	3			×	×	×
Ensenada de Cortés (61)	15			×	×	×
Punta Alta (36)	14			×	×	
La Cueva (19)	7			×	×	
Nopoló (4)	1			×	×	
Palma Sola (12)	5			×		
San Evaristo (90)	24	Paid government representative			×	×
El Pardito (16)	12		Niparajá staff member partly resided here for 1.5 years	×	×	×
El Portugués (3)	3		Resentment about previous Niparajá project			
Punta Coyote (35)	11			×	×	

*All towns except El Portugués are resident communities where fishers live with their families; El Portugués is a fishing camp. The population and number of fishers reflect census data collected in 2016 by Niparajá. For columns with *, × marks town where fishers discussed the respective issue in focus groups conducted in 2009 by Niparaja.*

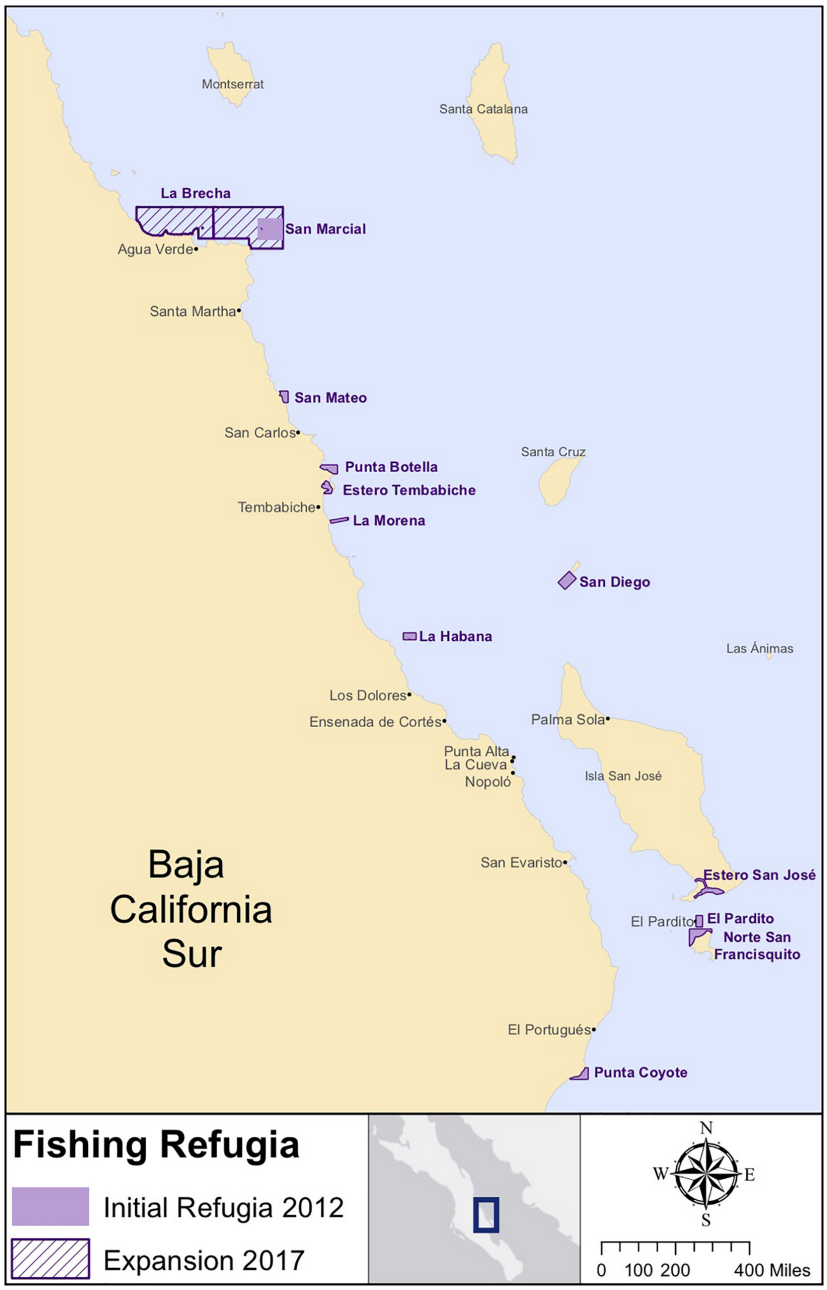


FIGURE 2 | Divergent pattern of fishing refugia adaptation after first 5 years. Original map is shown in light purple (established 2012 for 5 years). Note largest area in the north, San Marcial, created by fishers in the town of Agua Verde. In 2017, all fishing refugia were renewed for another 5 years with no changes, except San Marcial, which was expanded (shown in dark purple hatching). Map designed and created by Erin Ristig based on legal maps (DOF, 2012, 2017).

cooperatives and leadership in the north, was that the towns in the north proposed a greater area of fishing refugia (on average, 4.16 km^2 per town) compared to the south (on average, 0.46 km^2 hectares per town). The largest area by far was the "San Marcial" fishing refugia created by Agua Verde, at 5.92 km^2, compared to the median size of 0.64 km^2. **Figure 2** shows the location and extent of each fishing refugia in 2012 and the updated map from 2017.

Link 2: Ecological Effects of MPAs Mediated by Size and Socio-Ecological Factors

We found that on average, both the fishing refugia and their respective control areas had similar values for density and biomass in 2012 (**Figure 3**), when the network was first established. The fishing refugia presented clear signs of recovery

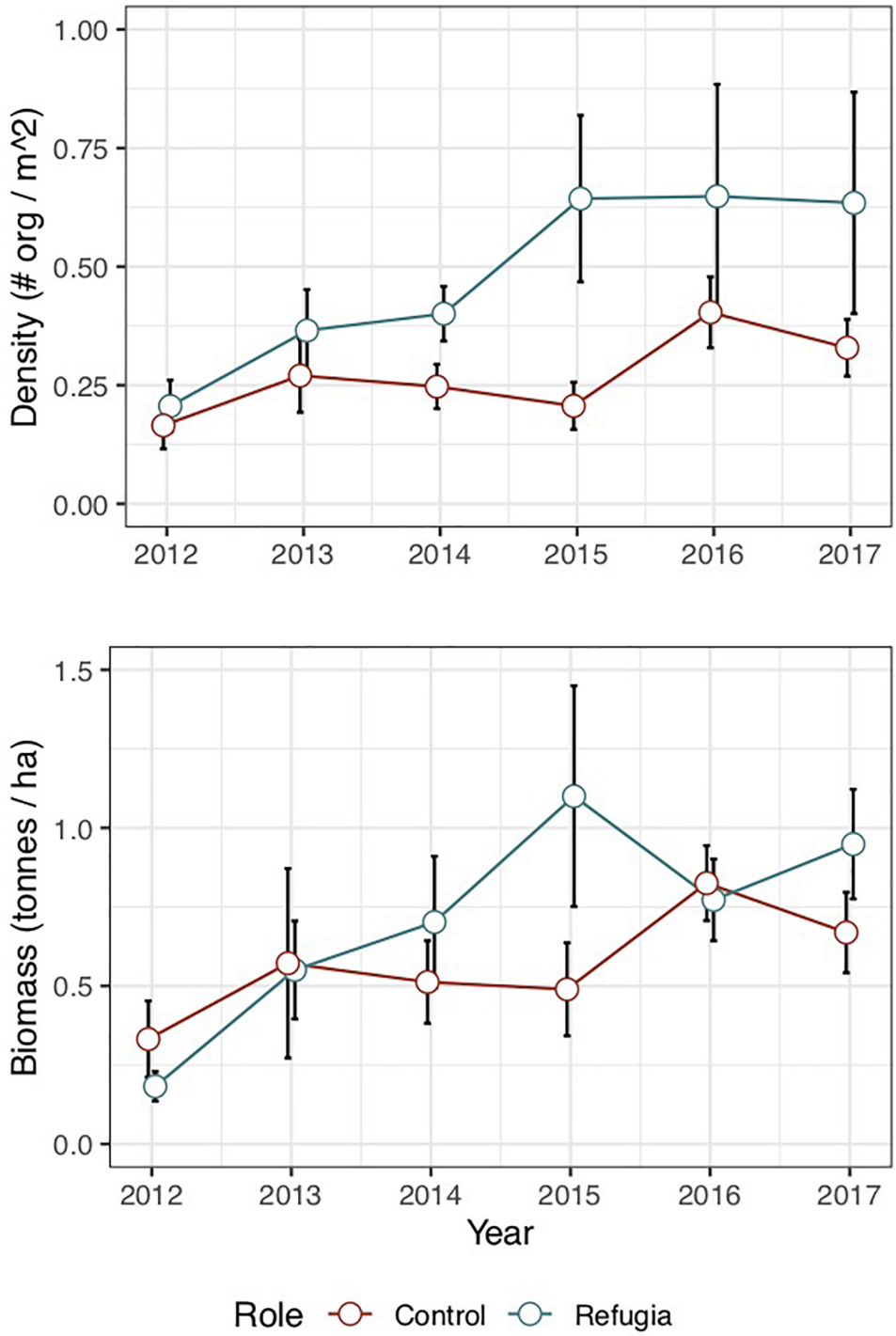


FIGURE 3 | Comparison of ecological parameters (biomass and density) between fishing refugia (blue) and control sites (red) from 2012 to 2017, from transect monitoring data. Trends show increase in both biomass and density over time, with significantly greater increases in fishing refugia.

between 2012 and 2017, with the average numerical density of fishes inside the fishing refugia going from 0.21 ± 0.05 fish/m^2 in 2012 to 0.63 ± 0.23 fish/m^2 in 2017. Conversely, the control areas went from an average density of 0.16 ± 0.05 fish/m^2 in 2012 to 0.33 ± 0.06 fish/m^2 in 2017. Additionally, the average biomass inside the fishing refugia went from 0.18 ± 0.05 tons/ha in 2012 to 0.95 ± 0.17 tons/ha in 2017; a greater recovery than the control areas that went from 0.33 ± 0.12 tons/ha

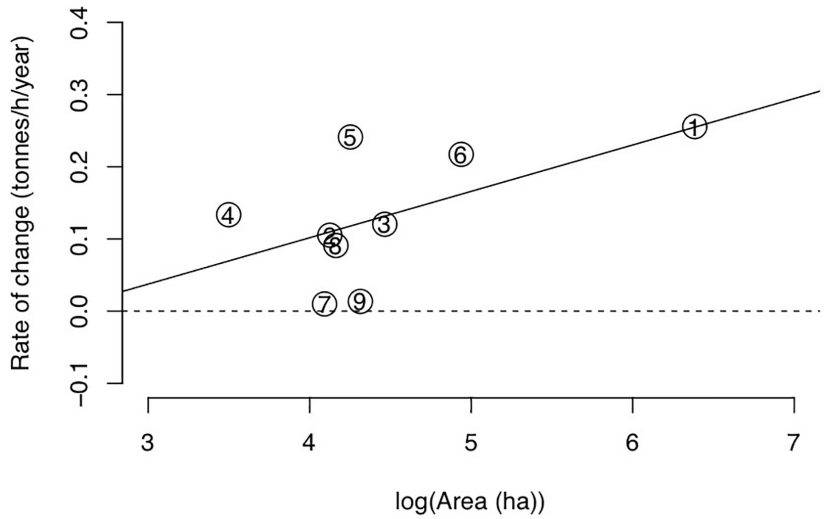


FIGURE 4 | Differential rates of biomass recovery based on total area for each fishing refugia. Each refugia is indicated by a number as follows: (1) San Marcial, (2) San Mateo, (3) Punta Botella, (4) La Morena, (5) La Habana, (6) San Diego, (7) El Pardito, (8) San Francisquito, and (9) Punta Coyote. La Brecha and Estero Tembabiche were excluded from this analysis given that those sites were established primarily to protect juveniles of important commercial in the coastal lagoons, thus no comparable metric of biomass recovery was available.

in 2012 to 0.67 ± 0.13 tons/ha in 2017 (**Figure 3**). These results highlight that even though adjacent areas are subject to similar environmental conditions and variability, the impact of protection was detectable.

We also found a marginally significant relationship between the logarithm of the total protected area and the average rate of change in biomass (**Figure 4**). Larger fishing refugia showed a faster biomass recovery ($R^2 = 0.33$, $P = 0.1$).

Link 3: Effect of Perception of Ecological Effects on Individual-Level Trust in Fishing Refugia

Based on the survey of El Corredor fishers conducted in 2016, about two-thirds of fishers reported that they perceived positive ecological results from the refugia 4 years after their establishment. Fishers who perceived positive effects were significantly more likely to propose the expansion of their fishing refugia and the creation of new ones than fishers who did not perceive positive ecological results (**Figure 5**). In contrast, fishers who perceived no ecological change resulting from the fishing refugia were more likely to propose eliminating the refugia (**Figure 5**).

Our interviews conducted in 2017 suggested that the Corredor fishers primarily drew on three sources of information to assess whether the fishing refugia were producing ecological benefits: (1) fisheries—whether there were detectable changes in catch or income; (2) underwater monitoring by "Buzos Monitores"; and (3) direct sampling by chumming the waters with bait, throwing a hook or fishing inside the fishing refugia. The fishers evaluated these perceptions differently, according to their own value systems and cost-benefit analyses: some fishers argued that the refugia were working on the basis of detectable differences with the promise of future potential, while others wanted to see more substantial results (e.g., "getting rich") in accordance to time sunk in meetings and loss of fishing area. Fishers thus combined perceptions with their value systems to arrive at a decision of whether the refugia were "working."

In the 2016 survey, El Corredor fishers were asked: "Let's suppose that the fishing refugia had never been established. How do you think the resources would be in this area?" In other words, "What was the effect of the fishing refugia on the resources?" Almost two-thirds (63%) said that the Fishing refugia had a positive impact in the resources. A third (31%) reported that there was no impact. A few (6%) said that the impacts were negative (**Figure 5**).

The same survey asked fishers several questions to propose modifications for the fishing refugia, which were going to expire in 2017. Fishers were asked whether they wanted to propose one or more sites for new fishing refugia, and then what action they would like to take regarding the 11 existing ones: keep as is, modify, or eliminate. If they said they wanted to modify the refugia, they were asked to describe how. In almost all cases of "modify," fishers then stated that they wanted to expand the respective area (**Supplementary Figure 1**). Compared to fishers who perceived no fishery changes resulting from the refugia, fishers who perceived that the refugia had benefited their fisheries were more likely to propose new sites for fishing refugia, were more likely to modify (expand) their existing refugia, and less likely to eliminate them. These two groups did not significantly differ in whether they decided to keep their refugia; overall (t-test, $P > 0.05$), most fishers proposed keeping the existing refugia. Evidence from El Corredor thus suggests that, for individual fishers, perception of ecological

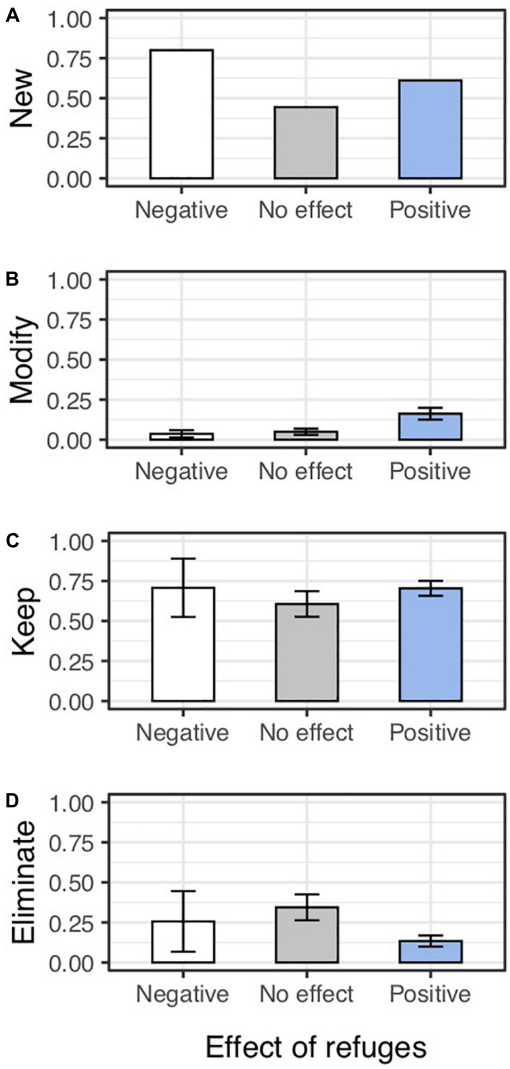


FIGURE 5 | Breakdown of respondents' management proposals by whether they perceived positive (*N* = 54, 63%), null (*N* = 27, 31%), or negative (*N* = 5, 6%) fishery results from the existence of fishing refugia. The y-axis represents the proportion of respondents from each group that proposed **(A)** a site for a new refugia, **(B)** the modification (in almost all cases, expansion) of existing refugia, **(C)** to keep their refugia as is, and **(D)** to eliminate refugia.

benefits from the refugia was associated with trust both in the particular refugia in specific locations ("modify") and trust in the broader tool of the refugia ("new") in the context of the Corredor.

Link 1, Again: Effect of Established Trust and Collective Action on Modified No-Take Zone Size

Given the variation in individual fishers' trust in the refugia reflected in the 2016 surveys (**Figure 5**), a second decision-making process mediated how individual trust in the MPAs was reflected in the ultimate re-design of the fishing refugia in 2017. As discussed above in Link 1, in the northern Corredor (Agua Verde and Tembabiche), decisions were made at the town level. In Agua Verde, which had the largest refugia and the largest ecological benefits measured in underwater surveys (**Figure 4**), fishers overwhelmingly reported that the refugia had benefited their fishery (**Figure 6A**) in the 2016 survey. Fishers from Agua Verde were also the most likely to propose new sites and to modify (expand) their existing site. In Tembabiche, which had proposed four smaller refugia, and where there were variable ecological benefits measured in underwater surveys, fishers were less likely to propose new refugia or to expand their refugia. In the southern Corredor, refugia had to be negotiated among multiple towns because of overlapping fishing areas. Towns in the south are also (in most cases) much smaller than the north, and because of these two factors we combined the responses of fishers on the 2016 surveys below in **Figure 6**. Compared to Agua Verde and Tembabiche, in the southern Corredor, fishers were less likely to report positive fishery outcomes from the refugia, less likely to propose new sites, and less likely to expand their existing sites. They were more likely to propose eliminating their existing refugia. Summing individual responses across the Corredor about the 11 existing refugia, the average fisher wanted to maintain the majority (64%) of refugia as is, eliminate 21%, and modify (expand) 14% of the refugia. Additionally, a slight majority of fishers overall (55%), including fishers from the southern Corredor, proposed new sites for refugia.

The individual fishers' opinions aggregated by town or region (**Figure 6**) in 2016 were the starting point for negotiations, which took place over 2017, largely facilitated by Niparajá. In February 2017, Niparajá hosted a 2-day meeting in the capital city of La Paz to kick-start negotiations, disseminate results from the 2016 survey and ecological monitoring from 2012 to 2016, and suggest recommendations. Government officials, university partners, Niparajá staff, and fishers themselves gave presentations to 173 attendees representing every town in El Corredor. One of the most salient design recommendations from ecologists at two local universities was to increase the size of all the refugia to improve ecological performance.

Community discussions and negotiations ensued. In almost every community, at least one fisher proposed a large fishing refugia, either at a new site or as a dramatic expansion of an existing one. However, the refugia were ultimately only expanded where a majority of fishers perceived that they had produced positive results and where there was leadership to generate a unified vision among the various individual perspectives. Each town and each refugia had its own path-dependent process through which a final decision was made, but three cases (Agua Verde, San Diego, and Portugues) illustrate the diversity of decision-making processes and the factors that influenced them; we describe these below.

Aqua Verde—Large Ecological Benefits, Strong Leadership, Expanded Refugia

Agua Verde was the town that, in the original design approved in 2012, proposed the largest fishing refugia (San Marcial). In the renewal process in 2017, strong leadership from the presidents

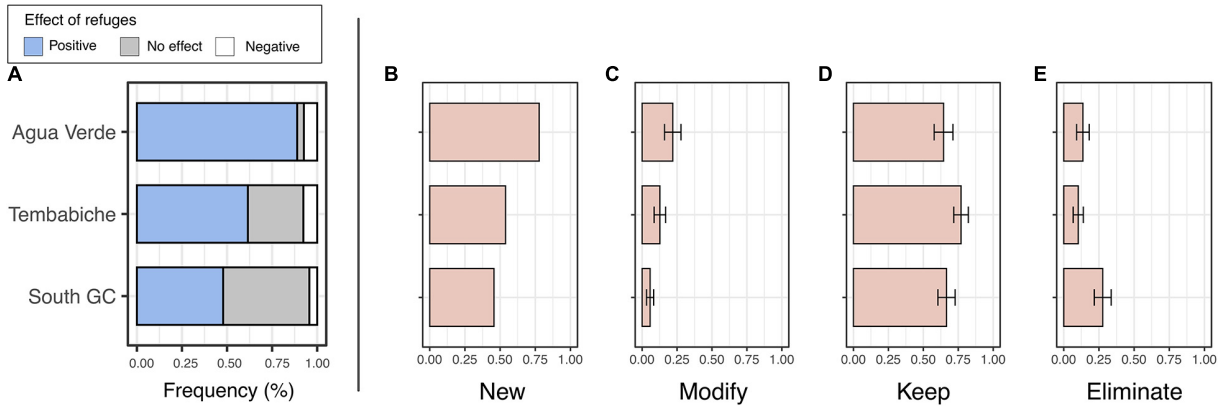


FIGURE 6 | Effect of perception of positive ecological changes on likelihood of proposing new refugia and expanding existing ones, based on 2016 social science survey. Individual survey responses are aggregated by community in the north (Agua Verde, Tembabiche) and together in the south, where fishing zones overlap, and multiple communities had to negotiate each refugia (see **Table 2**). **(A)** shows proportion of individuals who reported perceiving positive, neutral, and negative ecological effects of the refugia on fisheries. **(B–E)** show proportion of fishers who: proposed new refugia **(B)**, proposed to modify (mostly expand, see **Supplementary Material 1**) existing refugia **(C)**, proposed to keep existing refugia **(D)**, and proposed to eliminate existing refugia **(E)**.

of the two oldest cooperatives facilitated a unified vision ("go big"), ultimately resulting in a dramatic expansion of the fishing refugia. Both cooperative presidents were highly respected and able to engage their fishers, and they agreed that, if Agua Verde was going to keep having refugia, they would do it in earnest and make an even larger area. Fishers in Agua Verde had seen fishing improve over the previous 5 years since the refugia were established. The reason was unclear: whether there were fewer nets being used, or the water had coincidentally gotten more productive, among other reasons. However, there were stories of fishers coming back from San Marcial having seen positive results of fish recuperation inside the refugia. On this basis, the cooperative presidents were able to get strong support from their members for the idea of a single large refugia, leaving the precise details (e.g., which reefs or rocky areas to include) to the fishers who knew the area best and were most invested in the process. Ultimately, they dramatically expanded the fishing refugia of San Marcial and added another one nearly as large, connected on one side, where most fishing was banned although bait fishing would continue to be permitted. Both areas left a 50-m strip along the coastline where fishing was allowed, so as not to affect people fishing non-commercially with hook and line from the shore, primarily women and children (**Figure 2**).

San Diego Island—High Ecological Potential, Poaching, and Fractured Leadership, No Change in Refugia

In comparison, the fishing refugia at San Diego Island was a case of high hopes and ultimate disappointment. The refugia at San Diego possesses many of the characteristics that ecologists have associated with good MPA design, including a diversity of habitats and having once been extremely productive. Fishers from El Corredor who agreed to establish the refugia, and thus give up fishing there, had high hopes for strong recovery of fish. However, fishers from six different towns participated in designing the San Diego fishing refugia, leading to a lack of a sense of ownership or responsibility to monitor and enforce it. Unlike San Marcial, which is near the town and which most Agua Verde fishers pass by to go fishing, San Diego is out of the way of most fishers' daily fishing trips. As a result, monitoring is time-consuming and expensive for fishers. Lack of compliance from external fishers eventually led to decreasing compliance from fishers within El Corredor, who felt it unfair to give up their fishing grounds only to be raided by outsiders. By 2017, fishers from the six towns who originally agreed to San Diego still agreed that the site had great potential. One fisher, arguing that larger size would lead to better enforcement from authorities and monitoring by fishers from El Corredor, proposed a large and ambitious extension of San Diego, including the entire island extending all the way to the reef it currently encompasses. However, lacking a clear leadership among all communities, and after years of poor compliance, the ecologically ambitious proposal to expand San Diego did not gather enough support. Ultimately San Diego was renewed with no changes.

El Portugués—No Ecological Benefit, Strong Ringleader, No Change in Refugia

A third case of the decision-making process took place in El Portugues, a fishing camp in the southern Corredor which transitioned from apathetic/oppositional to oppositional from 2012 to 2017. In 2012, fishers from El Portugues declined to participate in the process of designing the original fishing refugia. Opposition partly stemmed from a fisher who had moved to Portugues after losing his previous fishing ground to an MPA established in 2007 that was supported by a different branch of Niparajá. The refugia closest to the camp is Punta Coyote, generally considered by El Corredor fishers to be the poorest in ecological design, and which had no demonstrable ecological benefits by 2016 in transect or fishing data. By 2017, fishers from El Portugues decided to participate in the renewal process. Fishers from Punta Coyote proposed a new fishing refugia in a shared

fishing ground with El Portugues, but fishers from El Portugues opposed the area. While Punta Coyote agreed and was willing to sacrifice the fishing area, Portugues was not. Their opposition prevented the area's establishment in 2017. In the proposal that ultimately resulted from the intra- and inter-town negotiations through the collective action process, almost all the fishing refugia were renewed with no changes (**Figure 2**). While new potential sites or expansion of existing sites were proposed in many towns, all but one (San Marcial) of these proposals got bogged down in conflict and uncertainty and were ultimately rejected by the majority of relevant fishers.

DISCUSSION

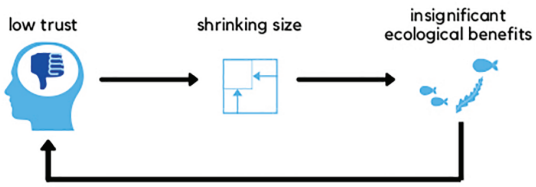
Managing Expectations of No-Take Zones

Our results and the conceptual model they support (**Box 1**) suggest that the success of community-based no-take zones depends on stakeholders' expectations. When users have the power to design temporary no-take zones, "good enough" ecological design, leadership, and collective action can result in growing trust and improving ecological benefits, while "not good enough" areas can result in loss of trust and poor ecological outcomes. Stakeholders, themselves, decide what is "good enough," and this is likely to depend on whether outcomes align with their expectations, including non-ecological outcomes such as attention from the government and compliance. Whether the game is "win-win" or "lose-lose" thus depends on expectations. If, as has been documented (Christie, 2004; Bennett and Dearden, 2014), scientists promise strong ecological benefits from no-take zones that do not materialize, resource users' trust in the no-take zones' future success is likely to deteriorate, and they are likely to remove it. In the case of the Corredor, while NGO staff at Niparajá point to significant increases of biomass within the fishing refugia as a "win," fishers from the Corredor have reported feeling disenchanted by ongoing poaching by outsiders, lack of enforcement by the fisheries agency, and less economic recovery than they had expected. As the wife of a fisher told us, "We work more and more with Niparajá on the refugia, and who here has become rich? Nobody. Nobody has become rich" (interview 11/18/17). This pathway of stakeholder disenchantment could be one reason for the downgrading, downsizing, and degazettement of protected areas ("PADDD"), increasingly recognized as a widespread phenomenon and threat to biodiversity (Shrinking loop, **Figure 7**) (Mascia and Pailler, 2011; Symes et al., 2016; Golden Kroner et al., 2019).

