VULNERABILITY OF FISHERIES TO CLIMATE CHANGE

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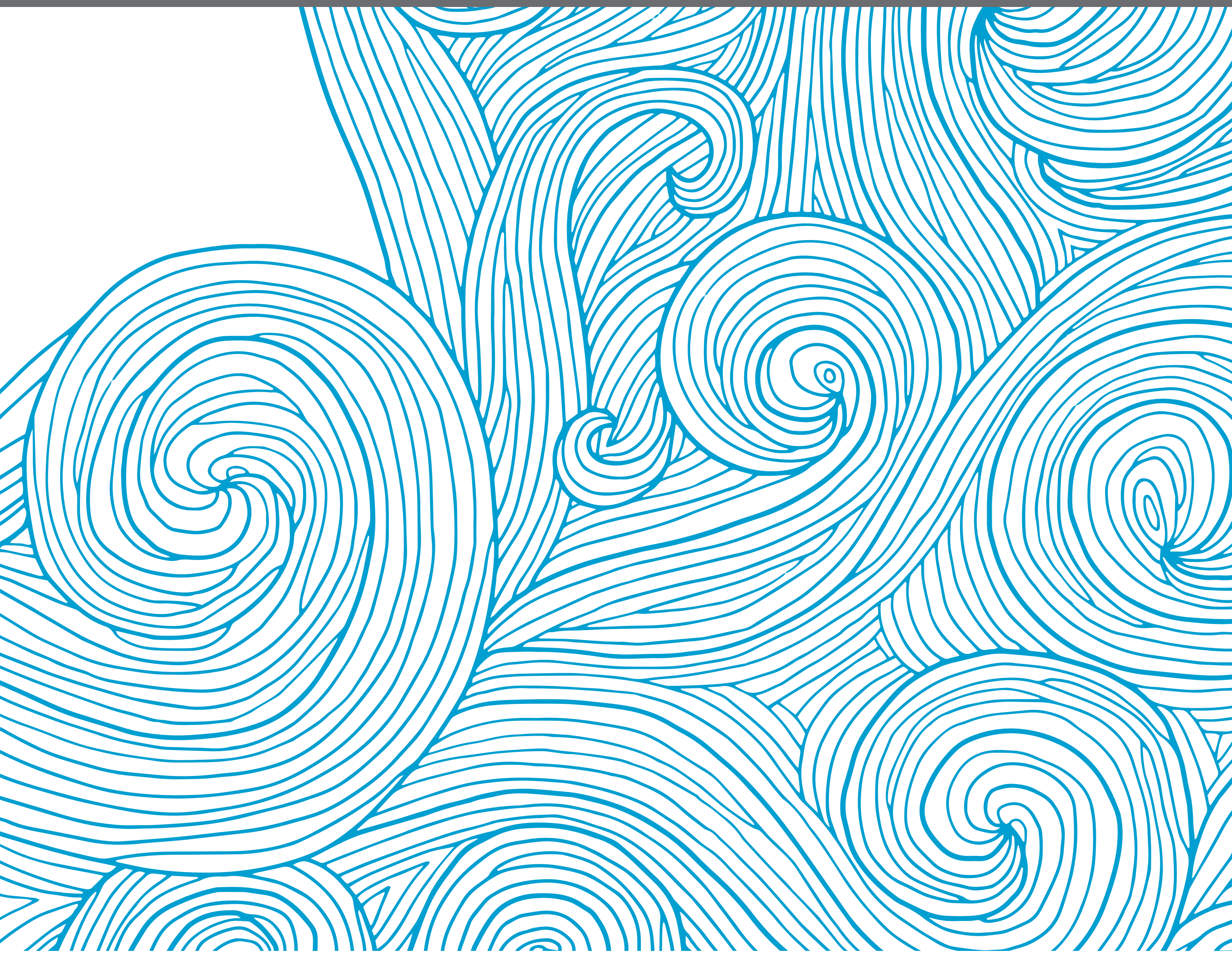

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VULNERABILITY OF FISHERIES TO CLIMATE CHANGE

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Editorial: Vulnerability of Fisheries to Climate Change

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Editorial on the Research Topic

Vulnerability of Fisheries to Climate Change

Evidence that environmental and climate change (CC) cause long-term and large-scale variability in the dynamics of marine species populations is growing. This new variability, combined with the well-known impacts of fishing itself, would need to be quantified and integrated in the sustainable management of fisheries. The relative importance of fisheries and CC (e.g., warming, acidification, and sea level rise) on marine and estuarine resources remains an issue of debate within the scientific community, the fishing sector, and the general public.

A workshop hosted by the FAO (Cochrane et al., 2009) concluded that general trends of change in fish stocks could be identified and attributed to CC. On one hand, tropical and subtropical stocks may experience reduced productivity, and on the other, high latitude stocks may benefit with increased productivity. In addition, the authors concluded that fish physiological processes and the seasonal timing of life history events may be affected. Shifts in habitat productivity and physiology imply that stock assessment models would need to allow for changes in vital parameters of population dynamics. Moreover, managers would need to consider changes in the perception of the magnitude of the rates of sustainable exploitation, given the expected impact of CC on stock productivity.

This Research Topic aimed to assemble different perspectives on the role of climate change in fisheries, with research from different disciplines including fisheries oceanography, climatic modeling, time series analyses, sociology, economics, and stock assessment. Ogier et al. developed a two-step participatory approach to evaluating options for key fisheries. Species whose distribution and abundance are highly to moderately vulnerable to climatic effects were selected. A production spectrum from data collection (species biology-ecology traits, policy and management staff from fisheries management agencies, research scientists, and commercial and recreational fisher representatives) and analyses, to information gathering, knowledge production and communication was investigated. Stakeholders, whose broader function is to provide advice to decision makers on fishery management options, considered results of the study for adoption and undertook any agreed co-management actions. It was clear that planned adaptation to CC and subsequent vulnerabilities demand logistic, scientific, and societal effort and coordination.

Workshops with representatives from the regional sea food sector, science, NGOs, and local authorities identified important issues linked to CC affecting environment, society, economy (Hoerterer et al.). These authors identified policies that consequently allowed assessment of opportunities and challenges in achieving sustainable growth of the blue economy under CC. Hoerterer et al. conclude that synergies and conflicts between the sectors and subsequent political decisions threaten sustainable growth of the blue economy in highly contested regions. Thus, calling for a more flexible and adaptive approach to policy making in fisheries, considering the

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changing environmental, social and economic realities of each region.

A number of studies set background larger scale scenarios for CC, but effective vulnerability assessment and adaptation practices for fishing communities also require more local or regional approaches. Martins and Gasalla applied the Intergovernmental Panel on Climate Change (IPCC) vulnerability approach where societal vulnerability is measured as a function of sensitivity, exposure, and adaptability. Findings revealed that remoteness and the lack of climate change-related institutional support increase vulnerability among fishing communities in the region. Community organization, leadership, research partnerships, community-based co-management, and livelihood diversification reduce vulnerability and facilitate a better understanding of the nature and extent of exposure and vulnerability to CC. Moreover, these communities in examining their capacities to mitigate can cope with the adverse implications of CC on their long-term well-being. There is thus an urgent need to investigate the most effective vulnerability and adaptation practices for specific coastal communities, notably, small-scale fishers communities who play an important role in the food supply chain.

Increasingly uncertain futures of climate-induced changes generate more policy choices, leading to a "snowballing" of possible futures facing decision-makers. Thus, "The Melting Snowball Effect" that considers a chain reaction ("domino effect") increasing the number of plausible scenarios ("snowball effect") with CC (melting snow, ice, and thawing permafrost) was applied by Dankel et al. Scenarios were designed for informed decision-making in response to CC complexities based on participatory stakeholder workshops and narratives from in-depth interviews for deliberative discussions among academics, citizens, and policymakers.

Management strategy evaluation (MSE) is a powerful computer simulation methodology to evaluate courses of action in the management of fisheries. The International Commission for the Conservation of Atlantic Tunas adopted a harvest control rule (HCR) for the fishery of North Atlantic albacore stock which was evaluated using MSE. Merino et al. used the same MSE framework to evaluate the impact of changes in productivity and in recruitment variability potentially triggered by CC, finding that the adopted HCR was robust to those expected impacts. They conclude that the establishment of adequate HCR help maintain sustainable fisheries even under CC expected variability.

CC could be the epitome of a density-independent impact on the population dynamics of fish stocks. Canales et al. used per capita population growth models to quantify the influence of CC, fishing and density-dependence in the control of anchovies and sardines in northern and central-south Chile. The picture that emerged from their work was quite nuanced. They found that the northernmost anchovy stock was driven by density-dependent forces, as well as by climate, fishing, and the interaction between climate and fishing. Further south, both sardines and anchovies exhibited weaker density-dependence and stronger impact of fishing on anchovies and stronger impact of climate on sardines. Another very large pelagic stock in the South Pacific is the jack mackerel stock, exploited mostly off Central Chile, collapsed in the mid-2000s. Lima et al. attributes this collapse on the dynamics of fishing effort as the proximate cause, which was modulated by economic forces and climate variability acting on fishing effort.

Several inter-disciplinary approaches were presented in this special issue, encompassing a wide range of topics that needs to be considered to cope with the impact of CC on fisheries. These inform decision makers of the influence of CC-driven environmental variability on the biological and socioeconomic aspects of fisheries.

AUTHOR CONTRIBUTIONS

FL was responsible for the idea of this special volume, wrote, and review this editorial topic. RR-U wrote and review this editorial topic. FC review this editorial topic. All authors contributed to the article and approved the submitted version.

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Adaptation of North Atlantic Albacore Fishery to Climate Change: Yet Another Potential Benefit of Harvest Control Rules

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Fisheries are constrained by ecosystem productivity and management effectiveness. Climate change is already producing impacts on marine ecosystems through overall changes in habitats, productivity and increased variability of environmental conditions. The way how these will affect fisheries is under debate and, also there is uncertainty on the best course of action to mitigate climate change impacts on fisheries. Harvest control rules are sets of pre-agreed rules that can be used to determine catch limits periodically and describe how harvest is automatically controlled by management in relation to the state of some indicator of stock status. In 2017, the International Commission for the Conservation of Atlantic Tunas adopted a harvest control rule for North Atlantic albacore. This harvest control rule was evaluated using Management Strategy Evaluation against the main sources of uncertainty inherent to this fishery. Here, we used the same framework to evaluate the robustness of the adopted rule against two types of potential climate change impacts on North Atlantic albacore dynamics. First, we evaluated how the control rule would perform in the event of overall changes in productivity in the North Atlantic and second, against increases in climate driven recruitment variability. Overall, our results suggest that the adopted harvest control rule is robust to these climate driven impacts and also suggests bounds at which the current management framework would be vulnerable to climate change. Throughout the manuscript we also discuss the potential of harvest control rules and harvest strategies to adapt fisheries management to a changing environment. Our main conclusion is that despite the many uncertainties on climate impacts on fisheries, efficient fisheries management and HCRs will be critical to ensure the sustainability of fisheries in the future.

Keywords: North Atlantic albacore, harvest control rule, management strategy evaluation, climate change, adaptability

INTRODUCTION

Marine fisheries are an important source of food and livelihood worldwide (Garcia and Rosenberg, 2010; Rice and Garcia, 2011). Traditionally, fisheries management has aimed at maintaining fish stocks at levels that can produce their Maximum Sustainable Yield (MSY), i.e., the exploitation rate where the response of stocks to fishing through individual growth and recruitment operates at its maximum capacity (Merino et al., 2014). In a deterministic sense, at this level, average fish biomass remains stable over time and the amount of fish that can be sustainably harvested is maximized (Schaefer, 1954). In reality, marine fisheries are all but stable, they are subject to drivers of change such as environmental variability and shifts, inefficient management and to the many sources of uncertainty inherent to natural systems (Kiureghiana and Ditlevsen, 2009; Fromentin et al., 2014; Strong and Oakley, 2014).

Climate change (CC) has emerged as an important driver of change of marine ecosystems and fisheries. Global warming is modifying oceanic biological response patterns by changing habitats' physical and chemical properties (Sarmiento et al., 2004), by amplifying environmental fluctuations (Lehodey et al., 2006) and by modifying the overall flux of energy and production through marine ecosystems (Brander, 2007; Blanchard et al., 2012). Climate change influences fishery production through changes in primary production, food web interactions and the life history and distribution of fish (Blanchard et al., 2012). Changes in primary production follow from oceanic physical and chemical environment (Sarmiento et al., 2004), while changes in primary production affect the productivity of the food webs (Brander, 2007; Blanchard et al., 2012). Also, fish are adapted to their environment through life-history strategies or traits, such as their growth and fecundity (Moyle et al., 1986; Vila-Gispert et al., 2005), which are predicted to be affected by climate driven environmental changes (Chavez et al., 2003; Cheung et al., 2012).

The most prominent biological response from fish stocks are changes in distribution (Cheung et al., 2010), phenology (Poloczanska et al., 2013; Asch, 2015; Poloczanska et al., 2016) and productivity (Cheung et al., 2010, 2012; Merino et al., 2012; Free et al., 2019). Overall, global warming is predicted to increase fisheries catch potential in higher latitudes and to decrease in tropical regions due to the poleward shift in the geographical distribution of fish stocks in the Northern Hemisphere (Cheung et al., 2010). Fisheries productivity will also be affected by climate driven changes on key processes such as growth and recruitment. For example, it is expected that lower oxygen and changes in metabolism will produce an overall reduction in fish size (Cheung et al., 2012). Long-term changes in temperature can also affect the early stages' survival and produce regime shifts in recruitment (Brander, 2007; Shoji et al., 2011). With regards to fish life cycle events, CC is expected to amplify the variability, frequency and intensity of fluctuations, in particular for pelagic stocks (Chavez et al., 2003; Alheit et al., 2009; Barange and Perry, 2009). However, there is still significant uncertainty in projecting marine fisheries under CC (Cheung et al., 2016) and on quantifying the direct impacts of climate on fisheries performance (Brander, 2007).

In this context, there is also considerable uncertainty on the course of action to manage fisheries subject to a changing climate (Arnason, 2006). One way to address uncertainty in fisheries is the application of the principles of the Precautionary Approach, including the adoption of *harvest strategies*. The Precautionary Approach (PA) aims at improving the management of fish resources by exercising prudent foresight to avoid unacceptable or undesirable situations, taking into account that changes in fisheries systems are not well understood and are only slowly reversible (FAO, 1995). *Harvest strategies* are the systematic series of human actions undertaken to monitor fish stocks, assess its state, implement scientific advice and make management decisions. A *harvest strategy* is a pre-agreed set of steps that can specify changes to the total allowable catch (TAC), or any other measure, based on updated monitoring data and methods of analysis. Among others, adopting a *harvest strategy* requires specifying management objectives, performance indicators, the data and methods of analysis to estimate stock status and a decision rule (harvest control rule, HCR) based on the status of the stock or fishery indicators.

Tunas sustain some of the world's most valuable fisheries and dominate marine ecosystems worldwide (Juan-Jordá et al., 2011). The International Commission for the Conservation of Atlantic Tunas (ICCAT) is responsible for the sustainable management of Atlantic tunas and has a generic management objective of achieving long-term yields with a high probability of stocks not being overfished ($B < B_{MSY}$) and no overfishing occurring ($F < F_{MSY}$) and with a low probability of stocks being outside biological limits. ICCAT's objective is In line with the United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks (UN, 1995) that defines the fishing mortality associated to MSY (F_{MSY}) as an upper limit instead of a target, but until 2017, the probability associated to not being overfished and overfishing not occurring was not specified. Note that when a stock is fluctuating around its MSY, the probability of not being overfished is approximately 50%, and the same happens with overfishing occurring. Therefore, a management objective that is in line with international conventions and with the PA should assign a probability higher than 50% for overfishing not occurring and not being overfished. In 2017, ICCAT specified components of a *harvest strategy* for North Atlantic albacore, including a HCR. This rule was adopted to achieve a management objective of maintaining North Atlantic albacore at biomass (B) levels above, and fishing mortality (F) below, that corresponding to its MSY with a probability higher than 60%, i.e., [$p(B > B_{MSY}$ and $F < F_{MSY}) \geq 60\%$] (ICCAT, 2017).

In essence, the adopted HCR specifies a maximum fishing mortality that will be used to fix TAC when biomass is estimated to be above B_{MSY}, and a gradual reduction of fishing mortality when biomass is estimated to be below B_{MSY}. The HCR also contemplates a limit reference point that would trigger the automatic closure of the fishery or setting the fishing mortality to a minimum. This HCR has been used to set catch limits for North

Atlantic albacore for the period 2018–2020 calculated using the data and methods of analysis used in the latest stock assessment of North Atlantic albacore (ICCAT, 2016c, 2017).

Management Strategy Evaluation (MSE) is considered the most appropriate way to assess the consequences of uncertainty for achieving fisheries management goals (Punt et al., 2014) and it is being used to support the adoption of HCRs and *harvest strategies* worldwide. The capacity of the HCR adopted for North Atlantic albacore to achieve ICCAT's management objectives was evaluated against the most important sources of uncertainty inherent to this fishery using MSE (Merino et al., 2017b,c). The characterized uncertainty includes using different data sources, values for key biological parameters such as natural mortality and steepness [which is defined as the fraction of recruitment from an unexploited population obtained when the spawning biomass is at 20% of the unexploited level (Lee et al., 2012)] and fishery dynamics (catchability). When using MSE, uncertainty is generally characterized through the Operating Models (OM). These represent alternatives for the "true" underlying dynamics of the fishery resource and generate data that is used in the Management Procedure (MP) component that describes *harvest strategies* (the data and methods of analysis to estimate stock status and the *HCR*) in a numerical simulation framework. The evaluation of North Atlantic albacore HCR includes scores in fisheries performance indicators of sustainability, safety (the probability of the stock remaining above the biomass limit), catch and variability (ICCAT, 2016a; Merino et al., 2017c).

How CC will affect tunas in general, and North Atlantic albacore in particular, is being investigated (Dufour et al., 2010; Dueri et al., 2014; Arrizabalaga et al., 2015; Lehodey et al., 2015; Chust et al., 2019; Errauskin-Extramiana et al., 2019) and given the long life-span of albacore (compared to other tuna stocks) it is crucial to evaluate the combined influences of fishing, environmental variability and CC on this species (Dragon et al., 2015). Here, we build a series of exploratory scenarios to characterize climate impacts on North Atlantic albacore to evaluate if the HCR adopted for this stock would still be an adequate tool for achieving sustainability goals and for maintaining fisheries performance under CC. Future scenarios are alternative images of how the future might unfold and are an appropriate tool for exploring how driving forces may influence the future and assess on the associated uncertainties (IPCC, 2007). Here, we build scenarios from the OM considered for North Atlantic albacore (Merino et al., 2017b) by modifying the albacore growth, recruitment variability and productivity in the MSE simulation framework. The scenarios for these three biological processes include gradual changes from lowest to highest from possible values that will ultimately affect productivity and fisheries performance. The aim of this is to gain confidence in the current management system of North Atlantic albacore and to identify at which levels the sustainability of this stock may be jeopardized.

To sum up, the objective of this work is to evaluate the robustness of the HCR adopted for North Atlantic albacore against a range of exploratory scenarios of climate change impacts on this stock. These include potential changes in fish growth, recruitment productivity and variability.

MATERIALS AND METHODS

The MSE for North Atlantic Albacore

Management strategy evaluation involves using simulation to compare the relative effectiveness of different combinations of (i) data collection schemes, (ii) methods of analysis, and (iii) subsequent process leading management actions (Punt et al., 2014), i.e., different MPs, for achieving fisheries management objectives. In this document, MSE is used to evaluate if the HCR adopted for North Atlantic albacore is robust to the uncertainties derived from a changing climate. For this, a MSE framework has been developed following a series of guidelines and best practices, including six basic steps (Rademayer et al., 2007; Punt et al., 2014):

Identification of Management Objectives and Performance Statistics

The foundational objective of ICCAT is to maintain populations at levels that can permit the MSY (or above). This is converted into operational objectives relative to stock status, safety, catch and stability through ICCAT's recommendation 16–06 (ICCAT, 2016b) for North Atlantic albacore: The management objective is to maintain the stock in the green quadrant of the Kobe plot ($B > B_{MSY}$ and $F < F_{MSY}$) with at least 60% probability and a low probability of being outside biological limits (low probability not specified), while maximizing long-term catch (how much catch is maximum is not specified), and minimizing the inter-annual fluctuations in Total Allowable Catch (TAC) (variability not specified). The use of *biological limits* is generic in ICCAT recommendations but it refers to values of biomass where the recruitment for future years would be jeopardized. To evaluate how the HCR can help achieving those objectives, we use four performance indicators: Probability of being in the green quadrant, probability of biomass falling below the limit reference point established for this stock ($Blim = 0.4\ x\ B_{MSY}$), long term catch, and interannual variability. We evaluate these performance metrics for the period 2040–2060. This period was chosen because it is in the temporal range of climate change impact predictions (IPCC, 2007; Cheung et al., 2012; Merino et al., 2012; Barange et al., 2014). Here, we evaluate the capacity of the HCR to achieve management objectives by scoring its performance on four indicators.