At the same time, our model also implies that adaptive no-take zones do not have to be optimally designed at the outset, so long as they align sufficiently with users' expectations to build trust. In the case of the Corredor, the refugia were initially much smaller than most MPAs globally, with a median size of 0.64 km^2 and mean size of 1.2 km^2, compared to global MPA median size of 4.6 km^2 and global mean size of 544 km^2 (Wood et al., 2008). They were also much smaller than the suggested minimum size of MPAs in a network, of 4–6 km^2 (Shanks et al., 2003) or 10–100 km^2 (Halpern and Warner, 2003). However, when the refugia were adapted and renewed after the first 5 years, the town where a majority of fishers perceived that there were ecological benefits from the refugia (Agua Verde) had established two refugia within or above recommended size ranges for MPAs, 33 km^2 and 27 km^2 (see **Supplementary Material 3**; Growth

Shrinking loop

In this idealized scenario, low initial confidence in the no-take zone's potential leads to poor initial design (in this example, small initial size) and thus insignificant ecological results. This further reduces trust in the no-take zone's potential, leading to shrinking size and continued lack of ecological results. Trust deteriorates and area size ultimately reaches 0.



Growth loop

In the alternative idealized scenario, high initial confidence leads to large enough initial no-take zone size to produce significant and detectable ecological results, leading in turn to greater trust in the no-take zone's likelihood of success. This leads to increasing area size until costs (e.g. loss of fishing area) outweigh benefits.

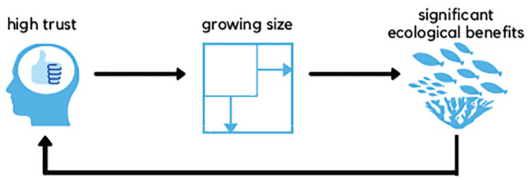


FIGURE 7 | Two predictions of the feedback loop described in **Box 1**: shrinking loop and growth loop.

loop, **Figure 7**). No-take zones that were sufficiently effective in the initial design grew dramatically in the second, at least where the design and decision process supported a collective vision. An implication of this conceptual model is that networks of fisher-designed no-take zones with variable ecological success are predicted to become more successful over time, at least from the perspective of resource users, who in theory improve and grow effective zones and reduce or eliminate the ineffective ones.

Contrary to predictions from our conceptual model (**Figure 7**), fishers did not reduce or eliminate low-performing refugia, but instead re-instated them all. During the process of adaptation and renewal (2017), not a single fishing refugia was eliminated despite low ecological performance by some, and widespread perception in the southern towns that their refugia did not produce ecological benefits. One explanation is that a network of no-take zones increases the likelihood of a "win-win" game even if initial design includes some poor-performing areas. Information and people flow between communities of the Corredor, which could allow the ecological success of the largest area (San Marcial) to build trust in the likely efficacy of refugia in other towns. Another possible reason is inertia and conflict avoidance, especially in the southern Corredor where towns disagreed about how and where to change the refugia, and where it may have been politically easier to simply keep things the same for another 5 years. A well-documented behavior given uncertainty about preferences is to defer to the default (Davidai et al., 2012). Inertia could lead to continued protection of ecologically pointless sites, such as one refugia that is generally agreed-upon by Corredor fishers as a site unlikely to benefit their fisheries, and thus reinforce cynical predictions about the uselessness of no-take zones. On the other hand, decision inertia could be beneficial, if biomass recovery was not yet detectable within 5 years in the smaller refugia and only requires more time. Inertia could thus buy time for fishing communities to organize better, reduce fishing by outsiders, increase monitoring, and increase the efficacy of their refugia over time. Decision inertia and information flow can also support the creation of networks of community-based no-take zones, of which the Corredor refugia are an example. Some heterogeneity is expected, and some elements of the network will be more biologically successful than others. However, if enough trust is built through engagement with external actors or fishers in other areas where ecological performance is better, the local population will likely be willing to continue to support and allow longer-term effects to become visible.

Another reason that none of the fishing refugia in the Corredor were eliminated, despite some being ecological failures, might be because of benefits independent from ecological outcomes. These alternative benefits include building a relationship with Niparajá, which assists with fisheries paperwork and legal issues; building a relationship with the fisheries agency in charge of enforcement and fishing permits; and increased subsidies, including in some towns the ability to enter a lottery for MX$8000 (approximately US$360) intended to compensate lost fishing grounds from the refugia. In the 2016 survey, 48% of fishers reported an increase in government attention (40% reported no change) and 68% reported an increase in government subsidies (20% reported no change). Relationships with Niparajá and the government have led to tangible benefits in the Corredor, such as a doubling in the number of fishing permits in the Corredor (Quintana and Basurto, 2020). In an interview, a professor from a local university told us, "One of the advantages of the refugia is not just fishing: there is a massive broader benefit, that there is regulation, that there are permits for people, that people organize themselves, that the [shrimp] trawlers don't enter. The social impacts of the refugia are much greater than the economic benefits of the refugia in 5 years" (interview 11/29/17). These benefits are effectively independent of the quality of the refugia's design, but could provide a strong incentive to keep refugia even if they are not producing ecological benefits, particularly if the opportunity cost is small in terms of lost fishing area.

"Means Are After All Everything": No-Take Zone Design as a Means Not an End of Adaptive Management

In a global push to protect the oceans, international bodies have agreed to protect 30% of the global oceans by 2030 (IUCN, 2016). This has generated a rapid expansion of area-based conservation tools and increased ambitious commitments by political leaders to establish MPAs and other no-take zones. Riding this political momentum, scientists have tried to come up with models and strategies to design no-take zones that will attend ecological, economic and societal goals. Perceiving that the establishment of these zones is a one-shot game, these models consider as much information as possible to come up with the optimal design (Sala et al., 2002; Possingham et al., 2006). However, optimizing initial design of a permanent area concentrates power in those who are at the table from the beginning. This process excludes and alienates stakeholders who are initially mistrustful or skeptical of the area design process, as is the case in many fishing communities (Holm and Soma, 2016; del Mar Mancha-Cisneros et al., 2018). Ultimately, "optimal" ecological design that generates social conflicts often leads to long-term problems for no-take zones (Christie, 2004; Gray and Campbell, 2009; Mascia et al., 2017).

Building from our results, we propose that instead of trying to get the perfect socio-ecological design in one try, the process of getting there is even more important and offers a sensible way to adapt to changing social and environmental conditions. In particular, the model of co-managed temporary fisheries closures (such as the fishing refugia of the Corredor) represents an opportunity to practice collective action, foster collaborations with universities, NGOs and other communities, and engage fishers in curbing marine resource decline. While this approach to area-based conservation may not initially be as attractive to political leaders aiming to meet international agreements, since the areas may start out quite small, our theoretical model (**Box 1**) and empirical data suggest that successful sites are likely to grow in size when they build collective trust, in our case, by a factor of five within 5 years. The establishment of this kind of management tool can still take advantage of political support generated by international commitments for area protection, as was the case

for Mexico's fishing refugia (Quintana and Basurto, 2020). This model may also be attractive to governments as a tool to adapt to climate change and other emergent local pressures, as the iterative process provides a continued opportunity to adapt the design to current environmental variability as well as to social dynamics within and between communities.

This alternative model of no-take zone design as a means, rather than an end, of adaptive co-management reflects the idea of collective action around conservation and environmental management as a practice ("practicing the commons") rather than an outcome of resource and property rights allocation (Müller, 2020). This process-oriented approach aligns with emerging research on the "commons," which we define as social-ecological systems governed by collective tenure and management institutions (Dietz et al., 2002; Velicu and García-López, 2018), and which frequently characterizes fisheries and marine ecosystems (Partelow et al., 2018). Because of the centrality of the process of ongoing negotiation, some have argued for the noun "commons" to be replaced with the verb "commoning" to emphasize the practice and role of ongoing collective use and management (Linebaugh, 2008; Bresnihan, 2015; Basurto and Garcia Lozano, 2021). The opportunity to practice commoning allows resource user communities to develop affective relationships like care toward the commons and to develop identities as "commoners" (Singh, 2017). It also allows resource users to test whether they can trust each other, governments, and non-governmental collaborators. This is particularly important where initial trust between fishers and government agencies is low, for example from widespread enclosure and neoliberal reform (Nayak and Berkes, 2011; Bresnihan, 2016). In Mexican fisheries, for example, neoliberal reforms in the 1990s eroded collective management institutions and trust in centralized management (Young, 2001). In such places, practicing the commons allows for "re-commonization" of resource systems (Basurto and Garcia Lozano, 2021). Re-commoning can be seen in the Corredor via the fishing refugia. Initially "the people here did not really agree, because we did not know how a refugia would function" (longer quotation above; interview 11/13/17). However, through the process of working together within and between the Corredor communities, with the organization Niparajá, and with government scientists and bureaucrats, fishers have developed trust and confidence in the process, as well as a greater sense of responsibility and power over their coastal resources (Quintana and Basurto, 2020).

Based on our results, we argue that it may be productive for international bodies to consider no-take zones as a means, not an end, of marine conservation and resource sustainability. No-take zones like fishing refugia have the potential to unite the fishery sector under the common principle that protecting an area for a specified period of time can provide benefits on various levels, from providing food for local people, to restoring species populations, to developing a tourism industry. Such tools can complement other management instruments, with the advantage of centralizing participation of fishers and working through institutions that they may trust more. Being temporary gives stakeholders a chance to negotiate their adaptation in response to learning, social-ecological changes, and evolving objectives.

In such cases, benefits to biodiversity conservation seem most likely where trust increases, compliance is high, and fishers are engaged in the process (see **Box 1**). If fishers can identify alternative benefits of no-take zones unrelated to ecological performance, iterative design can allow for re-commoning, becoming a tool to practice fisheries co-management with governmental agencies. However, this requires fishers to conceptualize and imagine no-take zones beyond their typical selling points (i.e., fisheries and biodiversity benefits), such as in Mexico where they are legally defined as a tool for rebuilding fisheries. Such alternative benefits could provide an incentive for resource users, governments, or non-governmental partners to practice commoning even without rapid ecological improvements. Trust among fishers and their allies for marine management could grow if ecological benefits later materialize—or trust could grow for another reason, like improved collaborative relationship or seeing benefits in other areas especially if part of a network (e.g., in the case of El Corredor, fishers in the south could look north to Agua Verde). Thus it is not about the no-take zone itself but about the process that it creates for fishers' ability to adaptively co-manage by learning to common and do commoning. This ability then can prepare them to address future conservation challenges in the region.

CONCLUSION

We argue that the optimal size of community-based no-take zones could be much smaller than sizes recommended by ecologists—at least when we consider initial size, for areas that can later be expanded. Rather than adhere to minimum size recommendations based on ecological objectives (such as 4–6 km^2 or 10–100 km^2, depending on target species; Halpern and Warner, 2003; Shanks et al., 2003), the minimum size suggested by our model is primarily determined by fishers' willingness and perceptions, though mediated by ecological processes. When we reconceptualize temporary no-take zones as opportunities for "commoning" in an iterative, multi-step game of adaptive management, the minimum initial size is simply the sufficient size to produce ecological benefits, as perceived by stakeholders. In this case, 11 no-take zones with a mean size of 1.2 km^2 were able to build trust, with the largest (initially 5.9 km^2) expanded to 33 km^2 after 5 years. In this model, fishers' perceptions are critical; for this, informal information-gathering pathways (e.g., chumming the water; sample fishing in the reserve; participation in a monitoring program) may be more important than data produced through the familiar methods favored by ecologists, such as transects or statistical analyses (Quintana et al., 2020). Notably, multiple no-take zones arranged in a network may lead to greater opportunities for fishers to play with size and design, so that trust is built even if some areas fail. Ultimately, we challenge assumptions about no-take area size and design, arguing that possibilities for more just governance may be found in temporary, adaptive areas that do not optimize initial design.

Based on this case and conceptual model, our recommendation for policy makers and scientists is to facilitate

processes where fishers and other stakeholders can design temporary no-take zones that are likely to produce visible ecological benefits. Policy-makers could support community monitoring programs and enact policies that give fishers the power to design temporary no-take zones. Multiple zones assembled in a network of areas may provide opportunities for learning across areas, even if some end up as failures. However, no-take zone design can be a dangerous game, if areas fail to result in benefits or trust is eroded. For example, where compliance is low (e.g., if outsiders cannot be prevented from fishing in the areas), trust can erode in the general tool and process. We call for a research agenda to explore the positive potential of temporary fisher-designed no-take zones, in order to identify the characteristics of places where growth feedback loops exist vs. where trust is eroded ("shrinking loop")—as well as how these positive feedbacks are disrupted. With a diagnostic understanding of positive feedbacks in community-based conservation, policy-makers and civil society organization staff could find ways to tap into community potential, foster win-win outcomes, and avoid spiraling into social-ecological failure.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: the quantitative datasets analyzed in this study are proprietary information owned by the NGO, Niparajá, and the Coasts and Commons Co-Laboratory at Duke University (contact: XB, xavier.basurto@duke.edu) and thus are not publically available. For inquiries about the ecological monitoring data from 2012 to present and the 2009 social science survey of the Corredor fishers, please contact SR-VD, Director of the Sustainable Fisheries Program at Niparajá, SR-VD at vandyck@niparaja.org. For inquiries about the social science survey data from the survey of Corredor fishers conducted in 2016, please contact XB at xavier.basurto@duke.edu. For inquiries about the in-depth qualitative data (interviews and observation) used to contextualize the study, please contact AQ at anastasiaquintana@ucsb.edu. Requests to access these datasets should be directed to AQ, anastasiaquintana@ucsb.edu.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Duke University IRB. All participants gave oral informed consent to participate in research. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

AQ AG-N, SU, and AC conceived the initial idea for this manuscript at the Eco-DAS conference in Oahu, HI in 2018. AW, XB, and SR-VD designed and collected the social science surveys. AQ collected the qualitative social science data. AG-N, AW, and SR-VD collected the ecological data. AQ, AG-N, SDS, and OAO conducted the analysis. All authors developed the concepts and contributed to the writing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.652318/full#supplementary-material

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Conflict of Interest: SR-VD and AW work for the organization, Sociedad de Historia Natural Niparajá, which facilitated the implementation of the fishing refugia in the Corredor. To reduce the potential for conflict of interest, Niparajá colleagues did not participate in data analysis or interpretation used for this manuscript, although they provided contextualizing information and feedback on patterns that other authors identified. Data was analyzed skeptically and patterns were only identified using multiple lines of evidence, including in-depth qualitative data collected separately from Niparjá by AQ over 6 months living in the study region.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Look Who's Asking—Reflections on Participatory and Transdisciplinary Marine Research Approaches

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Marine conservation transdisciplinary researchers often get to the field with a previously designed question, often formulated outside the actual geographical, social, cultural and ecological setting in which the research projects are supposed to be anchored. Involving people on the ground in the initial phase of formulating the questions and setting the research agenda is still uncommon. Once in the field, transdisciplinary researchers may or may not have the support of local communities to sample their data, although they will regularly need to count on these same communities if a collaborative regime is to be pursued and informed by the research outcome. This paper discusses measures that can be taken by marine fisheries and marine conservation researchers to improve participation in, and ownership of, the research by local counterparts, most importantly members of the communities where research is being conducted. The data was generated with a purposively sampled survey of 18 members of our research networks. Key proposed measures derived from this data include: (1) build rapport; (2) engage and exchange; (3) be accommodating and attentive; and (4) be respectful. Knowing who is asking the questions and assuring that all stakeholders have a voice in this process becomes especially relevant under extreme circumstances (e.g., disasters, pandemics), when problems are numerous but can only be accessed by those on the ground. We advise for faster progress in transforming academic and funding environments for true "level-playing-field" transdisciplinary and co-designed research projects that can help change top-down research tendencies.

Keywords: transdisciplinary research, research questions, marine conservation, stakeholder, participation and inclusion, co-design, build rapport

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INTRODUCTION

Research collaboration is often understood as a partnership between different scientific research groups. Collaborating improves research quality and diversity (e.g., represented by different geographies), and provides new approaches to problems and different sources of knowledge. These collaborations have increasingly included transdisciplinary research, as the complexity of many societal problems expose the limitations of "traditional" disciplinary approaches. The goals of nature conservation, for example, are hardly ever achieved through a pure ecological lens, as humans make use of most of the landscapes and seascapes of the planet (Bennett and Roth, 2019).

Transdisciplinarity has become part of marine conservation, although it still needs to properly integrate both different disciplines and knowledge systems (e.g., Davies et al., 2020; Vierros et al., 2020). This means rethinking transdisciplinary approaches from question framing to interpretation of results (Bracken et al., 2015; Partelow et al., 2019; Davies et al., 2020; Freitas et al., 2020; Wisz et al., 2020).

Similarly, participatory research (disciplinary or transdisciplinary), done in collaboration with local communities, have been increasingly adopted in marine conservation (Ban et al., 2013; Foale et al., 2017; Turner et al., 2017). However, questions remain regarding the degree of participation and autonomy assigned to local communities. On the natural science side of marine conservation, participatory research has been widely driven by the necessity to collect data, rather than the necessity to connect with stakeholders. Insights from social science have led to a more emancipatory outlook, by pointing out conservation-related misunderstandings, unfulfilled expectations and social injustices, including exclusionary decision-making processes, failure to consider equity and local people's needs and livelihoods, or even dispossession of areas and resources (West, 2006, Filer, 2014; Clifton and Foale, 2017; Bennett, 2018). Since natural and social sciences have started to develop stronger dialogue around shared interests, it is expected that the next steps will be both more transdisciplinary and participatory (Davies et al., 2020).

Such a change of course is welcome, given that recent global calls invite us all to rethink conservation in general—and marine conservation in particular—in order to make it inclusive and just, from deciding what conservation wants to achieve, to how the unavoidable costs and eventual benefits will be shared (de Vos, 2020). Achieving this leap in inclusivity requires a change in focus to who is framing the research question? Are they based on local interests and within the actual geographical, social, cultural, and ecological setting in which the research projects are supposed to be anchored? Are the questions that the local people and institutions would like/need to ask being considered by academics? How do these questions translate into actual collaboration between researchers and stakeholders? Does information flow both ways (e.g., Partelow et al., 2019)? Whose lens is used to undertake the data analysis, draw conclusions, and write recommendations? Are the research questions and projects responding to local research and knowledge generation needs (e.g., Foale, 2001)? Reflecting on these questions may help guide conservation toward a transdisciplinary and participatory path where not only the academic voices and expertise are heard.

With a focus on marine (protected) areas and small-scale fishing projects, and examples from Bangladesh, Brazil, Fiji, and India, this paper aims to trigger and re-awaken the much-needed discussion on the potential overlaps between initially funded research questions, and those questions that are relevant for the local stakeholders (e.g., Marijnen et al., 2020). By drawing on experts' opinions, we discuss whether transdisciplinary participatory research is going beyond stakeholder participation in data collection (or as information providers), to being agents that also shape the process of identifying the most meaningful questions. Finally, we propose some preliminary insights on how to improve transdisciplinary research so that it raises the profile of people on the ground (Chakraborty and Kaplan, 2020) so that their research priorities are also (inter-)national research priorities. Much needs to change for local communities to be "in the driver's seat" of research (Cripps, 2018; Schmidt et al., 2020), and making research relevant for local stakeholders could help dramatically improve conservation outcomes, by empowering communities to pursue their own nature-related interests (Peres, 2011; Barley Kincaid and Rose, 2014).

MATERIALS AND METHODS

To understand how the views and demands of stakeholders on the ground are being considered in the recent setting of research questions and agenda, we shared a survey via email among our professional networks, after identifying colleagues working in transdisciplinary and/or participatory conservation. Out of 20 directly contacted colleagues in June 2019, 18 fully completed the surveys by October 2019. We asked our colleagues to provide information from ongoing or past research projects focusing on small-scale fisheries, marine protected or managed areas in Australia, Bangladesh, Brazil, Fiji, and India. The semi-structured survey (**Supplementary Appendix**) included 22 questions on:

- Approaches and requests by the community stakeholders to investigate aspects they deemed relevant;
- Options and rationale to accommodate these whenever possible;
- Funding options;
- Consequences for the research and the rapport to the communities, the application of results, and the overall relevance of the project; and
- Researcher and stakeholders' perceptions and experiences.

We included only those colleagues who we knew were already engaged in participatory transdisciplinary conservation (purposive sampling) to understand whether and how they actually succeed in doing so. Given their scientific approach, it is not surprising that most of the researchers in the survey have been contacted by community members asking to investigate specific issues. We accept this bias (as well as the small sample size) for the purpose of this perspective, yet we are aware that in many more cases, especially in more disciplinary studies, locals' previous demands were possibly not utilized in research.

With the open feedback questions, we opted for a qualitative assessment of the information provided by our colleagues. Specifically, we sought for commonalities in the responses, which were then analyzed collectively. Some important quotes from the researchers themselves (**Table 1**) showcase key aspects, contextualities and sub-themes of their transdisciplinary work.

RESULTS

The main findings of the survey can be summarized under three main themes: (1) the need for participation beyond data collection, (2) acknowledgment and mitigation of an

TABLE 1 | Summary of insights by transdisciplinary researchers working with marine socio-ecological systems (2019 survey).

Insight	How?	Why?	Quotes
1. Invest in rapport	a. Plan for extra time b. Keep in touch	1. Participatory research depends on social relations, and these require time and effort. Building rapport is essential not only for good data, but also for meaningful data 2. Although regular meetings are difficult to organize on a regular basis, find ways to keep in touch with the diverse community stakeholders throughout the project. If on site meetings are not always possible, invest in other communication platforms (social media, WhatsApp groups, etc.) where stakeholders can discuss research results and change the course of the research, if necessary.	1 and 2. "Researchers have to approach the local people first (from all walks of life, not just the local representatives/NGOs), go on transect walks, have key informant interviews, focus group discussions—to understand the scenario. If the locals are consulted, their views are incorporated in research design and results, then there is a fair chance that local communities can be more involved and interested. For instance, I had worked on a pictorial book in Noakhali, southern Bangladesh, on climate change adaptation. After it was printed, I took back several copies for to those who we photographed and interviewed. The response was remarkable—we were able to work further with the same communities, as they saw first-hand the results of our research. " (Bangladesh, S17)
2. Engage and exchange	a. Practice truly networking b. Be ready for other points of view: there is more to it than it meets the eyes c. Be humble: they may know more than you do	1. The more you connect with local organizations, key people and local leaders, the more (reliable) information you will have access to and the higher are the chances that you will actually hear what people want to say. You may be heard better in return. 2. Involve as many stakeholders as possible to have a better grasp of the problem. Different stakeholders may frame it in different ways, according to their interests 3. This may be a hard pillow to swallow for some, but participatory research might show you that you got your hypotheses wrong. Pay attention to how stakeholders interpret facts and make connections between cause and effect.	1. "To change this, more networking is necessary, specific funding to reach both scientific and societies' demands and more integrative work among actors involved in these matters are essential features. In developing countries, where you are usually trying to survive as a researcher or an extensionist, and where effective organizational networks are usually missing, this is a very hard and usually unsustainable activity." (Brazil, S10) 2. "Fishers wished to enter the no-take zone during the swell season to catch sardines. . .but managers argued that fishers' presence in the MPA would affect the sharks, one of the main local (tourist) attractions. Turns out fishers increased their fishing and type of fishing (demanding the use of fresh sardines to catch tuna and billfish) due to increased tourism; i.e., MPA managers were afraid the fishers would interfere with the success of tourism, but fishers were fishing more exactly to attend their (tourists') demand" (Brazil.Fernando de Noronha). 3. ". . .For the identification of three priority areas for threatened freshwater dolphins in the Sundarbans, we relied on long-term information collected through a network established among captains of tourist vessels." (Bangladesh, S18)
3. Be accommodating and attentive	a. Adopt the policy of leaving no one behind (unless they ask for it) b. Be aware of power grabbing	1. The research design should have enough room to accommodate the various communities' desires and aspirations. This includes from respecting their (individual and communal) autonomy to participate or not in any phase to leaving time and funding to investigate some of their own priorities. 2. Understand the governance landscape (incl. corruption), chances are that only the powerful will have a voice, leaving others without the opportunity to express their unbiased opinions.	1a. "Maybe, after initiating research elaborated by the researchers and following presentation and discussion of the results from these studies, future research could be proposed accommodating communities' demands or directed to solve problems perceived by local people." (Brazil, S1) 1b. ". . .Following a survey focusing on two villages in the area, other villages felt "left behind," consequently a larger survey was designed, covering all of the 150 fisher villages in the region, with overwhelming response to this general survey had brought to light (India, Chilika Lagoon)." (India, S13) 2. "My 30 years of research in Brazil had one main obstacle: the Brazilian environmental governmental agencies. Obstacles were through visits in the sites (and punitive behaviors with fishers); through favoring prestigious politicians (in detriment of fishers), and through draconian legislation that did not have the support of researchers and fishers." (Brazil, S6)
4. Be respectful	a. Keep in mind that communities and community members are not guinea pigs b. Make promises you can keep	1. Stakeholders, especially members of diverse communities, are not the means to answer the research question. If they feel used and not see why they should participate in your research, not only your project may fail, but you may close the doors for future truly participatory research. 2. Scientists often have little decision-making power, but the beginning of a research project can create expectations of how the responses will change the locals' lives (for better or worse). Managing expectations is crucial for maintaining reliable relationships	". . . it is extremely important to address issues to deal with the socio-ecological problems of fishers and including them in real time policy making as a core to understand what will be sustainable in terms of problem solving and also projects. If they are not included in the mainstream financial systems and keep on only being the tools of testing many theories from conservation to climate change adaptation, none will be sustainable. It's probably not about choosing from any one of them (popular or scientific). It is the amalgamation of both to tackle problems." (Bangladesh, S12)

agenda mismatch between funded and needed research, and (3) emphasizing the power of the transdisciplinary processes of learning together.

Participation Beyond Data Collection

Among the interdisciplinary researchers surveyed, local participation goes far beyond data collection, provision of information and valuable support in fieldwork (**Table 1**). Yet, often, there is still no clear acknowledgment of the stakeholders' role in transdisciplinary research beyond data collection and provision of information. Hence, how can we move toward having local communities as agents that help identify meaningful research questions and co-develop research protocols? And how can research institutions accommodate projects and allocate funding that integrate local knowledge and requests, and use these for innovative future research pathways (e.g., Outeiro et al., 2019; Davies et al., 2020).

> Research needs to evolve and first and foremost researchers need to expand their horizons. As researchers, we often start with our hypotheses and take it to the field site and try to test and find answers around it. I think that needs to change and made more relevant to the local context. (Bangladesh, S17).

Working with researchers who intend to have locals' participation from the beginning shows us that this approach is indeed possible—albeit often complicated. To have people involved, from the designing of ideas, field research, and interpretation of results requires a broad understanding of existing networks and socioecological relations. For example: what marine resources are used? How are these harvested? What is the cultural and economic importance of each resource? The aspect of spending "free time" (i.e., additional time to the initially planned research time) in the communities to build a relationship, trust and to be accessible as researcher is therefore vital. Most local communities *are* indeed interested, but are tired of promises, research visits without visible effect and no support. According to our colleagues, more transparent consultations are needed, with real intentions to incorporate the information gathered (**Figure 1**).

> "In my experience most projects use consultative meetings only to comply with donor or Government requirements, rather than to actually address concerns, discuss potential benefits and evaluate impacts. Due to these lackings, community meetings are generally viewed as presentations by NGOs rather than a two-way information-sharing platform." (Bangladesh, S18).