Selection of Hypotheses of System Dynamics

MSE requires characterizing the main sources of uncertainty inherent to fisheries. These generally include gaps in biological processes and fishery dynamics. The first are often dealt with hypotheses on input biological parameters to population dynamics' models; and the second with hypotheses over the available datasets or parts of them. The uncertainties explored in the original North Atlantic albacore MSE (Merino et al., 2017b,c) include hypotheses on the available data series, together with natural mortality, stock recruitment relationship and fishery dynamics scenarios (see **Table 1**, Past dynamics).

Here, we add three additional hypotheses in relation to the potential responses of the stock to CC: (a) *Climate change will affect recruitment variability:* An increase in future recruitment variability [from current values (20%) to extreme variability (+200%)], (b) *Climate change will affect fish body size:* variations in the average body weight [from severe reductions (-30%) to a slight increase (+10%)] in response to sea warming and lower oxygen and, (c) *Climate change will produce long term changes in recruitment:* a recruitment regime shift [from moderately negative (-20%) to moderately positive (+ 20%)], reflected in the expected recruitment at unfished biomass. These changes are introduced in the simulation by modifying the average weight-per-age, the productivity parameter (generally formulated as α) in the Beverton-Holt stock-recruitment model, and on a recruitment variability coefficient.

Constructing OMs

OMs are representations of the "true" dynamics of the system and may include a set of the most plausible hypotheses or unlikely but not impossible situations (ISSF, 2013). In MSE frameworks the OMs represent the system that will be managed through MPs, i.e., the "true" system that is observed, analyzed and managed through data collection systems, stock assessment and HCRs. The OM built for the North Atlantic albacore are conditioned from the hypotheses and assumptions made in the 2013 assessment using the model Multifan-CL (Kleiber et al., 2012; Kell et al., 2013; Merino et al., 2017b). The different model set-ups were prepared choosing alternative model and data options (see **Table 1** and Merino et al., 2017b for a more detailed description of the OMs). The OMs were conditioned using R (Project for Statistical Computing[1]) functions and libraries from the FLR-project[2]. The conditioned OMs are objects composed by a single fishery and include parameters (selectivity, growth, natural mortality, stock-recruitment and maturity), time series of catch and biomass (in total and by age) and harvest time series, among other information. Finally, the OMs were projected forward to 2015 with total catch information from 2012–2014, and to 2019 with catch and TAC from 2015–2018.

Overall, there were 132 initial OMs. For this work, we modified the initial set of OMs to represent CC impacts by changing stock recruitment relationships (4 options), variability in the recruitment dynamics (4 options) and changing the age vs body weight curve (4 options), resulting in 1,584 OMs (132 × 12).

Defining MPs

MPs represent how the true dynamics underlying fisheries exploitation are represented through stock assessment and driven by fisheries management. A population-model-based framework within which the data obtained from the fishery are analyzed and the current status and productivity of the fishery are estimated through a stock assessment model (Rademayer et al., 2007). The outputs of this are plugged into a HCR that, provides recommendation for management action. In this study, one observational error model (OEM) generates simulated abundance indices for fitting the biomass dynamic model used to evaluate North Atlantic albacore in 2016, to estimate stock status and productivity. These are used in combination with the HCR adopted in 2017 to determine TAC every 3 years (as happened when the HCR was adopted in ICCAT). The following sections provide a detailed description of the components of the MP:

Observation Error Model

In MSE, the OM is used to simulate resource dynamics in order to evaluate the performance of a MP. Where the MP is the combination of pre-defined data, together with an algorithm to which such data are input to provide a value for a management control measure. To link the OM and the MP it is necessary to develop an OEM to generate fishery-dependent or fishery-independent resource monitoring data. The OEM reflects the uncertainties, between the actual dynamics of the resource and perceptions arising from observations and assumptions by modeling the differences between the measured value of a resource index and the actual value in the OM (Kell and Mosqueira, 2016). A procedure to simulate catch per unit of effort data (CPUE) from the OM and compare the

[1]https://www.r-project.org/

[2]http://www.flr-project.org

TABLE 1 | OMs of the North Atlantic albacore MSE and future CC scenarios used for this study.

Past dynamics (1950–2015)				Future climate change impacts (2050–2100)		
Multifan- CL runs	**Natural Mortality**	**Steepness**	**Catchability dynamics**	**Recruitment shift**	**Recruitment variability**	**Body weight change**
Base case	0.2, 0.3, 0.4	Estimated and fixed (0.75, 0.85, 0.95)	· Constant and 1% increase	(−20%, −10%, +10%, +20%)	(+25%, +50%, +100%, +200%)	(−30%, −20%, −10%, +10%)
Longline freq data and dome shaped selectivity			· Constant			
Size data downweight						
Include Japanese size data						
Include age-sp M						
Exclude data 2008-2011						
Equal weight to size and cpue data						
Catch in weight, effort in numbers						
Include tag data						

properties of the simulated to those used in the latest assessment of North Atlantic albacore was used (Merino et al., 2017a). This method (eq. 1) is used to generate four abundance indices (Spanish baitboat, China Taipei longline, Japanese longline, and a combined index to simulate Venezuelan and United States longline, which were the indices used in the 2016 assessment of this stock) from the OMs:

$$Index_f = \frac{\sum_a^{max} Catch_{a,f}\ x\ Selectivity_{a,f}}{f_{bar}}\ x\ \varepsilon;$$

$$f = fleet;\ a = age;\ fbar = fishing\ mortality\ (eq.\ 1)$$

Stock Assessment

The indices generated with equation 1 are used to fit the biomass dynamic model *mpb*, which was used in the 2016 stock assessment of North Atlantic albacore (ICCAT, 2016c; Kell, 2016). The fits are made using the same specifications and modeling choices as in 2016, i.e., CPUE series starting as in the stock assessment (**Table 2**) and the same starting values used in 2016 with the Fox model (Fox, 1970; **Table 3**).

Harvest Control Rules

Harvest control rules describe how harvest is automatically controlled by management in relation to the state of some indicator of stock status (ISSF, 2013). In the rule adopted for North Atlantic albacore (**Figure 1**), when the stock level is above the precautionary threshold ($B_{thresh} = B_{MSY}$), the fishing mortality applied to the stock will be the target fishing mortality ($F_{tar} = 0.8xF_{MSY}$). When the stock falls below B_{thresh} but above the limit reference point B_{lim} ($0.4xB_{MSY}$), the fishing mortality will be gradually reduced from F_{tar}. When the stock falls below B_{lim}, the remedial management action will be determined by F_{min} (0.1 x F_{MSY}). As part of HCRs, threshold and limit reference points are intended to restrict harvesting to avoid highly undesirable states of the stock, such as the impairment of the recruitment, from which recovery could be irreversible or slowly reversible.

In addition, in the spirit of avoiding the adverse effects of potentially inaccurate stock assessments and to increase stability, two control parameters are included in the adopted HCR: First, TAC will not exceed a maximum of 50,000 tons and, second, a maximum 20% of change in TAC will be allowed when the stock is estimated to be above B_{MSY}.

TABLE 2 | CPUE series used in the 2016 stock assessment and their starting and ending years.

Index	First year of series
Chinese Taipei late Longline	1999–2015
Japan bycatch Longline	1988–2015
Spanish Baitboat	1981–2015
United States continuity Longline	1987–2015
Venezuela Longline	1991–2015

TABLE 3 | Specifications of the biomass dynamic used for the 2016 stock assessment and also used in this MSE.

Software	Model	Catch series	Starting values
mpb	Fox	1930–2014	Intrinsic growth rate: $r = 0.1$ Carrying capacity: $K = 3.6 \times 10^6$ tons Biomass at t = 0 (fixed): $1 \times K$

Simulation With Feedback

The OMs and the MPs were linked through specifically tailored R functions and libraries from the FLR project in the MSE framework (**Figure 2**). The OMs produce series of biomass, catch and fishing mortality, which are measured every 3 years to generate series of catch and abundance indices through the OEM. These are then used to fit the surplus production stock assessment model, *mpb*. The outputs of this model include estimates of biomass and fishing mortality, reference points (B_{MSY}, F_{MSY}, MSY) and model parameters. These are plugged into the HCR to set catch limits, which are then used to project forward the OMs for three more years. This process is simulated every 3 years for the duration of the simulation, until 2065.

Summary and Interpretation of Performance Statistics

The evaluation of HCRs is completed with the summaries and interpretation of the performance of the OMs. Four groups of indicators relative to stock status, safety, catch and stability are used and compared to the values estimated for the HCR without the CC included.

RESULTS

The CC scenarios formulated here predict changes on North albacore stock's dynamics, changes including productivity and variability. In the modeling framework used here, stocks' productivity is specified from stock recruitment relationships, growth equations and mortality parameters. With these, we can calculate stock's equilibria between spawning stock biomass (SSB), recruitment, fishing mortality and catch (**Figure 3**). These figures illustrate how CC would modulate stocks' productivity and abundance and how we have accounted for these changes in our modeling framework. For this, we have generated scenarios of body shrinkage (-30, -20, and-10%) and increase (+ 10%), and recruitment baseline variations from moderate (± 10%) to high (± 20%). We show how CC affected one OM (the Base Case considered in the 2013 stock assessment), but the 132 OMs are modified likewise for the simulations. The productivity of the stock (equilibrium catch) would be more affected by recruitment shifts than by changes in fish body weight (**Figure 3**).

Figure 4 shows how CC would affect albacore's productivity and abundance (MSY and unfished biomass, K), in all the OM used in this study. The characterized response of fish stocks to CC were predicted to be larger through changes in recruitment than through changes in body growth (**Figure 4**). A differential impact of ±10% in body weight would produce a 0.99 thousand tons change on stocks' productivity (MSY) while the same differential impact on recruitment shift would produce a variation of 4.19 thousand tons. The stock's response to climate will also modify the niche they could occupy. This is reflected on stocks' carrying

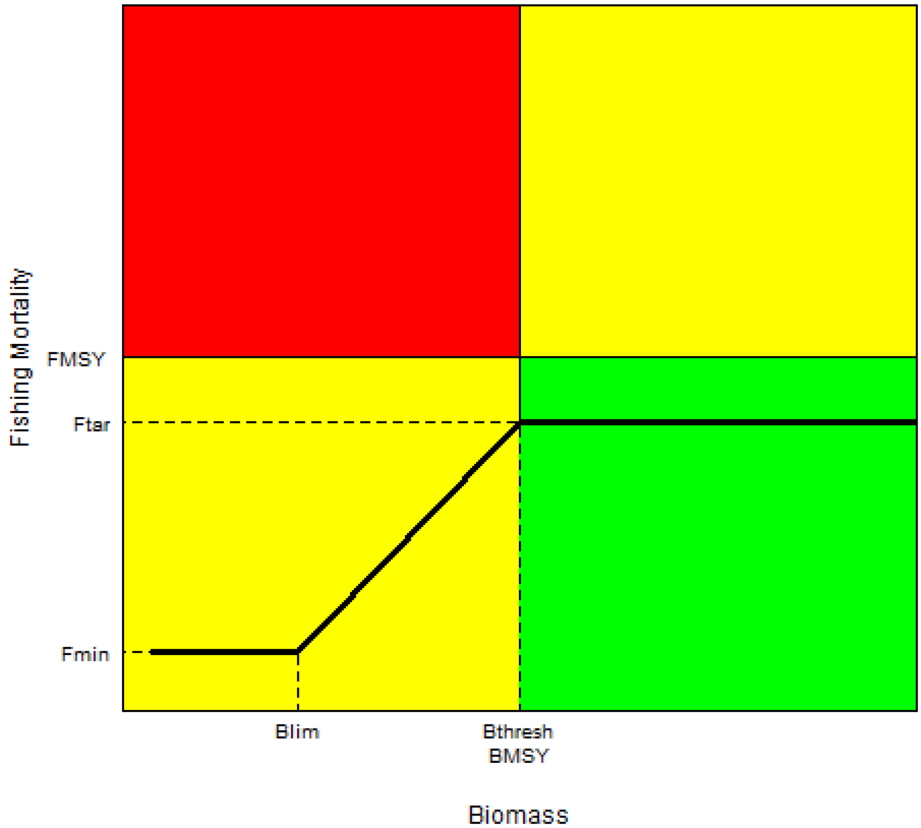

FIGURE 1 | The HCR adopted for North Atlantic albacore displayed in a Kobe plot. The coordinates of the HCR are: B_{thresh} (= B_{MSY}), Blim (Limit RP), Fmin (F that would be applied if the stock is assessed to be below Blim and, Ftar = target fishing mortality, which will be applied when the stock is assessed to be above B_{thresh} = B_{MSY}.

capacity (K) or unfished biomass, the SSB level that would be achieved if fishing mortality was reduced to zero. In this case, the differential impact is very similar when recruitment

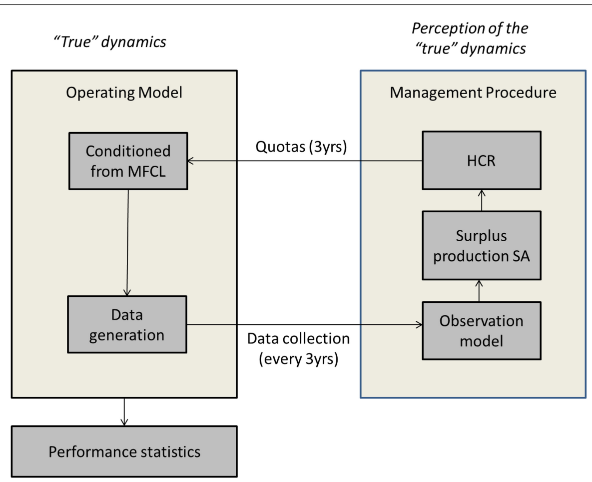

FIGURE 2 | Scheme of the numerial framework used in the North Atlantic albacore MSE.

or body growth are modified: A change of ± 10% produces a change of ± 70 thousandtons in K in both cases. **Figure 4** also shows the differences in productivity across OMs for the same differential impact. For example, for the assumption of no climate impact, North Atlantic albacore MSY ranges between 60 to 25 thousand tons, with most OM estimated MSY between 25 and 40 thousand tons.

Figure 5 shows one OM projected forward through the simulation period with no CC impacts. This figure shows how for a single projection the numerical framework produces a range of estimates for each year and that the uncertainty expands through the simulation. In the simulations, variability is caused by the stochastic recruitment model in the OM and to the uncertainty on the CPUE indices used in the MP, generated by the OEM. Thus, the results of each simulation can be expressed as probability distributions similar to what happened when results were aggregated for all OMs for each climate impact.

For all the climate impacts characterized in this study, the HCR adopted for North Atlantic albacore in 2017 would achieve ICCAT's management objective of maintaining the stock in the green quadrant of the Kobe plot with a probability higher than 60% (**Figure 6**). With regards to keeping the stock above biological limits, North Atlantic albacore would be above the limit reference point adopted for this stock at least with a

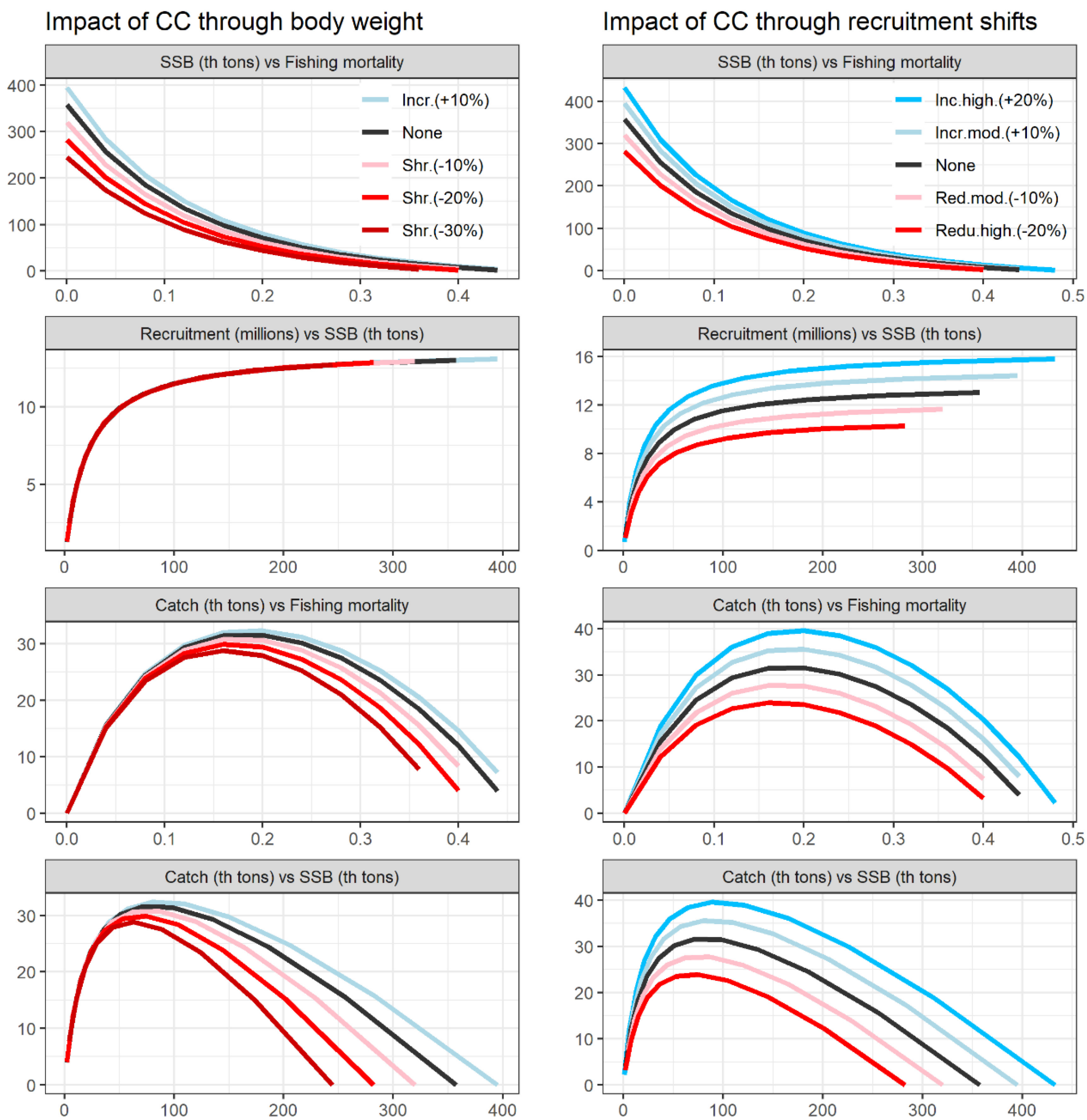

FIGURE 3 | Climate change driven changes in the North Atlantic albacore equilibria based on hypothetical but realistic changes in body weight and recruitment. Colors reflect from large negative effects (red) to positive effects (blue) and the intensity of the color reflects the expected change from large (dark colors) to small changes (light colors).

probability of 95.7% (Recruitment shift of -10%). With regards to long term-catch, this would range between 20.6 thousand tons and 35.5 thousand tons (similar to recent catches). The stability of catches would be very similar across scenarios with Mean Absolute Proportional (MAP) change in catch ranging from 7.4 to 10.3%.