This includes being prepared to acknowledge the fact that stakeholders may understand their resources better than many researchers. It is also important to be flexible with initial research interests and demands—as they may not be compatible with local demands—and try to reduce the gap between the priorities of the research project and the priorities of the stakeholders. This is also what is meant by co-designing research, which remains difficult (e.g., Polk, 2015; Sugiyama et al., 2017). The researchers from the survey know the types of settings that can make it difficult to generate a whole "community perspective" on the research questions they might like answered. These settings can include aspects related to the heterogeneity of stakeholder groups (e.g., age, gender and profession), local politics (sometimes old or fresh conflicts), socioeconomic problems, local power asymmetries, financial obligations and hurdles, or differing environmental perceptions. Therefore, if a project is supposed to be collaborative and transdisciplinary, this should be made evident throughout, and such an engagement and research relationship cannot be rushed; it takes time and hence requires longer project cycles. Time that usually does not exist if the study is guided and funded by conventional research approaches, where scientists are majorly assessed and graded on bibliometric indicators of performance (Bornmann and Marx, 2014). Specific and accommodating research calendars, funding deadlines, previous trips and meetings are needed to define the logistics of a project, as well as the demands and engagement of the involved persons.

An Agenda Mismatch

There is mismatch in the marine research agendas on several levels. First, there is a clear geographic mismatch between where the research is designed and funded, and where the urgent research needs are (Oliveira Júnior et al., 2016). Also, while scientists from developed countries tend to have the funding to carry out the research, it has been argued that local scientific knowledge and scientists from developing countries are the ones capable of better linking up the research findings with policy makers and have a better understanding of local stakeholder needs (Cvitanovic et al., 2015). Lastly, the funding bodies or donors, which often are from developed countries, have different agendas (e.g., poverty, gender, environment), which do not necessarily consider the interlinkages between these issues in the geographic foci of the research (Oliveira Júnior et al., 2016).

> "Specific funding to reach both scientific and societies' demands and more integrative work among actors involved in these matters are essential features. In developing countries, where you are usually trying to survive as a researcher or an extensionist, and where effective organizational networks are usually missing, this is a very hard and usually unsustainable activity." (Brazil, S10).

There is also mismatch between project timeframes and allowing the flexibility and time to build in local demands. Rapport remains one of the most important moments of applied research. If we want to include "popular demand" in our research, we need to spend time listening to people and building social relations. A deeper understanding of local social-ecological system is needed to build strong hypothesis and approaches. This includes providing robust training to students and researchers interested in social-ecological applied research, encompassing the need to include local demands in research and building rapport, and how this can translate into actual collaboration between researchers and stakeholders.

Learning Together

The accumulated experience of transdisciplinary researchers has therefore taught them some powerful lessons, which we summarize here in four interrelated pieces of insights (**Table 1** and **Figure 1**).

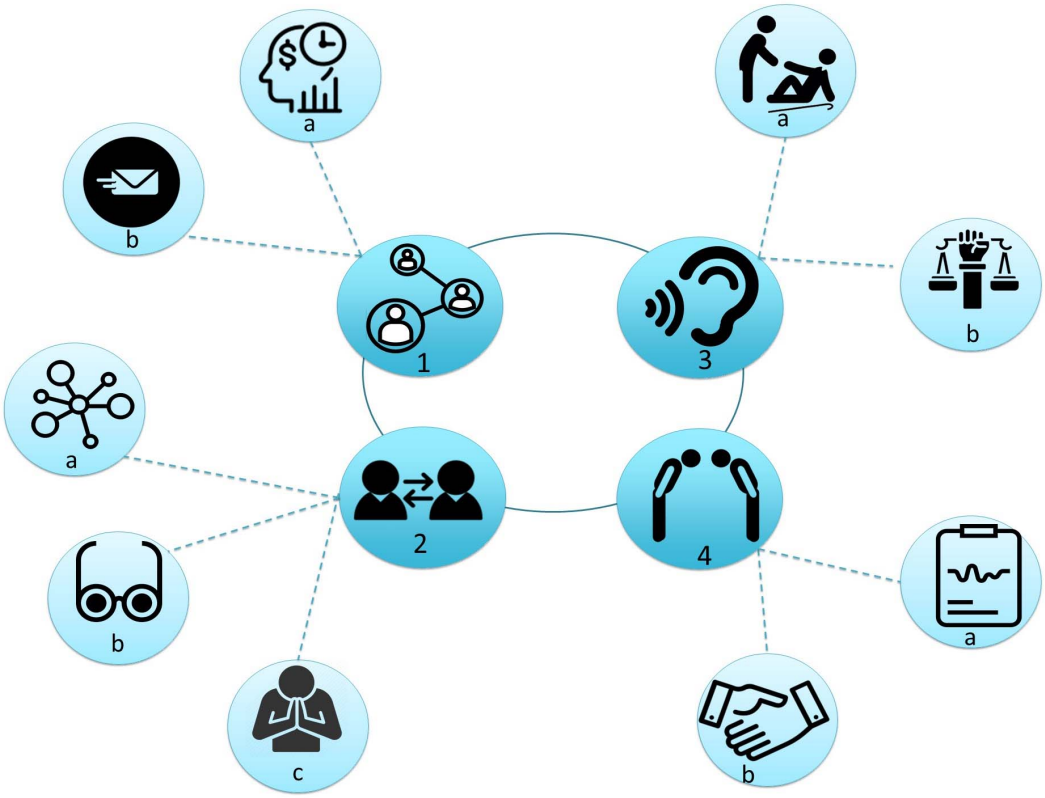

FIGURE 1 | Four insights from interdisciplinary researchers working with coastal communities. *Insight 1*: Invest in rapport by planning to (a) dedicate enough time to communities and (b) keeping in touch with them. *Insight 2*: Engage and exchange: (a) invest in networking, (b) be open to new points of view and sources of knowledge, (c) be humble. *Insight 3*: Be accommodating and attentive to communities' aspirations by (a) leaving no one behind and (b) avoiding creating mechanisms that promote power grabbing or imbalance. *Insight 4*: Be respectful by (a) not treating communities as a simple means to test scientific hypotheses and (b) by promising them only what can be reasonably delivered.

Insight 1 regards the need to invest in rapport in order to truly listen to those on the ground. This requires, for example, establishing meaningful partnerships. It takes time to build meaningful rapport with communities (again, problematic for time-constrained research calls) and once it is established, it needs to be nurtured (Abbe and Brandon, 2014). Transdisciplinary researchers seem to be aware of that and often maintain their fieldwork on the same site for many consecutive research rounds, which also helps them see more tangible results. Meanwhile, during and in between research periods, it is important to stay in touch with the communities to maintain the rapport.

Insight 2 pertains to the need to engage with communities and exchange knowledge. This begins with acknowledging the power of networking to facilitate not only knowledge exchange, but also trust building. For example, during the COVID-19 pandemic, much of fieldwork has been stalled (Sastry et al., 2020), except for studies that rely on strong connections with those on the ground, be they NGOs or fishers' associations (authors' own experience). From the local perspective, networking may also represent a chance to have access to external support during an unexpected crisis, as the one caused by the pandemic. Better connected communities are likely to have been more engaged in relief campaigns during this crisis, for example, as researchers reach out to their partners and advocate for immediate action (Bennett et al., 2020). Networking may also represent an opportunity for knowledge co-production and for knowledge exchange in general (Reed and Abernethy, 2018). Knowledge sharing is a two-way street if researchers and communities are ready for it (Johannes et al., 2000; Mauser et al., 2013). Accepting that we have incomplete knowledge or a biased view is not necessarily easy, but it can build bridges and also accelerate knowledge accumulation (Butler et al., 2012).

> "What I understood from my experience is, currently for Bangladesh fisheries sector, it is extremely important to address issues to deal with the socio-ecological problems of fishers and including them in real-time policy-making to understand what will be sustainable in terms of problem solving and also projects. If they are not included in the mainstream financial systems and keep on only being the tools of testing many theories from conservation to climate change adaptation, none will be sustainable. It's probably not about choosing from any one of them (popular or scientific). It is the amalgamation of both to tackle problems." (Bangladesh, S12).

Insight 3 refers to the need to being accommodating, including when faced with unpredictable situations related to the interaction of coastal communities. This comprises, for

example, the flexibility to include or exclude community members, respecting their agency and based on Free, Prior and Informed Consent, or the sensitivity to perceive that favoring some in detriment of others can lead to power grabbing (Green and Adams, 2015). Based on the authors' own experience, it is normal that the first to join an initiative are the most articulate and confident individuals, and/or those related to leadership. Although it is positive and often necessary to have the support of leaders (Gutiérrez et al., 2011), true partnerships should encourage wide participation and power balance within the limits of the initiative.

Directly following from this, Insight 4 regards being respectful of communities' expectations and desires. It is important for researchers to know that once dealing with people it is not acceptable to simply see them as means to test hypotheses. People need to know what they are getting into and accept to join or not based on a realistic picture (Suich, 2013). It is normal that communities want to see fast results or changes in legislation, but these are often beyond the immediate capacity of researchers, and this should be clear from the outset.

(A HOPEFULLY NOT FINAL) DISCUSSION

Some of the main challenges faced by those who want to advance a participatory transdisciplinary agenda include: (1). how to continue a project long enough to accommodate local research demands, (2). understanding the importance of the local social-ecological setting and knowledge, and (3). keeping the promises to the communities one is working with. These challenges are especially due to inherent funding limitations and project durations that do not accommodate for truly interdisciplinary research while demand researchers to perform according to bibliometrics indicators. Also, these challenges can be worsened by embedded local socioeconomic problems, such as local violence, lack of health care services, and wider issues around inequality, corruption and poor governance. Thus, it may be the case that the immediate and urgent local demands at low levels of local organization are not directly related to the researcher's questions. In addition, the time investment required by local people to propose research questions must be noted, as not all of them may be willing to make such personal investment, at the expense of their regular activities.

Despite these limitations, to integrate scientific and popular demand for science, it is cardinal to have a productive team of people who can try relentlessly for innovative ways to answer questions and keep the primary resource users' demands and necessities also at the core of the research. Secondly, current research funding models will need to be flexible enough to accommodate such dynamic processes of research and engaging with local communities, keeping research away from something resembling a "donor culture", where the wishes of the donor are to be granted even if they disrespect or ignore local cultures (West, 2006). We are already seeing the need for such flexibility with the recent COVID 19 pandemic, as both funding bodies and ongoing funded projects are having to adapt the focus of their work to meet the new demands caused by the pandemic on local communities. At the same time, COVID 19 has highlighted the importance for academics of having partners in the communities they work with. Thus, without disregarding the significant changes of the last decades that favored more inclusive approaches (e.g., Massarella et al., 2021), the time is ripe for a paradigm shift that will truly include those who are at the forefront of ocean conservation: from framing research questions onward.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are based on findings from the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

The study was jointly designed and developed by AB, PL, and SS, as was the methodology. The survey was mainly conducted by PL and SS with their respective colleagues. The analysis was done mainly by AB, and the manuscript was structured and written jointly by all authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.627502/full#supplementary-material

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frontiers in Marine Science

ORIGINAL RESEARCH
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Assessing South Africa's Potential to Address Climate Change Impacts and Adaptation in the Fisheries Sector

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The marine fisheries sector is one of the most important income sectors in South Africa and plays an important role in food security for small-scale and subsistence fishers. Climate-driven impacts have resulted in distribution shifts and declines in abundance of important fisheries targets, with negative consequences to the users dependent on these resources. The sustainability of the sector depends on its readiness to adapt to climate change. The inclusion of climate change impacts and adaptation in fisheries management documents in South Africa is essential to ensure adequate climate adaptation responses are implemented at the short- and long-term. This study aims to 1) determine if the relevant fisheries national management documents address climate change and adaptation, 2) determine if the relevant national climate change documents address climate change and adaptation in the fisheries sector and 3) evaluate the extent to which fisheries management documents address climate change and adaptation. A content analysis of fisheries management and climate change documents was carried out to determine if they incorporated information on climate change impacts and adaptation and marine fisheries respectively. Fisheries management documents were then screened against nine pre-determined criteria (or themes) based on climate change adaptation to determine the level of inclusion of best practice for climate change adaptation. Results indicate that climate change impacts and adaptation are rarely incorporated in the main fisheries management documents, except for the Climate Change Adaptation and Mitigation Plan for the agriculture, fisheries and forestry sectors. However, this document is still waiting to be adopted. The only direct reference identified in all the fisheries documents that supports climate change adaptation was 'conservation and sustainable management of biodiversity'. With regards to indirect references to climate change adaptation, 'equity,' 'participatory management,' and 'capacity building' were most frequently incorporated in fisheries management documents. There is a need to explicitly incorporate information on climate change impacts and adaptation in South African fisheries management documents and increase the human and financial capacity at national institutions to ensure that the fisheries sector can adequately adapt to climate change.

Keywords: fisheries, climate change, adaptation, aquaculture, management instruments

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INTRODUCTION

Climate change is impacting marine ecosystems around the world, with effects that include changes in species abundance and distribution, reductions in catch potential and changes in other ecosystem services provided by oceans (Doney et al., 2012; Cheung et al., 2018). This is especially evident in fast warming areas, or hotspots, and will likely have even stronger impacts on areas with high numbers of people dependent on these services (Hobday and Pecl, 2014). South Africa, a fast warming area, has experienced changes in sea surface temperature, sea level rise, rainfall and primary production among others over the past decades (Jarre et al., 2015; van der Lingen and Hampton, 2018). Warming rates vary spatially and seasonally in South Africa, but some areas such as the Agulhas Current have consistently warmed over the last decades (Rouault et al., 2009; Sweijd and Smit, 2020). Climate-driven biological changes, including distribution shifts of species of commercial importance such as west coast rock lobster *Jasus lalandii*, sardine *Sardinops sagax* and anchovy *Engraulis encrasicolus* (Cockcroft et al., 2008; Coetzee et al., 2008; Crawford et al., 2008), have resulted in severe economic impacts for the users dependent on these resources highlighting the need for dynamic and adaptive approaches to respond to the impacts of climate change (Cochrane et al., 2020a).

The fishing sector is one of the most important income sectors in South Africa, contributing less than 1% of the total Gross Domestic Product (Brick and Hasson, 2016). It is valued at R 8 billion per year and generates over R 3.4 billion (∼ 254 million USD, 1 USD = 13.38 ZAR) in total foreign exchange from sales (Brick and Hasson, 2016). The South African fishing sector has two components: wild capture fisheries and aquaculture sectors. The former comprises the commercial, small-scale[1], subsistence[2] and recreational sub-sectors. The commercial sector provides direct employment to 28 000 people, and indirect employment to 100 000 -130 000 people (Brick and Hasson, 2016). There are 22 commercial sub-sectors in South Africa with the demersal hake trawl and the small pelagics fisheries being the most important in economic terms. Estimates indicate that there are approximately 30 000 subsistence fishers in South Africa (Clark et al., 2002). Small-scale and subsistence fishers heavily rely on fishing since it represents a source of employment and food security in coastal communities with limited opportunities (Isaacs and Hara, 2015). The aquaculture sector in South Africa is relatively small and contributes approximately 6,400 tons annually (Britz et al., 2019). The aquaculture sector generates approximately US$77 million and provides direct employment for 2 300 people (Aquaculture SA, 2017 values).

Several initiatives have been conducted to incorporate the effects of climate change into South African fisheries and identify possible adaptation options for the sectors (e.g., Hampton et al., 2017a,b,c). A vulnerability assessment of South African marine fisheries to climate change indicated that the small pelagics and linefish (commercial small boat, small-scale and net fisheries) fisheries were the most vulnerable to climate change, while the aquaculture sector was identified as moderately vulnerable (Hampton et al., 2017b). This led to the establishment of the Benguela Current Convention (BCC) and the FAO project 'Enhancing Climate Change Resilience in the small and large scale fisheries of the Benguela Current Large Marine Ecosystem,' which assessed the vulnerability and possible adaptation options of the stakeholders of the small pelagics fishery and small-scale fishing communities in the three BCC countries: Angola, Namibia and South Africa (Cochrane et al., 2020b,a; Sowman, 2020).

Most climate governance studies in South Africa have focused on sectors such as energy, transport and agriculture with no inclusion of the fisheries and aquaculture sectors (e.g., DEA, 2011a; Averchenkova et al., 2019). Some of the main challenges identified by these studies were the lack of alignment and policy coherence, limited implementation, lack of coordination and clarity on how policies will be jointly implemented as well as limited capacity in the public sector and available funding (Averchenkova et al., 2019). A recent ocean governance baseline assessment for the Benguela Current Large Marine Ecosystem (BCLME) evaluated the environment, fisheries, mining and transport sectors of three BCC countries. This assessment recognizes that climate change is an important threat and factor to be considered in all three countries but it did not address it specifically (Cochrane et al., 2019a).

Despite widespread awareness and considerable exposure to the impacts of climate change on fisheries, there are few examples of approaches taken to address them (Ogier et al., 2016; Lindegren and Brander, 2018). This is, perhaps, not surprising because climate change is usually one more stressor that fisheries management agencies have to take into account in addition to, for example, preventing overfishing, conflicts over space and resources, impacts of pollution and habitat loss, and others (Barange and Cochrane, 2018). Nevertheless, in an increasing number of cases the additional impacts of climate change cannot be ignored. Changes in distribution of species can affect the effectiveness of spatial management measures and lead to conflicts between users, including international conflict when stocks are shared or straddle international boundaries (Lindegren and Brander, 2018; Pinsky et al., 2021). Climate change also frequently adds to the uncertainty in stock trends and status and can result in changes in composition of catches and fishing dynamics (Pinsky et al., 2021). The responses in fisheries management that are required and feasible vary according to the specifics of each case but common themes emerge. Adaptive management is critical, which requires the availability and monitoring of robust indicators and appropriate flexibility in management frameworks and measures, and should

[1]Small-scale fisheries refers to 'persons that fish to meet food and basic livelihood needs, or are directly involved in harvesting/processing or marketing of fish, traditionally operate on or near shore fishing grounds, predominantly employ traditional low technology or passive fishing gear, usually undertake single day fishing trips, and are engaged in the sale or barter or are involved in commercial activity' (Policy for the Small Scale Fisheries Sector in South Africa, pp. 6–7). The definition of small-scale fishers varies considerably between countries, changes according to context and also depends on who is defining themselves as a small-scale fisher.

[2]Subsistence fishers refers to 'a natural person who regularly catches fish for personal consumption or for the consumption of his or her dependants, including one who engages from time to time in the local sale or barter of excess catch, but does not include a person who engages on a substantial scale in the sale of fish on a commercial basis (Marine Living Resources Act 1998, pp. 12).

be embedded in an ecosystem approach that strives to maintain or increase the adaptability and resilience of the fished resources and ecosystems and of the stakeholders engaged in the fishery. Co-management is also recognized to be fundamental to effective management within this adaptive framework (Ogier et al., 2016; Barange and Cochrane, 2018; Lindegren and Brander, 2018).

Management of South African fisheries is undertaken by the Department of Forestry, Fisheries and the Environment (DFFE, previously Department of Agriculture, Forestry and Fisheries). The current effectiveness of marine fisheries management differs between the inshore and offshore fisheries of the country. In general, management of the offshore fisheries, which are easier to monitor and control than inshore fisheries, is effective in ensuring productive and sustainable fisheries, while management of inshore fisheries has been less effective, in large part as a result of the difficulties in controlling illegal and unreported fishing (Cochrane et al., 2020a). Management of the commercial fisheries in South Africa is conducted through Operational Management Procedures (OMP) (Plagányi et al., 2007), an adaptive process which allows for adjustment of management measures in response to changes in resource abundance and productivity, including any caused by climate change. However, the long-term risks and possible impacts of climate change on resources or stakeholders in the country's fisheries are currently not considered in strategic planning.

The marked changes in the abundance, distribution, productivity and availability of marine resources observed in South Africa (reviewed in van der Lingen and Hampton, 2018) has prompted responses by private actors (i.e., commercial sector) from the fisheries sector. These responses have been driven by the necessity to maintain the viability of the fisheries and have been possible due to the resources available to the commercial fishing sector (Cochrane et al., 2020b,a; van der Lingen, 2021). Government has a central role to play in aiding the response of the economic sectors and society to the impacts of climate change. For the fisheries sector, good practice adaptation measures include enhancing monitoring programs through community-based approaches, incorporating environmental variables in fisheries assessments, development of early warning systems among others (Bahri et al., 2021). Reviewing legislation to ensure it guides adaptation responses and explicitly addresses climate change is necessary to ensure effective adaptation (Bahri et al., 2021).

The level of inclusion of climate change in the management documents for the marine fisheries and aquaculture sectors (hereafter the fisheries sector) in South Africa has not been assessed, although, the main legal framework has been evaluated to determine its adequacy to support the implementation of an ecosystem approach to fisheries in South Africa (Cochrane et al., 2015). This study aims to address that gap by (1) determining if the relevant fisheries national management documents address climate change and adaptation, (2) determining if the relevant national climate change documents address climate change and adaptation in the fisheries sector, and (3) evaluating the extent to which fisheries management documents address climate change and adaptation.

BACKGROUND

Climate Change Impacts in South Africa

The observed and predicted impacts of climate change in South African marine resources and systems have been reviewed in van der Lingen and Hampton (2018) and Cochrane et al. (2020b; 2020a). A summary of climate change impacts based on the information from these reviews can be found in **Table 1**. Several environmental, biological and social changes have already taken place in South Africa, however, direct attribution to climate change has been established only for sea surface temperature (Hampton et al., 2017b). The link between the observed changes in other environmental variables and climate change is likely. Some predicted impacts of climate change include increase in sea temperature, frequency and intensity of extreme events (e.g., marine heatwaves and harmful algal blooms), sea level rise, ocean acidification and changes in rainfall (**Table 1**). Sea temperature changes have been associated with a number of biological impacts in South African marine systems including eastward shifts in the distribution of several species (Roy et al., 2007; Bolton et al., 2012). Climate-driven distribution shifts have in turn caused changes in community structure, competition for resources and interactions (e.g., abalone and urchins) (Blamey et al., 2010) and ultimately severe economic impacts. Increases in fishing and steaming costs, decreases in the availability of fish to fisheries, changes in landing sites and processing facilities are some of the observed economic impacts in South Africa, and have affected the livelihoods of people dependent on these fisheries (van der Lingen and Hampton, 2018; Cochrane et al., 2020b,a).

Institutional Arrangements in South Africa

The arrangements for coordination, stakeholder engagement, policy development, implementation and research on climate change in South Africa are quite broad and include several national, provincial and local institutions. An overview of these arrangements is presented below to provide context on the institutions responsible for policy development and other initiatives (**Figure 1**).

National Institutions

The Department of Forestry, Fisheries and the Environment (DFFE, former Department of Environmental Affairs and Tourism and subsequently Department of Environmental Affairs), specifically the Deputy Director General of the Climate Change and Air Quality branch, is mandated with climate change functions in South Africa (e.g., coordination and integration, policy development, mitigation and adaptation responses). The Department of Environmental Affairs and Tourism (DEAT) was created in 1994 and mandated with environmental management, including fisheries and aquaculture, and tourism development. In 2009, the government departments were reconfigured and staff and functions related to fisheries and aquaculture were divided between an Oceans and Coasts Branch in the newly configured Department of Environmental Affairs (DEA) and a Fisheries Management Branch in the reconfigured Department

TABLE 1 | Observed and predicted climate change impacts in South Africa associated to the nine pre-determined climate adaptation themes.

Category	Impacts	Observed/Predicted	Climate adaptation themes
Environmental	Ocean acidification	O, P	1
	Changes in rainfall, river inflow and run-off	O, P	1, 3, 5
	Circulation patterns	O, P	1
	Extreme events (Marine Heatwaves)	O, P	1, 3, 5, 6
	Frequency and severity of storms	P	1, 3, 5, 6
	Incidence of Harmful Algal Blooms	O, P	1, 3, 5, 6,
	Intensification of mesoscale variability	O, P	1
	Poleward shift of the St Helena Anticyclone	O, P	1
	Sea Level Rise	O, P	1, 3, 5, 6
	Temperature changes	O, P	1, 3, 5, 6
	Wind strength, speed and direction	O, P	1, 3, 5, 6
Ecological	Decreases in invertebrate and fish abundance and catch	O, P	1, 3, 4
	Changes in size structure, reproductive scope, community composition, growth rates, recruitment and spawning behavior and success	O, P	1, 3, 4
	Loss or reduction of breeding and nursery areas	P	1, 3, 4
	Changes in production and food availability in estuarine and nearshore areas	O, P	1, 3, 4
	Phenology changes (spawning, breeding, availability to fisheries)	O, P	1, 3, 4
	Distribution shifts of species	O, P	1, 3, 4
Social	Increase in fishing/steaming costs	O, P	2, 3, 5, 7
	Changes in landing points and processing plants	O, P	2, 3, 5, 7
	Mismatch of Territorial Use Rights for Fishing and species distribution	P	2, 3, 5, 7
	Increase in unemployment	P	2, 3, 5, 7
	Increase in compliance issues (poaching)	P	2, 3, 5, 7
	Damage to coastal infrastructure	P	2, 3, 5, 6, 7
	Changes in Food security/nutritional content of species	P	2, 3, 5, 7
	Poverty levels	P	2, 3, 5, 7
	Safety at sea	O, P	2, 3, 5 6, 7
	Changes in Food supply/higher variability of product availability	P	2, 3, 5, 7

*See **Table 2** for the theme numbers. Source: van der Lingen and Hampton (2018) and Cochrane et al. (2020b; 2020a).*

of Agriculture, Forestry and Fisheries (DAFF). In 2019[3], the Fisheries Management Branch was brought into the newly created DFFE, alongside Oceans and Coasts.

Climate change functions are shared by the environment, risk management and planning directorates in other sector departments with environmental functions (DEA, 2018b). DFFE coordinates with other government departments at different levels to integrate and align climate change strategies under the National Climate Change Response White Paper (NCCRWP). There is no climate change unit in the Fisheries Management or Oceans and Coast branches of the DFFE but the Climate Change Task Team (CCTT, formed by volunteer scientists in 2011) from the Fisheries Management Branch has recently been appointed as a DFFE Scientific Working Group.

Inter-departmental Arrangements

There are several structures and mechanisms responsible for the inter-sectoral coordination of climate change issues in South Africa including the Inter-Ministerial Committee on Climate Change (IMCCC), the Forum of South African Directors General (FOSAD), the Intergovernmental Committee on Climate Change (ICCCG) (DEA, 2011a) and the recently formed Presidential Climate Change Coordinating Commission (PCCCC). The IMCCC is a coordination committee at the Executive (Cabinet) level, chaired by the Minister of Environment and composed of ministers with a mandate in climate change policy. The IMCCC sets out the coordination and alignment of actions with national policies and legislation. The FOSAD is formed by directors from the main departments and is grouped in the Economic Sectors and Employment, Infrastructure and International Cooperation clusters (DEA, 2011b). FOSAD coordinates policy development, cross departmental alignment of policies, monitors implementation of programs and provides technical support to ministerial departments. The PCCCC (approved by Cabinet in September 2020) will coordinate South Africa's transition to a low-carbon and climate-resilient economy and society by 2050. The Commission will be formed by government, civil society, representatives from academia and research institutions. Finally, the ICCCG is the mechanism through which DFFE

[3]https://www.gov.za/speeches/president-cyril-ramaphosa-announces-reconfigured-departments-14-jun-2019-0000 Accessed 01/12/2020.