Figure 7 illustrates the heterogeneity of the "true dynamics" considered in the North Atlantic albacore MSE. As the impact goes more negative (i.e., lower body weight, lower recruitment and higher variability), the amount of OMs that deviate from the median value increases. Thus, the uncertainty considered in the initial set of OMs is amplified when stocks are subject to CC impacts and many of the potential "true" trajectories diverge. For example, when the OMs are projected without any climate impact, more than 75% of the OMs reach the management objective of 60% probability of being in the green quadrant of the Kobe plot (gray box above 60%, **Figure 7**). However, with the negative impacts on productivity due to body weight and recruitment reduction modeled here, nearly 40% of the OMs would not reach the management objective (values of -30, -20,

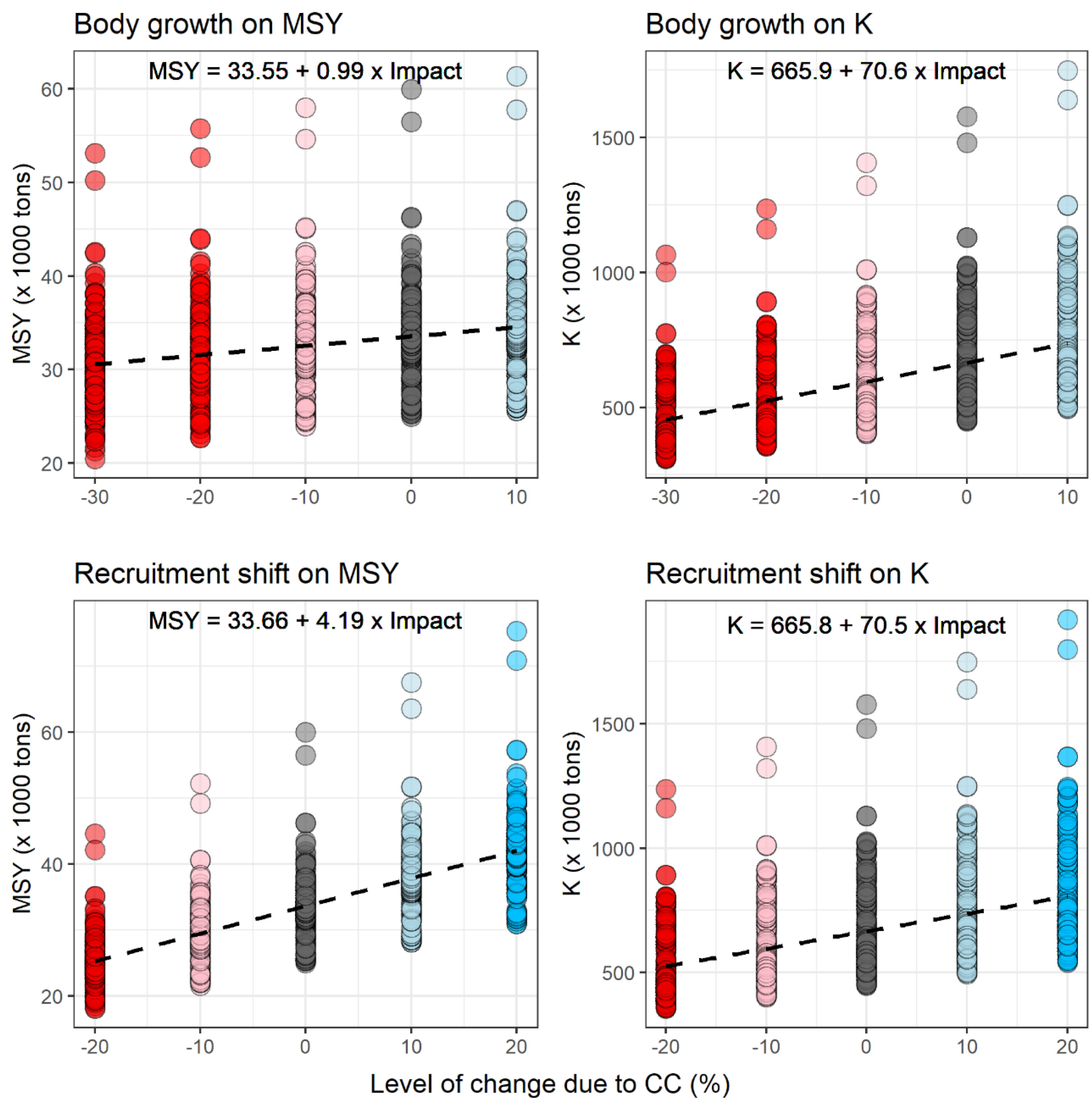

FIGURE 4 | Impacts of CC on stocks' productivity (MSY) and unfished biomass (K) explored in this study. Each point represents the reference point of one OM for different levels of impact of CC through body growth (**top**) and recruitment shift (**bottom**). Colors reflect from large negative effects (red) to positive effects (blue) and the intensity of the color reflects the expected change from large (dark colors) to small changes (light colors).

and -10%). In contrast, the increased variability leads to lower average catch and an increased probability of being in the green quadrant of the Kobe plot. This appeared to be because with larger values of variability, the MP stock status estimator is underestimating biomass and therefore, setting TACs at lower levels. When looking at catch and stability indicators a wide range of performances are observed across OMs for the same climate impact, with variability also increasing for the more negative impacts.

Should the impact of CC on North Atlantic albacore productivity be positive [i.e., greater body growth (+ 10%) or increased recruitment (+10%, +20%)], the median catch would likely increase. The HCR adopted for this stock contemplates a maximum TAC of 50 thousand tons and for some OMs, this value is well below their MSY. Therefore, for a number of model runs the increased productivity would not result in a proportional increase in catch and this would lead to higher values of probability of being within the green quadrant, which means that this may be a very precautionary management outcome.

DISCUSSION

Our results demonstrate that the HCR adopted in 2017 for North Atlantic albacore is adequate to achieve ICCAT's sustainability objectives under CC. Albacore's biological response to global warming will modulate the maximum productivity and predicted long term catches of North Atlantic fisheries but will also increase their variability. Importantly, CC is predicted to amplify the uncertainties identified for this fishery. These conclusions rely

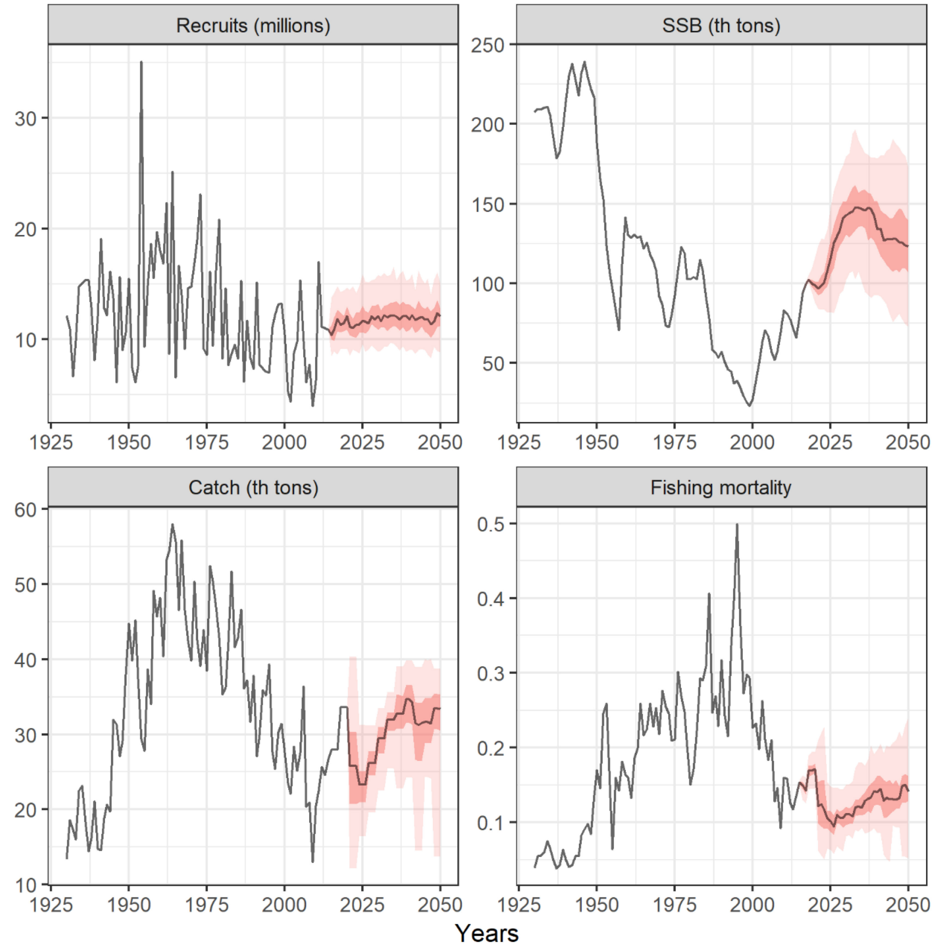

FIGURE 5 | Example of one OM projected forward with the HCR adopted for North Atlantic albacore under no climate change effects. Solid lines are median trajectories and pink and light-pink areas represent the 25–75% and the 10–90% quantiles, respectively, for recruits, spawning stock biomass, catch and fishing mortality.

upon the results of an MSE framework specifically tailored to characterize the uncertainties inherent to this fishery and to the predictions of stocks response to global warming. The MSE was built from the most recent stock assessments of North Atlantic albacore and the decision rule adopted ICCAT's Recommendation 17-04.

This study aims at reducing the uncertainties on the course of action necessary to mitigate the impacts of global environmental change on fisheries (Arnason, 2006) under the principles of the Precautionary Approach (FAO, 1995). This principle recommends to determine the status of fish stocks relative to target and limit reference points, to predict the outcomes of management alternatives for reaching the targets and avoiding the limits and to characterize uncertainty in all cases (Garcia, 1996). A target is a management objective based on a level of biomass that should be achieved and maintained with high probability and a limit indicates the stock size below which the stock is in serious danger of collapse. In the case of North Atlantic albacore, ICCAT adopted the management objective of maintaining the stock in the green quadrant of the Kobe plot with at least 60% probability while maximizing long-term catch and recommended testing alternative target, threshold and limit reference points (ICCAT, 2015). To achieve the management objective, ICCAT adopted reference points and a HCR (ICCAT, 2017) that wwere evaluated against the most important sources of uncertainty identified for this stock (Merino et al., 2017a,b,c). Previous studies by Merino et al. (2017a,b,c) evaluated a range of alternative HCRs against the performance indicators used here to support ICCAT adopting the HCR evaluated here (ICCAT, 2017). This study adds to the previous works by characterizing the uncertainty on CC impacts on North Atlantic fish stocks and by evaluating the robustness of the HCR to keep the stock at sustainable levels under these impacts. Also, this study predicts the performance of North Atlantic albacore fisheries in the long term under CC including its catch and variability in annual catches.

Predicted changes in ocean productivity have been used to estimate proportional changes of fish catch under CC (Lehodey et al., 2006; Cheung et al., 2010, 2012; Blanchard et al., 2012; Arrizabalaga et al., 2015; Errauskin-Extramiana et al., 2019;

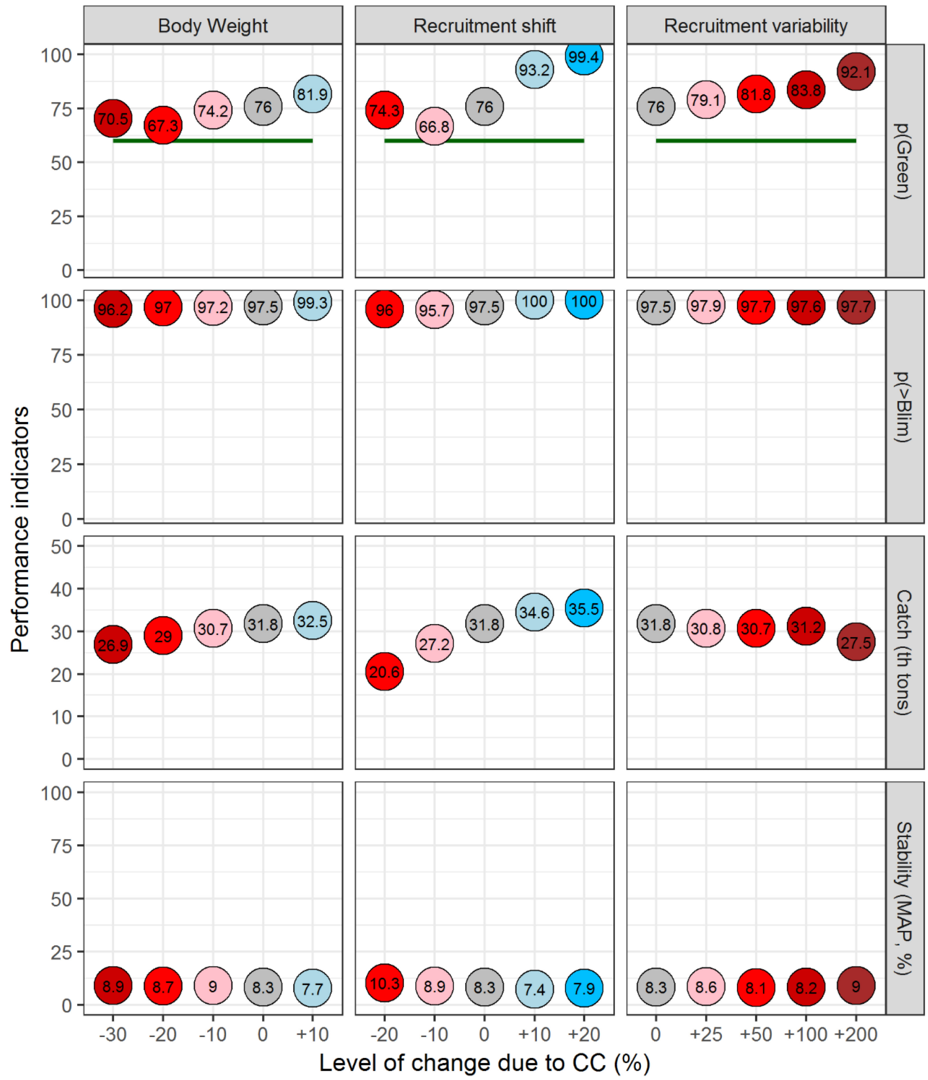

FIGURE 6 | Performance of the North Atlantic albacore fishery represented with median values of indicators of sustainability (pGreen = probability of being in the green quadrant of the Kobe plot), safety (probability of biomass staying above Blim), catch and stability (Mean Annual Proportional change of TAC). A single probabilistic estimate (median) is used to illustrate fisheries performance of sustainability, safety, catch and variability across OMs. The values for each indicator are printed inside the circles. Colors reflect from large negative effects (red) to positive effects (blue) and the intensity of the color reflects the expected change from large (dark colors) to small changes (light colors).

Plagányi, 2019). However, decreases or increases from current catch levels may depend on management decisions now and in the future, rather than on the fish response to CC alone (Barange, 2019). Therefore, it is of great importance to incorporate fishery management when projecting future fisheries scenarios. Few studies have evaluated the synergic impact of CC and management in marine fisheries (Chavez et al., 2003; Merino et al., 2012; Barange et al., 2014). For example, Barange et al. (2014) conclude that despite the projected human population increase and predicted CC impacts, global demands for fish will be met if strategies for sustainable fisheries are implemented. Merino et al. (2012) suggest that efficient management and technological development in aquaculture, and not climate change, will be the most significant factor in securing sustainable fish production in the future. Here, we first evaluate the direct impact of CC on North Atlantic albacore's maximum productivity alone using scenarios built from a range of predicted fish responses through body weight and recruitment. Then, we evaluate the ability of the current stock assessment and decision rule for North Atlantic albacore for each fish response scenario by estimating the probability of the stock being in the Green quadrant of the Kobe plot, the risk of falling below safe limits, the long-term catch and its variability. Our results suggest that the capacity of the management scheme adopted by ICCAT is likely to achieve sustainability objectives under CC, representing yet another benefit of well-designed HCRs.

MSE is the appropriate tool to characterize the impacts of uncertainty in fisheries and to evaluate the robustness of

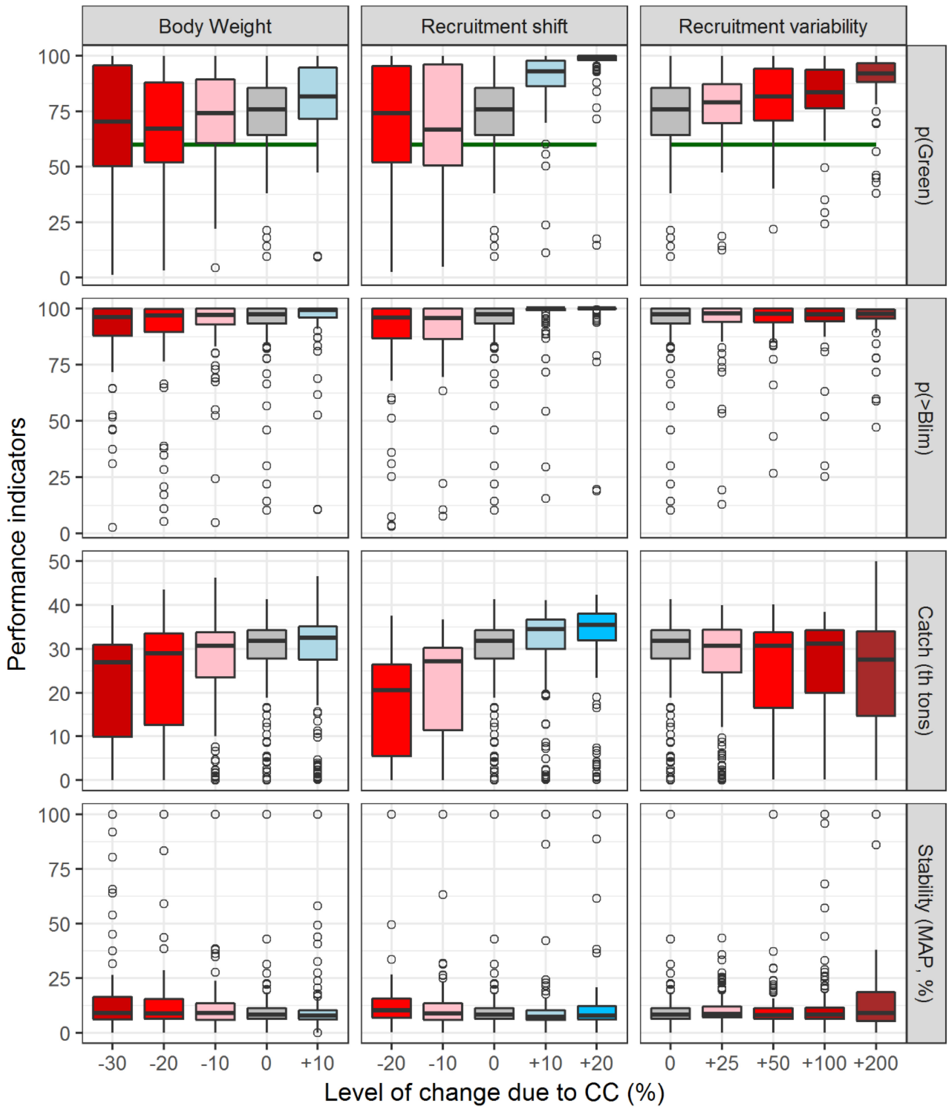

FIGURE 7 | Performance of the North Atlantic albacore fishery represented with box and whisker plots that represents the variety of results achieved across OMs. Boxes represent the 25–75% of OMs and whisks represent 5–95%. Points are outlier OMs. This figure shows indicators of sustainability (pGreen = probability of being in the green quadrant of the Kobe plot), safety (probability of biomass staying above Blim), catch and stability (Mean Annual Proportional change of TAC). Colors reflect from large negative effects (red) to positive effects (blue) and the intensity of the color reflects the expected change from large (dark colors) to small changes (light colors).

management plans toward achieving sustainability (Punt et al., 2014). The MSE used here was peer reviewed and overall, it was found that the MSE framework used in 2017 "*appears to be high quality and robust to uncertainty*" (Scully, 2018). However, some suggestions for improvement were made and therefore, the code used here is not exactly the same used in 2017. For example, the MP model did not have a mechanism to set TACs if a stock assessment failed to converge in a year of the MSE simulation. We have improved that by setting a rule for maintaining the previous TAC in these cases. In the previous version, the model estimated very low biomass and catch was decreased to a minimum. Also, we don't only show point estimates with medians across OMs (**Figure 6**) but we also report on the uncertainty around the medians by using boxplots with outliers (**Figure 7**). Finally, the OMs used in this study don't include one group of OM used in the MSE evaluation of North Atlantic albacore, the Multifan-CL scenarios starting in 1950s. This is because when we tried to run the CC scenarios the OMs of this group showed problems in the projections, which will need to be understood. These problems consist on the model crashing during the simulation but the underlying reasons for this will need to be further investigated.