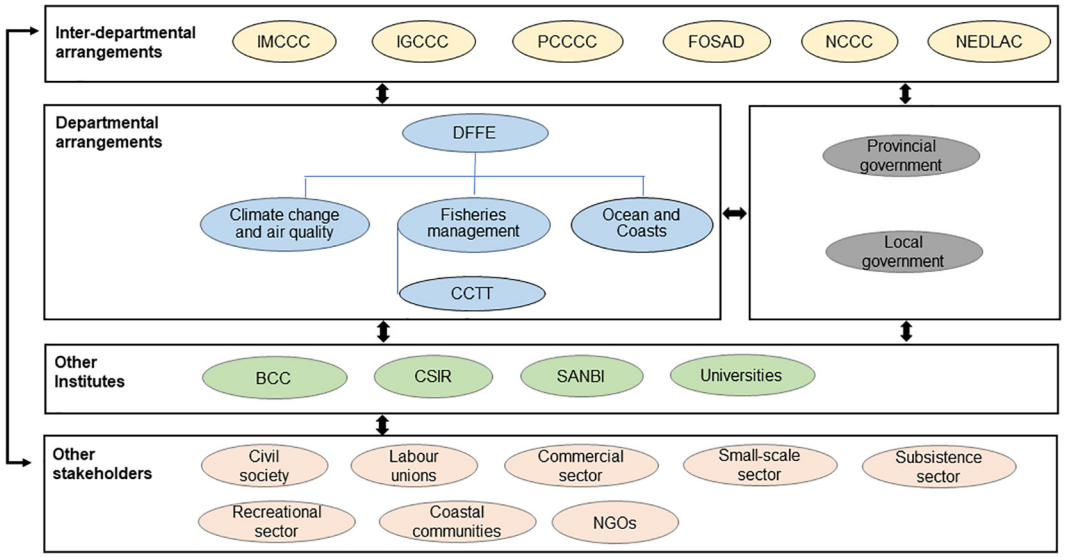

FIGURE 1 | Schematic representation of the institutional arrangements for climate change and fisheries in South Africa. The figure shows a clear delineation between stakeholders, however in reality, there is an overlap between different institutions, mandates and roles which the figure does not show. See section "Background" for abbreviations.

encourages cooperative governance in the area of climate change (DEA, 2016). It is formed by key national agencies, representatives from the provincial departments responsible for environmental management, science councils, and conservations bodies amongst others.

Stakeholder engagement and consultation takes place through the National Committee on Climate Change (NCCC) and the National Economic Development and Labour Council (NEDLAC). The NCCC is also responsible for overseeing the coordination of climate change activities, and was established to ensure that appropriate adaptation responses are mainstreamed into development plans and implemented. Through NEDLAC, government, organized business, labor and community groupings ensure that climate change policy implementation is balanced and meet the needs of all sectors of the economy. The outcome of the discussions is reported to the ministries for consideration in policy design and have been taken into account in policies such as the NCCRWP, Carbon Tax Bill and the Integrated Resource Plan 2019 (Averchenkova et al., 2019).

Provincial and Local Institutions

Provincial and local governments are required to integrate climate change into their planning, and each province is required to develop a climate response strategy and to coordinate adaptation responses across their departments and between municipalities within the province (DEA, 2011b). The provincial government departments relevant to the marine fisheries sector are the Department of Environmental Affairs and Nature Conservation -Northern Cape, Department of Environmental Affairs and Development Planning – Western Cape, Department of Economic Development and Environmental Affairs - Eastern Cape and the Department of Agriculture, Environmental Affairs and Rural Development – KwaZulu-Natal (**Figure 2**).

The South African Local Government Association (SALGA) supports, represents and advises local government action, participates in the intergovernmental system, ensures climate adaptation and mitigation actions are integrated into development plans, and plays an important role in public education, awareness and communication of information on climate change.

Other Institutions

A number of international and national institutions are involved in climate change initiatives and research in South Africa and a list of national stakeholders conducting climate change research relevant to the fisheries sector can be found in Hampton et al. (2017c). In addition to DFFE and other government departments, institutions implementing projects relevant to climate change impacts, vulnerability and adaptation include the Council for Scientific and Industrial Research (CSIR), the South African National Biodiversity Institute (SANBI) and the Benguela Current Commission (BCC).

MATERIALS AND METHODS

This study aims to determine if the South African fisheries management documents address climate change and adaptation and the extent to which climate change and adaptation has been accounted for in these documents (see **Figure 3** for a summary of the methodology). This study conducted a review of South African legislation relevant to climate change and the fisheries sector. Our approach involved the use of content analysis, a research method that 'systematically categorizes and records features of text (e.g., aural, textual, visual material) for analysis' (Krippendorff, 2004; Coe and Scacco, 2017).

FIGURE 2 | Map of South Africa including provincial boundaries. The coastal provinces listed in Provincial and Local Institutions are highlighted in light blue.

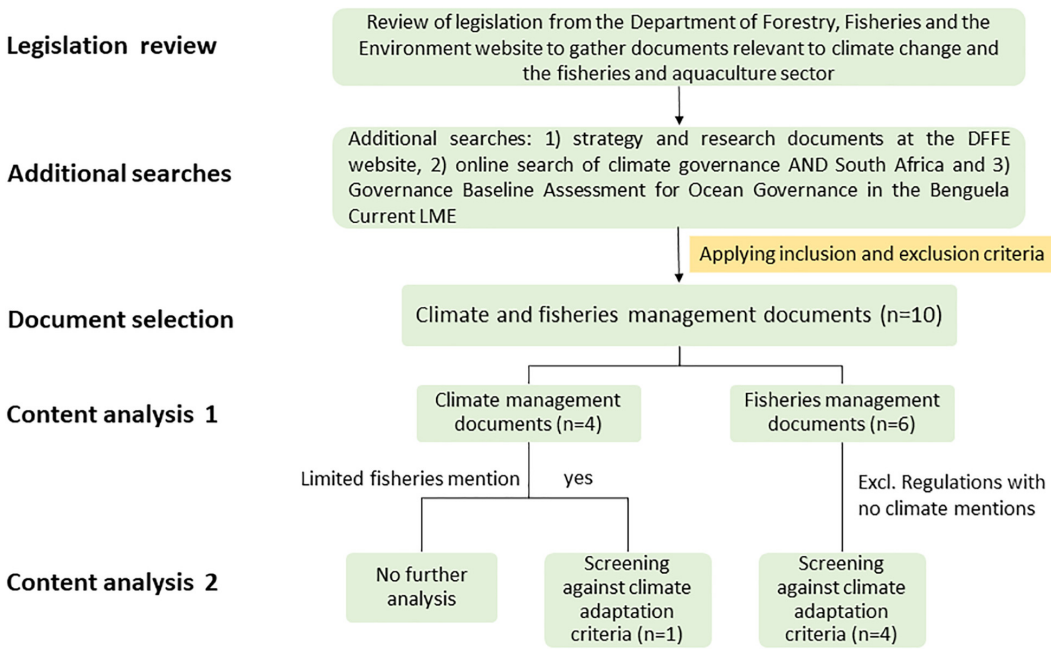

FIGURE 3 | Schematic representation of the methods used in this study.

Content analysis on two set of documents (i.e., climate and fisheries) was conducted to determine the level of inclusion of specific climate and fisheries search words (see section "Content Analysis"). This was followed by a second content analysis of fisheries management documents to determine the level to which climate adaptation has been included in fisheries management documents (**Tables 2**, **3**).

Review of Climate Change and Fisheries Management Documents

A review of climate and fisheries management documents (gray literature) was conducted using the website of the Department of Forestry, Fisheries and the Environment (DFFE)[4] to gather relevant documents for this study (accessed on June 2020 and revised March 2021), spanning year 1997 to 2020. Relevant documents were identified on this website under the legislation section. The Legislation section has eight sub-sections including Green papers, White papers, Bills, Acts and regulations, Guidelines and policies, International agreements and obligations, Gazetted notices and Public notices. Green papers were not included in the analysis because they are still in a formative stage. The documents in the International agreements and obligations section were also excluded because this study is focused on national documents on the intersection of climate change and the fisheries sector. Gazetted and public notices were similarly excluded from the study as they do not represent the final version of a policy and have several purposes such as call for nominations or invitations to apply for committees or rights. The titles of the documents in the five remaining sections (White papers, Bills, Acts and regulations, Guidelines and policies) were screened and only those documents referring to aquaculture, climate, marine (systems or resources), mitigation, fisheries, ocean or vulnerability were considered for the purpose of this study (n = 98). The next step was to check the documents to look for duplicates or different versions of the same document (n = 16). Only the adopted policy or latest draft version of a document was included in the analysis. 82 records were assessed for eligibility and the exclusion criteria in **Table 4** were applied. The aim and purpose of the document was verified to ensure the exclusion criteria was correctly applied. After this selection process, a total of nine documents were included in this study.

Finally, the Draft Climate Change Adaptation and Mitigation Plan (CCAMP) for South African Agriculture, Forestry and Fisheries sectors was also included in our analysis due to its importance informing adaptation for the fisheries sector. CCAMP is the only instrument that integrates the fisheries and aquaculture sectors and climate change. The last version of CCAMP (including the fisheries sector) was not available on the government website, but was provided to the authors by the CCAMP developers.

The Documents section of the website of the DFFE (accessed on June 2020 and revised March 2021) was then searched. The Documents section has five subsections: Annual reports and strategic plans, Strategy and framework, Research, Forms and Other documents. The documents on the Strategy and framework and Research subsections (specifically "Sustainable development' and "Oceans and coasts") were scanned to determine if there were other relevant documents to this study and complement our findings. The tittles of all the documents (n = 42) in these two subsections were screened using the criteria listed above (**Table 4** and **Supplementary Table 1**) to determine their relevance to this study. One document from these sections were considered relevant to the study (policy-informing study). The second step of identifying relevant documents included an online search for publications and gray literature (i.e., reports, policy brief) on climate governance for South Africa. Google search engine was used (March 2020) with the search terms 'climate governance' OR 'climate change governance' AND 'South Africa'. The search was considered to be complete after scanning the first ten pages of results since no new information appeared on the search. The exclusion and inclusion criteria referred above was applied and documents limited to a single sector (i.e., energy, agriculture) were not further scanned. Recent reviews on climate governance in South Africa (e.g., Averchenkova et al., 2019; CAT, 2019) and the third National Communications submitted to the United Nations Framework Convention on Climate Change (UNFCCC) were, identified through the online search, reviewed to evaluate the totality of information on climate documents. Similarly, the Governance Baseline Assessment (GBA) and Strategy for Strengthening Ocean Governance in the Benguela Current Large Marine Ecosystem Region (Cochrane et al., 2019a) was reviewed to ensure information completeness for the fisheries sector.

Content Analysis

When all documents were identified (n = 10), they included acts, laws, strategies, bills and white papers. Some of which have already been formally adopted while others have not. These ten documents were split into fisheries and climate documents based on the aim or focus of the document, and a content analysis was conducted using Nvivo12 Pro for (1) fisheries management documents (n = 6) (hereafter fisheries documents) to determine if they included information on climate change and (2) climate change documents (n = 4) to determine if they included information on climate change relevant to the fisheries sector. For the climate documents, the following search terms were coded for: 'fish' (including fishing, fisheries, fisher, shellfish), 'aquaculture,' 'marine,' and 'ocean.' For the fisheries documents, the following seven search terms were used: 'climat' (for climatic, climate), "change," "impact," "vulnerab" (for vulnerable, vulnerability), "adapt" (for adaptive, adaptation), "resilien" (resilient or resilience), and "risk." The occurrence of these search words was recorded to provide an overview of the inclusion of the given topics (either climate change or fisheries) in the fisheries and climate change documents. For words such as change or impact that can be used in a context outside climate change, the identified reference was checked to make sure it was relevant to the aim of the study.

The fisheries documents were then analyzed to identify the prevalence of nine pre-determined climate adaptation criteria (deductive codes) (see **Table 2**). Relevant references (i.e., text

[4]Department of Forestry, Fisheries and the Environment (https://www.environment.gov.za/).

TABLE 2 | Themes, description and sub-themes used to determine the adequacy of fisheries documents to incorporate climate change.

Themes	Description	Sub-themes	Typology of climate adaptation action (following Biagini et al., 2014)
(1) Develops and applies data and knowledge for impact assessment and adaptation	Based on the assessment of climate change impacts on marine systems and the sector, and the role and implications of vulnerability. Determine knowledge gaps and research priorities	1.1 Climate change as a challenge to the sector 1.2 Climate change impacts and sector vulnerability 1.3 Climate-related research as priority 1.4 Uncertainty in climate predictions	Management and planning Policy Capacity building Practice and Behavior Management and planning
(2) Supports governance for climate change adaptation	Promotes political commitment, effective coordination, infrastructure and capacity. Foster stakeholder engagement and transparency	2.1 Development of policies, organizational infrastructure and institutional capacity in support of climate adaptation 2.2 Participatory stakeholder engagement central to climate governance 2.3 Institutional coordination and collaboration key to climate adaptation 2.4 Communication, awareness, knowledge dissemination 2.5 Barriers to adaptation	Information Warning or observing systems Technology Physical infrastructure Green infrastructure Warning or observing systems Management and planning Policy
(3) Focus on building of livelihood resilience to climate change	Provide clear considerations on the importance of building resilience on the fisheries and aquaculture sector by identifying and implementing effective adaptation responses	3.1 Strategies to improve the resilience and adaptative capacity of the sector	Capacity building Practice and Behavior
(4) Targets approaches for conservation and sustainable management of biodiversity	Accounts for the ecosystem impacts of the fishery (e.g., habitat, other species) and the precautionary approach. Includes approaches such as spatial and temporal management, input and output control	4.1 Effective management to improve resilience to climate change 4.2 Principles to achieve effective management	Management and planning Information Warning or observing systems Technology
(5) Identifies, supports and applies innovative technologies	Promote and applies technological innovations to minimize the impacts of climate change on the sector and increase resilience	5.1 Development of innovative technologies to minimize climate change impacts 5.2 Increase access to information and technological developments	Physical infrastructure Green infrastructure Warning or observing systems
(6) Improves disaster risk management (DRM)	Provide clear disaster risk reduction strategies (e.g., how to prevent new risks, reduce existing risks)	6.1 Climate change poses the risk of increased climate variability and frequency of extreme events 6.2 Development of strategies that directly reduce disaster risk (i.e., warning systems, climate resilient infrastructure)	Management and planning Policy
(7) Identify resources to support prioritized actions at all levels.	Provide a detailed and comprehensive budget, and identifies source of finance to support climate change adaptation	7.1 Access to finance critical to climate change adaptation 7.2 Funding sources	Capacity building Practice and Behavior
(8) Includes implementation framework	Provide information on sequencing and prioritization of actions, responsible implementing actors etc.	8.1 Implementation plan in place to respond to climate impacts and address adaptation	
(9) Includes detailed monitoring and evaluation (M & E) framework	Provide specific targets and responsible actors for monitoring	9.1 Development of M & E plan as a key priority	

in the document) were categorized to one of these nine pre-determined criteria (hereafter referred as themes). Both direct and indirect references to climate change were considered relevant. Indirect references refer to those initiatives that contribute to climate change adaptation but do not directly refer to it. For instance, increasing resilience of the fisheries sector or dependent communities was considered a relevant, indirect reference since it requires the response of the sector or community to the impacts of climate change. A number of sub-themes emerged while reviewing the documents (under the nine pre-determined themes), these were revised to combine similar ones, reduce overlap and develop the subject of the

TABLE 3 | List of climate and fisheries documents included in the analysis.

Document	Year	Type	Content analysis 1	Content analysis 2
National Climate Change Response White Paper (NCCRWP)	2011	Climate	✓	
Climate Change Bill (CCB)	2018	Climate		
National Climate Change Adaptation Strategy (NCCAS)	2020	Climate	✓	
Draft Climate Change Adaptation and Mitigation Plan (CCAMP) for South African Agriculture, Forestry and Fisheries sectors	2018	Climate and Fisheries	✓	✓
White Paper on Fisheries Policy (WPFP)	1997	Fisheries	✓	✓
Marine Living Resources Act (MLRA), Act No. 18 of 1998 (RSA, 1998) and Amendment Act, 2014 (Act no5 of 2014)	1998, amended in 2014	Fisheries	✓	✓
Regulations in terms of the Marine Living Resources Act, 1998	1998	Fisheries		
MLRA (18/1998): Policy for the Development of a Sustainable Marine Aquaculture Sector in South Africa (PDSMAS)	2007	Fisheries	✓	✓
Policy for the Small-Scale Fisheries Sector in South Africa (SSFP)	2012	Fisheries	✓	✓
Marine Living Resources Act (Act 18 of 1998): Regulations relating to small-scale fishing	2016	Fisheries	✓	

TABLE 4 | Inclusion and exclusion criteria used to select document for analysis.

Inclusion	Exclusion
Climate- climate change is addressed as a cross-sectoral issue and document provides guidelines, regulations for climate change in South Africa	Climate: Climate change specifically addressed only other key economic sectors (i.e., agriculture, energy) (n = 1)
Climate: Climate change specifically addressed the aquaculture and fisheries sector by itself or in combination with other key economic sectors	
Fisheries: Setting guidelines, regulations and management actions for marine fisheries in South Africa	Fisheries: Sector specific permit conditions and allocation of fishing rights, including subsequent amendments (n = 24)
	Fisheries: Regulations for the management of Marine Protected Areas (n = 24) or other sectors (i.e., tourism) (n = 5)
	Fisheries: General aquaculture guidelines (including authorization requirements, funding organizations, water guidelines, application process) (n = 19)

specific sub-themes (n = 20). All identified codes were double-checked to ensure they were allocated to the correct sub-themes. The pre-determined themes were based on the Food and Agriculture Organization (FAO) priority action areas for climate change adaptation in agriculture, forestry and fisheries (FAO, 2009) and additional themes: identifying financial sources (Theme 7), implementation (Theme 8) and monitoring and evaluation plans (Theme 9) (Gogoi and Harshita, 2018; CAT, 2019). These additional themes were included because of the central role of implementation effectiveness on adaptation success (e.g., Villamizar et al., 2017; Leal Filho et al., 2018). While developing implementation plans does not directly result in effective implementation, these plans represent important steps to implement climate adaptation.

The themes (adaptation criteria) were also linked to the observed and predicted impacts of climate change in South African marine environments (**Table 1**) to ensure they reflect the specific adaptation responses that will be needed by the South African fisheries sector. Adaptation responses for the fisheries sector with regards to observed and predicted impacts of climate change have been identified in previous studies, and include increasing awareness on the potential impacts of climate change (Theme 2), technological developments (i.e., early warning systems for storms, Theme 5), and increasing access to finance (Theme 7), among others (see Hampton et al., 2017a; van der Lingen and Hampton, 2018; Cochrane et al., 2020b,a; Sowman, 2020 for a list of adaptation options). The themes were also reviewed against the adaptation typology developed by Biagini et al. (2014), based on an analysis of 92 projects financed by the Global Environment Facility adaptation funding portfolio (**Table 2**).

For each document, a score was assigned of either (1) the number of direct (from 0 to 9, based on the nine pre-determined themes) and indirect (from 0 to 3, emergent themes) themes, (2) the number of direct and indirect sub-themes referred to (0 to 20 and 0 to 15 respectively), and (3) the number of direct and indirect references to provide a more detailed view of the extent of inclusion of climate change for the sector.

RESULTS

Limited Reference to Climate Change in Fisheries Management Documents

We reviewed six fisheries documents including three acts, one White Paper and two policies (**Table 3**). Fisheries documents reviewed contained no or very limited reference of the impacts of 'climate,' 'change,' 'impact,' 'resilience,' 'risk,' 'vulnerability,' or 'adaptation.' Two of the six fisheries documents analyzed included climate change search words, i.e., The Marine Living

Resources Act (18/1998): Policy for the development of a sustainable marine aquaculture sector in South Africa (PDSMAS) and the Small-Scale Fisheries Policy (SSFP) (see **Supplementary Table 2**). The SSFP, adopted in 2012, aims to recognize the rights of the small-scale fisher communities in South Africa (RSA, 2012). The SSFP contained the highest number of climate change references (n = 9) and search words (n = 4). 'Climate,' 'change,' 'impact,' and 'vulnerability' were referenced in the SSFP, while 'risk' was only referred in the PDSMAS (**Supplementary Table 3**). Risk management is referred to under section 4 (Policy considerations, p. 8) of the PDSMAS, as one of the proposed policy measures aimed at creating an enabling environment for the development of marine aquaculture.

Limited Reference to Fisheries in Climate Change Documents

Four climate change instruments were reviewed, including a strategy, white paper, bill and a plan. The Climate Change Bill and the Climate Change Adaptation and Mitigation Plan for South African Agriculture, Forestry and fisheries sectors (CCAMP) are awaiting approval. The Climate Change Bill (CCB), developed by the DEA and gazetted in 2018, aims to guide South Africa's climate change response and the transition to a climate resilient and low carbon economy and society (DEA, 2018a, p. 6). The CCB made no reference to 'marine' or 'ocean' or 'aquaculture' or 'fish'.

Fisheries search words were referred to in the National Climate Change Response White Paper (NCCRWP) and the National Climate Change Adaptation Strategy (NCCAS). 'Marine' and 'ocean' were more frequently referred to in the NCCRWP, and 'fish' in the NCCAS, while no reference was made to 'aquaculture' in these documents (**Supplementary Table 3**). The NCCRWP, released in 2011 by the former Department of Environmental Affairs (DEA), is a comprehensive framework outlining potential responses to climate change, an approach to mitigation and adaptation in South Africa, and includes eight near-term priority flagship programs including adaptation research. The NCCRWP refers to 'marine' (n = 10) and 'ocean' (n = 3), specifically in terms of the impacts of climate change on South African marine ecosystems and users on the 'Biodiversity and Ecosystems' section (section 5.5, p. 20). 'Fish' (n = 3) were referred to in relation to the need to improve research to determine the impacts of climate change on coastal fishing communities (p. 24) and impacts on marine systems (p. 20). The NCCAS, developed by the DEA, was released in 2017 and approved by Cabinet in August 2020. The NCCAS consists of four objectives, nine strategic interventions and 12 strategic outcomes covering the water, oceans and coast, biodiversity and ecosystems sectors among others. There were seven relevant references to 'fish' (including fishers, fishing and fisheries) on the NCCAS. The search words 'marine' (n = 2) and 'ocean' (n = 4) were also referred in the NCCAS.

CCAMP had references for all the fisheries related search words (**Supplementary Table 3**). An important document identified on the DFFE website is the Long-Term Adaptation Scenarios (LTAS) released in 2013 and developed by DEA in collaboration with SANBI. The LTAS was not included in the analysis as it is a policy informing study and not legislation. The LTAS informs the policy planning process across different sectors, such as agriculture and forestry, human health, marine fisheries and biodiversity. The LTAS for marine fisheries provides information on climate change impacts, adaptation response options and research requirements (DEA, 2013). Some of the proposed adaptation options for the fisheries sector include effective spatial management, adaptive and dynamic management and enhanced social resilience in the face of uncertainty and variability among others (DEA, 2013, pp. 34–35).

Climate Change Adaptation in Fisheries Documents

The first content analysis indicated that three of the four climate documents included fisheries search words. A closer inspection of these documents revealed that the 'fish' references in the NCCRWP were very limited (n = 3), and rather identified climate change as a threat to marine ecosystems with less focus on the fisheries sector. This was noted on section 5.5 'Biodiversity and Ecosystems' (p. 20), referring to impacts of climate change on the main South African ecosystems (including marine and oceans). Adaptation for the water, agriculture and commercial forestry, health and other sectors are included in the NCCRWP but not for fisheries. The fisheries references in the NCCAS (n = 7) are higher than in the NCCRWP (see section "Limited Reference to Fisheries in Climate Change Documents" and **Supplementary Table 3**), however, these are general with limited specific adaptation strategies or actions identified to improve its resilience. The fisheries sector is not recognized as a key socio-economic sector in the strategy, therefore its sensitivity, exposure, vulnerability and adaptive capacity are not addressed as there are for other sectors such as agriculture and forestry. While the coastal zone is evaluated as a sector, it does not fully represent the sensitivity and exposure of the marine environment and economic activities such as fisheries. It is still advised by the authors of this paper to recognize the fisheries sector explicitly in the NCCAS so adaptation options for the sector can be prioritized. It is important to note that the NCCAS was reviewed in relation to the fisheries sector in the context of climate change. The applicability of this strategy to the agricultural sector would most likely render a different outcome. Since the fisheries sector was not considered a priority in these two documents as reflected by the first content analysis, they were not included in the second content analysis addressing climate adaptation for the fisheries sector.

Only two of the six fisheries documents included climate change references, and therefore it was anticipated that climate adaptation would have very limited direct references in these documents. Five documents (four fisheries documents plus CCAMP, **Table 3**) were included in the second content analysis using pre-determined themes for climate change adaptation (**Table 2**). The fisheries documents excluded at this stage were the Regulations in terms of the Marine Living Resources Act, 1998 and Marine Living Resources Act (Act 18 of 1998): Regulations relating to small-scale fishing. These documents list

specific regulations for the right of access, permit conditions, use of gear for the different commercial sectors, offenses and penalties, and are of a technical measure. It was thus deemed that these documents would not indirectly refer to climate change adaptation to warrant further analysis.

All remaining documents included references to at least one of the nine themes and 20 sub-themes. CCAMP had references for all 20 sub-themes and nine themes, while the SSFP and PSDMAS referred to two sub-themes and two themes each. Considering the specific sub-themes and themes, all documents referred to sub-theme 4.2 'Principles to achieve effective management' within theme 4 'Targets approaches for conservation and sustainable management of biodiversity'. The precautionary approach, marine spatial planning, adaptive management and the ecosystem approach were some of the principles referred to in order to achieve effective management in the fisheries documents. These references were not specific to climate change but statements supporting conservation and sustainable management that nevertheless will contribute to climate change adaptation. The sub-themes 1.2 'Climate change impacts and sector vulnerability' and 6.2 'Development of strategies that directly reduce disaster risk' were referred to in CCAMP and PSDMAS respectively.

A total of 210 direct references to the nine themes and 20 sub-themes were identified in five documents. CCAMP had the highest number of references (n = 154), while PSDMAS had the lowest (n = 7) (**Table 5**). CCAMP contains 73.1% of all the direct references. Theme 4 'Targets approaches for conservation and sustainable management of biodiversity' and sub-theme 4.2 'Principles to achieve effective management' had the highest number of references (n = 61 and 59 respectively) from the five documents analyzed. Sub-theme 4.2 alone represents approximately a third of all the direct references. Theme 1 'Develops and applies data and knowledge for impact assessment and adaptation' and 2 'Supports governance for climate change adaptation' followed in terms of number of references, with 52 and 45 references each from two and one documents respectively. Similarly, sub-themes 1.2 'Climate change impacts and sector vulnerability' and 3.1 'Strategies to improve the resilience and adaptive capacity of the sector' had the highest number of individual references from two and one documents.

The content analysis identified a total of 167 indirect references from all documents, grouped into three themes and 15 sub-themes (**Table 6**). CCAMP had the lowest number of indirect references (n = 7), covering one theme and 2 sub-themes. While the SSFP had the highest number of references (n = 79) from 3 themes and 13 sub-themes. SSFP contains 47% of the total indirect references identified in the content analysis. Theme 1 'livelihood' had the highest number of indirect references, while sub-themes 2.3 'participatory management,' 2.1 'equity,' 2.3 management,' and 3.2 'capacity building' were the sub-themes with the highest number of references. These three sub-themes represented 45% of all indirect references. The sub-theme 1.1 'environmental variability' was found only in CCAMP, recognizing the high natural variability that characterizes South African marine systems.

The MLRA does not refer to 'climate,' 'change,' or 'variability' and thus climate change is not recognized as a significant challenge to the sector. However, the act does recognize the importance of building livelihood resilience and the need to use approaches to fisheries management that contribute to food security, socio-economic development and the alleviation of poverty. The MLRA does not directly refer to funding instruments to support prioritized actions related to climate change but does state that the Marine Living Resources Fund will provide for the administration of the provisions of the Act to achieve its objectives, which include sustainable management, a precautionary approach, MPAs, and pollution prevention among others. The policy acknowledges the need for conservation and the sustainable management of biodiversity and has a chapter on Marine Protected Areas, prohibited fishing methods and emergency measures (sub-theme 4.2, n = 17).