In this study we have characterized CC impacts by modifying the biological properties of the simulated stock of North Atlantic albacore. Starting from a suite of OM developed to characterize current uncertainties (Merino et al., 2017b), we have built a set of new OM by modifying the initial OM with changes in body-growth and recruitment equations. The new set of OM represent a number of potential "true dynamics" for North Atlantic albacore under CC. From the climate impacts characterized in the OM, variations in recruitment levels are the major driver of change on fish stocks' maximum sustainable catch. The range of impacts characterized here is not arbitrary: Cheung et al. (2012) estimate changes in individual-level maximum body size of fishes for the Atlantic within a range of -30 to 10% with median at ∼-10%. With regards to the impact of environmental regime shifts, Chavez et al. (2003) identify warm and cool periods in the Eastern Pacific that are directly linked with the abundance of anchovy and sardine, which end-up modulating the recruitment of yellowfin tuna (Maunder and Watters, 2001). Using coupled ocean-biogeochemical-population dynamics models, Lehodey et al. (2003), identify climate related changes in Pacific skipjack, yellowfin and South Pacific albacore within a range comparable with the values used here. For North Atlantic albacore in particular, stock-recruitment-environment models have been fitted to identify changes in recruitment (Arregui et al., 2006). The Beverton–Holt model used here was tested with the added factor of the NAO index and yielded estimates of the productivity parameter (α) ranging from ∼0.7 to $\sim 1.1 \times 10^7$, approximately in a range of -20 to +20% of its value without the environmental impact (Arregui et al., 2006). With regards to the recruitment variability scenarios explored here, current state is described with a coefficient of variability (CV) of 20% on recruitment which is similar to other studies (Maunder and Watters, 2001). From this value, we increase variability up to +200%, representing a CV of 0.8. This variability is linked to large-scale atmospheric forcing (Chavez et al., 2003) and could potentially decrease resilience to fishing (Kuparinen et al., 2014). The values used in this work range between the medium to large values considered in a recent study for a variety of Atlantic stocks (Kuparinen et al., 2014). This study is carried out with a model that does not have a spatial component and therefore, the impact of climate change on habitat was directly estimated.

Another salient conclusion of our study is that for increased impacts of CC, the variability of behaviors among OMs increases. For example, fishery's performance is relatively well centered in the median and boxes for the simulations without climate impacts (**Figure 7**, gray box). In contrast, the increased negative impacts seem to produce a wider range of results within the set of OMs. This effect is somehow masked by the relatively stable median performances (**Figure 6**) but corroborates that CC is predicted to increase the uncertainty on the dynamics of fish stocks and natural systems (Cheung et al., 2016) and therefore, further investigations will be necessary to reduce this uncertainty and to improve the understanding the environmental impacts on this stock and in fisheries in general. We also recommend further investigations to explore the combined impacts of biological responses to CC evaluated in this study. It is expected that changes in growth will happen simultaneously to changes in recruitment variability and productivity and this is not evaluated in this study.

Overall, our estimates of CC impacts on fisheries performance were expected: The higher the increase in overall productivity, the higher the catch. However, this study produced results that were initially unexpected: Those scenarios simulating the most negative impacts of CC (-30% of body growth and -20% in recruitment productivity) and increased variability lead to higher values of probability of being in the green quadrant of the Kobe plot (pGreen). This is explained by the capacity of the biomass dynamic model used in the MP. With the set of new OMs and for the more negative impacts of CC the MP has difficulties in fitting the generated data with the range of parameters used and, this lack of convergence leads to lower catches even if the stock is at safe levels. In these cases, the stock biomass continues to increase. With regards to the positive impacts (increased body growth and recruitment), the pGreen achieved may be undesirable and larger sustainable catches would be possible. In the current HCR, there is a limit to the increase of TAC and also a maximum limit of 50 thousand tons, which in the case of potential productivity increases could hamper the performance of fisheries unnecessarily. Therefore, the potential future adoption of a model based MP that includes not only the HCR but also the model and starting values should be flexible to modifying these values to reach a better convergence and a more accurate estimate of stock status. A possible way to do so would be to adopt the data, model and the HCR but leaving some modeling choices open to the working groups, like the bounds for the parameters or their initial values. Also, should there be evidence of environmentally driven changes on the productivity of the stock, there should be flexibility on the inclusion (or not) of parts of long data series. This was somehow done in the last assessment of North Atlantic albacore, when CPUE data prior to 1981 was discarded as potential proxy of stock abundance due to a number of reasons, including the potential change in recruitment regimes throughout the history of the fishery (ICCAT, 2016c; Kell et al., 2016). Finally, the stability clauses of the current HCR should also be eventually adapted if there is evidence of a large-scale environmentally driven change in productivity.

We have only characterized phenological changes through variability in recruitment but fish are subject to many other sources of climate-driven variability (Barange and Perry, 2009). For example, North Atlantic albacore has shown phenological and migratory trends that affect fisheries, specially a northward trend in habitat (Chust et al., 2019). The reasons for these changes are still uncertain and understanding their underlying causes would improve management significantly and contribute to mitigating their impacts. In particular, distribution changes will affect albacore fisheries performance in different latitudes. The nations that have historically targeted albacore (Spain, France) are prone to be negatively affected by geographical changes while nations at higher latitudes could be benefited.

The best option to address the CC challenge is still undefined (Maury et al., 2017), but the inefficient management can only amplify its effects and is considered responsible for the inefficient stewardship of global fisheries (Bank, 2009). A lagged response to natural productivity changes to reduce fishing pressure can amplify fish population collapses (Essington et al., 2015). Globally, effective management of fisheries is still an exception (Mora et al., 2009) and our study adds to previous research (Brander, 2007; Merino et al., 2012; Barange et al., 2014; Barange, 2019) in emphasizing the importance of ensuring efficient management of fisheries in a changing climate and that fisheries management appears to be more important than direct CC impacts predicted in fisheries.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

GM designed the study, ran the simulations, collected the results, produced the figures, and wrote the manuscript. LK, PD, and GM developed the numerical framework. All other authors contributed to the writing of the manuscript.

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Stakeholder Perspectives on Opportunities and Challenges in Achieving Sustainable Growth of the Blue Economy in a Changing Climate

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Coastal marine environments provide livelihoods as billions of people around the world depend greatly on sustainability efforts in the Blue Economy. In this study, we investigated how stakeholders from important Blue Economy sectors along the German North Sea coast perceive the impacts of climate change on their daily work life and the growth of the Blue Economy. In a two-stage approach we first conducted two stakeholder workshops with representatives from the regional sea food sector, science, NGOs and local authorities, in order to identify important issues linked to climate change affecting environment, society, economy and policy. In the second stage, we conducted semi-structured interviews with key knowledge holders from the Blue Economy, to evaluate and validate the most important issues identified during the first stage, and the impacts on the respective sectors. The workshop participants identified perceptible effects of climate change on their marine environment. Early career scientists showed that they possess a clear focus on measures for climate change adaptation, transdisciplinary approaches and knowledge transfer. The interviews revealed that the climate change effects could be perceived as both negative and positive, depending on the sector. Other issues, especially political decisions and developments are perceived to have a greater immediate impact on the Blue Economy than the slow progress of climate change effects. Additionally, increased human activities, in the form of new or intensified uses like marine renewable energy generation, have a greater influence and lead to conflicts between the Blue Economy sectors. Our study showed that economic and societal stakeholders in Germanys North Sea region are aware of climate change and already perceive its effects on their businesses. Synergies and conflicts between the sectors and political decisions might influence sustainable growth of the Blue Economy in highly contested regions, such as the North Sea basin, much stronger than the effects of climate change. This calls for a more flexible and adaptive approach to policymaking, taking into account the changing environmental, social and economic realities.

Keywords: adaptation, fisheries, tourism, North Sea, aquaculture, blue growth, seafood

INTRODUCTION

With 40% of human population living within 100 kilometers of the coast (UN, 2017), coastal marine ecosystems are among the most ecological and socio-economic valuable in the world. Livelihoods of people around the world are part of coastal socio-ecological systems (SES) and depend on the ecosystem goods and services that healthy coastal and marine systems provide (Seitz et al., 2013). However, there is a scientific consensus that coastal marine ecosystems and their goods and services are increasingly threatened by anthropogenic activities and pressures, such as marine resource use, building measures, and global climate change (IPCC, 2018). Shifts in water temperatures, ocean acidification, rising sea level, changes of ocean circulation patterns and increasing nutrient input are affecting physical, chemical and biological processes (Doney et al., 2012) that lead to changes in primary and secondary production, shifts in the distribution of species, changes in the biodiversity and population dynamics (Harley et al., 2006).

Understanding the Concepts of Blue Economy and Blue Growth

The above-described trajectories of change pose future opportunities and challenges for coastal communities, including people working in maritime economy sectors, such as fishery, aquaculture, and tourism. Endorsing the three pillars of sustainability, societal, ecological and economic aspects (Allison et al., 2009) need to be addressed in order to ensure sustainable development. There are different terms, concepts and strategies related to fostering and managing sustainable development of the oceans. Blue Economy emerged in the early 2010s from a need to incorporate sustainability and conservation into the management and development of the ocean economy in order to reduce environmental risks, e.g., lower greenhouse gas emissions, less pollution while fostering resource efficiency (UN, 2014). Along with Blue Economy, the concept of Blue Growth is used for a holistic management of marine SESs focusing especially on sectors with a high potential for sustainable growth. The European Union launched its Blue Growth strategy to stimulate the economic growth of five areas in European seas: aquaculture, coastal tourism, marine biotechnology, ocean energy and sea bed mining, whereas other Blue Economy sectors like transportation, fisheries, shipbuilding and offshore oil and gas are already well established in terms of value and jobs (EC, 2017). In previous years, the concepts of Blue Economy and of Blue Growth has received criticism from different sides, since the goals are not clearly defined and stakeholders thus interpret Blue Economy and Blue Growth in different ways (Voyer and van Leeuwen, 2019).

Silver et al. (2015) and Voyer et al. (2018) identified four lenses of how Blue Economy can be seen by the actors. These views can be synthesized representing two distinct contrasting perspectives: (1) ecosystem goods and services based: ocean as natural capital (lens 1) and livelihood for coastal communities (lens 2) such as small-scale fisheries and Small Island Developing States and (2) solely ocean economy based: oceans as good businesses (lens 3) and drivers of innovation (lens 4).

Many authors see the danger of the privatization of common property ocean spaces through blue economy (Voyer et al., 2018) and this leading to "ocean grabbing" neglecting the needs of and rights of smaller sectors in favor for private-profit interests (Barbesgaard, 2018). Furthermore, the question arises whether Blue Growth is achieved by "maximizing economic growth derived from marine and aquatic resources" or "by maximizing inclusive economic growth derived from marine and aquatic resources and at the same time preventing degradation of blue natural capital" (Eikeset et al., 2018). In this study, we investigated, how the local actors in the Blue Growth and Blue Economy sectors perceive sustainable development and if they try to achieve sustainable growth attaining economic, societal and environmental sustainability at the same time.

In the German North Sea region, the Blue Economy sectors with the most future potential are offshore wind energy, coastal tourism, shipping, cruise tourism, shipbuilding and ship repair and marine aquatic products (fisheries, aquaculture and fish processing) (EU, 2016). In this study, we investigated, how the local actors in the Blue Growth and Blue Economy sectors perceive sustainable development and their issues related to achieve sustainable growth to attaining economic, societal and environmental sustainability at the same time.

Climate Change Impacts of the Blue Growth and Blue Economy in the North Sea Region

The North Sea and especially its southern coastline are a focal point for the effects of global climate change and this is exacerbated by the intense anthropogenic use of the marine environment (Emeis et al., 2015). It is precisely here that the effects of climate change described above can be clearly seen as well as the resulting effects on the ocean economy (see **Table 1**). The main issue is the increase in sea surface temperature, which has, in combination with other climate change related factors, the biggest influence on the marine environment. Correlated to increasing sea surface temperatures is the increase in biomass production as it is observed and predicted for the North Atlantic and North Sea in phytoplankton and higher trophic levels (Brander, 2010). This increased biomass of lower trophic levels has a bottom up effect leading to an increased fish biomass, but also to blooms of harmful microalgae, macroalgae and jellyfish affecting the fisheries, aquaculture and tourism sectors (Peperzak, 2003; Attrill et al., 2007; Callaway et al., 2012). Furthermore, valuable fish and mussel stocks show geographic shifts northwards (Perry et al., 2005; Rijnsdorp et al., 2009; Jones et al., 2010) or into deeper waters (Dulvy et al., 2008) affecting seafood production and tourism. The rising sea surface temperature in the North Sea also leads to changes in the North Sea food web, resulting in a mismatch between trophic levels (Edwards and Richardson, 2004) and in changes of the community composition (Franke and Gutow, 2004; Wiltshire et al., 2009), which is mainly affecting the seafood and tourism sector. Climate change can facilitate the spread and settlement

TABLE 1 | Overview of climate change effects and impacts on Blue Economy sectors in the German North Sea region; sectors with * are considered as Blue Growth sectors (Schuchardt and Wittig, 2012).

Effects	Impacts	Fisheries	Aquaculture*	Fish processing	Transportation	Coastal tourism*	Wind energy*	Biotechnology*
Increase in sea surface temperature	Increase in biomass production	x	x				x	x
	Toxic algal blooms	x	x		x	x		x
	Geographic shifts of fish stocks	x				x		
	Migration of neobiota	x	x		x			x
	Change in food webs		x					
	New culture species		x					
Extreme weather events	Intensification of wind and sea conditions	x	x		x	x	x	x
	Flooding of coastal infrastructure			x			x	x
	Damage of production infrastructure		x		x	x	x	x
	Increased risk of diseases		x			x		
	Coastal erosion				x	x		
Ocean acidification							x	x
	Decrease in fish and mussel stocks	x	x					
Change in circular patterns		x			x	x	x	
	Variations in salinity	x				x	x	x
Increased air temperatures	Increased cooling requirement for equipment	x		x			x	
	Unsteady supply of feeds		x					
Sea level rise					x	x		x
Increased precipitation	Pollution (effluents, nutrients, and chemicals)	x	x		x	x		x

of new species introduced through human activities, such as shipping (trade and leisure) and aquaculture (Hellmann et al., 2008) posing challenges and opportunities for the Blue Economy sectors. This development can be positive, when new species are valuable for human consumption and other purposes can form a new income for fisheries (Cheung et al., 2012; Heath et al., 2012) and aquaculture. Challenges as the spread of potentially invasive species, pathogens and disease vectors, can be an opportunity for growth in the blue biotechnology (Burge et al., 2014). Due to changes in atmospheric and ocean circulation patterns it is predicted that extreme weather events will occur more frequently and wind and sea conditions will intensify leading to stronger storms, storm floods and harsh sea conditions affecting the fishing sector as well as coastal and offshore infrastructures (Westlund et al., 2007). For instance, high waves and strong winds may reduce sea time and destroy infrastructures for mussel culture at sea (Westerbom et al., 2019). Ocean acidification has the potential to threaten especially mussel farmers, by reducing mussel stock in vulnerable stages (Callaway et al., 2012). Increased precipitation combined with anthropogenic activities, such as agriculture, may lead to an increased riverine runoff loaded with harmful substances, ranging from toxins, heavy metals to high nutrient concentrations (Lowe et al., 2009). These pollutants can contaminate wild and cultured fish and shellfish stock, making them unsuitable for human consumption, leading to economic loss for fishermen and aquaculture producers (Callaway et al., 2012).

Point of Departure

Metcalf et al. (2015) showed how the knowledge of representatives from communities could help in identifying components of adaptive capacity and vulnerability as well as act as potential enablers and barriers to the implementation of adaptations. The point of departure of this article is rooted in the assumption that climate change may already limit coastal communities in their ability and capacity to move into more transformative pathways toward a sustainable Blue Economy and Blue Growth state. In order to unlock the transformative potential, we investigated how stakeholders from important Blue Economy and Blue Growth sectors perceive the impacts of climate change on their daily work life and how they judge the prospects of future sustainable growth of the Blue Economy. Toward this end, we employed a case study approach focusing on stakeholders along Germany's North Sea coast. Coastal inhabitants, who directly interact with the marine environment, are often acutely aware of the changes happening in their surroundings (Döring and Ratter, 2017). The results within this study stem from two consecutive projects, which focused on the impacts of climate change on the local seafood sector and other Blue Economy sectors in the German North Sea region around the city of Bremerhaven. The goal of the projects was not only to collect data regarding the perceived effects of climate change (Hörterer et al., 2017) but also to foster bi-directional knowledge transfer between all involved actors (Hörterer et al., 2018) in order to increase their collective transformative capacity. The study, the workshops and interviews presented in this paper built on preceding extensive stakeholder mapping to identify key actors and knowledge holders in the regions and relevant sectors.

METHODOLOGY

As part of a two-stage approach, we first conducted two stakeholder workshops in order to capture the perceptions and knowledge of climate change and its impacts on the region and its population. The second stage consisted of a number of personal semi-structured interviews with representatives of Blue Economy sectors located in the region.

Workshops With Key Knowledge Holders From Science, Fisheries, Fish Processing, Authorities and NGOs to Exchange Knowledge on the Most Important Effects of Climate Change on the Environment, Society, Economy and Politics in the Region

For the first stage, we chose a workshop setting to facilitate a dialogue between all participants on an even level. The first workshop (WS1), was hosted at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven in June 2016 as part of the "European Maritime Day 2016" activities and was directed toward a selected audience of 13 key local knowledge holders from fisheries (n = 1), aquaculture (n = 1) and fish processing industry (n = 1), science (n = 7), NGOs (n = 1) and local authorities (n = 2). The key knowledge holders were identified and selected through their position within a company or organization. We contacted 43 persons via telephone or email of which 70% (n = 31) responded and 42% (n = 13) participated in the workshop. The second workshop (WS2), hosted as a part of the "YouMaRes 7" conference in Hamburg in September 2016, focused on early career scientists (n = 23; 2 Bachelor students, 7 Master students, 8 Ph.D. students, 3 students undefined, 2 scientists (MSc degree), and 1 first year PostDoc) from different research fields (biology, ecology, chemistry, and social sciences) in order to get an unbiased view on environmental topics and research issues without the influence of more experienced scientists. Furthermore, the prospective scientists from tomorrow show a greater interest in climate change, sustainability and transdisciplinary dialogue and should be listened to and be given a voice. This two-pronged approach emulates a longitudinal study using two focus groups from different age brackets and career stages in order to achieve a cohesive overview of knowledge and perceptions about climate change impacts. Both workshops used the World Café methodology to support knowledge exchange and formation of opinions (Brown and Isaacs, 2007). In WS1, the participants were seated in mixed groups, while these groups were arranged in order to facilitate discussion and communication within their group but also with all participants in the room. In WS2, the participants were seated in a loose circle facing the front, facilitation communication with the moderation and with each other. Short impulse talks by experts from science introduced the participants into specific topics on the effects of climate change on the environment to help participants reach a common baseline of knowledge. After each impulse talk, an open discussion round with all participants showed the perceptions toward the presented topics. During all talks and sets of discussions, the participants were asked to note issues of climate change that they perceived as important on file cards. In the final discussion and synthesis round the participants rated the issues by their personal perceived importance with points. Each participant was able to give a maximum of five points in total – giving either one point to five different issues or five points for one issue or anything in between. In the final step, the most important issues with three or more points were discussed jointly in the audience and related to field clusters they may affect. Those fields were (1) environment, (2) economy, (3) policy, and (4) society. The aim of WS1 was to gather the knowledge from a broad audience, thereby getting multiple perceptions from different viewpoints. By identifying and discussing possible effects of climate change, stakeholders were able to identify risks as well as opportunities, which may arise from climate change. The aim of WS2 was similar to WS1, identifying and discussing impacts of climate change, risks and opportunities. On this basis, strategies for environmental education and future research strategies were discussed. Additional data were collected by qualitative transcription of the discussions throughout both workshops and analyzed as part of this study.

Semi-Structured Interviews

In the second stage of this study, we conducted 25 face-to-face semi-structured qualitative interviews from September to October 2018 with actors from various Blue Economy sectors situated in the region of three coastal states of North–West Germany bordering the German bight (North Sea): Bremerhaven/Bremen, Lower Saxony and Schleswig-Holstein. We conducted a stakeholder mapping of companies associated with Blue Economy sectors located and acting in the study area. In order to get an equal representation of the perceptions and views within the companies and the sectors, we targeted interview participants that we could expect to have high level of knowledge about the company's efforts and a good overview over the sector's challenges and opportunities. We selected the participants due to their position within the company, being executive directors, company communications manager, and head of department. The distribution of the participants reflects the number of Blue Economy sectors in the study area. In total, we contacted 46 companies of which 67% (n = 31) responded and of which 80% (n = 25) participated in the interviews. All companies from aquaculture (n = 2), fish processing (n = 5), and consulting (n = 1) contacted, also responded and participated in the interview. The wind energy sector had the second highest response rate 73% (8 respondents out of 11 contacted), and four of the respondents participated in the interviews. In the fisheries sector three out of five responded and two participated. In both, the transport and biotechnology sectors, seven companies were contacted and four responded respectively, all respondents of the transport sector participated, whereas in biotechnology three participated. In the tourism sector four out of eight responded and all respondents were interviewed.

The semi-structured interviews were divided into three parts, with the aim of affirming and validating the topical findings of both workshops. Central herein was the focus on the perceived causes and impacts of climate change on the local social communities and the environment. Furthermore, we asked how climate change affects the Blue Economy sectors they are a part of, drivers and pressures enabling or restricting the growth of the Blue Economy. The second part addressed the issue of sustainable development of the Blue Economy in the face of climate change, climate change mitigation and globalization. Under this umbrella, we asked specifically for constraints and opportunities for sustainable growth on local, regional, national and international levels.