The SSFP recognizes the impacts of climate change on coastal communities including changes in biodiversity distribution, potential loss of species and ecosystem services such as food provision on the policy problem statements. Poverty alleviation, ensuring food security and sustainable livelihoods are some of the policy principles, and thus the SSFP indirectly addresses the need to improve the resilience of the sector to adapt to the potential impacts of climate change but their direct relationship to climate change is not stated. This is a critical point since evidence indicates that small-scale fishers are among the most vulnerable groups to climate change impacts (Hampton et al., 2017b; Martins et al., 2019).

The sustainable management of biodiversity and the need for an ecosystem approach to fisheries is another strategic objective in the SSFP and substantial attention is given to this in the document (sub-theme 4.2, n = 20, **Table 5**), specifically in section 5 (Mechanisms and instruments for the management of small-scale fisheries). The policy briefly identifies the use of innovative technologies in Section 4.4.4 (Research for technology), where it states the need to promote and develop technologies for sustainable harvesting as well as the importance of technical and advisory support centers to provide information to fishers on research findings, weather forecasts, fish movements and other information (sub-theme 3.8, n = 3, **Table 6**). Small-scale fishers are at high risk to extreme events such as storms and increased wind speed among others, however, the SSFP includes only one reference to disaster management. While the policy does not include an implementation framework, a draft implementation framework for the small-scale fisheries policy was released for consultation in 2013 and finalized in 2019.

The PDSMAS in South Africa had the lowest number of direct and limited indirect references (**Tables 5**, **6**). Most of the indirect references belong to theme 3 'livelihood,' specifically the sub-theme 3.7 'financial assistance'. The policy highlights the need for financial support to ensure the viability of the sector. The sub-theme 3.2 'capacity building' was mentioned three times, however, information from consultations suggests that an understanding of potential climate change impacts on the aquaculture sector is lacking (Britz et al., 2019). Implementation is dealt with separately on the Marine Aquaculture Policy Implementation Plan 2009–2014, which

TABLE 5 | Number of direct climate references identified in the fisheries documents.

Themes	Sub-themes	WPFP	MLRA	PSDMAS	SSFP	CCAMP	No. of documents	No. of References
(1) Develops and applies data and knowledge for impact assessment and adaptation	1.1 Climate change as a challenge to the sector	–	–	–	–	2	1	2
	1.2 Climate change impacts and sector vulnerability	–	–	–	1	34	2	35
	1.3 Climate-related research as priority	–	–	–	–	12	1	12
	1.4 Uncertainty in climate predictions	–	–	–	–	3	1	3
(2) Supports governance for climate change adaptation	2.1 Development of policies, organizational infrastructure and institutional capacity in support of climate adaptation	–	–	–	–	10	1	10
	2.2 Participatory stakeholder engagement central to climate governance	–	–	–	–	6	1	6
	2.3 Institutional coordination and collaboration key to climate adaptation	–	–	–	–	6	1	6
	2.4 Communication, awareness, knowledge dissemination	–	–	–	–	11	1	11
	2.5 Barriers to adaptation	–	–	–	–	12	1	12
(3) Focus on building of livelihood resilience to climate change	3.1 Strategies to improve the resilience and adaptative capacity of the sector	–	–	–	–	21	1	21
(4) Targets approaches for conservation and sustainable management of biodiversity	4.1 Effective management to improve resilience to climate change	–	–	–	–	2	1	2
	4.2 Principles to achieve effective management	11	17	6	20	5	5	59
(5) Identifies, supports and applies innovative technologies	5.1 Development of innovative technologies to minimize climate change impacts	–	–	–	–	6	1	6
	5.2 Increase access to information and technological developments	–	–	–	–	3	1	3
(6) Improves disaster risk management (DRM)	6.1 Climate change poses the risk of increased climate variability and frequency of extreme events	–	–	–	–	3	1	3
	6.2 Development of strategies that directly reduce disaster risk (i.e., warning systems, climate resilient infrastructure)	–	–	1		5	2	6
(7) Identify resources to support prioritized actions at all levels.	7.1 Access to finance critical to climate change adaptation	–	–	–	–	7	1	8
	7.2 Funding sources	–	–	–	–	3	1	3
(8) Includes implementation framework	8.1 Implementation plan in place to respond to climate impacts and address adaptation	–	–	–	–	1	1	1
(9) Includes detailed monitoring and evaluation (M & E) framework	9.1 Development of M & E plan as a key priority	–	–	–	–	2	1	2
Number of themes		1	1	2	2	9	5 (Total)	210 (Total)
Number of sub-themes		1	1	2	2	20		
Number of references		11	17	7	21	154		

WPFP: White Paper on Marine Fisheries Policy, MLRA: MLRA 1998. Act No. 18 of 1998, incl. amendment in 2014, SSFP: Policy for the Small-Scale Fisheries Sector in South Africa., PDSMAS: the MLRA (18/1998): Policy for the Development of a Sustainable Marine Aquaculture Sector in South Africa and CCAMP: Climate Change Adaptation and Mitigation Plan for marine fisheries and aquaculture.

TABLE 6 | Number of indirect climate references identified in the content analysis of fisheries documents.

Themes	Sub-themes	WPFP	MLRA	PSDMAS	SSFP	CCAMP	No. of documents	No. of References
Environmental impacts and research	1.1 Environmental variability	–	–	–	–	6	1	6
	1.2 Research needs	6	–	6	1	1	4	14
Governance	2.1 Equity	7	4	–	16	–	3	27
	2.2 Need for legislation development and amendments	2	–	1	1	–	3	4
	2.3 Participatory management	8	1	3	15	–	4	27
	2.4 Transformation	3	–	3	1	–	3	7
	2.5 Transparency and accountability	4	–	–	2	–	2	6
Livelihood resilience	3.1 Activity as an opportunity to improve livelihoods (i.e., through poverty alleviation and food security)	1	1	2	15	–	4	19
	3.2 Capacity building	7	1	3	10	–	4	21
	3.3 Infrastructure development	1	–	–	3	–	2	4
	3.4 Processing and value adding	–	–	–	7	–	1	7
	3.5 Safety	1	1	–	–	–	2	2
	3.6 Disaster management	–	–	1	1	–	2	2
	3.7 Financial assistance	4	1	5	4	–	4	14
	3.8 Development of technical support services	2	–	2	3	–	3	7
Number of themes		3	2	3	3	1	5 (Total)	167 (Total)
Number of sub-themes		12	6	9	13	2		
Number of references		46	9	26	79	7		

*See **Table 5** for abbreviations.*

includes a comprehensive budget. Since climate change is not included in the PDSMAS, the implementation plan does not include specific actions related to climate change adaptation nor does the budget identify sources of finance to support adaptation.

CCAMP had the highest number of direct references ($n = 154$) to both the themes and sub-themes (**Table 5**). CCAMP outlines the projected impacts of climate change on marine fisheries and aquaculture in South Africa (section 3.5, pp. 37–42), adaptation options based on the available knowledge of climate impacts for the fisheries and mariculture sectors and on consultations with different stakeholders. Information on specific vulnerabilities is presented for smaller-scale fishers and industrial fisheries. Importantly, the policy recognizes the vulnerabilities and challenges faced by fishers (and also farmers) due to the limited access to information and technologies and the need to address these issues (theme 5, **Table 5**). CCAMP notes the relevance of using innovative technologies in the fisheries and aquaculture sector and their importance to improving the resilience and adaptive capacity of the sector, especially for small-scale fishers (see sub-theme 5.2, **Table 5**). Adaptation options are presented for large-scale industrial fisheries, small-boat commercial fisheries, small-scale fishers, recreational fishers and marine aquaculture.

CCAMP recognizes the need to obtain and provide funding to facilitate adaptation identifies possible sources of international funding, and the need to develop partnerships between the private sector, government and civil society to successfully implement climate change policies (Theme 7). Financial constraints are listed as a limitation to achieve adaptation: section 7.5 states 'Insufficient funding, lack of accessibility to funding resources for climate change research projects both nationally and internationally, is a long-standing challenge' (p. 84). CCAMP identifies the Marine Living Resources Fund, the BCC and the Water Research Commission as possible sources of local funding. Despite the extensive reference to funding sources, CCAMP does not include a detailed budget.

CCAMP also provides a comprehensive list of general recommendations to achieve successful implementation of the plan (p. 90). Some of the recommendations applicable to the fisheries sector include effective coordination among government departments, policy alignment with national plans, government/industry partnerships, incisive enforcement and implementation of current strategies, more effective science communication and further development of CCAMP into a more comprehensive plan for the marine fisheries and aquaculture, among others. In terms of monitoring and evaluation (M&E), CCAMP covers several aspects of monitoring in different sections but in section 11 specifies that a climate change monitoring system for the agriculture, forestry and fisheries sectors in South Africa, preferably placed under the DFFE, must be implemented.

DISCUSSION

Our review indicates that there are a number of climate change and fisheries documents in South Africa that mandate and encourage efforts to address climate change impacts and adaptation, and that progress has been made toward these goals. Our analysis suggests, however, that more attention has been paid to other sectors (i.e., energy) while the fisheries sector has not been fully accounted for in national climate change documents. As a result, the inclusion of climate change impacts in the main fisheries documents are mostly limited even though efforts have been made in recent years to address these gaps.

An important factor contributing to the somewhat limited attention being given directly to climate change is that while it is well recognized as a threat to the fisheries sector, at present any actual impacts are very difficult to differentiate from impacts of longer-term but potentially reversible variability. As reported in section "Climate Change Impacts in South Africa," direct attribution to climate change has only been established for sea surface temperature (Hampton et al., 2017b) and while a link between climate change and environmental changes and changes in species' distributions observed in recent decades is considered likely, there is still uncertainty. This uncertainty probably explains not only the limited attention so far given to climate change in fisheries policies and practices but also that most of the actions identified here as directly or indirectly addressing climate change are of a generic nature and applicable to efforts to ensure adaptability and environmental and social resilience in highly variable environments in general, rather than any additional threats brought about by climate change. This is also apparent amongst stakeholders. For example, in the South African fishery for small pelagics, there have been far-reaching actions to adapt to distributional shifts in the target species and the current low biomass of sardine, including substantial actual and planned investments in new vessels and processing facilities that reflect at least a medium-term perspective but without necessarily attributing the changes to climate change (Cochrane et al., 2020b,a; van der Lingen, 2021). It is likely to require wider, robust attribution and greater confidence in long-term forecasts of change for stronger and more urgent attention to be given specifically to the additional threats brought about by climate change. However, we hope this is not the case, since climate change will likely 1) make the existing limitations in South African fisheries management more serious and urgent to address and 2) bring new challenges to the sector or worsen conditions. In this sense, South Africa should prepare to the anticipated climate change impacts because the cost of inaction will certainly be very high.

Ogier et al. (2016) identified a number of 'critical capacities' required for fisheries management, and governance, in order to enable adaptation and develop resilience to climate change. While that study addressed different fisheries management approaches in Australia, the capacities required are globally relevant and include learning orientation, the capacity to deal with complexity and uncertainty, a focus on the long term and at ecosystem level, integration of the different sectors and scales involved, the ability to monitor and review developments, and effective stakeholder engagement and empowerment. The management agency in South Africa, the Fisheries Management Branch within the DFFE, has these capacities, to varying degrees (Cochrane et al., 2020a),

but the extent to which they are being applied to address the impacts of climate change is largely limited.

The MLRA (1998) did not include direct reference to climate change and the 2014 amendments were limited and aimed specifically at enabling implementation of the 2012 SSFP. While the MLRA does not directly address climate change, it includes management actions that can be used to reduce and mitigate the impacts of climate change. For example, measures aimed at the conservation of marine living resources and protection of the ecosystem as a whole help to maintain resilience of ecosystem to climate impacts, and allowance for emergency measures enables the authorities to take action if climate impacts are considered likely to endanger fish stocks or other components of the ecosystem. Management of the commercial fisheries in South Africa is adaptive, usually through application of operational management procedures (Plagányi et al., 2007), which allows for adjustment of management measures, such as total allowable catches, in response to changes in resource abundance and productivity, including any caused by climate change. At present there is no formal longer-term strategic planning that considers the longer-term risks and possible impacts of climate change on resources or stakeholders in the country's fisheries. Failing to consider the longer term can not only exacerbate the longer-term risks to the sustainability of resources but also to the fishing sector, which needs to plan in the long term in, for example, making decisions on investments (Pinsky et al., 2021). It would therefore be valuable to amend the MLRA to include direct reference to climate change and its implications for short term tactical management as well as the need for longer term strategic management, and to explicitly support 'indirect' climate change-related actions. A revision of the MLRA will take place in line with the Fishing Rights Allocation Process to account for the new allocation rights. This represents an opportunity to revise several aspects of the MLRA and explicitly include climate change impacts and adaptation.

CCAMP, the first adaptation plan for the South African fisheries sector, had the highest number of references to climate change adaptation. The main limitations of CCAMP were the lack of references to disaster risk management, implementation, and monitoring and evaluation plans. Disaster risk management strategies are however currently being drafted (Jean Githaiga-Mwicigi, DFFE pers. com), and this should increase the usefulness of CCAMP to guide climate adaptation for the sector. Using monitoring, evaluation, reflection and learning (MERL) tools is also advised, since MERL departs from the deterministic approaches of mainstream monitoring and evaluation (M&E) which focus on input/output over process and instead emphasizes adaptive learning to respond to dynamic problems such as climate change (Bours et al., 2013; Rosenberg and Kotschy, 2020). It is highly advisable that clear guidelines are developed to ensure successful implementation and monitoring of CCAMP at all levels (national, provincial and local). Information on prioritization of actions, responsible implementing actors and an implementation budget plan should also be included. Implementation of CCAMP should be included in fisheries management plans but at present, there are no formal management plans in place for any of the South African fisheries. Formulation and implementation of management plans encourages comprehensive planning, transparency and accountability and should include short and long-term objectives (Cochrane et al., 2015, 2020a). Plans should also include the likely impacts of climate change in both the short and longer-terms. Cochrane et al. (2015) proposed a revision of the MLRA to include, amongst other aspects, a requirement for formal fisheries management plans. This assessment reinforces the value of a revision of the MLRA, which should also facilitate the implementation of CCAMP when finalized. The technique of management strategy evaluation (Punt et al., 2016) uses simulations to test the effectiveness of alternative management options and different scenarios, which could be particularly useful in consideration of measures and adaptations to address climate change when developing plans (Lindegren and Brander, 2018). The development of management plans would also provide an opportunity to consider and incorporate those aspects of fisheries management that are generally neglected in the current management strategies, particularly the rigorous consideration of social and economic implications when deciding on specific management measures, policy choices and adaptation options.

The SSFP had the highest number of indirect references to climate change highlighting that this policy includes several actions that will indirectly improve the resilience of small-scale fishers to climate change. Participation, equity and a recognition of the key role of fishing to improve the livelihood of coastal communities are themes that emerged from the content analysis and had the highest number of references in the SSFP. While the incorporation of these actions in the policy will certainly improve the resilience of small-scale fishers to climate change, a concerted effort is required on the part of decision-makers based on the high vulnerability and low adaptive capacity of the small-scale sector (Hampton et al., 2017a,b). In this sense, we again suggest a revision of the SSFP to explicitly address climate adaptation actions following best practices in adaptive management of fisheries (Bahri et al., 2021) but to also account for specific contextual livelihood realities of small-scale fishers in South Africa (Sunde and Erwin, 2020). Sowman (2020), in consultation with small-scale fishing communities in the BCC countries, identified a lack of communication with and support from government, limited participation in decision-making, conflict with other fishing sectors and unclear administrative processes as the most 'common management/governance stressors'. Moreover, some of these stressors speak directly to the emergent themes identified in the SSFP, and it is expected that the implementation of the SSFP, which has so far been problematic (e.g., Cochrane et al., 2020a; Sunde and Erwin, 2020), will help to address these pressing issues. It is clear that government support is needed to build the resilience of this sector and to ensure that climate change does not become a major threat to the sustainability of this already vulnerable sector.

Effective implementation of policies remains a challenge in South Africa, as is the case in many areas of the world (e.g., Lombard et al., 2019; Taljaard et al., 2019; Alves et al., 2020; Reed et al., 2020). Some of the common challenges faced to achieve effective implementation are related to limitations in

climate change knowledge, institutional capacity, funding and awareness mechanisms, and coordination among and within government institutions (Spires et al., 2014; Totin et al., 2015; Ampaire et al., 2016; Taljaard et al., 2019). While there have been few assessments of the implementation of climate change actions, it is clear that there are a number of strategies available to guide climate change adaptation but very few examples of actual implementation (e.g., Ziervogel et al., 2014; Ogier et al., 2016; Alves et al., 2020; Bell et al., 2020; Fogarty et al., 2020). Bell et al. (2020) summarizes examples of climate-ready fisheries moving from policy to action with a focus on the Northern Hemisphere. These authors concluded that despite a substantial increase in the body of work on climate change impacts and vulnerability in recent years, integration of climate change impacts into fisheries management is still not adequate for the complexity of the issue (Bell et al., 2020).

Limited climate change knowledge is perceived as one barrier to achieve effective implementation of climate adaptation. The importance of integrating science into decision-making for natural resource governance has been extensively recognized, but an implementation gap between science and management persists (Knight et al., 2008; Kirchhoff, 2013; Cvitanovic et al., 2015; Fogarty et al., 2019). A study on coral dominated Marine Protected Areas (MPAs) in Australia, Belize and Kenya indicated that only 14% of information cited in management plans corresponds to primary scientific literature (Cvitanovic et al., 2014), with technical reports and local government documents being the most used information sources. Possible reasons include long publication times for articles, limited accessibility to articles (journal subscriptions needed) and articles not providing outcomes relevant to management. A number of efforts have been conducted to summarize the projected impacts of climate change on South African marine environments and fisheries (Jarre et al., 2015; Potts et al., 2015; van der Lingen and Hampton, 2018) and vulnerability assessments have been conducted for a number of South African marine species (Ortega-Cisneros et al., 2018) and fisheries (Hampton et al., 2017b; Cochrane et al., 2020b,a; Sowman, 2020). While some of this work has informed the development of CCAMP and a few local adaptation plans (St. Helena Bay fishing community, Sowman, 2020), there is still a need to improve uptake of research to explicitly address short—and long—term climate change impacts on natural resources as well as the socio-economic and cultural impacts on fishing communities in South Africa (Sunde and Erwin, 2020). Even with a reasonable evidence base, limited understanding by stakeholders of how this information is used or disseminated combined with limited access, adoption and integration of climate information by policy makers and government leads to stakeholders not knowing (1) how to interpret complicated and inaccessible legislative language, (2) who to contact and approach with regard to climate challenges and knowledge, and (3) who to hold accountable for implementation. These findings are supported by the most recent World Meteorological Organization (WMO) report stating that the capacity in disaster risk knowledge and forecasting in Africa is well advanced, but the information is not yet actionable and accessible highlighting the need to improve the transition from knowledge into action (WMO, 2020). A response to this challenge could be: (1) conduct a knowledge availability and needs assessment for the South African context across governance levels and sectors and (2) ensure that capacity (time, knowledge, skills, and funding) exists to translate climate change knowledge and science into meaningful action.

Co-production of knowledge, knowledge brokers and institutional reforms to support knowledge exchange have been suggested as possible responses to reduce the science implementation gap (Cvitanovic et al., 2015; Fogarty et al., 2019). A knowledge and information audit should be conducted for the South African fisheries sectors in order to understand why climate information is not reaching the people who need it (from policy-makers at national level through to fishers at a local level) and why it is not being integrated more effectively into policy and implementation. For example, is the information inappropriately technical and therefore inaccessible, is the problem a lack of time and capacity, and are there other barriers? Existing knowledge gaps also need to be identified such as the need for research on the socio-economic linkages of climate change impacts on the fisheries sector to other sectors (DEA, 2013). The knowledge audit should be considered a priority since previous studies have identified a lack of awareness of climate change information as a barrier to achieve climate adaptation in the Benguela region (Cochrane et al., 2020b,a). Lessons from the integrated water management and agricultural sectors in South Africa indicate that contextual factors must be understood in order for the development of relevant research and research dissemination to take place, not only in these sectors but across other sectors, including in fisheries and aquaculture (Lotz-Sisitka and Burt, 2006; Jiggins et al., 2007; Burt and Berold, 2012). Understanding contextual factors implies also understanding and integrating other forms of knowledge such as indigenous, local and experiential knowledge and how these knowledge systems can, and should, be integrated into policy recommendations (Klein, 2000; Smith, 2012; Reed et al., 2014; Gee et al., 2017).

Contextual factors need to be better understood in South Africa so knowledge and learning of climate change challenges can be better supported (Sunde, 2014; Rivers, 2015; Sowman, 2020; Sunde and Erwin, 2020). For this to happen, information needs to be packaged in a relevant manner (contextualized) and then presented in a way that best suits the needs of the users (i.e., DFFE managers, small-scale fishers, etc.). For research findings to be better taken up into policy and management. Fisheries scientists and managers need to communicate more effectively in order to interpret climate science information and what research results means in practice. Both parties need to take ownership of this knowledge exchange process with scientists understanding what research is needed to respond to climate issues holistically and managers understanding the science so they can implement it more effectively (Moser and Dilling, 2012; Cochrane et al., 2019b).

In order to ensure effective and sustainable climate change resilience and adaptation implementation, stakeholders impacted by climate change need to be engaged with. The overall design of stakeholder engagement processes around policy formulation needs to be truly inclusive and democratic. This

requires careful planning, early inclusion, transparency and trust building, capacity building of all stakeholders from decision-makers to local community stakeholders, acknowledging power imbalances and real decision-making power for marginalized communities and groups. Acknowledging the need for more democratic government stakeholder participation processes (Sunde and Erwin, 2020) call for an official review into the public participation processes comprising the implementation of the SSFP. Commenting on participation with small-scale fisheries in South Africa, Sunde (2014: 106) argues for best practice guidelines for participation that "include representatives of rights holders and stakeholders from the beginning of the planning process and to define the roles, powers and authority of these parties at different stages in the planning and management process."

Limited capacity and skills in the climate change field are identified as key challenges faced by government officials in responding to climate change in South Africa (DEA, 2016). This is not only a local problem, and the 2020 State of Climate Services report noted that Sub-Saharan Africa faces persistent technical and financial capacity constraints (WMO, 2020). As suggested above, synergies and knowledge exchange between managers and scientists can help address this issue. Resources in the form of funding, time and skills training need to be invested over a sustained period in order to build human and institutional capacity. Improved collaboration and coordination among and within government departments can also help to address capacity issues. The recent merger between the former DEA and the Fisheries Management Branch of DAFF into DFFE, bringing fisheries management and environmental expertise together in the same department, has been problematic with many challenges presently being addressed, but provides an opportunity to improve coordination of climate change aspects for the fisheries sector.

This study aimed to evaluate the extent to which climate change impacts and adaptation are incorporated into the fisheries sector in South Africa, and contributes to the attempts to effectively integrate climate adaptation with the fisheries sector by assessing to what extent climate change adaptation principles are currently incorporated. The general recommendations that emerged from this study were: (1) revise the primary fisheries management instruments to explicitly include climate change mentions or to strengthen them, for example in the case of the SSFP; (2) compile fishery management plans for all sectors, thus allowing climate change to be included in a comprehensive and logical framework; (3) improve communication, information and knowledge exchange among stakeholders, including between scientists and managers in DFFE; (4) develop implementation budgets with specific targets and responsible actors for monitoring and implementation of the climate change policy; and (5) allocate and prioritize funding to increase capacity building (institutional and human capacity) and effective stakeholder engagement in the DFFE. Overall, the fisheries sector does not yet appear to be given high priority for climate change adaption measures in South Africa. As suggested for other sectors (Ramanathan and Haines, 2016; Chersich and Wright, 2019), explicit framing of climate change adaptation for the fisheries sector as critical for the nation (i.e., food security) may secure more dynamic actions by government, and strengthen the engagement of civil society and local communities most vulnerable to climate change impacts.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

KO-C conducted the data collection and analysis. All the authors provided comments on and inputs to the manuscript.

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The Missing Layers: Integrating Sociocultural Values Into Marine Spatial Planning

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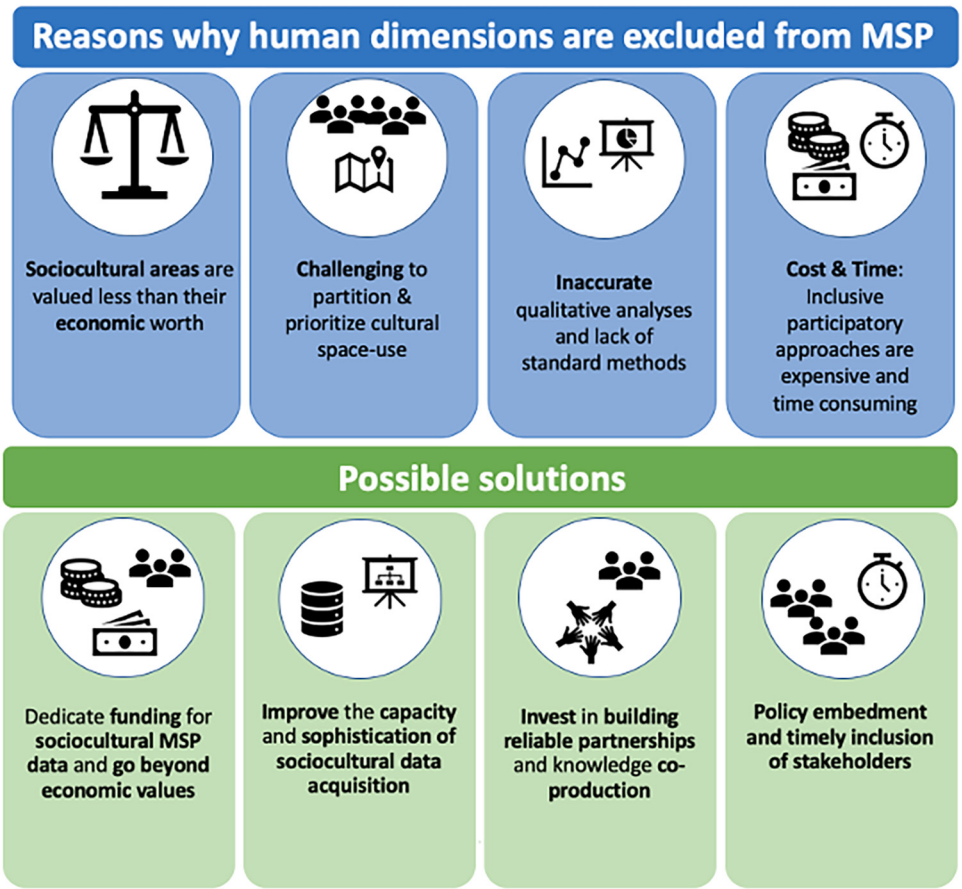
Marine Spatial Planning (MSP) is a relatively new approach to ocean management and has been widely implemented worldwide. Ideally, MSP should be established as a public process that analyzes and distributes human activities across space and time to achieve ecological, economic and social goals, which historically have been accomplished exclusively in the political arena. However, in most cases MSP seems to be driven primarily by economic interests rather than by sociocultural goals. In this paper, we discuss how integrating the missing sociocultural layers into MSP can help to reduce governance rigidity, promote adaptability in decision-making, support environmental justice, and improve MSP acceptance and uptake. In particular, we focus on identifying possible points of connection between MSP and frameworks based on social-ecological system theory, including co-management and other democratic and empowering alternatives. We conclude by proposing a new definition of the MSP process that is more inclusive, and mindful of users' rights and sociocultural objectives. If we bridge the gap between the dominant economic rhetoric and a *de facto* sociocultural-ecological system approach, we are likely to improve the chances of the MSP process succeeding on both the human and nature fronts.