The most important outcomes from both workshops were summarized and presented to the stakeholders of the different Blue Economy sectors in individual interviews. From a selection of 14 environmental changes identified by stakeholder groups (see **Table 2**), they were asked to name those which they already experienced in their daily business and classify whether that change has a positive, negative, or neutral effect on their business. Effects were rated with no relevance (0%), low level of relevance (1–35%), moderate level of relevance (36–70%), and high level of relevance (71–100%). Effects, which have been evaluated by the majority of the respective group (always $\geq$ 50%) positively, have been marked green. Yellow field marks suggest that the majority of the group consider the respective outcomes as neutral. Red field marks implied that the majority have valued the respective ramification negatively.

Conceptual Model

In both stages of the study, we encountered a large and narrative rich knowledge base about climate change and its effects on the environment. We adopted the conceptual model approach from Tiller et al. (2016), in order to display the coherences of the effects of environmental change as well as political and social influences mentioned by the participants. We created the conceptual model using the Vensim (2015) software, displaying the coherences graphically by placing the topics in circles, and their respective size equals the perceived importance to the stakeholders. Topics perceived as more important are represented by larger circles. Causal conjunctions between different topics as experienced and perceived by stakeholders are displayed with arrows between topics.

RESULTS AND DISCUSSION

In the following, we present and discuss the effects of climate change on the environment, economy and socio-economy, and the political, societal and cultural issues mentioned and perceived by participants of the two workshops. We then present and discuss the effects of climate change on the Blue Economy, the perceived limitations and opportunities, which derive from climate change and within the Blue Economy enabling sustainable growth for the region. As the seafood sector, combining fisheries, aquaculture and fish processing industry, is of great importance for the region, we discuss in detail the

TABLE 2 | Climate change related environmental changes ranked by stakeholders from different sectors of Blue Economy in single interviews (*n* = 25).

Effects	Impacts	Seafood	Transportation	Coastal tourism*	Wind energy*	Biotechnology*	Total
Increase in sea surface temperature		Low	Low	High	Low	Low	Low
	Increase in biomass production	High	Low	High	Low	Low	Medium
	Toxic algal blooms	High	Low	High	No	No	Medium
	Geographic shifts of fish stocks	High	Low	High	No	No	Medium
	Migration of neobiota	High	Medium	High	Low	Medium	Medium
	Change in food webs	High	Low	Medium	No	Low	Medium
Extreme weather events		Low	No	High	High	No	Low
	Intensification of wind and sea conditions	High	High	High	High	No	High
	Flooding of coastal infrastructure	Medium	High	High	Low	No	Medium
	Coastal erosion	Medium	Low	High	No	No	Medium
Ocean acidification		Low	Low	Medium	No	Low	Low
	Decrease in fish and mussels stocks	Medium	Medium	High	No	No	Medium
Increased air temperatures		Low	No	High	No	Medium	Low
	Increased cooling requirement for equipment	High	Low	High	No	Low	Medium

*The level of relevance for the respective sectors are given as no (0%), low (1–35%), medium (36–70%), and high (71–100%). The perception of the environmental changes are marked green for positively, red as negatively results and yellow as not clearly neutral. Sectors with * are considered as Blue Growth sectors.*

implication for the seafood sector as well as for the other regional Blue Economy sectors.

Overall, in the study, all involved stakeholders are aware of climate change and perceive the impacts in their daily life, private or work related. The conceptual model (see **Figure 1**) visualizes the coherences between the issues perceived as important by the stakeholders involved in this study.

Effects of Climate Change on the German North Sea Identified in the Workshops

In the workshops, the participants mentioned in total 50 issues, which they felt related to climate change: 21 of them where mentioned by the senior practitioners (WS1) and 29 by the early career scientists (WS2), respectively. The allocation of these issues into the fields (1) environment, (2) economy, (3) policy, and (4) society showed some differences between the two workshops. Environmental issues were in WS1 as well as WS2 the most mentioned topic, with 62% (13) in WS1 and 55% (16) in WS2. Only the participants from WS1 mentioned economic issues with 10% (2) allocations. Policy issues were the second most important issue in WS1 with 19% (4) allocations and 10% (3) for WS2. Societal issues were of great importance for WS2 with 28% (8) allocations and with lesser importance for WS1 5% (1). In both workshops, 6% (3) of the mentioned issues were related to scientific practice.

Environmental Impacts

The major issue often raised by various stakeholder groups in both workshops pertained to the impacts of climate change on the biological, chemical and physical components of the marine

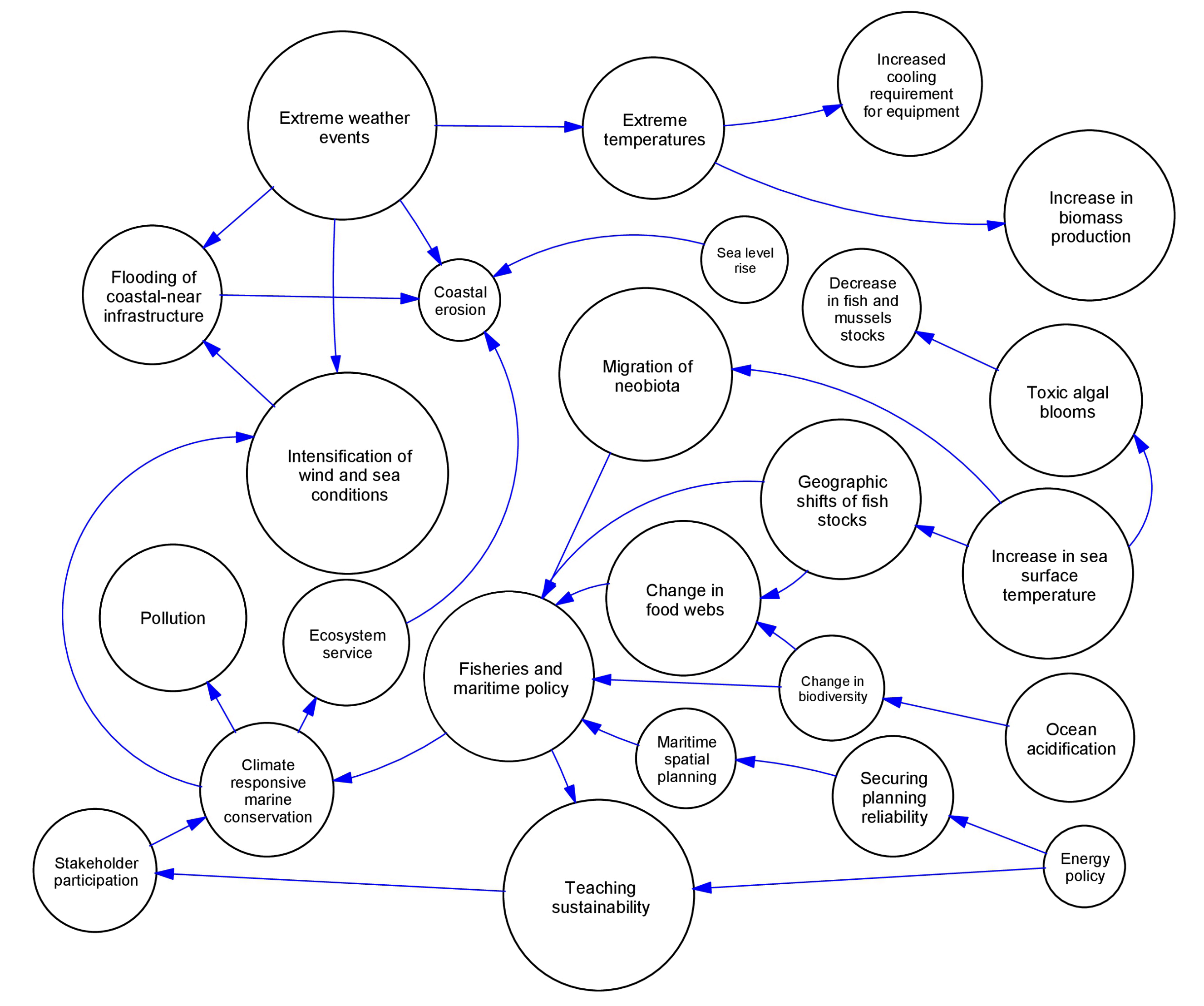

FIGURE 1 | Conceptual model of climate change induced environmental changes and socio-economic drivers as perceived by stakeholders of the Blue Growth realm transcribed from the workshops and interviews. Bubble size reflects importance. Created using Vensim.

environment. The participants identified the presently more frequent and more intense occurring extreme weather events as the most important issue affecting the natural environment and thus their work life. Scientists and practitioners were concerned that onshore, intertidal and subtidal habitats are being lost or degraded through a combination of climate change impacts and anthropogenic activities. Building measures such as dikes and other coastal protection to safeguard coastal populations from storm surges and increased wave heights may lead to a destruction of coastal habitats (on shore and intertidal). These coastal infrastructures may directly or indirectly restrict the natural movement of the habitats as response to rising sea level inland (Reise, 2005). For the aquaculture sector, in the German North Sea predominantly shellfish (blue mussel and pacific oyster), the participants voiced concern that these species will be affected by extreme warm water temperatures in summer and extreme cold water temperatures in winter, thus potentially limiting aquaculture production of these contemporary species as alternative future income option (Hawkins et al., 2013). Marine finfish aquaculture would be affected too (Callaway et al., 2012); however, to date finfish aquaculture is limited to the German Baltic Sea region. The main concern scientists have is that climate change is affecting the functional diversity of ecosystems. There are two scenarios; (1) that native species are declining in abundance or getting lost, so the functional diversity of the ecosystem is threatened; (2) the declining native species are replaced by new species either introduced by human activity vectors or migrated from the South to the North (Sorte et al., 2010). Representatives from science were also concerned about algal blooms caused by a combination of warmer water temperatures, eutrophication and new species with a great potential for forming blooms. The effect of algal blooms on the fisheries and aquaculture sector can be both, positive and negative. Greater availability of food in the ecosystem can increase the productivity of the system positively affecting fisheries and shellfish aquaculture production volume. On the other hand, harmful algal blooms can either reduce the productivity of fish stock and shellfish by toxins, or reduce the quality of shellfish, or the shellfish producers are not able to sell their products in certain months when toxic algal blooms may occur.

Early career scientists participating within the WS2 showed a different approach to the topic than the stakeholders of WS1 did. They perceive pollution with harmful substances (toxins, heavy metals and nutrients) of marine waters because of increased precipitation as an important issue. For early career scientists invasive species are seen as an important issue as climate change can facilitate the spread and settlement of new species. The representatives from seafood production and processing perceive the migration of southern warm adapted species to warming northern sea basin as both, positive and negative.

Economic and Socio-Economic Effects

Fishermen and representatives from the fish processing industry voiced concern about the price for raw fish, which is likely to increase in future due to the effects of a changing environment besides other factors. The participants from both workshops saw the livelihoods of local fishermen as well as of the coastal population employed in fish processing and tourism being critically threatened by environmental changes, as well as societal and political issues and framing. Additionally, the impacts on ecosystem goods and services providing value for the fish producing and processing sector as well as for tourism by a good environmental status were perceived as an issue on the economy and socio-economy along the North Sea coastline. More specifically, representatives from the fishing sector raised concern that the increasing frequency and strength of storms will affect the time on sea and therefore indirectly their income by more limited numbers of available fishing days. Furthermore, they raised the need to reconsider the contemporary design of fishing vessels, in order to adapt the design of ships to increasing strength and severity of storms and wave heights while providing work safety also under extreme conditions.

Policy Issues

Representatives from science and the fisheries sector concurred that fisheries policy and management has to adapt to climate change related shifts in the range of relevant species, both native and new species migrating north. Practitioners and scientists mentioned more flexible and faster adapting fisheries policy and management is needed to address the year-to-year changing distributions and abundances of commercially valuable fish stocks (Cheung et al., 2017). The participants argued that catch quota need to include new species to avoid a reducing effect on the total catch by "choke-species" such as cod and hake (Baudron and Fernandes, 2015; Mortensen et al., 2018) and to include new valuable species such as Sea bass and Red mullet (Brander et al., 2003). All participants from WS1 perceived a great need for marine spatial planning (MSP), taking the recent and future changes in the environment and ecosystem caused by a changing climate more strongly into account to avoid future conflicts between stakeholders and users. In the case of the German North Sea the needs of all actors, which use mobile resources (especially for fishermen), the range and abundance of target species and nature conservation interests need to be considered in future planning. Scientists and representatives from nature conservation agree on the implementation of marine protected areas (MPAs) as refuge for native species threatened by climate change. As aforementioned, all future planning for the use of marine areas, predicted changes in the abundances and species range under climate change need to be considered when new MPAs are planned or existing are going to be extended.

Societal and Culture Issues

Participants from both workshops agreed that society with all facets of employees, tourists, etc., need to adapt to the changing climate. Climate adaptation strategies for the sectors affected by a changing climate need to be developed. In the study area, climate adaptation strategies are developed and proposed for the state of Bremen (Koch et al., 2015) and for the metropole region Bremen–Oldenburg (nordwest2050, 2014). The participants from both workshops agreed that the efforts for knowledge transfer and education need to be intensified in all parts of society from early school onto third education schemes (i.e., into the curriculum of various science fields).

The early career scientists' group mentioned that local fishing communities have besides their economic value, also a cultural value from which especially the tourism sector is profiting. In northern Germany local communities developed 'integrated development strategies' for fisheries in 'Fisheries local action groups (FLAGs)' (AFW and COFAD, 2007; RegionNord, 2015; FBG and COFAD, 2016), targeting the integration of tourism, fisheries and climate change effects.

Climate Change Effects on Blue Economy: Limitations and Opportunities

In the interviews, 88% of the respondents (22 persons) stated that the major cause for climate change is attributed to anthropogenic activities. Furthermore, 76% (19 persons) defined specifically the emission of carbon dioxide as a driver for climate change. A correlation with natural climate change is mentioned by 36% of the respondents (9 persons). Intensive livestock farming and deforestation of rainforest are seen by 20% (5 persons) as a cause for climate change, respectively. Presenting the findings from the two workshops to actors from the Blue Economy in single interviews, they mostly agree and confirm the insights elaborated. The ranking of different environmental changes perceived by the different stakeholders in their realm are shown in **Table 2**.

Practitioners from sectors operating at sea, such as the wind energy, transport and seafood sector, are affected by increasing sea surface temperatures negatively, but the relevance of the impact is low. The tourisms sector will strongly benefit from warmer coastal seawater in summer attracting more tourists at the German beaches as an alternative to southern European destinations. The increase in biomass production and the subsequently increased fish biomass are of high relevance for the seafood and tourism sector, whereas the impact differs, not clearly negative or positive for seafood. Blooms of harmful microalgae, macroalgae and jellyfish have negative impacts for tourism fearing that the blooms deter tourists, when occurring close to the beaches. These blooms also have a high relevance for seafood, with mainly negative impacts, damaging fish and mussel stocks as well as decreasing the value of shellfish and other seafood products for human consumption. The geographic shift of fish and mussel stocks are of high relevance for the seafood and tourism sector, but the impacts are not clearly positive or negative. Representatives from the seafood and tourism sector perceive the changes in the North Sea food web as mainly negative because they fear that valuable native species disappear. The migration of neobiota and potential invasive species pose challenges and opportunities for the Blue Economy sectors. The maritime transport industry must focus on ballast water management, so non-native organisms are not transported as "stowaways" in the ballast water on ships worldwide and potentially become invasive species (Occhipinti-Ambrogi, 2007). Neobiota are of high relevance with negative impacts for seafood, if the new fish species have no or only small catch quota, or if low-value fish species replace high-value species. For the blue biotechnology industry neobiota pose the potential to develop new products in diagnostics for the detection of potentially invasive species, pathogens and disease vectors and thus to generate new revenues.

The respondents agreed with the findings from the first workshop that the increase in frequency and intensity of extreme weather events affects their sector, whereas the impact varied between the sectors. Respondents from the seafood and wind energy sector are mostly affected from intensification of wind- and sea conditions, affecting their activities on sea. As already mentioned by the participants in WS1, the representative from fisheries and aquaculture mentioned that high waves and strong winds may reduce sea time and destroy infrastructures for mussel culture at sea. The tourisms sector will not be affected strongly since cold temperatures and strong winds and storm mainly occur in the off-season, in winter. Ocean acidification threatens especially mussel farmers, by reducing mussel stock in vulnerable stages. This is also negatively affecting the tourism sector since locally sourced and produced seafood are attractive for tourists as they shape their perception of a viable waterfront at the coast.

Limitations for Sustainable Growth Within the Economic, Political and Societal Frameworks

Asking stakeholders from different Blue Economy sectors, which dimensions of sustainability (economy, society, and environment) are the limiting part in the sustainable growth of the company and the sector in general, 76% of the respondents named economical obstacles to be the greatest hurdle for sustainable growth. Societal and environmental obstacles play a similar role for 56 and 52% of the respondents, respectively. Sixteen percent of respondents saw no obstacles for sustainable growth of their company.

The representatives from fisheries and wind energy mentioned the spatial use conflict between the sectors as the main reason for limiting for sustainable growth. With the growing offshore wind energy industry available space for fishing becomes limited, since more space for offshore wind farms in the German EEZ is planned, where no others uses are allowed (BMVBS, 2009). Nature conservation interests add more pressure to the spatial use conflict between all actors. These conflicts are imminent for the German North Sea region, because the UNESCO world heritage site and national park Wadden Sea ranges along the entire North Sea coast from the Netherlands in the west, along the entire German North Sea coast to Denmark in the North. Protected areas, which are traditionally fished and used by the local fishing communities, may be closed for commercial and recreational fisheries (Carstensen et al., 2014). Most traditional fishing communities target coastal species such as flatfish, brown shrimp and mussels and are therefore most affected by restrictions in coastal waters. Additionally, respondents from the seafood sector hold a bad representation by nature conservationists in media. Another possible friction seen is the combination of tourism and transport sector. Cruise tourism is an increasing industry but the respondents are worried about the additional pollution coming from these vessels (Klein, 2011) adjoining to the pollution of cargo vessels in the harbors. Respondents from the single interviews emphasized the need of political and regulatory adaptations. Small and medium enterprises (SMEs) dread to promote for funding programs because of the administrative process, which is perceived as to complicated, obscure and too long.

Opportunities Between the Sectors to Enable Sustainable Growth

The respondents from the seafood and wind energy sector expressed that they themselves have a solution to spatial use conflicts and are asking for MSP, a tool to reduce use conflicts arising from the expansion of offshore wind energy, fisheries and other Blue Economy sectors (Douvere and Ehler, 2009). As mentioned by representatives of both sectors, multi-use of the space within the safety zones of wind farms for aquaculture of mussels and macro algae as well as for passive fisheries on brown crab might be an opportunity for enabling sustainable growth through spatial efficiency (Schupp et al., 2019). Interacting with the tourism sector in the region is perceived as an opportunity for these sectors as well. The traditional coastal fisheries and harbors are iconic for maritime environment and therefore important for the tourism sector. Locally produced and processed seafood is both beneficial for fishermen (Stoll et al., 2015) and tourism operators as it was shown for rural tourism (Sims, 2009). Likewise, the respondents from wind energy see the opportunity to present offshore wind farms as a tourist attraction and familiarize people with the technology and benefits of renewable energy. Respondents from the fisheries sector also see synergies with nature conservation, because the traditional coastal fisheries are also interested in the conservation of a functional environment, providing them with sustaining ecosystem goods.

Implications for Fostering Sustainable Growth in the Blue Economy

All addressed stakeholders were aware that political processes to change regulations and implement adaptation strategies take up to 10 years or longer. This makes short-term adaptations and measures difficult to implement, and long-time investments risky to plan. Additionally, short-term changes in societal and political trends on international, national, and regional levels within the slow moving political processes may interfere with sustainable growth and climate adaptation strategies on local levels.

For the practitioners in the Blue Economy sector climate change is a fact and they are willing to take measures for adaptation, transformation and mitigation. In order to achieve sustainable growth, all enterprises and especially SMEs are asking for reliable political framework conditions and low administrative obstacles to initiate new developments, also in cooperation with science, under the umbrella of sustainable development and innovation. Interestingly, senior scientist and experienced practitioners raised tangible physical, biological and economic issues and challenges as ways to adapt to climate change. Contrastingly, early career scientists mentioned mainly societal factors, asking for measures to stop climate change and to implement more sustainability in the Blue Economy and society. In order to implement sustainable growth of the Blue Economy in the face of climate change, we need to foster a better understanding of how climate, economic, societal and political developments interact with each other and on what time scales actions and transformations need to take place.