Keywords: ecosystem based management, human dimension, Marine Spatial Planning, stakeholder participation, sociocultural values, inclusive process

PAST AND CURRENT MARINE SPATIAL PLANNING PRACTICES

Marine Spatial Planning (MSP) has rapidly gained popularity and become one of the most endorsed alternatives for the sustainable management of ocean space. In some places, MSP has even become a requirement for some public lenders to ensure the sustainable use of ocean spaces (Smith and Jentoft, 2017). The United Nations Educational, Scientific and Cultural Organization (UNESCO) defines MSP as a "public process of analyzing and allocating the spatial and temporal distribution



GRAPHICAL ABSTRACT

of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process" (Douvere, 2008). Therefore, MSP is a process that seeks to mediate conflicts among marine resource users (e.g., fisheries, aquaculture, shipping, tourism, marine mining, energy production). In opposition to a sectoral approach, MSP also potentially allows seeing cumulative impacts of all these activities (Flannery et al., 2016). MSP recognizes the legal, political, economic and ecological complexity of ocean governance (Ehler and Douvere, 2009). The operationalization of MSP can be done through a cyclical and iterative process that includes continuous monitoring, evaluation, and revision of goals, data and results. Thus, MSP is supposed to incorporate new information over time and adapt its objectives and measures according to the evolution of the socio-ecological system (**Figure 1**).

Marine Spatial Planning has also been described as the spatial component of ecosystem-based management (EBM) (Ehler and Douvere, 2009). Although EBM encompasses a broad range of tools that are not traditionally labeled as "spatial" (e.g., fishing gear modification, and landing control, etc., Gilman et al., 2019), ultimately the application of every "non-spatial" tool could have spatial boundaries dictated by the limits of maritime jurisdictions (Dunstan et al., 2016). In this context, MSP is designed to offer countries an operational framework where spatial and non-spatial needs of biodiversity conservation and sustainable development can be balanced. Ehler and Douvere (2009) suggest that achieving this balance is one of the key components of any EBM approach.

The origins of MSP can be traced back to the 1980s, in the context of marine conservation planning (Day et al., 2002; Santos et al., 2019). Indeed, the Great Barrier Reef Marine Park in Australia is commonly viewed as a "pioneering example" of MSP (Jay et al., 2013). Currently, over 70 countries are developing MSP initiatives, with approximately 70% of them still in an early development phase (Santos et al., 2019; **Figure 2**). In 22 countries, MSP initiatives have already been approved by the government and are in force, representing almost 27% of the world's exclusive economic zones (EEZs) (Claus et al., 2017). These include cases in which MSP covers the majority of the domestic waters of Belgium, Germany, the Netherlands, Norway, China, and Belize, but also where MSP only covers a small region under national jurisdiction, such as the United States, Canada, and Croatia (IOC-UNESCO, 2020)[1].

[1] A complete list of countries using MSP can be accessed at http://msp.ioc-unesco.org/world-applications/overview/

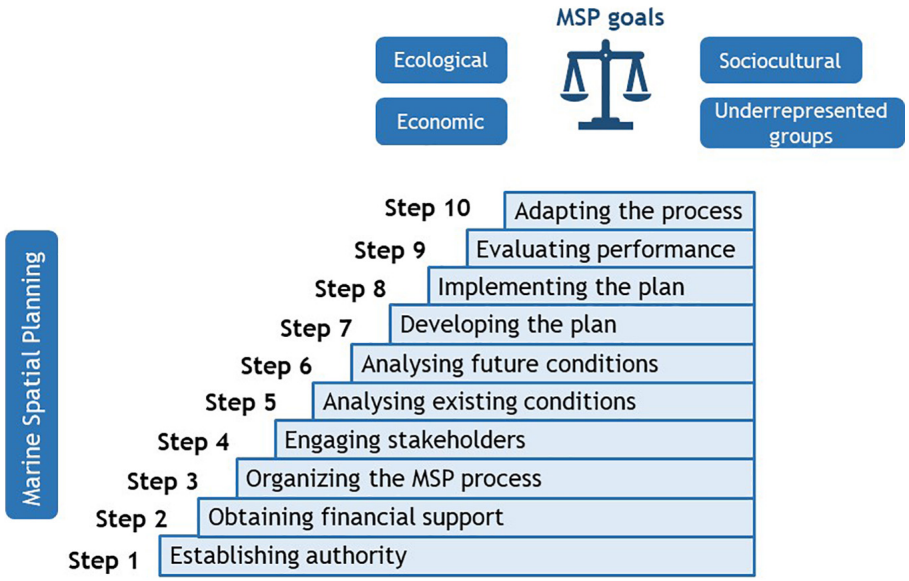


FIGURE 1 | A schematic representation of the Marine spatial planning implementation process. The missing layers must be addressed in all steps.

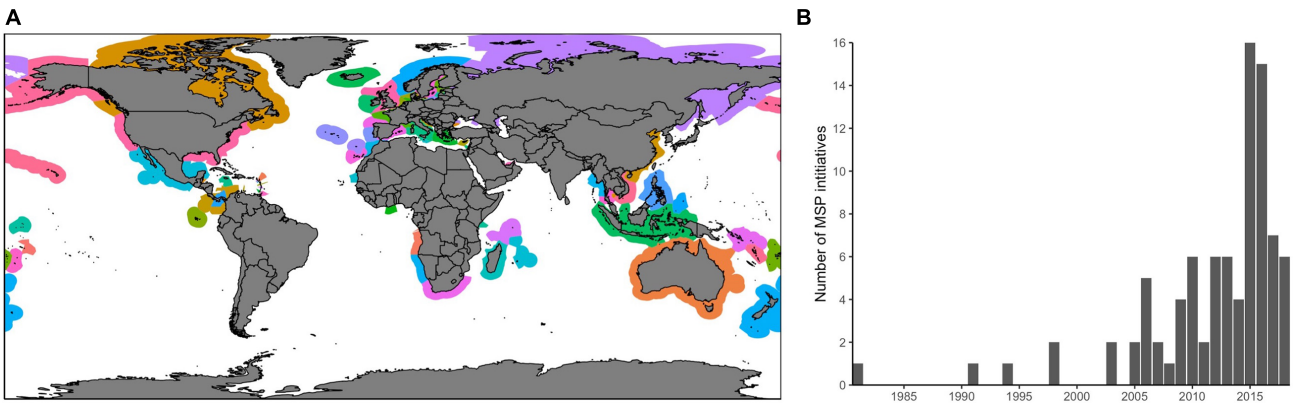


FIGURE 2 | (A) Map of countries exclusive economic zones (color) that have implemented MSP initiatives. Note that MSP does not cover the entire extent of EEZs shown. **(B)** Number of MSP initiatives per year. Data from http://msp.ioc-unesco.org/, accessed October 2020. Year is considered the first year mentioned in the comments section of the IOC-UNESCO MSP inventory, which can be the first year a draft plan was submitted or the year an MSP plan was passed by the government.

Throughout the MSP process, the responsible authorities should incorporate input from all stakeholders and community members, seeking a final zoning design that would minimize negative impacts on livelihoods and earn broad community support. Establishing legal zones without proper representation of local communities (e.g., indigenous fishers) can lead to strong opposition and/or inefficient management. Local communities may simply perceive MSP as a strategy to prevent their access to resources upon which their livelihoods depend (Johnson et al., 2020). Nevertheless, addressing lack of representativity is not an easy task for planners because spatial data that reflect the social and cultural dimensions (or more generally human dimensions; here the two terms are used interchangeably) of a given site are not easily produced. For example, MSP assumes that spatial layers containing the value of each location within an area for traditional communities must be developed and incorporated into the analysis. Yet, non-monetary values are not easily quantifiable and can be easily misinterpreted (Outeiro et al., 2019). The use of proper qualitative methodologies and a longer drafting stage could help to integrate sociocultural missing layers and underrepresented groups' rights in the MSP process (discussed below).

This perspective piece is a product of the Marine Spatial Planning Workshop "Balancing social, economic, cultural and ecological objectives" organized by the Interdisciplinary Marine Early Career Network (IMECaN). The lack of balance among

MSP objectives was a common theme identified across multiple examples in the 3-day workshop.

THE MISSING LAYERS: SOCIOCULTURAL VALUES AND UNDERREPRESENTED GROUPS RIGHTS

Marine Spatial Planning initiatives are supposed to integrate and seek optimal trade-offs between different economic, social, political and ecological goals, following its main overarching conceptual framework. However, in reality many of these initiatives have been driven primarily by one specific objective, often economic or ecological, such as meeting renewable energy targets or establishing marine protected areas (MPAs). The prioritization of one objective over the other is often case-specific but overall economic or ecological values often dominate over other aspects.

A recent study by Jones et al. (2016) analyzed in detail 12 European MSP initiatives and concluded that: (1) Blue growth was often the main priority, prioritizing specific sector objectives over strategic plans at national levels; (2) MSP case studies tended to be fragmented (e.g., pilot projects) and developed *ad hoc*, rather than as dynamic and adaptive processes as prescribed in the conceptual framework; and (3) overall MSP tended to have a top-down approach, and while participatory platforms did exist they were usually disconnected from executive decision making. In such a prioritized, fragmented and hierarchical framework, the exclusion of social and cultural values has been a common pattern.

The poor inclusion of social and cultural heritage values in MSP initiatives (Domínguez-Tejo et al., 2016) undermines the MSP process and its original defining objective. One of the real risks of adopting MSP without the proper consideration of social and cultural aspects involves its distributive impacts, which can simply reflect the existing power structures where the more powerful stakeholders have more of a say. By feeling left behind, the less powerful stakeholders might question the point of engaging in MSP processes at all (Flannery and Cinnéide, 2012). Also, when some stakeholders are given prominence over others, MSP is no different from previous top-down marine management approaches (Katikiro et al., 2015), except that powerful non-governmental users are likely to be the ones who will decide on how best to share and use the space.

Initiatives such as community-based management and participatory governance, among others, are alternatives to support more inclusive MSP (Berkes, 2003). The meaningful inclusion of indigenous and local communities in MSP not only decreases the odds of system sabotage (Msomphora, 2016; Metcalfe et al., 2018), but also allows the exchange of information and acceptance of new knowledge systems and distinct worldviews (Armitage et al., 2011). The effectiveness of conservation or any regulation is contingent on compliance (Arias et al., 2015), as clearly demonstrated in fisheries in general and in the assessment of the ecological performance of marine protected areas (Bergseth et al., 2015; Muhl et al., 2020). By promoting engagement, responsibility sharing and empowerment of all stakeholders in decision-making, greater compliance, lower surveillance costs (Freitas et al., 2020), and changes in the levels and types of information and knowledge exchanged are expected. Diversity (of stakeholders, gender, ethnicity, etc.) is a source of different points of view, solutions and knowledge base and can greatly contribute to improve creativity and problem-solving skills in otherwise homogenous groups (van Knippenberg et al., 2004). Additionally, the inclusion of different types of knowledge, such as those held by traditional and indigenous societies (Armitage et al., 2011), can not only point to overlooked problems and solutions, but it can also fill important scientific gaps (e.g., from species occurrence to changes in food webs) (Lopes et al., 2019; Cavole et al., 2020).

It is well recognized that successful MSP implementation depends on identifying and understanding the expectations and interests of various stakeholders (Pomeroy and Douvere, 2008; Mannan et al., 2020). Stakeholder engagement can lead to increased knowledge, institutional learning and adaptive co-management (Berkes, 2011), which are key processes to MSP. However, practical issues such as poor communication between science and policy, the perception that user's involvement is only included when the spatial plan is already in place, and fragmented governance contribute to the non- or limited engagement of stakeholders by raising questions about legitimacy, inclusiveness and social equity of the MSP process (Flannery et al., 2018). Without fair engagement to ensure that human livelihood security and social-ecological outcomes of MSP are not undermined, then there is a risk of MSP constituting "ocean grabbing"[2] (Bennett et al., 2015). With grabbing, resources are expropriated for the use of a minority (Corson et al., 2013), who tend to be either outsiders or the local elite, thus leading to the concentration of power, the displacement of local populations, and accentuated poverty in areas where social vulnerabilities can often be already high (Green and Adams, 2015).

CHALLENGES TO INCLUDE THE MISSING LAYERS

In a dynamic and iterative process like MSP there should always be room for establishing mechanisms for the inclusion of sociocultural aspects, underrepresented group voices, and their relationships with the marine environment (McKinley et al., 2019). Despite international objectives and increasing emphasis on the importance of considering human dimensions in environmental governance, it is clear that a lack of understanding of the flows and impact paths between sociocultural dimensions and MSP remain (St. Martin and Hall-Arber, 2008; Flannery et al., 2016). Below, we identify plausible reasons for why human dimensions are often excluded from MSP initiatives:

[2]Ocean grabbing refers to acts of dispossession or appropriation of marine resources or spaces.

Inclusive Participatory Approaches Are Expensive and Time Consuming

People have sociocultural relations with the sea, thus identifying sociocultural significant areas is crucial, although not easily done (Gee et al., 2017). Such highly intensive participatory steps may make MSP processes more time-consuming and expensive, requiring social science skills and cultural sensitivity.

Delineation of Spatial Activities and Potential Conflicts

Marine Spatial Planning often involves the spatial delineation of areas, for purposes such as restricting/promoting specific activities in particular zones. The ability to spatially delineate socioculturally significant areas may facilitate their inclusion in the MSP process. However, some sociocultural meanings may be difficult to articulate and delineate, and defining hard boundaries between areas considered significant and others that are not may find resistance.

A Worth Beyond the Economic Value

Identification and codification of sociocultural values associated with sea areas is complex, case-specific, and often include layers not associated with monetary value, making their inclusion and subsequent evaluation difficult in the MSP context.

Inaccurate Inclusion of Qualitative Aspects

Qualitative studies are usually used to collect data on sociocultural values and they are difficult to generalize beyond the context in which they were developed (McKinley et al., 2019). The lack of standardized methods and approaches for using qualitative data within MSP is likely prohibitive to addressing sociocultural voices.

POTENTIAL SOLUTIONS

Different aspects could be improved in order to achieve a more inclusive MSP that takes into account the mentioned missing layers.

Dedicate Funding for Sociocultural MSP Data

To date, limited funds are dedicated to the collection and incorporation of sociocultural data in MSP, including information on cultural ecosystem services, and local socio-ecological links (Le Cornu et al., 2014). We advise more efficient use of financial resources to understand sociocultural values and to improve stakeholder engagement and communication.

Improve the Capacity and Sophistication of Sociocultural Data Acquisition

Marine Spatial Planning initiatives should recognize both people's inherent differences and preferences along with the spatial-temporal distribution of their activities and interactions with the environment as well as factors that influence them (St. Martin and Hall-Arber, 2008; Dalton et al., 2010; Strickland-Munro et al., 2016). For that, a comprehensive approach that considers the complex and fine-scale interactions between people and their environment may be necessary (Dalton et al., 2010). Examples include the use of Bayesian network analyses to include stakeholder preferences into the MSP decision-making process (Coccoli et al., 2018; Laurila-Pant et al., 2019; Phan et al., 2019; Alexander et al., 2021). These techniques may help find an optimal compromise in the presence of potentially conflicting objectives (Laurila-Pant et al., 2019). Moreover, the codification and evaluation of cultural values and criteria for mapping and valuing/monetizing culturally significant areas should be more consistent. Standard methods for studies to address sociocultural values in MSP (e.g., heatmaps for each traditional activity, calculated using data from interviews as spatial access priority (SAP) per km2) should be developed and implemented (Johnson et al., 2020). For instance, maps of fishing areas that take into account financial, subsistence and culturally relevant areas may be produced (Outeiro et al., 2019).

Invest in Building Reliable Partnerships and Knowledge Co-production

This step requires an iterative and continual process of building mutually beneficial, respectful ongoing arrangements between users and holders of traditional knowledge, in order to build trust, good relations, mutual understanding, intercultural spaces, knowledge exchange, knowledge co-production and reconciliation (Ntona and Morgera, 2018). Giving traditional stakeholders a voice in relevant decision-making processes, understanding and addressing their views and preferences in that context is not a one-off exercise (Breckwoldt et al., 2021). It will be necessary to create more inclusive negotiation spaces where people's differences are acknowledged and included in the conversation at different stages, and where differences are opportunities for creative and accommodating solutions. Developing and implementing "equal opportunity" policies to ensure those differences are acknowledged should be a priority.

Policy Embedment and Timely Inclusion of Stakeholders

Timely and efficient stakeholder participation is an essential aspect of MSP and is also a legal requirement of several different international tools [e.g., Rio Declaration on Environment and Development (1992), Convention on Biological Diversity (CBD)]. However, the degree and scope of stakeholder participation can vary considerably between countries, and will largely depend on the existing local political or legal requirements for participation (Twomey and O'Mahony, 2019). Supporting policy embedment to truly involve stakeholders in MSP initiatives can ensure that all stakeholders are not only being informed or being used as information providers, but are also essential partners in collaboration and decision-making. Shifting a historical trajectory of persistent inequities will require embedded policies, strong leadership, inclusive governance and long-term planning that starts with a commitment to equity as

integral to a sustainable ocean economy and relationships within and across nations (Österblom et al., 2020).

Go Beyond Economic Values

Perhaps one of the shortfalls of MSP is that it has been increasingly associated to the concept of Blue Growth (Santos et al., 2014), which may find no resonance in traditional communities that share relational values that are hard or impossible to monetize, as their place attachment and place identities (Himes and Muraca, 2018). There is a chance to reconcile different worldviews in how the oceans should be managed and used if MSP can also partner with alternative and more inclusive concepts. One such concept is the idea of de-growth (Hickel, 2020), which is based on the inclusion of values, such as enjoying and promoting humanistic values, maintaining/decreasing the carrying capacity, reducing the north-south discrepancies, along with not seeing nature as a commodity (Martínez-Alier et al., 2010).

CONCLUSION

This perspective article provides a pragmatic view for connecting sociocultural values and underrepresented groups into the MSP process. It argues that bridging the gap between dominant economic rhetoric and a *de facto* approach to the sociocultural-ecological system is the first step in making the MSP process successful on both the human and the natural fronts.

Therefore, we propose to revise the traditional well-known definition of the MSP process in order to be more comprehensive as "*an inclusive political process of analyzing and allocating users activities and rights in the ocean to make informed and coordinated decisions on the spatiotemporal sustainable use of marine resources while achieving balanced ecological, economic, sociocultural objectives.*"

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

MP initially conceived the idea for the workshop, counting with the contribution of all authors to its execution. MP wrote the first draft of this manuscript, and all authors equally contributed to the subsequent versions of the manuscript. MP, SB, and KO-C generated the figures.

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Bioenergetic Model Sensitivity to Diet Diversity Across Space, Time and Ontogeny

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Consumption is the primary trophic interaction in ecosystems and its accurate estimation is required for reliable ecosystem modeling. When estimating consumption, species' diets are commonly assumed to be the average of those that occur among habitats, seasons, and life stages which introduces uncertainty and error into consumption rate estimates. We present a case study of a teleost (Yellowfin Bream *Acanthopagrus australis*) that quantifies the potential error in consumption (in mass) and growth rate estimates when using diet data from different regions and times and ignoring ontogenetic variability. Ontogenetic diet trends were examined through gut content analysis (n = 1,130 fish) and incorporated into a bioenergetic model (the "primary" model) that included diet variability (n = 144 prey sources) and ontogenetic changes in metabolism (1–7 year) to estimate lifetime consumption. We quantified error by building nine model scenarios that each incorporated different spatiotemporal diet data of four published studies. The model scenarios produced individual lifetime consumption estimates that were between 25% lower and 15% higher than the primary model (maximum difference was 53%, range 11.7–17.8 kg). When consumption (in mass) was held constant, differences in diet quality among models caused a several-fold range in growth rate (0.04–1.07 g day^{-1}). Our findings showcase the large uncertainty in consumption rate estimates due to diet diversity, and illustrate that caution is required when considering bioenergetic results among locations, times, and ontogeny.

Keywords: bioenergetics, diet diversity, ecosystem model, energy-balance model, fish, trophic dynamics, estuary

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INTRODUCTION

Reliable consumption and growth rate estimates are needed for trophodynamic and ecosystem models, which quantify the flow of energy through ecosystems (Pauly et al., 1990; Christensen et al., 2005; Dawson et al., 2019; Leaf and Oshima, 2019). Such models are used to inform fisheries management and restocking programs (Fulton et al., 2011), estimate biodiversity loss in the Anthropocene (Pereira et al., 2010), predict ecosystem shifts (Heithaus et al., 2008) and

manage ecosystem services (Christensen et al., 2005; Daily and Matson, 2008). Consumption rates are commonly estimated using energy-balance models such as bioenergetic models (Kitchell et al., 1977; Lawson et al., 2019). This is done by quantifying energy expenditure of an animal, such as that required for growth, metabolism, reproduction, digestion, and excretion/egestion, and assumes that consumption rate is at least equal to the rate of energy expenditure (Kitchell et al., 1977). Such models further consider that consumption rate is dependent on the energy density (ED) of prey items (Kleiber, 1961). For example, predators must consume more low-ED prey compared to high-ED prey to ingest equal calories. The ED of prey species may vary substantially for a generalist predator with a diverse diet (Lawson et al., 1998). Thus diet composition and prey ED are important considerations when quantifying consumption rate estimates using bioenergetic modeling (Luecke and Brandt, 1993; Surma et al., 2018).

Biological models should be reliable approximations of reality but are rarely completely precise. Such models enable an understanding of populations and ecosystems based on physiological processes, relying on regularities that emerge despite individual and interspecific variability (Pérez-Ruzafa et al., 2018). By quantifying sources of variability in predictive models, we can increase their precision. Diet studies, which inform models, can employ gut content analysis (GCA) from deceased animals or sample from live animals with lavage, scat, stable isotope, and fatty acid analyses (Fryxell et al., 2014; Hazen et al., 2019). These methods are often invasive, difficult or costly due to the need to sample large numbers of individual animals to detect diet trends (Fryxell et al., 2014). As a result, fine resolution diet data are lacking for many species and regions. Differences in food environment can lead to altered consumption rates (e.g., Lefcheck et al., 2021) and accounting for these differences may be important for effective management (e.g., Pfeiffer and Anderson, 2021). Despite these limitations of diet data, models that estimate consumption rate or trophodynamics will, by necessity, use what diet data are available, even if the dietary information is collected from different locations or with small sample sizes. This relies on the assumption that a species would occupy a similar trophic niche among regions, which may be suitable for studying a species' basic ecology but may not hold for other applications such as ecosystem models. This is particularly true for opportunistic species that can have a region- and habitat-specific diet. There will be differences between the assumed diet and actual diet specific to a location or habitat, and these differences may impact estimates of consumption rate and other energy-dependent parameters, such as growth rate. While earlier work has shown the importance of using multiple prey items in bioenergetics models to estimate consumption (Lawson et al., 2018), there are no studies to the author's knowledge that use detailed diet data (i.e., multiple prey items) to quantify the uncertainty of consumption and growth estimates introduced by supplementing diet information from different spatiotemporal regions.

The objective of this study was to quantify the uncertainty of individual consumption and growth rate estimates when using diet data from different locations, seasons and collection methods. This was achieved by creating a bioenergetic model using highly detailed diet information, including previously unavailable ontogenetic diet changes and consumption rates, and comparing the resulting consumption estimates with those derived from region- or habitat-specific diet information (using nine other datasets). We used Yellowfin Bream (*Acanthopagrus australis*, hereafter "Bream") as a study species and describe its diet and consumption rate. Bream is a well-studied species in terms of both energetics and diet, and hence represents an ideal species to assess limited input data for bioenergetic models. Further, Bream has a diverse diet including bivalves, polychaetes, decapods and terrestrial invertebrates, as well as algae and other teleosts (Bell et al., 1984; Morton et al., 1987; Hadwen et al., 2007; Sheaves et al., 2014). However, each study of Bream diet showed differences in prey composition depending on study location, habitat type, season, sampling method, fish life stage, and sample size (Bell et al., 1984; Morton et al., 1987; Hadwen et al., 2007; Sheaves et al., 2014). This variability in the described diet composition implies different ED values of prey, and in turn different food consumption or growth rate estimates of individual predators, depending on which diet data are used.

MATERIALS AND METHODS

Primary Model Diet

The primary diet data set (compared later with other studies) was measured in Bream collected during a large survey in Botany Bay and Georges River system, New South Wales, Australia (Pease et al., 1981). Fish (n = 1,130, 1.1–40.5 cm total length) were sampled using a variety of commercial fishing methods [gill net (various sizes), beach seine, and beam trawl] across the entire estuary between February 1978 and October 1979. Biometric information [total length (mm), weight (g)] was collected prior to fish dissection, and then fish stomachs were removed and prey contents sorted. Prey species were identified to the highest taxonomic level possible, were blotted and weighed, and expressed as the proportion-by-biomass of the total stomach contents for each individual, which was then averaged across all non-empty stomachs. Energy density per wet mass (kJ g^{-1}) of prey types were taken from published sources (**Supplementary Table 1**).

Respirometry

The routine metabolic rate (RMR; Chabot et al., 2016) of Bream was estimated using respirometry experiments. Mass-specific RMR to be used in a bioenergetic model was determined as:

$$\mathbf{R_T} = \mathbf{R_a W^{R_b}}$$

Where R_T is RMR (g O_2 g^{-1} h^{-1}) at temperature T (°C), W is body weight (g), and R_a and R_b are constants (**Table 1**). R_a (gO_2 g^{-1} day^{-1}) was derived in respirometry experiments (0.0163) and R_b was taken from the literature as a mass-specific universal allometric scaling exponent (−0.25; Brown et al., 2004) because there was limited variation in Bream size in the respirometry experiments, and available evidence suggests -0.25

TABLE 1 | Summary of parameter mean values used in the bioenergetic model.

Parameter description	Symbol	Value	Units	Source
Proportion of ingested energy lost to egestion, excretion, and digestion	A	0.319	–	Hartman and Brandt, 1995
Energy density of Bream	F	5750	J g^{-1}	Lawson et al., 2018
Von Bertalanffy growth curve parameter	t_0	−0.32	–	Pollock, 1982
Von Bertalanffy growth curve parameter	k	0.51	–	Pollock, 1982
Von Bertalanffy growth curve parameter	L_∞	29.5	cm FL	Pollock, 1982
Mass-dependent intercept of metabolic rate	R_a	0.0163	gO_2 g^{-1} day^{-1}	Derived
Mass-dependent gradient of metabolic rate	R_b	−0.25	–	Brown et al., 2004
Activity multiplier	ACT	1.1	–	Roell and Orth, 1993; Petersen and Paukert, 2005; Mateo, 2007;
Oxy-caloric coefficient	oxy	14140	J $gO_2{}^{-1}$	Elliott and Davison, 1975
Temperature-dependent gradient of metabolic rate	R_Q	0.060	–	Clarke and Johnston, 1999
LOESS smoothing parameter	–	0.75	–	Cleveland, 1979; Junhe et al., 2017

is approximately a median exponent value for fish (Clarke and Johnston, 1999; Payne et al., 2015).