The stakeholders involved in the study are aware of climate change and its impact on the local environment. Practitioners from the German North Sea regions Blue Economy depend on various levels on a functioning ecosystem and future changes will have both negative and positive effects on the economy. Representatives from the seafood sector, including fisheries, aquaculture and fish processing, see threats and opportunities coming with a changing climate. For local fisheries, the geographical shift of species pose a threat to the income, if fisheries management and policy will not become more flexible in order to adapt to changing abundances of valuable fish species (Gaines et al., 2018). A shift in fish species caught in the area will also affect the fish processing, since machines for processing are mostly adapted to certain species. Therefore, an increased financial effort will be necessary to adapt the processing to new species. As mentioned by the participants of WS1 the ships design needed to be adapted to future sea conditions, with higher waves and stronger storms in order to retain sea time for fishing (Cheung et al., 2012). Here the participants also saw a need for cooperation between enterprises and science to integrate predictions of climate change impacts and ship design.

All the interviewed companies in the seafood sectors (n = 9) have already or are in the process of implementing strategies for sustainable development and climate change mitigation and are hoping to achieve a competitive advantage compared to international competitors. Most of them do not see climate change as an urgent threat. Many participants mentioned that international competition and globalization in the Blue Economy sectors pose a greater immediate threat for a sustainable development of the seafood sector in the area. A strategy small-scale fishermen and fish processors are following, is increasing the value of the seafood products through local processing and marketing in the region. In the integrated development strategies for fisheries of coastal communities along German North Sea coast, synergies between fisheries, fish processing and tourisms are clearly mentioned as a future way to keep coastal communities culturally and economically viable (AFW and COFAD, 2007; RegionNord, 2015; FBG and COFAD, 2016).

Environmental changes related to climate change are already affecting or will affect the different surveyed sectors in the future. These changes are in a certain way predictable, the pace of change is relatively slow, and continuously, so the different sectors may adapt to these changes, with or without the help of politics. Other issues not related to climate change, such as political decisions and anthropogenic activities are affecting sustainable growth much faster and stronger. These interactions and dependencies of environmental changes and socio-economic drivers as narrated by the participants of the workshops and interviews and are visualized as a conceptual model in **Figure 1**. The conceptual model shows in complex social-ecological systems ecological factors influence and are influenced by social, economic and political factors.

A major concern mentioned by the practitioners in WS1 and in the interviews was that political decisions and developments are less predictable, occur in shorter time scales and have a greater impact on the sectors than the slow progress of climate change. The Brexit vote and its long-lasting negotiations pose an uncertainty especially for the seafood sector since British waters are fished by different EU-countries, including Germany (Defra, 2019). Additionally, other anthropogenic activities, like dredging of rivers for shipping pose a great threat for locally produced shellfish and tourism through increased sediment load and turbidity of the waters (de Jonge, 2000). This may become one reason of declining blue mussel production in the region before increasing sea surface temperatures and ocean acidification. In the future, actions at sea would have to be coordinated differently implementing MSP (Douvere and Ehler, 2009), securing common ocean space for the users (Childs and Hicks, 2019).

CONCLUSION

Despite the observed increase in contested science findings and ongoing societal polarization, the actors in the local Blue Growth and Blue Economy sectors show a strong consensus that climate change is real, happening and affecting local communities in their daily livelihoods. Additionally, they are aware that sustainable growth derived from marine resources also make it mandatory that they are at the same time not depleted and preserved for the following generations. Most stakeholders see the ocean as natural capital and especially for the coastal communities involved in traditional sectors such as the small-scale shrimp and mussel fisheries and coastal tourisms the ocean is providing livelihoods. Fostering climate change adaptation and mitigation through further financial support from the government alongside with the development of novel strategies for the development of local sustainable livelihoods will ensure economic viability of the Blue Growth and Blue Economy sectors in the German North Sea region. However, other drivers like national and international political developments and other anthropogenic activities might interfere with the quest for long term transformative planning, since the current fast pace of observable changes in the environment may strongly differ from those in society and politics. Therefore, decision-making processes in politics and economics need to be faster, more flexible but at the same moment exhibit resilience in future proofing their planning. Fostering networks between practitioners, scientists and political decision makers will help both the Blue Economy and Blue Growth sectors to position themselves well for the future and increase adaptive capacity through increased knowledge sharing.

The study shows that the two cohorts of scientists address climate change effects differently. It is noteworthy that younger scientists place a large importance on the inter- and *trans*-disciplinarily of research approaches as well as on teaching sustainability, especially to younger generations. This observation is very much reflected in the recent "Fridays for Future" movement, where young people are increasingly calling for stronger measures from politics to stop the accelerating climate change to sustain a livable future earth. Sustainability means to meet the current generations' needs while sustaining the ability of future generations to do the same. Future generations are exactly asking for this, and we, the scientific community and citizens of the Earth need to follow this call.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

This project was exempted from ethics approval in accordance with the regulations of the German Research Foundation (DFG) and the Council for Social and Economic Data (RatSWD), as all collected information was anonymous and non-sensitive and participants are not identifiable. Participants were explicitly informed about and consented to the aim of the study, the methodology and about what data will be collected, processed, stored and published. All data were collected, stored and processes in compliance with the General Data Protection Regulation (GDPR).

AUTHOR CONTRIBUTIONS

CH is lead author, conceptualized and designed the study, wrote and reviewed the manuscript, and prepared it for submission. MS and AB conceptualized and designed the study, conducted the research, provided input to introduction, methodology and results, and reviewed the manuscript. DN conducted the research, provided input to the introduction, methodology and results, and reviewed the manuscript. GK provided input to introduction, methodology and discussion, and reviewed the manuscript. BB conceptualized the study, provided input to introduction, methodology and discussion, and reviewed the manuscript.

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Responding to Climate Change: Participatory Evaluation of Adaptation Options for Key Marine Fisheries in Australia's South East

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Planned adaptation to climate impacts and subsequent vulnerabilities will necessarily interact with autonomous responses enabled within existing fisheries management processes and initiated by the harvest and post-harvest components of fishing industries. Optimal adaptation options are those which enable negative effects to be mitigated and opportunities that arise to be maximized, both in relation to specific climate-driven changes and the broader fisheries system. We developed a two-step participatory approach to evaluating adaption options for key fisheries in the fast-warming hotspot of south-eastern Australia. Four fisheries (southern rock lobster, abalone, snapper, and blue grenadier) were selected as case studies on the basis of their high to moderate vulnerability to climatic effects on species distribution and abundance. Involved stakeholders undertook a "first pass" screening assessment of options, by characterizing and then evaluating options. In the characterization step potential adaptation options for each fishery, contextualized by prior knowledge of each species' climate change exposure and sensitivity, were described using a characterization matrix. This matrix included: the specific climate vulnerability/challenges, the implications of each option on the fishery system as a whole, the temporal and spatial scales of implementation processes, and realized benefits and costs. In the evaluation step, semi-quantitative evaluation of options was undertaken by stakeholders scoring the anticipated performance of an option against a pre-determined set of criteria relating to perceived feasibility, risk (inclusive of potential costs), and benefit. Reduction of the total annual commercial catch as well as reductions in both effort and catch through spatial and temporal closures were the options scored as having the highest level of expected benefit and of feasibility and the lowest level of risk of negative outcomes overall. Our screening assessment represents a pragmatic approach to evaluate and compare support for and the effects of alternative adaptation options prior to committing to more detailed formal and resource intensive evaluation or implementation.

Keywords: adaptation options, climate change, commercial fisheries, evaluation, participation

INTRODUCTION

Climate-driven changes in the productivity and distribution of marine fish stocks targeted for commercial use are being observed and predicted globally (Cheung et al., 2009, 2010; Hiddink et al., 2015; Weatherdon et al., 2016). Secondary effects in fisheries in the form of changing fleet dynamics, fishing location choices, gear deployment, targeting and discarding behaviors, supplies to market and ultimately, social and economic returns from these fisheries, are increasingly evident (Michael et al., 2017; Senapati and Gupta, 2017; Stoeckl et al., 2017). This is particularly the case in marine warming "hot spot" areas (Dulvy et al., 2008; Pecl et al., 2014a; Caputi et al., 2016), such as Australia's south-eastern marine region where exposure to climate-driven changes and sensitivity, for a number of species, is high (Pecl et al., 2014c, 2019; Champion et al., 2019).

Planned responses to reduce the vulnerability of commercially important fish stocks and associated fisheries include increasing the resilience of fish stocks to the ecological effects of climate-driven changes and to fishing pressures (Szuwalski and Hollowed, 2016; Pratchett et al., 2017; Le Bris et al., 2018), as well as increasing the adaptive capacity of fishing industries and management systems to adjust to secondary effects of changing productivity and distribution (Aguilera et al., 2015). Such responses may vary in timeframe, spatial extent, degrees of change, and level of state agency or private actor involvement (Miller et al., 2018; Pecl et al., 2019). Hence, responses span both public domains (i.e., public agency management of fisheries) and private interest domains (i.e., recreational and commercial fishery industries) and highlight the complex system properties of fisheries (Lehuta et al., 2016; Selim et al., 2016) and the need to apply a broader governance framework in order to optimize outcomes of adaptation responses (Dutra et al., 2019).

Coordinating adaptive responses across this spectrum of decision and action domains is an increasing requirement of fisheries management and marine governance more broadly. "Mainstreaming" the full array of planned adaptation responses requires that both non-state (i.e., resource-user)-led and public management agency-led adaptation responses are evaluated for their robustness to uncertainty, their capacity to achieve management objectives (Jennings et al., 2016) and the potential for unintended knock on effects (including those leading to maladaptation). Additional planning and assessment processes are necessary for enabling adaptation pathways for managed fisheries (Plaganyi et al., 2011; Leith et al., 2013; Lindegren and Brander, 2018). Mechanistically, these processes include multiple, and potentially iterative, stages of description and evaluation of climate challenges and adaptation options prior to selection and implementation (see **Figure 1**, which incorporates Moser and Ekstrom's (2010) model of adaptation processes). In terms of scope these additional adaptation planning processes require the following:

- A long-term temporal focus to incorporate changing climate effects and the feedback effects of a series of interacting adaptation responses (Wise et al., 2014), as well as transformative options (Kates et al., 2012).
- A social-ecological system conceptual focus to capture the interactions between pressures and primary and secondary responses of the linked ecological and social sub-systems (Leith et al., 2013).
- A multi-stakeholder focus to incorporate a diversity of both public and private sector responses (Miller et al., 2018) and enable co-production of the evaluation of adaptation options by scientists, managers, fishers, and other directly affected stakeholders through participatory and deliberative processes (Stöhr et al., 2014).

Increasingly, integrated assessment frameworks are being developed which incorporate the steps of identifying alternative management options within vulnerability assessments [for example, see Brugère and De Young (2015)]. However, these frameworks have not included formative evaluation of identified options or sets of alternatives. Within the body of adaptation science, a limited number of empirical studies involving forecast assessments of adaptation response options aiming to addressing climate vulnerability in fisheries have been undertaken [examples include: Koehn et al. (2011), Fleming et al. (2014), Pratchett et al. (2017), Blair and Momtaz (2018), Miller et al. (2018), and Young et al. (2019)]. The range of analytical methods applied to assess adaptation options for fisheries includes:

- Qualitative criteria-based assessment, in which criteria are typically normative and drawn from social-ecological systems resilience framework and assessment is based on categorical scoring, such as presence/absence – for example, see Ojea et al. (2017).
- Semi-quantitative criteria-based assessment, in which criteria are more typical of those used in formative evaluation techniques, such as feasibility and risk, and assessment is based on ordinal scoring of criteria (i.e., ranking or Likert scale) – for example, see Marshall et al. (2010).
- Quantitative, model-based simulation of a candidate management option to compare effectiveness at achieving management objectives, such as management strategy evaluation (MSE) – for example, see Castillo-Jordán et al. (2019).

Criteria used in qualitative and semi-quantitative assessments of adaptation options for social-ecological systems are typically highly generic (**Supplementary Table S1**) but specific measurement criteria concerned with spatial, temporal, and governance characteristics of adaptation options are not precluded. Quantitative assessments are resource-intensive – precluding assessment of multiple options or more transformative options – and limited to those options which are state agency-led and directed at achieving current fisheries management targets. Reliance on these evaluative methods alone for adaptation planning risks missing opportunities for optimal adaptation outcomes.

In this paper we describe a "first pass" method based on rapid assessment procedures (Beebe, 1995; Pecl et al., 2014c) which was developed to screen potential adaptation options for responding to vulnerability in marine species targeted

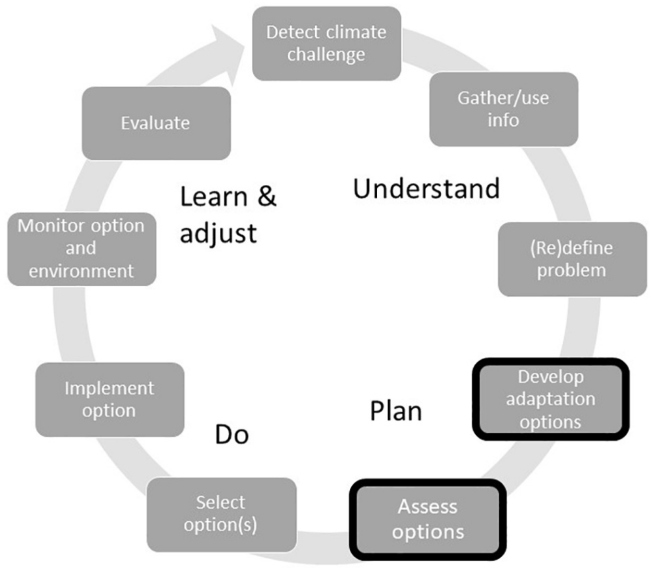

FIGURE 1 | Phases and subprocesses throughout the adaptation process [adapted from Moser and Ekstrom (2010): 22027)] as they apply to the fisheries adaptative management cycle. Highlighted boxes refer to the subprocesses the reported study addresses.

by commercial and recreational fishers. Preferred adaptation options can then be further evaluated using empirical or model-based methods. The two-step method draws on available risk or vulnerability assessments for the initial characterization stage and involves expert-informed semi-quantitative evaluation with key stakeholders from fisheries management agencies, industry, and science organizations. In a second step, semi-quantitative evaluation of options is undertaken by stakeholders scoring the anticipated performance of an option against a pre-determined set of criteria relating to perceived feasibility, risk (inclusive of potential costs) and benefit. The approach was designed to allow comparison of the relative preferences for alternative options between stakeholder groups (fisheries management agencies, industry and science organizations); and support social learning by participants through co-production and review of evaluations (Berkes, 2009; Leith et al., 2013). We report on the application of this method to four case study fisheries and assess the extent to which the method provides a pragmatic solution to the need to *ex ante* evaluate and compare the effects of a potentially large number of alternative responses of fisheries to climate driven changes.

We developed and tested this method as part of a larger study (Pecl et al., 2014b) in which current and expected key climate impacts were identified for four highly targeted marine species in south-eastern Australia. Climate driven challenges, barriers to adaptation, and adaptation options were elicited from industry and management agency experts. The four fisheries investigated were abalone (*Haliotis rubra and Haliotis laevigata*), blue grenadier (*Macruronus novaezelandiaei)*, snapper (*Chrysophrys auratus)*, and southern rock lobster (*Jasus edwardsii)*. In the broader study, results of a rapid biological sensitivity assessment (Pecl et al., 2014c) of the relative risk to climate change impacts on the four selected fisheries species were combined with data obtained through participatory and expert elicitation methods to identify likely key effects of climate change (see summaries of these effects in **Boxes 1–4**).

The south-eastern Australia region is a global marine warming hot spot (Hobday and Pecl, 2013; Caputi et al., 2016). The availability of early observations of climate-driven oceanic and biological change coupled with a history of planned adaptation and supporting stakeholder networks make such regions ideal cases for research to guide management in other locations (Frusher et al., 2014). Ocean warming over recent decades has been considerable (Hobday and Pecl, 2013), and the oceanography of the region is complex, with changes in the physical environment likely to be heterogeneous within the region (e.g., different between the eastern and southern coasts). Fisheries in south-eastern Australia are based on a wide range of species and involve a diversity of fishing methods; fisheries resources are utilized by commercial, recreational and Indigenous stakeholder groups leading to complex social considerations associated with resource access and equity. There are five marine jurisdictions within the region (four States and the Commonwealth) with different environmental and fisheries management legislation and systems; consequently, jurisdictional and political issues may complicate adaption. While species- and population-level responses and secondary effects vary markedly as a result of climate change, commonly occurring responses are evident: changed productivity; changed availability; disease expression; changed product quality; altered habitats; altered weather patterns; acidification; and indirect effects arising from changed availability of co-occurring target species. These properties provide optimal conditions for testing the "first pass" method developed.

BOX 1 | Summary of climate change impacts on abalone fisheries in south-eastern Australia (Pecl et al., 2014b).

Abalone have limited ability to cope with high water temperatures and increased acidification. Of the two key species caught in south-eastern Australia, blacklip (*Haliotis rubra*) prefer lower water temperatures and have lower thermal tolerances than greenlip (*Haliotis laevigata*). Abalone at locations with higher summer water temperatures have lower sizes at maturity and smaller maximum sizes than abalone at locations with cooler summer water temperatures. For blacklip, warmer water temperatures during summer were typically associated with lower blacklip catches (however, there were exceptions to this pattern). Relationships between greenlip catches and the oceanographic variables considered in this study were weaker than those for blacklip, but the general trend was for larger greenlip catches to have been obtained from areas with (1) slower tidal flow rates; and (2) relatively stable water temperatures with a low incidence of high summer, cold summer and cold winter temperatures. Greenlip catches have been smallest in areas with intense and lengthy summers and winters.

Determining the extent to which climate change may influence the Australian abalone stocks was challenging. However, abalone stocks and fisheries are likely to be influenced by three elements of climate change: (1) gradual increases in water temperature and ocean acidification; (2) increased frequency and magnitude of extreme events (e.g., marine heatwaves); and (3) range shifts and altered recruitment and growth rates of competitors and predators (e.g., range expansion of the long-spined sea urchin *Centrostephanus rodgersii)*. Collectively these changes are likely to result in reduced productivity and catches.

Summary:

- For blacklip abalone, the most likely outcome will be a reduction in total production – but with these changes being variable across space, less clear for greenlip abalone.
- Increased water temperatures likely to reduce larval development period, resulting in increased survival and decreased dispersal for both blacklip and greenlip abalone.
- Acidification may negatively affect the development of larvae, if they are unable to adapt to changes in pH.
- Increased acidification could reduce the availability of crustose coralline substrates for larval settlement and early development.
- Range shifts, altered recruitment and altered growth rates of competitors and predators likely to influence abalone production, in part through altered habitats.
- Increased frequency and magnitude of extreme events (e.g., marine heatwaves).

BOX 2 | Summary of climate change impacts on the blue grenadier fishery in south-eastern Australia (Pecl et al., 2014b).

The study involved an extensive review of current knowledge of the location and timing of spawning, larval life history and recruitment of blue grenadier because the production dynamics of this fishery are characterized by extreme variations in year class strength.

Analyses indicated a positive relationship between recruitment strength and wind strength in the autumn (i.e., just prior to the winter spawning period), and a negative relationship between recruitment strength and sea surface temperature during July to November (i.e., the spawning and larval development period in surface waters).

Predicted increases in sea surface temperature off western Tasmania may therefore have a long-term negative impact on average recruitment, while changes to the dynamics of wind strengths, although less certain from prediction models, could influence recruitment dynamics. Preliminary investigation of the link between recruitment dynamics and larval dispersal patterns (i.e., offshore vs. inshore dispersal/retention) also suggested that larval dispersal trajectories are likely an important influence on recruitment dynamics.

Climate change may influence recruitment dynamics of blue grenadier in uncertain ways. The performance of the current harvest control rule to various simulated scenarios of recruitment dynamics was tested. Importantly, the current harvest control rule proved suitable for preventing stock collapse under a range of recruitment dynamics. But the impact on stability/uncertainty of harvests and associated fishery economics was not formally evaluated.

Summary:

- Fishery characterized by highly variable recruitment.
- Recruitment success correlated with windy periods during autumn that create greater vertical mixing and cooler winter-spring Sea Surface Temperatures (SSTs).
- Relationship between oceanographic variables and other factors influencing productivity such as growth, mortality and migration largely unknown.
- Larval dispersal dynamics appears to be an important component of recruitment success.
- Potential negative effects on recruitment and therefore productivity.
- Potential change in dispersal patterns in relation to climate change is unknown; oceanographic projection models currently being developed may provide a useful tool for better understanding of potential changes.
- Increased SST poses greatest risk of the predicted changes through potential negative impacts on egg/larval development and survival.

MATERIALS AND METHODS

Data collection and preliminary descriptive analysis of results at the case study level were undertaken and reported as part of the larger study, *Preparing fisheries for climate change: identifying adaptation options for four key fisheries in South Eastern Australia* (see Pecl et al., 2014b for further details). Characterization and evaluation exercises were conducted at a series of stakeholder workshops held across 2012 and 2013. Stakeholders were members of the advisory or management communities for the four case study fisheries. This included policy and management staff from fisheries management agencies, research scientists, and commercial and recreational fisher representatives. Recruitment of committee members as participants in the characterization and evaluation of options activities was undertaken on the basis that the membership of the committees included a range of direct stakeholder groups (i.e., fishing representatives, policy and management agency staff, and fishery assessment scientists). In addition, the role of the committees was to consider adoption of the outcomes of the study as part of their broader function to provide advice to decision makers on options for managing the fishery and undertake any agreed co-management activities. Ethics approval was not required as participants were aged 18 or older and public representatives appointed to a Management/Fishery Advisory Committee. All workshop activities were conducted as activities within advisory committee meetings, which were administered by the fisheries management agencies in each case. This was consistent with the UTAS Social Sciences Human Research Ethics Committee's application of the Australian Code for the Responsible Conduct of Research. Workshop participants were informed of the characterization and evaluation activities prior to them taking place through the communication mechanisms used for the relevant committees, and then on the day prior to the activities themselves. Committee members were provided with the option to not participate prior to the characterization and evaluation activities taking place. Consent was therefore inferred from participant's decision to participate.

BOX 3 | Summary of climate change impacts on snapper fisheries in south-eastern Australia (Pecl et al., 2014b).

Throughout the broad latitudinal range of snapper around the Australian continental shelf, temperatures between 18 and 22°C were consistently identified as the optimal for spawning and survival of snapper eggs and larvae. Forecast modeling was conducted to assess how this optimal temperature window may change under climate change over the next 50 years.

There is high regional variability in predicted availability of water temperature is suitable for snapper spawning relative to historical patterns, or changes to the timing and/or length of periods of optimal spawning temperatures. While spawning behavior is intimately linked to water temperature regimes, the survival of the larvae and juveniles appears to be related to different climatic factors in different areas.

An additional set of factors in some regions are river flow and associated nutrient input regimes and plankton food chain dynamics, which in these regions are more critical in influencing larval survival rates and juvenile recruitment than water temperature alone. While changes to the overall time period of optimal spawning temperature are predicted to be minimal in these regions, there will be significant changes to the timing and continuity of the optimal period. This may affect migratory dynamics and will have important consequences for how spawning timing overlaps with the optimal periods of prey availability for the planktonic larval stages, with uncertain implications for recruitment dynamics.

Summary:

- Population dynamics strongly driven by inter-annual variation in recruitment.
- Interactions between SST dynamics and plankton productivity thought to affect recruitment success; however, there is no simple environmental/climatic relationship that is consistent across the broad geographic range.
- Predicted temperature increases likely to create adverse conditions for spawning/larval survivorship
- Predicted SSTs through central and southern New South Wales, Victoria (excluding Port Phillip Bay) as well as the northern and eastern waters of Tasmania will increase the period of optimal spawning conditions facilitating southern range extension and consolidation.
- Abundance and distribution changes to predators, competitors and prey will be key ecosystem factors affecting snapper. These may be positive or negative and are likely to vary across distribution.
- Current projected changes to weather patterns are not considered specific enough to predict impacts on access to open coastal water fishing areas, although the impacts are likely to be limited for sheltered water fisheries.
- Climate change predicted to reduce optimal conditions for spawning and larval survival in warmer areas and provide increased opportunities in south-eastern Australia, particularly northern and eastern Tasmania.
- Climate change likely to alter existing recruitment variability due to changes in SSTs and nutrient supply dynamics which are not currently well understood.

BOX 4 | Summary of climate change impacts on southern rock lobster fisheries in south-eastern Australia (Pecl et al., 2014b).

The study examined the effects of environmental variables on southern rock lobster (*Jasus edwardsii*) puerulus settlement across South Australia, Victoria and Tasmania, at monthly and annual scales. Monthly investigations aimed to identify environmental signals immediately prior to settlement while the annual analyses acknowledged the long planktonic larval phase (∼1 year).

There were no clear signals between environmental variables (current, wind speed, temperature and rainfall) and monthly puerulus settlement. However, within specific regions, signals were identified at the annual scale.

Overall, the results highlighted a number of environmental variables that impacted on settlement but these varied regionally. In addition, the explanatory strength of these variables was not strong, suggesting that other unknown processes also impact on settlement. As a result, it is difficult to predict the impact of climate change on rock lobster fisheries. However, given that puerulus settlement is highly variable between years, the impact of recruitment variability is important in relation to potential climate change scenarios.

Summary:

- Juveniles and adults live on rocky reef in a wide range of different marine communities.
- Climate change can potentially affect recruitment by altering patterns of larval dispersal and survival.
- Climate change effects more likely to impact recruitment during the larval development phase.
- A number of environmental variables impacted on settlement, but these varied regionally.
- Predicting impact of climate change is difficult, however, puerulus settlement is influenced by a complex set of environmental factors that expose the fishery to risks resulting from climate change.
- Climate change impacts likely to affect rock lobster predator/prey relationships.
- Increased rock lobster mortality through octopus predation has been identified during years with higher average water temperatures.

Potential adaptation options were identified at an initial workshop held for the four fisheries in March 2012 which involved 40 stakeholders from the combined committees [see Pecl et al. (2014b) for further details]. The initial list of adaptation options for each fishery was then reviewed and revised by members of the project team specializing in each case study fishery to reduce any redundancies or duplication and to link individual options to the specific climate challenges they addressed. The revised options for each fishery were validated with stakeholders participating in the characterization and evaluation activities for that fishery case study. This validation was undertaken via out-of-session committee procedures prior to the second and third rounds of workshop activities, held for each fishery case study throughout 2013 in conjunction with advisory committee meetings (Pecl et al., 2014b).

Characterization of Options

The objective of the second workshop activity in 2013 was to characterize adaptation options for each case study fishery. The purpose of the characterization exercise was to describe those characteristics which needed to be considered in the evaluation of the perceived risks, benefits and feasibility of each option, and in decision-making processes for fisheries more broadly. Adaptation options were analyzed during these activities using the purpose-designed adaptation characterization matrix (**Table 1**).

The characterization matrix was developed by the broader project's scientific working group on the basis of a review of typologies of adaptation responses to climate driven effects. Typologies included those developed on the basis of both empirically observed adaptation responses (Biagini et al., 2014) and conceptual frameworks for identifying types of adaptation options in planning exercises [for example, the resilience framework (Nelson et al., 2007) and the Exposure-Sensitivity-Adaptive Capacity assessment framework (IPCC,, 2007)]. Commonly used characteristics include the domain of adaptation activity (Biagini et al., 2014); the goal of adaptation; the degree of intent and planning

TABLE 1 | Characterization matrix used to identify the key attributes of adaptation options to specific climate-driven challenges.

Characteristic	Typology/Score
Degree of adaptation	• Autonomous (i.e., within range of existing adjustment responses by operators or managers, not requiring any collective or institutional change or approval) • Business-as-(mostly)-usual (i.e., a minor adjustment to an existing management or industry strategy) • Incremental • Transformative
Implementation	
Scale of application	National, State, Zone, Sub-zone
Jurisdiction/s	State, territory, or commonwealth
Significance of difference between jurisdictions	Low, medium, high
Lead time to implementation	<1 year, 1–5 years, >5 years
Who implements	Management, industry, research, multiple
Additional cost	Nil, low, medium, high
Who pays	Industry, government, consumers, post-harvest, local coastal communities
Level of controversy	Low, medium, high
Benefits	
Primary beneficiary	Fishers, fishery, fish stock, ecosystem
Scale of benefit	National, state, zone, sub-zone
Consequence period after implementation	<1 year, 1–5 years, >5 years
Addresses other climate challenges	List other challenges
Barriers	Individual barriers listed

Sources: *Lebel et al. (2006), Grafton (2010), Miller et al. (2010), Stafford Smith et al. (2011), and Wise et al. (2014).*

(Fankhauser et al., 1999; Adger et al., 2005; Grüneis et al., 2016); the type of agent and level of agency (Tompkins and Eakin, 2012; Sova et al., 2014; Bradley and Steele, 2015; Pecl et al., 2019); the degree of system change the adaptation would produce (Stafford Smith et al., 2011; Mushtaq, 2018); and the extent of path dependency between adaptation responses (Haasnoot et al., 2013; Wise et al., 2014; see **Supplementary Table S2**).

The degree of adaptation presented by an option was incorporated in the matrix by developing the following typology: Autonomous (i.e., options already within the range of existing adjustment responses by operators or managers, and not requiring any collective or institutional change or approval to implement); Business-as-(mostly)-usual (i.e., a minor adjustment to an existing management or industry strategy); Incremental (i.e., a major adjustment to an existing management or industry strategy but not a change to fundamental attributes); and, Transformative (i.e., a change to fundamental attributes or results in irreversible regime change of a system) (Stafford Smith et al., 2011; Mushtaq, 2018). A further characteristic, "Primary implementation stakeholder," was constructed in the data analysis stage based on a synthesis of the way in which implementation of an adaptation option was described under the "Who pays" and "Barriers" characteristics (**Table 1**).

The characterization matrix was circulated to participants prior to the second round of workshops, and then populated for each fishery with participants at the workshops. Descriptive statistical analysis was used to determine the proportion of adaptation options deemed to have specific characteristics.

Evaluation of Options

Semi-quantitative evaluation of adaptation options was undertaken by the same participants in the third round of workshop activities held in late 2013 by scoring the anticipated performance/outcome of an adaptation option against a pre-determined set of normative criteria and related indicators. Candidate criteria and indicators were identified on the basis of the review of literature (**Supplementary Table S2**). Criteria were then selected and refined for the fishery-specific context at a technical workshop in August 2013 with input from the broader project's scientific working group (**Table 2**). The three major evaluation axes selected were: Feasibility, Risk and Expected benefits [after Prober et al. (2011)]. A numeric rating scale was used to score indicators for each criterion (Colman et al., 1997). Participants in the third round of workshops collectively discussed then individually scored options on a scale of 1–5 for each indicator, where 1 = Less Feasible/Low Risk/Low Expected benefits and 5 = More Feasible/High Risk/High Expected benefits.

Evaluation was undertaken for all options for each fishery, however, evaluation results which could be used in the analysis were available for only a sub-set of options. Response rates were low for a number of options and for a number of fisheries due to the decision by some stakeholders to not evaluate their least preferred options and to low numbers of attendees at the committee meetings for some fisheries. Options with less than two responses for any of the stakeholder groups were deemed not suitable for further analysis in the study and excluded. Responses of "N/A" were treated as a non-score for the purposes of analysis. If more than one third of responses for a given indicator were N/A then the "Consensus" level was deemed to be "Unsatisfactory." Evaluation classes were developed for classification and interpretation of the results when combined and averaged for each stakeholder group (**Table 2**) and the results for each comprehensively evaluated option for each fishery were plotted for comparison.

Results were collated and analyzed by averaging the scores given by respondents for a given option for each indicator. Scores of all workshop participants and of respondents of a specific stakeholder group (i.e., fishing industry, managing agencies) were calculated to generate both a combined mean score and a mean score for each stakeholder group for each criterion. Results of the analysis of the evaluated options for each fishery were then compared to determine the extent of variation in the levels of assessed feasibility, risk, and expected benefits. This was undertaken to appraise the extent to which the evaluation criteria and assessment

TABLE 2 | The three major evaluation criteria selected: feasibility, risk, and expected benefits.

Criteria	Scoring system	Score range	Mean evaluation score class
1. Feasibility			
1.1. Cost of implementation	1 – 5, Lower score = less feasible, Higher score = more feasible	0.1–1.0	Negligible feasibility
1.2. Ongoing cost		1.1–2.0	Very low feasibility
1.3. Legal and procedural barriers		2.1–3.0	Low feasibility
1.4. Social and political barriers		3.1–4.0	Moderate feasibility
1.5. Need for additional skills, knowledge and expertise		4.1–5.0	High feasibility
2. Risk			
2.1 Failing to address climate challenge	1 – 5, Lower score = lower level of risk, Higher score = higher level of risk	0.1–1.0	No risk
2.2 Negative impact of action on biological sustainability of fish stock		1.1–2.0	Very low risk
2.3 Negative impact on wider ecosystem		2.1–3.0	Low risk
2.4 Reduced economic sustainability of the fishery		3.1–4.0	Moderate risk
2.5 Reduced fisher profit		4.1–5.0	High risk
2.6 Reduced employment			
2.7 Reduced social license to operate			
2.8 Limiting other adaptation options			
3. Expected benefits			
3.1 Benefit to biological sustainability of fish stock	1 – 5, Lower score = lower level of expected benefit, Higher score = higher level of expected benefit	0.1–1.0	No expected benefit
3.2 Benefit to wider ecosystem		1.1–2.0	Very low expected benefit
3.3 Benefit to economic sustainability of fishery		2.1–3.0	Low expected benefit
3.4 Benefit to fisher profit		3.1–4.0	Moderate expected benefit
3.5 Benefit to employment		4.1–5.0	High expected benefit
3.6 Benefit to overall fisheries management			
3.7 Benefit after implementation			

A numeric rating scale was used to score indicators for each criterion evaluation classes were developed for interpretation of the results.

rubric were sensitive to the different attributes of the options being evaluated. A summary analysis was also undertaken to compare the overall extent to which different stakeholder groups view various types of adaptation options by comparing the percentage of respondents from each stakeholder group who scored different evaluation classes for each type of option.

Analysis of the level of consensus between all respondents within and between stakeholder groups, as well as collectively, was undertaken by determining the percentage of scores for an evaluated adaptation option and criterion in each evaluation class. The following categories of consensus were used [after Lemieux and Scott (2011)]: High = 70% of responses in one evaluation class or 80% in two adjacent classes (i.e., "low" and "very low"); Medium = 60% of responses in one evaluation class or 70% in two adjacent classes; Low = 50% of responses in one evaluation class or 60% in two adjacent classes; and, None = Less than 60% of responses in two adjacent evaluation classes.

RESULTS

Across the four fisheries 100 adaptation options were identified to address the vulnerability arising from the following broad climate challenges: changed productivity; changed availability; disease expression; changed product quality; altered habitats; altered weather patterns; acidification; and indirect effects arising from changed availability of co-occurring target species (**Table 3**).

Characterization of Adaptation Options by Fishery

Climate challenges and associated adaptation options identified across the four fisheries reflected the specific drivers of climate vulnerability identified for each fishery as part of early stages of the project (see **Boxes 1–4**). For example, abalone as a sessile species is comparatively more exposed to higher rates of mortality associated with marine heatwave events and was the only species to specify productivity change due to mortality from thermal shock as a climate challenge (see **Table 3A**, climate challenge 1 and options 1a–1e). Reduced productivity from a broad range of drivers was identified as a climate challenge for all four fisheries (**Tables 3B–D**) however, for the snapper fishery, increased productivity was also identified due to a southward shift in distribution (**Table 3C**). Increased disease expression was another challenge identified for abalone, blue grenadier and southern rock lobster (**Tables 3A,B,D**) but not for snapper, which may reflect the large geographic range of and number of species (in addition to snapper) within this fishery, reducing its disease exposure.

For all four fisheries, adaptation options ranged from those characterized as autonomous adjustments by industry (2% of the total number of options), as business-as-(mostly)-usual (29%), as incremental (46%), to those characterized as transformative (23%) (**Figure 2**). Options characterized as transformative were identified for a range of broad climate

TABLE 3A | Summary characterization of adaptation options identified for abalone.

Climate Challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
1. Mortality from thermal shock (extreme events)	1. Locally (e.g., Actaeon Is. 2010)	1a	Reduce Total Allowable Commercial Catch, or TACC (by for example 30–40%)*	Business-as-(mostly)-usual	Management
	2. Regionally (e.g., South Australia Southern Zone 2013)	1b	Spatial management – catch controls	Incremental	Management
		1c	When forecast, bring harvest forward*	Transformative	Management
		1d	Closed season (within annual season)	Incremental	Management
		1e	Stock enhancement – selective breeding for thermal resistance	Transformative	Industry
2. Reduced productivity	1. Locally (block/area level)	2a	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
	2. Regionally (zone level)	2b	Spatial management – catch controls	Incremental	Management
		2c	Review Harvest strategy	Business-as-(mostly)-usual	Management
		2d	Stock enhancement – selective breeding for thermal resistance	Transformative	Industry
		2e	Translocation	Transformative	Industry
3. Biological changes	1. Changes in size at maturity	3a	Periodic review of biological parameters	Business-as-(mostly)-usual	Management
	2. Changes in growth rate, max size and weight	3b	Spatial management – variable Minimum Legal Lengths, or MLLs, and catch controls	Incremental	Management
	3. Changed time period from size at maturity to MLL	3c	Review Harvest strategy	Business-as-(mostly)-usual	Management
	3. Spatial and/or temporal recruitment changes	3d	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
		3e	Closed season (within annual season)	Incremental	Management
4. Disease expression	1. *Perkinsus*	4a	Design comprehensive biosecurity system	Incremental	Management
	2. Abalone Viral Ganglioneuritis or AVG	4b	Stock enhancement – selective breeding for disease resistance	Transformative	Industry
	3. Algal blooms	4c	Closed season (within annual season)	Incremental	Management
		4d	Spatial management – variable MLLs and catch controls	Incremental	Management
		4e	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
5. Product quality	1. Changed product characteristics	5a	Alter handling practices, including timing of fishing	Incremental	Industry
		5b	Vary/develop alternate products/markets for greenlip and blacklip	Incremental	Industry
		5c	Closed season (within annual season)	Transformative	Management
6. Altered habitats	1. Changed abundance of predators/competitors	6a	Undertake competitor/predator kills	Transformative	Industry
	2. Changed abundance of preferred algal species	6b	Fishery and product development [e.g., urchin (*Centrostephanus*)]	Transformative	Industry

(Continued)

TABLE 3A | Continued

Climate Challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
		6c	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
		6d	Spatial management – catch controls	Incremental	Management
		6e	Review Harvest strategy	Business-as-(mostly)-usual	Management
		6f	Habitat enhancement	Transformative	Industry
		6g	Closed season (within annual season)	Incremental	Management
7. Altered weather patterns	1. Changes to wind/swell patterns	7a	Prioritize fishing trips including fleet mobilization*	Incremental	Industry
		7b	Increase use of mother boats*	Incremental	Industry
		7c	Change number of divers*	Transformative	Industry
		7d	Stop fishing to increase biomass (raise catch per unit effort)*	Transformative	Management
		7e	Carry quota across years (Tasmania and Victoria only)*	Transformative	Management
		7f	Flexibility in quota transfers*	Incremental	Management
8. Acidification	1. Changed larval development	8a	Reduce TACC (by for example 30–40%)	Business-as-(mostly)-usual	Management
		8b	Spatial management – variable MLLs and catch controls	Incremental	Management
		8c	Review Harvest strategy	Business-as-(mostly)-usual	Management

*Characteristics included are: climate challenge being addressed; degree of adaptation; and, key implementation stakeholder (inferred from combination of responses to "who pays" and "barriers"). *indicates evaluated options.*

challenges, including: changed productivity; changed availability; disease expression; altered habitats; and altered weather patterns. Transformative options included stock enhancement and development of new fisheries, products and product markets. The abalone fishery had the highest proportion of options characterized as transformative (31%) while in contrast, the southern rock lobster fishery had the lowest proportion (16%).

Implementation was primarily dependent on management agencies for 63% of the total identified options across all fisheries, while for 37% of the options industry was the primary implementation stakeholder. For the abalone fishery, this result differed as only 14% of options were dependent on industry stakeholders for implementation. In contrast, for the southern rock lobster fishery 47% of options were dependent on industry as the primary implementation stakeholder (**Figure 2**). Overall, options characterized as business-as-(mostly)-usual and incremental in terms of degree of adaptation were predominantly dependent on management agencies as primary implementation stakeholders (79% and 63%, respectively). Transformative options were predominately dependent on industry as the primary stakeholder (57%).

The adaptation options identified ranged across all the available categories of temporal and spatial characteristics for all four fisheries. Full results of the characterization of adaptation options are provided in **Supplementary Tables S3A–D**.

Evaluation of Feasibility, Risk, and Benefit by Fishery

For the abalone fishery, eight adaptation options in response to two climate challenges were available for evaluation based on sufficient levels of responses across the three stakeholder groups (**Figure 3A** and **Table 4**). In addressing the challenge of increased mortality from thermal shock, the option of an up to 40% reduction in the Total Allowable Commercial Catch, or TACC, (1a) was scored as having greater expected feasibility and similar level of risk and expected benefit ("high," "low," and "low," respectively) compared to the alternative option. In addressing the climate challenge to the abalone fisheries posed by altered weather patterns, all six adaptation options were scored similarly when responses of all stakeholder groups were combined, with none of the options being ranked above "low" in terms of level of expected benefit (**Figure 3B** and **Table 4**).