Respirometry trials of smaller Bream (n = 12, 0.015–0.08 kg) were performed at a different time and location to large Bream (n = 5, 0.411–0.738 kg). Smaller fish were caught by hook and line in Sydney Harbour, Australia, and transported to the Sydney Institute of Marine Science (33° 50′ 31.6″ S; 151° 14′ 51.18″ E) where they were kept in captivity throughout the respirometry trials (during Autumn 2016). Bream were held in a 1000-L seawater flow-through holding tank that was maintained at 24°C (approximately ambient water temperature at time of capture) using aquarium bar heaters and provided natural light. Fish were fed daily a diet of frozen fish and invertebrates, and held for one week before respirometry trials began. The RMR of fish was measured individually at 24°C in an insulated and darkened 8-L rectangular custom-built respirometry chamber. Individuals were fasted for 24 h prior to the respirometry to prevent any increased oxygen consumption associated with digestion, based on the gastric evacuation rates of other species and temperature used for the trials here (Plaut, 2000; Chang et al., 2005; Das et al., 2018). After a 3-ho acclimation period inside the chamber, the chamber was isolated from atmospheric air, and oxygen content of the water measured (Hach HQ40d, Loveland, CO, United States). Each respirometry trial ran until dissolved oxygen in the chamber reached 80%. All respirometry trials were performed in the morning to minimize diurnal changes in metabolic rate or activity (Clark et al., 2013). A background respirometry trial was performed without any fish, to account for any microbial respiration, which was subtracted from the oxygen consumption measured for each individual fish. Respirometry trials of larger Bream used the same protocol and equipment as the smaller bream, but were undertaken in August 2012 at the Cronulla Fisheries Research Centre (34° 04′ 21″ S, 151° 08′ 56″ E), and on animals that had been captured in the nearby Port Hacking estuary and subsequently held in large (10 m × 5 m × 2 m) flow-through mesocosms for several years prior to experimentation. These Bream were captured by netting and transferred to 1,000-L flow-through tanks one week prior to respirometry trials, in which they were held under the same conditions as the small Bream. They were then fasted for 24 h and individual Bream transferred to a darkened 91-L respirometer. The respirometer was continuously flushed with fresh seawater for the 3-h acclimation period, then sealed while RMR was measured at 24°C for 20–30 min per fish (sufficient time to see large, linear declines in dissolved oxygen concentration). Background respiration trials were run daily as per small Bream experiments.

For all fish, the mass-dependent intercept of RMR (R_a) was estimated using linear regression of log-transformed RMR values with mass-specific slope (R_b) forced at −0.25 (Brown et al., 2004). All statistical models were done using R statistical computing (v3.3.1; R Core Development Team, 2016). Experiments were conducted under approval of the University of New South Wales Animal Care and Ethics Committee (No. 15/152B), and

TABLE 2 | Frequency of occurrence (FOC) of prey groups in gut contents of Yellowfin Bream in primary diet data (Pease et al., 1981).

Phylum	FOC (%)	Class	FOC (%)	Order	FOC (%)
Annelida	50.3	Polychaeta	50.3	Eunicida	2.4
				Phyllodocida	22.9
				Sabellida	5.2
				Spionida	10.2
				Terebellida	0.1
Arthopoda	70.5	Malacostraca	62.9	Amphipoda	31.6
				Cumacea	0.4
				Decapoda	18.9
				Isopoda	1.5
		Ostracoda	0.5		
		Insecta	0.5		
Bacillariophyta	0.5				
Brachiopoda	0.4				
Chlorophyta	7.9				
Chordata	4.0	Actinopterygii	1.8		
		Ascidiacea	0.2		
Cnidaria	3.0	Scyphozoa	1.3		
		Hydrozoa	0.4		
		Anthozoa	1.3		
Echinodermata	0.6	Ophiuroidea	0.4		
		Echinoidea	0.2		
Mollusca	30.8	Bivalvia	26.4	Veneroida	15.6
		Gastropoda	3.4		
		Cephalopoda	0.1		
Nemertea	0.1				
Phaeophyceae	0.6				
Streptophyta	3.0				
Xanthophyceae	0.2				

Some prey items were only identified to phylum, class, or order, hence frequency counts are minimum values and summed values of classifications may not equate to the total of the higher classification.

all experiments were performed in accordance with relevant guidelines and regulations of this ethics approval as well as the Guide for the Care and Use of Laboratory Animals (8th edition, National Academies Press).

Consumption Rate

Consumption rate estimates for Bream were estimated using a bioenergetic model, based on the format of Kitchell et al. (1977) and modified as in Lawson et al. (2018):

$$\mathbf{C_J = \frac{R_J ACT + G}{1 - A}}$$

Where C_J is consumption rate (J day^{-1}), R_J is metabolic rate (J day^{-1}), ACT is a multiplier of metabolic rate to account for costs of activity, G is energy required for growth (J day^{-1}), and A is the proportion of ingested energy lost to assimilation costs (**Table 1**). Assimilation was assumed constant and taken from the literature (**Table 1**; Hartman and Brandt, 1995). A generalized metabolic rate R_J (J day^{-1}) was determined, using R_T estimated in the respirometry experiments, by:

$$\mathbf{R_J = 24 R_T\, W\, e^{R_q(T - T_r)} oxy}$$

Where R_q is the slope of the temperature-dependent function of RMR (Clarke and Johnston, 1999), T is ambient water temperature (°C; variable, see below), T_r (°C) is the temperature at which respirometry trials were performed to derive R_T, and *oxy* is the caloric-coefficient of oxygen used to convert metabolic rate from oxygen consumption (g O_2) to energy requirement (J) (**Table 1**). R_T was multiplied by 24 to determine daily metabolic rate. Energy cost of growth G (J day^{-1}), at body weight W, was determined by:

$$\mathbf{G(W) = \Delta WF}$$

Where ΔW is the growth rate (g day^{-1}) at body weight W (g), and F is the energy density of Bream tissue (J g^{-1}; **Table 1**). Growth rate was taken as the slope at W of a published von Bertalanffy growth function for Bream (Pollock, 1982; **Table 1**) and converted from fork length (FL, cm) as in Steffe et al. (1996):

$$\mathbf{W = 0.020 FL^{3.0045}}$$

To convert an energy requirement (in joules) accurately to a food requirement (in grams), information on the ED of prey consumed is required. Based on the diet reported here and associated prey ED values found in the literature

(**Supplementary Table 1**), a linear LOESS regression function (smoothing parameter = 0.75; Cleveland, 1979) was fitted to determine the relationship between prey energy density and Bream length (Lawson et al., 2018). This indicates the mean prey energy density (*ED*, J g^{-1}) throughout ontogeny of Bream. Prey energy density was used to convert energy consumed (C_J; J day^{-1}) to consumption rate of prey *C* (g day^{-1}):

$$\mathbf{C} = \frac{\mathbf{C_J}}{\mathbf{ED}}$$

Consumption: biomass ratio ($Q : B$) is a metric often used to compare annual consumption rates of populations (Polovina, 1984). $Q : B$ (g g^{-1} $year^{-1}$), at body weight *W*, was calculated:

$$\mathbf{Q{:}B(W)} = \frac{\mathbf{C}}{\mathbf{W}}\mathbf{365}$$

Where 365 is a multiplier to calculate annual $Q : B$. Bream lifespan (7 years), growth rate and maximum size parameters for the bioenergetic model were taken from Pollock (1982). $Q : B$ was calculated across the life-span of a fish by calculating weight-dependent growth, consumption, and size-dependent prey energy density at each age based on the above relationships. Temperature was also varied according to a seasonal cycle, assuming a birth date of 1 September (start of Spring; Pollock, 1982). Daily temperature was measured at the inlet to the aquarium at the Sydney Institute of Marine Science in Sydney Harbour (33° 50′ 31.6″ S; 151° 14′ 51.18″ E) over 3 years (2013–2016) to generate a sine function (range 15.6–22.1°C) that provided seasonal variation in *T*. The bioenergetic model using the diet data found in the current study (n = 1,130) will hereafter be referred to as the "primary model scenario."

Comparing Model Scenarios Using Different Diet Information

To compare consumption and growth rates using different sources of diet data, we produced nine comparative model scenarios based on four published studies on Bream diet (Bell et al., 1984; Morton et al., 1987; Hadwen et al., 2007; Sheaves et al., 2014). Each study provided diet as percent composition of major prey types (**Supplementary Table 2**), but variability among methods meant we were able to build in multiple comparative model scenarios from two studies. Two scenarios were created using diet data from Hadwen et al. (2007); the first using GCA and the second using stable isotope analysis (SIA). Five scenarios were created from Morton et al. (1987) GCA; Autumn (day and night combined), Spring (day and night combined), day (Spring, Summer, Autumn combined), night (Autumn, Winter, Spring combined), and mean (using all data). One scenario was created from Sheaves et al. (2014) using gut contents analysis, and one scenario was created from Bell et al. (1984) using gut contents analysis. Each comparative model scenario was compared against the primary scenario described above, to test the effect of using different sources of diet data on consumption and growth rate estimates.

A weighted mean ED of prey was calculated for each comparative scenario based on the proportion (by volume) of each prey item and its ED (**Supplementary Tables 1**, **2**). This weighted mean ED was used as a constant prey ED for each comparative scenario to produce estimates of consumption rate. Unlike the primary model dataset, there was insufficient data to produce ontogeny-specific prey ED values in comparative scenarios. The lifetime and daily consumption rate produced by each comparative scenario were then compared with the primary scenario presented here. All parameters except ED were identical in all scenarios. Temperature of Sydney Harbour was used in all scenarios, despite some scenarios using dietary data from different regions, to isolate the effect of dietary composition. ED values for identical prey groups used the same values in the comparative scenarios as the primary scenario, with ED values for new prey items taken from the literature (**Supplementary Table 1**).

Differences in diet may not always reflect proportional change in consumption, and energy budgets can be dynamic, such that an increase in energy content of the diet may not represent a decrease in consumption rate—instead, consumption may remain the same, but the consumer is able to invest more energy into growth (Kitchell et al., 1977). We explored this in additional scenarios; we examined the effect of diet composition on potential growth rate if consumption rate (in mass) was held constant. Differences in growth rate based on the diet quality of the comparative scenarios were estimated when Bream were 100 g (∼1.4 year), 250 g (∼2.7 year), and 400 g (∼4.5 year; representing fast, moderate, and slow instantaneous growth rates, respectively). Growth was estimated by keeping consumption rate constant, based on the mean percentage of body mass consumed daily of the primary and all comparative scenarios (described above) at each of the three chosen masses. The total ingested energy, and therefore energy allocated for growth, differed between the scenarios depending on the prey composition. Energy allocated for growth (J day^{-1}) was calculated as:

$$\mathbf{G} = \mathbf{(1-A)\,C_B{}^*W^*ED_m - R_J{}^*ACT}$$

Where C_B is percent body mass consumed daily (%) estimated as the mean consumption rate of all scenarios above at each weight (100, 250, and 400 g) and ED_m is the weighted mean prey energy density of each respective scenario (J g^{-1}). Growth rate (ΔW, g day^{-1}) was calculated as:

$$\Delta\mathbf{W} = \frac{\mathbf{G}}{\mathbf{F}}$$

RESULTS

Diet

Gut content analysis of Bream using the primary diet data (n = 1,130; Pease et al., 1981) showed a diverse diet with ontogeny, with prey items from at least 34 orders and 13 phyla (**Table 2**). Actual prey diversity was likely higher, as some prey items were only identified to phylum or class (e.g., many polychaetes). The most common prey groups were

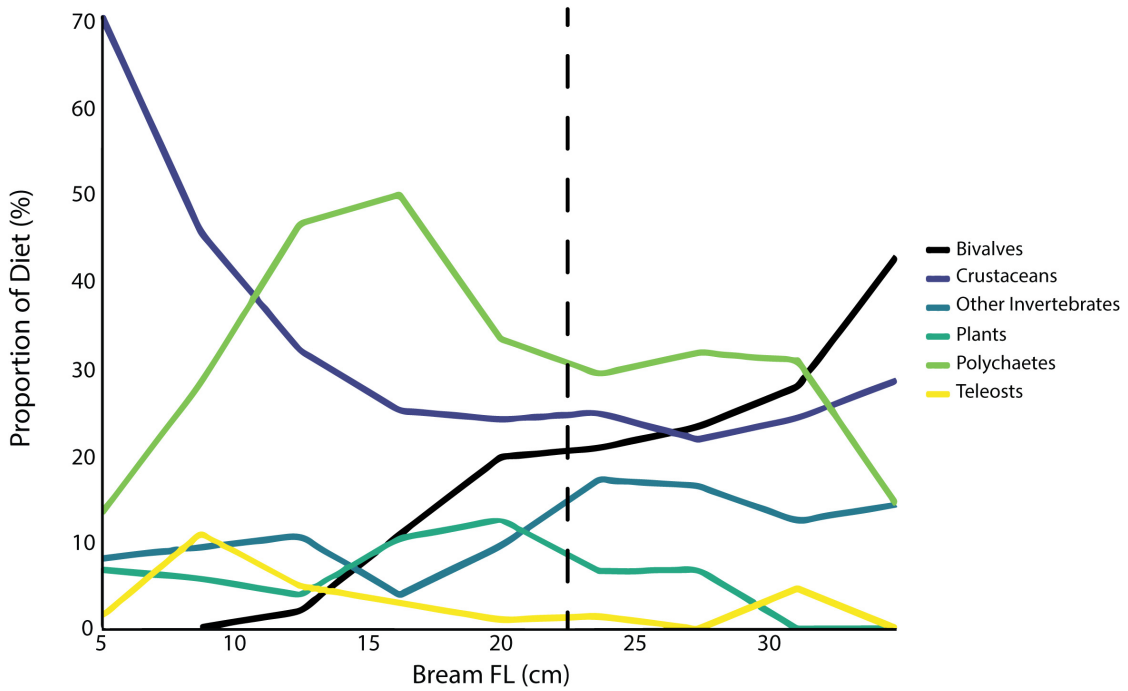

FIGURE 1 | Proportion of diet of major prey types by volume with Yellowfin Bream length. The dashed vertical line at 22 cm indicates length at maturity.

crustaceans (found in 70.1% of guts), polychaetes (50.3%), and bivalves (26.4%; **Table 2**). Of the crustaceans, amphipods (31.6%) and decapods (18.9%) were the most prevalent (**Table 2**). Invertebrates made up at least 80% of the diet by volume at all ages (**Figure 1**).

Some ontogenetic diet changes were observed, namely crustaceans (primarily amphipods and copepods) constituting up to 70% of diet by volume for Bream under 5 cm, but then the contribution of crustaceans generally decreased with size, and bivalves increased for Bream >10 cm. However, ontogenetic diet change had only a small influence on mean prey ED (**Figure 2**).

Respirometry and Energetics

The bioenergetic model showed mass-specific consumption rate was higher in younger individuals. A one-year old individual (14.5 cm FL) consumed 3.90% of its body weight daily, with a Q:B of 14.25, whereas a seven-year old adult (28.8 cm FL) consumed 1.42–2.12% (mean 1.79%) of its body weight daily, with a Q:B of 5.21–7.75 (mean 6.52; **Figure 3**). Oscillations in predicted consumption rate estimates were caused by seasonal fluctuations in water temperature and its subsequent impact on RMR (**Figure 3**).

The Importance of Diet Data in Consumption Rate Estimates

The comparative scenarios that used prey compositions derived from the literature estimated lifetime consumption (g) of Bream between 24.9% lower (Morton—Autumn) and 14.7% higher (Hadwen GCA) than the primary model presented here (maximum difference 52.7%, range 11.7–17.8 kg; **Table 3**). The daily consumption rate (g day^{-1}) for the scenario with the highest consumption rate (Hadwen GCA) was up to 53% higher than the scenario with the lowest consumption rate (Morton Autumn; 7.7–11.8 g day^{-1}; **Figure 4**).

Keeping consumption rate (in mass) constant resulted in highly variable growth rates among the model scenarios. There were consistently greater than five-fold ranges in daily growth rates among scenarios; the fastest (Moreton Autumn) and slowest growing scenario (Hadwen GCA) in the 250 g size class had a daily growth range of 0.04–1.07 g day^{-1} (**Table 4**). The slowest growing model scenarios in the 400 g size class showed negative growth rates (**Table 4**), i.e., energy consumption was inadequate to meet the demands of assimilation, RMR and activity, so these individuals must either divert energy away from these processes, increase their consumption rate, or lose weight.

DISCUSSION

Consumption is the primary trophic interaction in ecosystems but estimating accurate consumption rates is challenging (Lawson et al., 2019). We used a series of bioenergetic model scenarios to quantify the uncertainty in consumption rate estimates when using diet data from four published studies. We found that diet information used in bioenergetic models can strongly influence consumption rate and growth rate

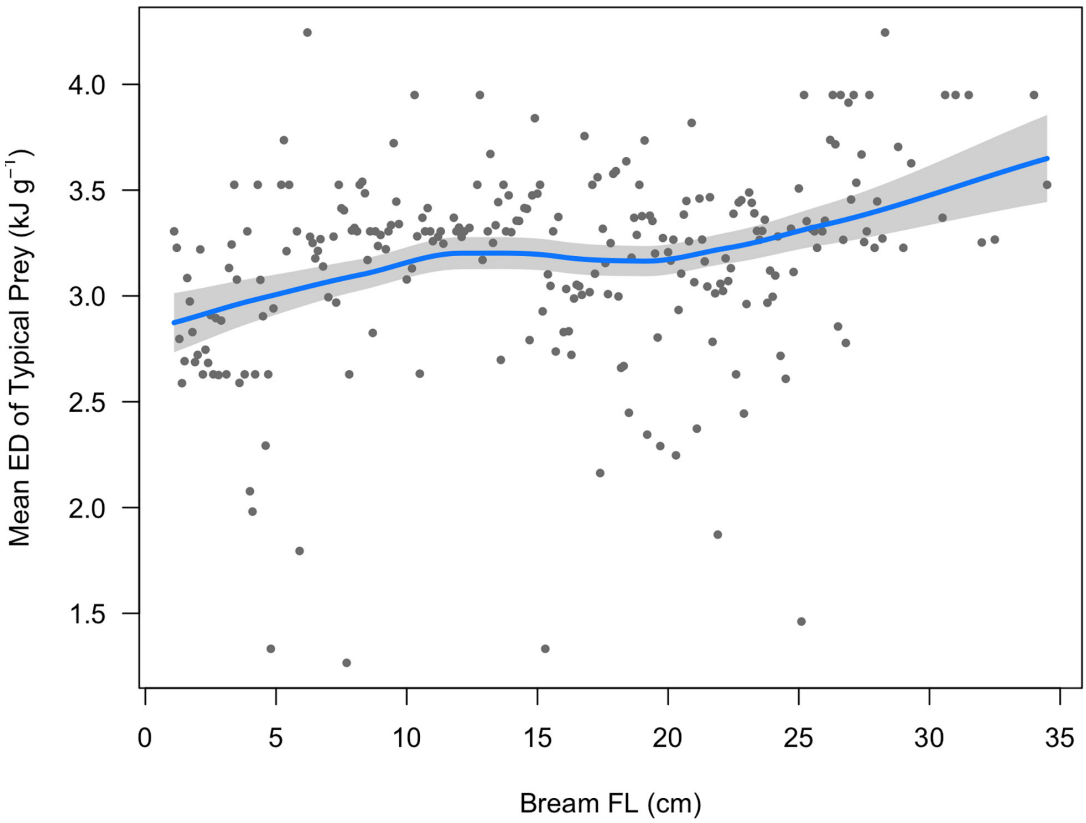

FIGURE 2 | The mean energy density of prey typically consumed by Yellowfin Bream (ED, n = 1,130 bream stomach contents) of sizes sampled in this study, in 1 mm bins. The solid blue line is the fitted LOESS curve (smoothing parameter = 0.75). The shaded area depicts the 95% confidence band.

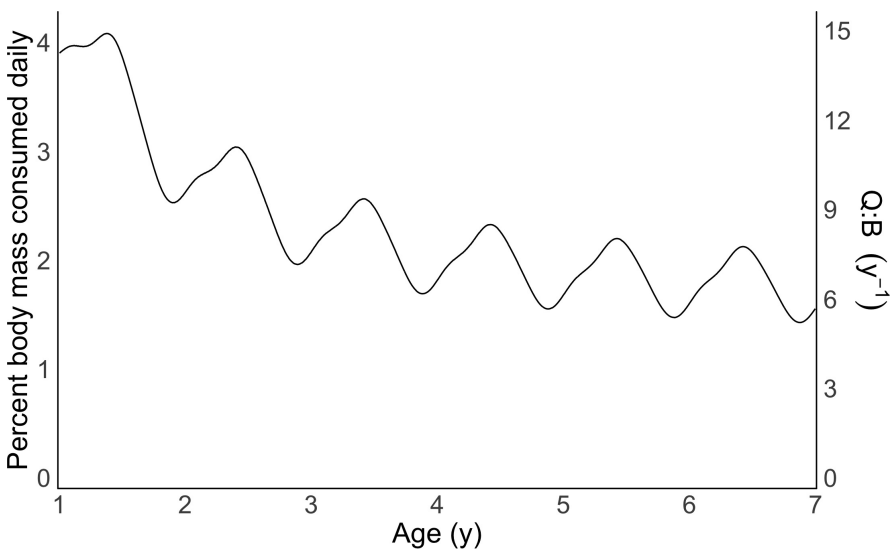

FIGURE 3 | Body mass consumed daily (%) and consumption: biomass ratios (Q: B) of Yellowfin Bream based on the bioenergetic model and prey composition presented here. x-axis truncated to start at year 1 for clarity.

TABLE 3 | Details of the four studies (with nine data sets in total) from which prey composition was extracted and comparative bioenergetic model scenarios constructed.

Model source	Difference in lifetime consumption (g; %)	Weighted mean ED (kJ g^{-1})	Location	Habitat type	Sampling method	Sample size	Fish total length range (cm)
Primary model	0 (0)	(Variable)	NSW, Australia	Estuary	Gut contents	1130	1.1–41.5
Hadwen GCA	2286 (14.7)	2.905	NSW, Australia	Intermittently open estuaries	Gut contents	13	9.0–25.5
Hadwen SIA	−253 (−1.6)	3.388	NSW, Australia	Intermittently open estuaries	Stable isotope analysis	14	9.0–25.5
Sheaves	1327 (8.6)	3.070	QLD, Australia	Mangrove estuaries	Gut contents	134	14.8–35.0
Bell	258 (1.7)	3.278	NSW, Australia	Tidal mangrove creek	Gut contents	160	1.4–11.2
Morton Autumn	−3856 (−24.9)	4.434	QLD, Australia	Mangrove/salt marsh	Gut contents	83	4.5–28.0 (approximate)
Morton Spring	−194 (−1.3)	3.375	QLD, Australia	Mangrove/salt marsh	Gut contents	14	4.5–28.0 (approximate)
Morton Day	−3123 (−20.1)	4.172	QLD, Australia	Mangrove/salt marsh	Gut contents	90	4.5–28.0 (approximate)
Morton Night	−469 (−3.0)	3.436	QLD, Australia	Mangrove/salt marsh	Gut contents	97	4.5–28.0 (approximate)
Morton mean	−1917 (−12.4)	3.802	QLD, Australia	Mangrove/salt marsh	Gut contents	187	4.5–28.0

The difference in lifetime consumption represents the total difference over a 7 year lifespan of a Yellowfin Bream with consumption calculated based on the energy density of the weighted mean prey composition in those data, and compared to the estimate produced by using the prey composition in the present study.

estimates. In reality, neither consumption or growth rate are likely to be constant, and all non-metabolic processes probably trade-off in an energy budget based on the complexities of a consumer's environment and available prey. Our analysis quantifies, however, that observed spatial-temporal variation in prey composition for a single species, and the subsequent impact on the amount of energy available to be consumed, can result in a 53% difference in life-time consumption, and a several-fold difference in potential daily growth rate, between the least and most energy-rich diet scenarios. Our nine comparative bioenergetic model scenarios highlight that accurate estimates of consumption and growth rates of generalist predators may require detailed ontogenetic dietary information from local samples, large sample sizes, spatial and temporal variation in samples, or a combination of methods such as gut contents and SIA. This study highlights the uncertainty associated with integrating observed diet data in consumption and growth rate estimates.

The Importance of Accurate Diet Data in Consumption and Growth Rate Estimates

We show that there are substantial differences in consumption or growth rate estimates despite using seemingly detailed diet data (i.e., more detailed than simply choosing the one or two most common prey items to represent the entire diet composition; Lawson et al., 2018). The diet data described here includes ontogenetic changes in prey composition and therefore ED, but ontogenetic diet changes were not included in the comparative model scenarios because the previously published diet studies had a limited sample size or had missing/limited data for specific fish sizes. This poor ontogenetic diet resolution accounts for some of the observed differences in consumption and growth rates among model scenarios.

When consumption (in mass) was kept constant, negative growth rates were observed in two comparative scenarios, i.e., the energy consumed was less than that required for RMR, assimilation and activity costs, and so energy was taken from bodily stores. Consistent use of energy stores leads to weight loss and, if representative of actual diet composition, implies three options for individuals. First, this poor-quality diet composition is temporary and represents only a brief period when individuals rely on stored energy. Second, the individuals move to other areas or increase foraging time if prey quality declines. Third, changes in metabolic efficiency reduce the cost of standard metabolic rate to avoid weight loss (Halsey, 2018; Redman et al., 2018). Similarly, a decline in activity may also reduce total energy expenditure when experiencing a poor-quality diet, and thus prevent weight loss, but could reduce foraging intensity. So while loss of body mass is possible under certain conditions, in reality these negative growth scenarios indicate conditions under which individuals would need to either increase consumption or divert less energy to foraging or reproductive activity.

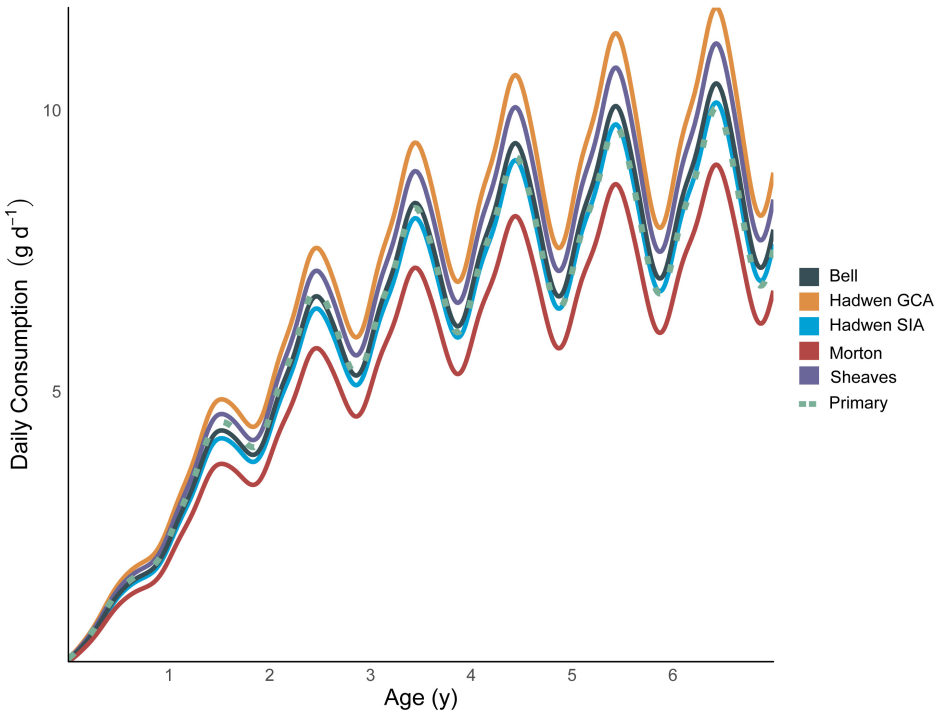

FIGURE 4 | Daily consumption rate throughout Yellowfin Bream ontogeny calculated from bioenergetic models using different prey data. Differences in consumption arise from different energy densities of the prey observed in each study. Oscillations are caused by seasonal fluctuations in water temperature and its subsequent impact on standard metabolic rate. Each model scenario was calculated using the same bioenergetic parameters, but each using different sources of dietary data (and hence prey energy density): "Bell" used the mean of 160 gut contents samples from a tidal mangrove creek, "Hadwen GCA" used the mean of 13 gut contents from intermittently open estuaries, "Hadwen SIA" used the mean of 14 muscle stable isotope samples from intermittently open estuaries, "Morton" used the mean of 187 gut content samples from mangrove/tidal salt marsh habitat, "Sheaves" used the mean of 134 gut content samples from mangrove habitat, and "Primary" included detailed ontogenetic diet variation from 1,130 gut content samples (see main text for details). For clarity, only five of the nine comparative scenarios are plotted here. See **Tables 3**, **4** for results from all nine comparative scenarios.

TABLE 4 | Growth rates (g day^{-1}; % day^{-1} in parentheses) for each model scenario when consumption (in mass) is held constant, at different size classes.

Model scenario	100 g (g day^{-1}; % day^{-1})	250 g (g day^{-1}; % day^{-1})	400 g (g day^{-1}; % day^{-1})
Primary	0.31 (0.31)	0.29 (0.12)	0.16 (0.04)
Hadwen—GCA	0.18 (0.18)	0.05 (0.02)	−0.33 (−0.08)
Hadwen—SIA	0.41 (0.41)	0.39 (0.16)	0.18 (0.04)
Sheaves	0.26 (0.26)	0.16 (0.07)	−0.16 (−0.04)
Bell	0.36 (0.36)	0.31 (0.13)	0.06 (0.02)
Morton—Autumn	0.91 (0.91)	1.14 (0.46)	1.27 (0.32)
Morton—Spring	0.40 (0.40)	0.38 (0.15)	0.16 (0.04)
Morton—Day	0.79 (0.79)	0.95 (0.38)	1.00 (0.25)
Morton—Night	0.43 (0.43)	0.43 (0.17)	0.23 (0.06)
Morton—Mean	0.61 (0.61)	0.69 (0.27)	0.61 (0.15)

Consumption at each weight was calculated as the mean consumption rate, at that weight, of all previous scenarios that varied consumption rate (and held other parameters constant). Differences are due to variation in energy density arising from diet composition in each scenario. Growth rate was determined from the ingested energy remaining after energy required for RMR, assimilation and activity was allocated.

This highlights the importance of accurate dietary information when using consumption and growth rate estimates to inform ecosystem models.

When diet information is lacking for a certain region, it can be common practice to instead use dietary information from a different region. Regional dietary information may be absent in terms of both prey composition and nutritional values such as ED. Here, each comparative scenario used different prey compositions that drove the discrepancies in consumption and growth estimates, likely because the original studies that informed the scenarios were conducted in multiple locations and habitats along eastern Australia. Similarly, the lower consumption rates estimated by the comparative Morton scenarios (up to 24.9% over 7 years; **Table 3**) arise largely from a high ED of terrestrial invertebrate prey (**Supplementary Table 1**). However, the ED data for terrestrial

prey items were collected from different regions from the diet information of Bream, as no local data were available. The resultant high ED values of terrestrial prey used in the models may not necessarily produce erroneous consumption estimates, as terrestrial invertebrates appear to be more energy-dense in general than aquatic invertebrates. Cummins (1967) summarized ED values for 78 invertebrate species and found the mean ED of aquatic invertebrates sampled was 12.27 kJ g^{-1} dry weight, compared to 22.61 kJ g^{-1} for terrestrial invertebrates. Nevertheless, the actual ED values of terrestrial prey of Bream in eastern Australia, and hence associated error in consumption estimates, remain unknown. Therefore, local diet information is important for estimating consumption rates.

The Effect of Differences in Methods and Reporting of Diet Data

The method used to assess diet may also have implications for the overall diet composition and prey ED. SIA was more effective at estimating typical prey than GCA for small sample sizes, and similar trends are observed with other species (Hadwen scenarios; **Table 2**; Parkyn et al., 2001; Davis et al., 2012). Unlike gut contents, SIA can provide dietary information from previous weeks or months (Hyslop, 1980; Davis et al., 2012). This also accounts for individuals sampled that have empty stomachs, which can be a large portion of the total sample if species are irregular binge feeders or eject their stomach contents on capture (Hughes et al., 2014; Schilling et al., 2017). Stable isotopes may also be useful for examining diel and seasonal variation in diet that are not easily measured by GCA. For example, large differences were seen in prey composition, and hence ED, between Bream in the same location depending on season and between day and night (**Table 2**; Morton et al., 1987), and across these timeframes the use of stable isotopes may enable a more realistic representation of the standard diet. Hence it may be important to consider the effect that sampling method has on the resulting diet composition when estimating consumption rates. Like other methods of diet sampling, SIA requires calibration to determine the ED of prey items.

Most studies report ED as energy per dry mass, but estimating consumption requires the ED of prey as wet mass (i.e., in the form that the predator consumes the food). It may be easy to quantify how much dry prey material a consumer requires to meet a certain energy intake, but percent water content is needed to determine the amount of prey that consumer must actually forage. The difference between ED per dry mass and ED per wet mass—determined by percent water—is therefore crucial for use in bioenergetic models, but can vary substantially between prey items. For example, percent water in invertebrates ranges from 41 to 93% which, when converting from ED per dry mass to ED per wet mass, creates an eight-fold range in possible values (James et al., 2012). Most studies do not report the water content of their study species, and so ED per dry mass must be converted to ED per wet mass based on a handful of publications that state percent water content, as was performed here (**Supplementary Table 3**). For example, in an attempt to form a regression of prey ED vs dry-to-wet mass ratio to eliminate the need for bomb calorimetry, James et al. (2012) found just eight published studies that provided ED and percent water of any invertebrate (regardless of habitat, location, or season); just one study was found from Australia, and provides data only for coleopterans (beetles). It is therefore possible that unknown water content values contribute substantially to errors in the mean ED of prey, and hence consumption and growth rates.

Caveats and Other Sources of Error

There are sources of error in bioenergetic models other than diet quality/source that arise from uncertainty of the input parameters. This is especially true for species that lack basic bioenergetic data such as the scaling of metabolic rate with temperature or body size, which can cause several-fold ranges of energy requirement estimates (Lawson et al., 2019). Similarly to prey energy density, uncertainty in assimilation efficiency can lead to linear deviations in consumption estimates, i.e., a 10% change in assimilation efficiency can cause a 10% change in consumption estimate (Essington, 2003). However, while assimilation efficiency typically ranges from 65 to 95% (Peck et al., 2003; Fu et al., 2005; Fitzgibbon et al., 2007), prey ED may vary >10-fold (**Supplementary Table 1**; McCluskey et al., 2016).

While the present study focused on prey ED, it should be noted that predator ED also varies. An individual's ED—and hence their cost of growth—can vary with ontogeny or season (Pothoven et al., 2012; Canale and Breck, 2013). For a given amount of energy allocated to growth, the growth rate (in mass) of an individual is inversely proportional to the individual's ED (see methods). Here, a 60% linear increase in bream ED (4,000–6,400 kJ) with ontogeny results in a 1.1% reduction in lifetime consumption compared to using the mean bream ED value (**Supplementary Material**). This difference is likely greater at particular life stages or seasons; a variable bream ED causes up to a 30% increase in growth rate for 100-g individuals compared to a constant bream ED (**Supplementary Material**). However, at the same age, differences in prey ED among our model scenarios caused a 521% difference in growth rate estimates. Therefore, the effect of variable predator ED appears to be substantially smaller than the effect of variable prey ED.

Similarly, the individuals involved in the respirometry of the present study may have had altered metabolic rates or activity costs that aren't representative of wild animals. Such differences may be associated with capture stress or a diet requiring minimal search and foraging costs. However, the objective of this study was to isolate and quantify the effect of uncertainty in one parameter—the prey source–while keeping other parameters constant. Importantly, any sources of error in such parameters will affect the early stage of the bioenergetic model, i.e., when its output remains in energy (kJ) and not mass of prey (g). As a result, the errors will be applied to all of the comparative model scenarios here equivalently, and it is unlikely that the results of the study experience substantial change. For example, if RMR of individuals was 10% lower than estimated here, the absolute amount of prey required to meet energetic demands would be altered but the relative differences among the model scenarios would be identical to those presented here.

CONCLUSION

Accurate estimates of species-specific consumption and growth rates are needed to model ecosystem processes, yet estimates of these rates can vary depending on the diet information used in bioenergetic models. Diet composition may be particularly variable for generalist predators and species that are found in a range of habitats. Many parameters that are lacking in specific locations, for example diet change through ontogeny, prey energy density, and Q:B, are required for ecosystem models which are used to understand trophic dynamics (Christensen et al., 2005; Leaf and Oshima, 2019). Small sample sizes may be useful for understanding general diet patterns, but large sample sizes that include ontogeny provide more realistic data for quantitative analysis and models. The magnitude of variation seen here in both consumption and growth rate show that variation attributed to diet diversity is far too large to ignore in bioenergetic models. Bioenergetics or ecosystem modeling studies can create multiple models or include uncertainty encompassing the range of diet composition a species experiences.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The animal study was reviewed and approved by The University of New South Wales Animal Care and Ethics Committee (No. 15/152B).

AUTHOR CONTRIBUTIONS

CL, JAS, IS, and SB conceived the study. CL led the writing of the manuscript, with input from all authors. CL, SB, JMS, and NP performed fieldwork and laboratory work. MT provided diet data. CL performed model-building and data analysis, with input from JAS. All authors contributed critically to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.625855/full#supplementary-material

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Unpaid Work in Marine Science: A Snapshot of the Early-Career Job Market

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Unpaid positions in environmental sciences are common yet controversial. While they exclude already marginalised groups and are detrimental to the entire job market, many voices maintain that these positions are crucial, support science and conservation in economically disadvantaged areas, and allow early-career scientists their first step into the field. To better understand the real scale and nature of these positions, we reviewed relevant job offers within marine biology and conservation, advertised globally in English, from three random months in 2019–2020, both preceding and during the COVID-19 pandemic. Unpaid and pay-to-work positions were more common than paid jobs, and offered mostly in economically privileged areas, such as North America and Europe. Most of these postings required some or strong experience and education background. Most non-governmental and private organisations offering uncompensated work did not produce any peer-reviewed research output in the last 3 years. This review shows that a considerable proportion of unpaid work contributes to private businesses, and may often breach local labour laws.

Keywords: early-career, unpaid work, ecotourism, volunteering, unpaid internships, work abuse

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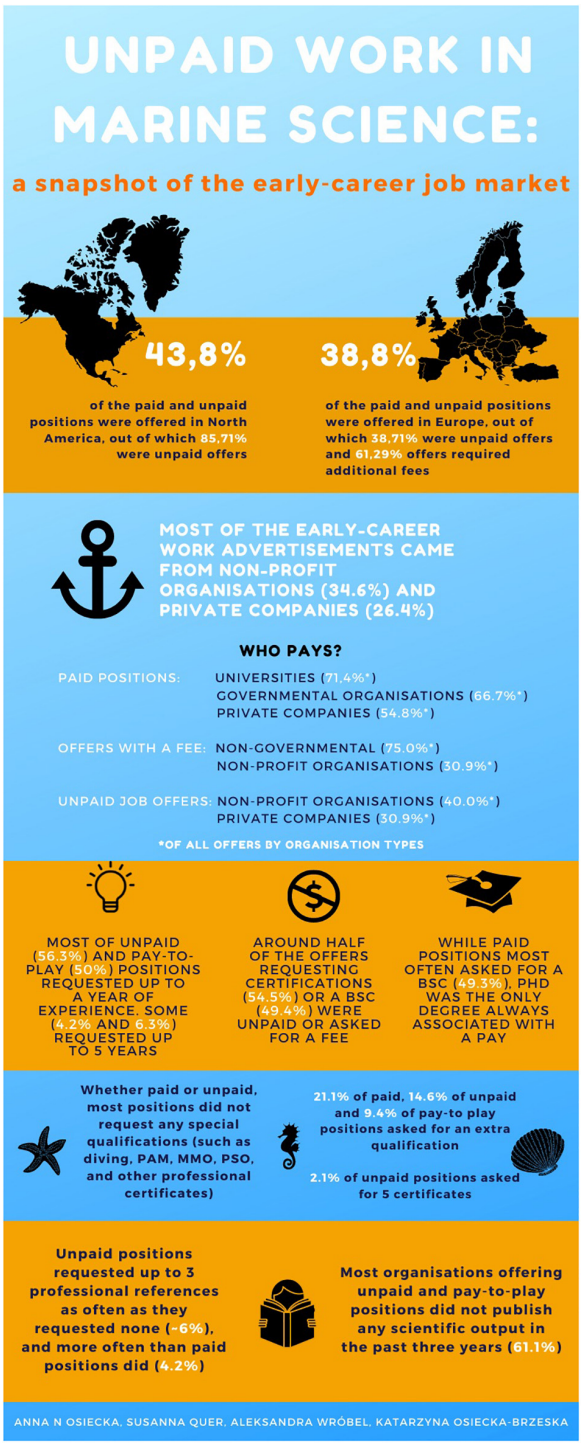
INTRODUCTION

Uncompensated positions are common in conservation and environmental science. Such positions often require prolonged periods of full-time commitment, while offering little or no support to the workers, or requesting a fee for the opportunity to work ("pay-to-work" or "pay-to-play" positions). Because of their direct costs, but also indifference to the family composition, health, and financial security of participants, unpaid positions are only accessible to the privileged few. This further deepens the already acute racial, gender, health, and class issues in STEM (e.g., Johnson, 2011; Thompson et al., 2011; Williams, 2014; Swan, 2015; Mellifont et al., 2019; Eaton et al., 2020; Wanelik et al., 2020). At the same time, unpaid work does not generally offer significant career advances (Fournier et al., 2019) and its pitfalls are often bigger than the benefits (Siebert and Wilson, 2013). Moreover, it can be difficult to prove as work experience (Allan, 2019).

The problem of discrepancies between paid and unpaid work opportunities was addressed before and has been thoroughly discussed by Whitaker (2003) and Fournier and Bond (2015) with regard to the United States wildlife job market. There was previously no information on the situation



GRAPHICAL ABSTRACT | Brief summary of the early-career job market in marine biology and conservation.

outside the United States, or on the nature of such unpaid positions. Even though more perspectives are being slowly included (e.g., Orcutt and Cetinić, 2014; Hooker et al., 2017; Srinivasan, 2018; Michalena et al., 2020; Miriti, 2020), the discussion about the ethics of unpaid labour in ocean science seems to be based largely on personal opinions (Society for Marine Mammalogy, 2020). Yet one cannot improve the situation without looking at it objectively. Here, we provide a snapshot of the early-career (i.e., aimed at students and professionals up to 7 years post doctoral degree) job market in marine biology and conservation, hoping to shed some light on the extent, sources, and legality of unpaid work.

JOB MARKET REVIEW

We reviewed a total of 159 job postings related to marine biology and conservation from all over the world. Our search was narrowed to three professional platforms sharing both paid and unpaid work opportunities in English: a marine mammal-oriented mailing list (MARMAM), a website listing ocean conservation jobs[1], and a widely used social media group dedicated to early-career job opportunities (Marine Biologist network and job postings). While these platforms do not present an exhaustive list of all work opportunities worldwide, they do provide a good overview of the job market and are widely used by early-career marine scientists, many of whom suggested to use those platforms in our review. Using a random number generator, we selected three random months from the period of a year preceding the data collection: November 2019, February 2020, and April 2020. We screened the platforms for selected keywords representative of the early-career job market ("experience," "internship," "job," "opportunity," "Ph.D.," "post-doc," and "volunteer"), and included only full-time positions requiring up to 7 years of experience. We noted down all relevant information about the postings, paying special attention to the requirements (in terms of experience, education, professional references, and additional qualifications), salary, and location. If the same job was posted repeatedly, or advertised on more than one channel, it was only included once. Since very few postings informed on the actual wages, we grouped the postings into paid, unpaid, and requiring a fee to work.

Additionally, we included the research output of private companies, non-profit organisations (NPOs) and non-governmental organisations (NGOs). To do this, we searched the organisations' websites (e.g., "Research" and "Communication" sections, as well as blog entries) for information on the total research output (peer-reviewed publications and official reports) of each institution in the past 3 years. If no such information was available, we have classified the institution's research output as unknown. We have excluded universities and governmental organisations, since these are expected to and do in fact publish immense quantities of scientific output.

Less than a half of all posted positions offered compensation (44.7%), with most of the postings being either unpaid (30.2%) or requiring a fee for the possibility to work (20.1%). Most of the paid and unpaid positions were offered in North America and Europe, and the positions requiring a fee to work were most common in Europe.

[1]SevenSeasMedia.org

Most of the early-career (i.e., requiring not more than 7 years of experience) work advertisements came from non-profit organisations (34.6%) and private companies (26.4%). Universities and governmental organisations offered mostly paid positions (71.4% and 66.7%, respectively), while only roughly half of the private companies' postings offered compensation. Proportions of offers requiring a fee were exceptionally high in the non-governmental and non-profit organisations (75% and 30.9%, respectively). Most of the unpaid job offers came from non-profit organisations (45.8%) and private companies (27.1%).

Among all wage types, the highest proportion of cases required up to 1 year of experience, and the lowest 5–10 years of experience. Among all wage types, a B.Sc. was requested most frequently, while a Ph.D. was not needed in either unpaid or pay-to-work positions. The proportion of paid work grew with requested qualifications, from no paid positions for unqualified work, 45.5% of paid positions requesting professional certifications or a B.Sc., to a 100% of positions requiring a Ph.D. offering a wage.

Paid positions requested no (40.9%), one (21.1%), two (1.4%), or four (1.4%) additional qualifications (such as diving, Passive Acoustic Monitoring, Marine Mammal Observer, Protected Species Observer, and other professional certificates). Both unpaid and pay-to-play positions usually did not request any additional qualifications (68.8 and 71.9%, respectively). Few positions specifically requested references. Positions requiring a fee did not request any references in 15.6% cases, which constitutes the highest proportion among all wage types.

Although most private and non-governmental institutions published no or up to five scientific outputs in the 3 years preceding the data collection, institutions offering paid work seemed to be less likely to publish nothing at all than these offering no compensation (34.48% vs. 61.11%). However, in nearly half of the cases we were unable to establish the institution's research output, and this result should be interpreted with caution. Data generated in this review are freely available in an online repository (see section "Data Availability Statement").

DISCUSSION

The early-career job market for marine environmentalists offers few, and mostly uncompensated opportunities – over 3 months, only 45% of all the positions we were able to find, and 42.4% of positions requiring up to a B.Sc., were paid. Our survey shows that the overall situation is even worse than previously reported for undergraduate temporary wildlife workers in the United States (54% of positions paid; Fournier and Bond, 2015) in the United States. Additionally, since in most cases information on the exact wage offered was not provided, we are missing information on the proportion of positions waged below the local minimum rate. It is thus possible that the problem is even worse than what we believe, with many paid positions not paid a liveable wage (Whitaker, 2003).

It is worthwhile to note that two of 3 months used for this review preceded the COVID-19 pandemic. In the third month, April 2020, some impact of this situation could already be seen, with very few job advertisements posted. It is possible that the job market has seen some changes since then. One easily noticeable turn was the appearance of online internships with a fee. These offers typically require the candidate to have strong analytical skills and experience, and perform data analysis remotely, using their own hardware, without being offered co-authorship (based on personal inquiries to the organisations). Such remote internships were offered by a few organisations relying on internships with a fee before the coronavirus pandemic.

Interestingly, a large part of the unpaid job postings came from countries with strict labour protection laws, most notably the United Kingdom. In these situations, unpaid internships are illegal, except in few controlled situations, such as vocational placements as a part of an education, or work shadowing, where the intern does not perform any duties (Government UK, 2021). Only about half of private company postings offered compensation. These job postings referred almost entirely to tour operators in private whale watching companies, and contributed to one fourth of all unpaid offers. A number of private for-profit companies went as far as to request a fee from their tour operators. It is extremely important to stress that in many such cases the unpaid work offers may violate local labour laws. What is quite interesting is that some of the unpaid and pay-to-work positions were offered by governmental organisations themselves, particularly in Venezuela and the United States Universities advertised mostly paid positions, and offered unpaid internships exclusively to students.

Work availability is very unevenly distributed, with most positions, and an even larger proportions of the unpaid positions, based in North America and Europe. At the same time, unemployment and temporary work in these regions affect women, immigrants, and Black, Indigenous, and people of colour (BIPOC) population particularly strongly (European Commission, 2016; NSF Report, 2019; Eurostat, 2020). These are the same groups already burdened with issues from systemic discrimination to direct harassment (e.g., Viglione, 2020), and most vulnerable in situations of crisis (e.g., Spector and Overholser, 2020; Staniscuaski et al., 2021; Garcia et al., 2021; Tai et al., 2021; Wright et al., 2021). When taken into account the additional psychological (Woolston, 2019, 2020) and financial (Favaro and Hind-Ozan, 2020) strain on early career scientists, the overall pressure on any minority in STEM is alarming. Providing fair wages is crucial to increasing retention of groups underrepresented in the field (Jensen et al., 2021). As an early-career scientist, one is often advised to "simply find a second job," though rarely followed by ideas on how to do so in a strongly biassed job market, remote location, and often unregulated working hours. The narrative of finding a side job to support unpaid work in one's own discipline is thus not only quite unrealistic, but also excluding to those that do not start their career from a position of privilege.

Unpaid workers can unwillingly perpetuate the vicious circle of labour abuse, making it possible for companies to lower the rates of employed staff (Siebert and Wilson, 2013) and deepen social inequalities (Shade and Jacobson, 2015). Yet in the scarcity of paid work, desperate early-career environmentalists are often forced to accept pays below the industry standard.

The results of this are very clear: for example, the wages of Marine Mammal Observers and Protected Species Observers are dramatically lower than these of any other offshore employees, comparable only to these of unskilled workers, such as pot washers (Glassdoor, 2021a,b; Wind Rose Network, 2021), and well below the average salaries of skilled staff in the oil industry (SPE Research, 2019). Yet these are people directly responsible for running or halting large, invasive operations of a billion dollar business, and as a result for the life or death of protected marine animals. Furthermore, professional field technicians can be pushed out of the job market by workers willing to work for little or no compensation, which can hinder the quality of research and conservation (Fournier and Bond, 2015). Protecting early stages jobs is thus crucial to protecting the entire job market and ensuring fair wages for everyone.

It is widely understood that finances are tight for environmental organisations, and competition for funding is fierce. This indeed often comes up as an argument in defence of unpaid positions, since for some organisations these could be the only way to get enough labour and funding to do the necessary work (Elwen and Gridley, 2020; Society for Marine Mammalogy, 2020). We recognise that the laws protecting against unfair work conditions need to be complemented by an increase in funding to research, and that access to the existing funds may be hindered by many factors. Especially in economically less advantaged countries or countries with no or limited access to funding schemes, internship fees might be the main or only source of income for the NGOs. However, we would like to stress that most of the unpaid work in our review was offered in wealthy countries, and a large amount of this work is illegal and/or contributes to private businesses. The problem does not come from underfunded organisations in marginalised countries.

Non-governmental organisations and non-profit organisations offer a large part of the unpaid and pay-to-work positions, but also an important part of all marine jobs, and some of them have great contributions to science and conservation. To limit parachute science and provide training for locals, some organisations introduced policies that only require fees of foreign interns. Volunteering can be an enriching experience and a great tool to include marginalised groups (Miller et al., 2002; O'Brien et al., 2010, 2011). In voluntourism, the participant pays a fee for an organised volunteering or internship opportunity, often in locations seen as "exotic" by the Eurocentric world. Such arrangements are often dictated by neoliberal market laws, where the intern is a demanding client rather than a worker (e.g., Wearing et al., 2005; Lyons et al., 2012; St-Amant et al., 2018), and can perpetuate neocolonialist relations (e.g., Mahrouse, 2012; Pastran, 2014; St-Amant et al., 2018). Yet, they can be beneficial when practiced responsibly (Palacios, 2010; Coghlan and Gooch, 2011; McGehee, 2014). Not every unpaid work is abusive, but volunteering should be truly voluntary, and never required.

While income from voluntourism might be very necessary for some organisations, is a person paying for the right to work really a worker? In situations where paid interns are absolutely necessary to maintain the running costs of NPOs and NGOs, we suggest considering such experiences as "courses," "training," or "eco-tourism," especially when no or minimal skills are required. To avoid labour abuse, it is necessary to carefully name positions according to their workload and compensation, and follow not only the local legal requirements, but good practices guidelines within the field (Parsons and Scarlett, 2020). Words matter, and such a change in language can hopefully help remove the unrealistic expectations for entry-level positions in our field and move past the notion that one needs years of experience to deserve to pay their bills.

Finally, one reason to engage in unpaid work is the necessity of building up a strong publication record, since paid Ph.D. and post-doc positions are often extremely competitive, and early co-authorship with top scientists is very beneficial (Li et al., 2019). Our review focussed only on the scientific output of private, non-governmental, and non-profit organisations. Within this group, the highest proportion of organisations that published at all was found among those offering paid positions. While many NGOs did not produce any scientific output, some of them had a very strong publication record, and many were engaged in outreach and education (see Supporting Data). These observations may indicate a general pattern, though they must be interpreted with caution, since in many cases we were unable to determine the organisation's research output. Should publishing be the motivation to engage in unpaid work, it is advisable to carefully check the academic output of an organisation, as well as its authorship policies, since volunteering can, but rarely does translate into authorship.

This review should be understood as a snapshot of the situation, and not an exhaustive market study. We have excluded platforms listing exclusively paid work opportunities, as well as those directed to one nationality, and in languages other than English. While this is the dominant language in the field, this can be a source of potential bias. A larger-scale review would lead to a more robust inference, yet the total sample size of only 159 advertisements over 3 months emphasises just how limited the job market is for marine biologists and conservationists. One of the platforms we used focuses specifically on marine mammalogy – field that tends to attract enthusiastic workers, sometimes happy to simply have the opportunity to interact with charismatic megafauna, and may thus offer higher numbers of unpaid positions than other marine fields.

We focussed on early-career options in the understanding of up to 7 years after the completion of a doctoral degree, and as such our review is not representative of the entire marine environmental job market. The situation may of course be very different for senior colleagues. However, it is important to stress that the jobs we reviewed here were not addressed solely to people on the very first steps of their careers or undergraduate students. In this review, only the few available positions requiring a Ph.D. always guaranteed a pay. While it seems understandable that the more qualified positions are more likely to be paid, it is unreasonable to demand a doctoral degree as a minimum qualification securing a wage, especially in non-academic positions. Yet such seems to be the case in marine biology and conservation. If one wants to make their way in the field, there is often no other choice but to work

for free. Additionally, there is a strong expectation of multiple "specialisations," even though such a lack of professional focus can often be detrimental to science and conservation (Cosentino and Souviron-Priego, 2021). This leads to a situation in which professionals with experience, education, a network of referees, and expensive professional certifications are asked to volunteer for years, with no insurance or future job security.

While unpaid or "pay-to-play" labour is common both in and outside academia, we should make an effort to stop normalising it. Recently, the issue of unpaid work has been taken up within the Society for Marine Mammalogy, sparking quite an intensive debate and leading to declarations of action toward a more inclusive field (Jacobson et al., 2020). In October 2020, the European Parliament adopted a resolution urging the member states to stop the exploitation in unpaid internships, clearly stating this practice is a violation of workers' laws (European Parliament, 2020; Nadkarni and Kolinska, 2020). After years of discussion, this measure offers a promising situation in which action backed with funding is and will be taken against such practices.

Unpaid positions are more common than paid jobs, creating unrealistic expectations to enter the field of marine biology and conservation. Many of these positions may breach local labour protection laws, and contribute to private profit rather than science and conservation. It is high time we remove the harmful practices and rethink the ways to sustain small or non-profit organisations.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: http://doi.org/10.17605/OSF.IO/C36JN.

AUTHOR CONTRIBUTIONS

AO and SQ: idea of the review. AO, KO-B, and SQ: design of the study. SQ: data collection. KO-B, SQ, and AW: data processing and analysis. AO: first draft and the review process. AO, SQ, AW, and KO-B: contribution to final manuscript. KO-B, AO, and AW: **Graphical Abstract** preparation. All authors contributed to the article and approved the submitted version.

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