For blue grenadier three different adaptation options designed to address the climate risk of reduced productivity and availability (blue grenadier climate challenge 1) were available for evaluation based on sufficient levels of responses across the three stakeholder groups. Reducing the TACC scored highest ("high") in terms of feasibility, while in

TABLE 3B | Summary characterization of adaptation options identified for Blue grenadier.

Climate challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
1. Changed productivity and/or availability	1. Smaller than anticipated spawning stock biomass, or SSB	1a	Reduce TACC*	Business-as-(mostly)-usual	Management
	2. Changes in recruitment (magnitude, frequency)	1b	Reduce effort	Incremental	Management
		1c	Adapt gear to reduce impact on juveniles	Incremental	Industry
		1d	Improve larval survival	Transformative	Management
		1e	Harvest alternative species	Incremental	Industry
		1f	Temporal or spatial closure for juveniles*	Incremental	Management
		1g	Extend quota period*	Incremental	Management
2. Spawning Biomass Changes	1. Changes in timing of spawning	2a	Improved fish finding technology	Incremental	Industry
	2. Changes in density (spread of SSB)	2b	More smaller vessels to find fish	Transformative	Industry
	3. Changes in location (depth/area)	2c	Shift timing/location of operations	Incremental	Industry
		2d	Spatial management/assessment	Incremental	Management
3. Biological changes	1. Changes in size at maturity	3a	Periodic review of biological parameters	Incremental	Management
	2. Changes in growth	3b	Adapt assessment accordingly	Incremental	Management
4. Disease expression	1. Disease expression	4a	Design comprehensive biosecurity system	Transformative	Management
5. Product quality	1. Changed product characteristics	5a	Alter handling practices, including timing of fishing	Business-as-(mostly)-usual	Industry
		5b	Develop alternate products/markets	Incremental	Industry
6. Altered habitats	1. Changed abundance of predators/competitors/prey	6a	Periodic review of biological parameters	Incremental	Management
		6b	Adapt assessment accordingly	Incremental	Management
		6c	Reduce/increase TACC	Business-as-(mostly)-usual	Management
		6d	Review Harvest strategy	Incremental	Management
7. Altered weather patterns	1. Altered weather patterns	7a	Change frequency/duration of trips	Incremental	Industry

*Characteristics included are: climate challenge being addressed; degree of adaptation; and, key implementation stakeholder (inferred from combination of responses to "who pays" and "barriers"). *indicates evaluated options.*

terms of expected benefit, reducing the TACC and spatial or temporal closures both scored ("moderate") which was above the option of a 2-year quota period ("low") (**Figure 3C** and **Table 4**).

For snapper, the options available for evaluation based on sufficient levels of responses across the three stakeholder groups addressed the climate challenge of reduced productivity and availability (snapper climate challenge 1). The highest scoring adaptation option with regard to the level of expected benefit was to implement single cross-jurisdictional management, which was ranked as "high." However, this option was also ranked the lowest ("very low") in terms of feasibility (**Figure 3D** and **Table 4**). The adaptation option with the next highest level of expected benefit was to change seasonal fishing activities/methods, which was scored as "moderate," however, as with single cross-jurisdictional management this feasibility was scored as "low."

For southern rock lobster, adaptation options to address two climate challenges were available for evaluation based on sufficient levels of responses across the three stakeholder groups; reduced productivity (southern rock lobster climate challenge 1) and altered ecosystem – increased octopus predation (southern rock lobster climate challenge 3). For reduced productivity all three options were scored quite similarly, with all options scoring "moderate" for level of expected benefit. However, in terms of feasibility, reducing the TACC was scored "moderate" with the other options both ranked "low" (**Figure 3E** and **Table 4**). With regard to addressing the challenge of increased octopus-induced mortality, there were two evaluated options. Spatial closures was scored as having a

TABLE 3C | Summary characterization of adaptation options identified for Snapper.

Climate challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
1. Reduced productivity and availability	1. Northward extension of distribution is reduced	1a	Reduce targeted effort*	Business-as-(mostly)-usual	Management
	2. Timing of peak local abundance changes (local and regional)	1b	Shift fishing operations (regional)*	Incremental	Industry
	3. Negative effects on recruitment	1c	Change target species (local)	Business-as-(mostly)-usual	Industry
		1d	Change seasonal fishing activities/methods*	Incremental	Industry
		1e	Implement single cross-jurisdictional management/access arrangements across stock range (i.e., east stock)*	Transformative	Management
2. Increased productivity and availability	1. Southward shift in distribution – Tasmania	2a	Initiate research/monitoring program: Find out the origin of the new fishery – life history/movement/ecological impact, abundance research	Incremental	Management
		2b	Developmental fishery plan/fishery expansion plan	Business-as-(mostly)-usual	Industry
		2c	Establish new fishery	Transformative	Management
		2d	Implement restrictions (size/bag/gear etc.)	Incremental	Management
		2e	Implement single cross-jurisdictional management/access arrangements across stock range (i.e., east stock)	Transformative	Management
3. Altered habitats	1. Changed abundance of predators/competitors/prey	3a	Reduce fishing effort on snapper	Business-as-(mostly)-usual	Management
		3b	Shift fishing effort to other species	Business-as-(mostly)-usual	Industry
		3c	Alter fishing activities/methods	Incremental	Industry
		3d	Stocking of nursery areas	Transformative	Industry
		3e	Review management (harvest) of prey species	Incremental	Management
		3f	Implement control measures on pest species/new competitors	Incremental	Management
4. Declines in other associated target species	1. Increased targeting of snapper	4a	Reduce fishing effort on snapper	Business-as-(mostly)-usual	Management
		4b	Restrict transfer of effort to snapper	Business-as-(mostly)-usual	Management
5. Altered weather patterns	1. Reduction in freshwater flows	5a	Stocking of nursery areas	Transformative	Industry
	2. Local population decline	5b	Reduce fishing effort on snapper	Business-as-(mostly)-usual	Management
	3. Negative effects on recruitment	5c	Shift fishing effort across species	Business-as-(mostly)-usual	Management

*Characteristics included are: climate challenge being addressed; degree of adaptation; and, key implementation stakeholder (inferred from combination of responses to "who pays" and "barriers"). *indicates evaluated options.*

TABLE 3D | Summary characterization of adaptation options identified for Southern rock lobster.

Climate challenge	Specific climate effect	Option no.	Potential adaptation options	Adaptation degree	Primary implementation stakeholder
1. Change in productivity	1. Negative effects on recruitment	1a	Change/reduce TACC*	Business-as-(mostly)-usual	Management
	2. Timing of peak local abundance changes (local and regional)	1b	Adjust size limits	Incremental	Management
		1c	Seasonal/spatial closures	Business-as-(mostly)-usual	Management
		1d	Alter sector allocations (ie. reduce recreational share of resource)	Incremental	Management
		1e	Translocation*	Transformative	Industry
		1f	Stock enhancement*	Transformative	Industry
2. Biological changes	1. Change in distribution	2a	Finer spatial scale management	Incremental	Management
	2. Changes to timing and synchronicity of molting	2b	Seasonal/spatial closures	Business-as-(mostly)-usual	Management
		2c	Processor setting limits	Transformative	Industry
		2d	Develop holding technology (land based)	Incremental	Industry
3. Altered ecosystems	1. Increase in octopus predation (abundance)	3a	Seasonal/spatial closures to avoid using areas/seasons of high predation*	Business-as-(mostly)-usual	Management
	2. Increased predation/mortality (post release)	3b	Increase the take of octopus (bycatch/dedicated targeting)*	Business-as-(mostly)-usual	Industry
	3. Increase in on-board mortality through increases water temp	3c	Retain discarded species	Incremental	Industry
		3d	Gear technology investment	Autonomous	Industry
4. Disease expression	1. Increased frequency/intensity of toxic algal blooms	4a	Early detection and monitoring	Incremental	Industry
		4b	Spatial/temporal closures	Business-as-(mostly)-usual	Management
5. Altered weather patterns	1. Increase/decrease in suitable fishing days due to weather	5a	Allow multiple licenses on boats	Incremental	Management
		5b	Increase pot limits	Incremental	Management
		5c	Increase vessel size	Autonomous	Industry

*Characteristics included are: climate challenge being addressed; degree of adaptation; and, key implementation stakeholder (inferred from combination of responses to "who pays" and "barriers"). *indicates evaluated options.*

higher benefit, than increased take of octopus (**Figure 3F** and **Table 4**) while its feasibility was scored "moderate" for both and risk "low."

Level of Consensus by Fishery

For the abalone fishery, there was a high level of consensus within and across stakeholder groups for feasibility, risk and level of expected benefit (**Table 4**). The two exceptions to this were, firstly; the option of bringing the harvest forward in response to marine heatwave forecasts, for which the level of combined consensus was low for feasibility and high for level for expected benefit (all stakeholder groups deemed the level of expected benefits to be "low"); and, secondly; the option of increasing the use of mother boats to address the challenge of altered weather patterns, for which the combined consensus level was also low for feasibility but high for risk and level of expected benefit (both of which were scored as "low"). Overall, industry respondents generally scored options as having a lower feasibility and lower expected benefit than management and research respondents.

For blue grenadier, the level of combined consensus across all stakeholder groups was high for feasibility, risk, and benefit for each of the three adaptation options assessed (**Table 4**). This could be explained by the low sample size, or the single jurisdictional management arrangements for this fishery wherein the issues being faced are consistent in terms of management arrangements, industry participant and fleet characteristics, and research programs.

For the snapper fishery, the level of combined consensus was low for the feasibility of two adaptation options designed to reduce effort through spatial or temporal closures (**Table 4**). For

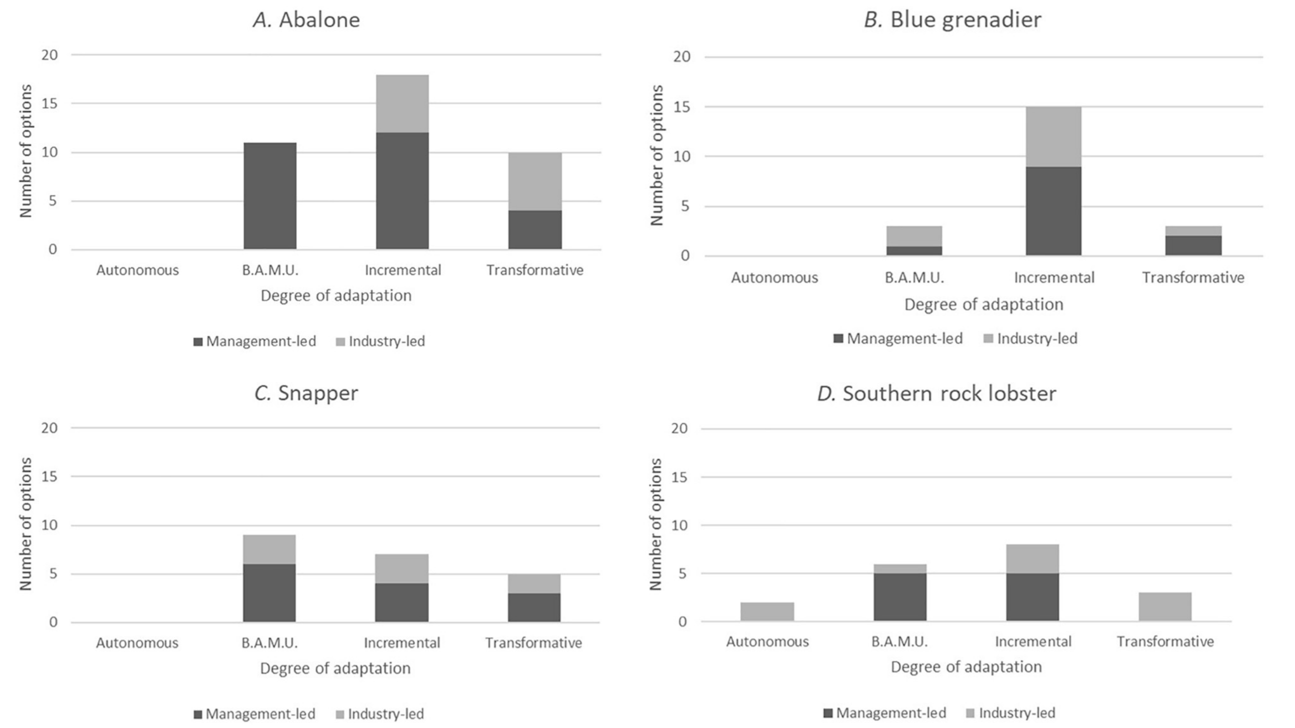

FIGURE 2 | Comparison of number of adaptation options for abalone **(A)**, blue grenadier **(B)**, snapper **(C),** and southern rock lobster **(D)** fisheries in south-eastern Australia by their summary characteristics: degree of adaptation and primary implementation stakeholder.

risk and level of expected benefit the level of combined consensus was either low or moderate for both options also. However, for the options of changing seasonal fishing activities/methods, and implementation single jurisdictional management arrangements, levels of combined consensus were generally medium to high.

For southern rock lobster, the combined consensus levels for feasibility and risk for all five options evaluated was moderate to high overall (**Table 4**). The notable difference in consensus was between the industry, management and research scores for the level of expected benefit of reducing the TACC by up to 40%, translocation and stock enhancement options proposed to address reduction in productivity. For the option of reducing the TACC both research and management respondents scored a "moderate" level of expected benefit, while industry respondents scored the level as "low." In contrast, for translocation and stock enhancement options, research and management respondents considered the benefit to be "low," whilst industry considered the benefit to be "high" and "moderate," respectively.

Summative Evaluation Across Fisheries

For the majority of adaptation options, feasibility was scored at moderate, and risk of negative outcomes and level of expected benefits were scored at low when scores for all stakeholders for each fishery were combined (**Table 4**). Combined scores for feasibility showed the greatest variation (30% of the twenty options were scored low for feasibility, 55% moderate and 10% high). In contrast, combined scores for risk of negative outcomes were low for 85% of the options. Combined scores for level of expected benefits were more widely distributed across the options (65% of options were scored low, 30% moderate).

Comparison of the averaged scores of commonly selected adaptation options across fisheries by the different stakeholder groups found few differences between groups. The option to reduce TACCs by up to 40% was selected for the abalone, blue grenadier and southern rock lobster fisheries. Research and management respondents scored the level of expected benefits from this option as moderate while industry respondents scored it as low (**Figure 4A**). For the same option averaged evaluation classes for feasibility and level of risk of negative outcomes were the same for all stakeholder groups (moderate and low, respectively), indicating higher levels of support for this option from research and management stakeholders overall. The option to extend the quota catching period was selected for the abalone and blue grenadier fisheries. Research and management respondents scored the level of feasibility of this option as moderate while industry respondents scored it as low (**Figure 4B**). For the same option the averaged evaluation class for level of risk of negative outcomes and of expected benefit was low for all stakeholder groups. The option to introduce additional seasonal or temporal closures was selected for the blue grenadier, snapper and southern rock lobster fisheries. Research, management and industry respondent scores of the level of feasibility, risk of negative outcomes and of expected benefit were the same for all groups (moderate, low, and moderate, respectively) for this option (**Figure 4C**).

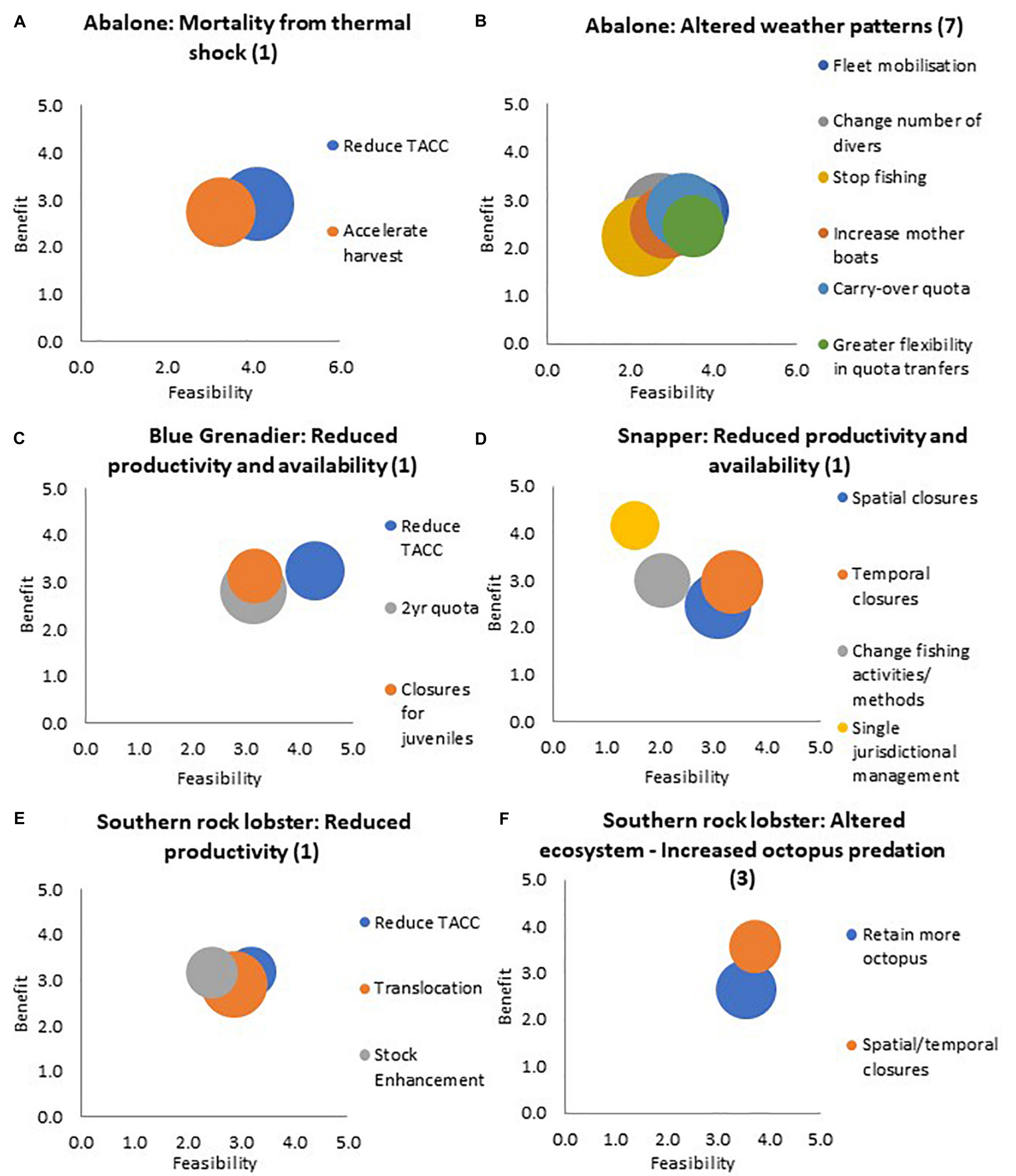

FIGURE 3 | Evaluation scores for level of expected benefit, feasibility, and risk of selected adaptation options addressing specific climate challenges for abalone **(A,B)**, blue grenadier **(C)**, snapper **(D)**, and southern rock lobster fisheries **(E,F)** in south-eastern Australia. The size of the bubble reflects the level of risk. The number in brackets refers to the broad challenge from the respective tables.

DISCUSSION

The nature and effectiveness of adaptation planning is strongly affected by the analytical approach to generating decision support to inform adaptation choices and coordination (Wise et al., 2014) and the evidence base for the system in question. Existing evaluative techniques are unlikely to be sufficient to support planning of optimal adaptation outcomes on their own. Qualitative assessments of adaptation options based on normative criteria are subject to participant biases and do not parameterize the technical effectiveness or efficiency of alternative options and this limits their value in assessing impact (Choy, 2014; Miles et al., 2014). Quantitative techniques, such as MSE, have high data requirements, presume linear cause-and-effect relationships and high certainty regarding management objectives and can therefore be less suitable for planning processes seeking to identify inter-temporal adaptation pathways (Haasnoot et al., 2013; Wise et al., 2014).

The semi-quantitative "first pass" screening method demonstrated in this paper was effective in distinguishing and comparing adaptation options for and across the four case study fisheries. The options ranged from those intended to decrease exposure of the fish stock to climate driven effects on productivity (for example, translocation and stock enhancement of southern rock lobster) to those designed to increase adaptative capacity/resilience of the stock (e.g., reduce the TACC) and socio-economic resilience of the fishing fleet (e.g., extending quota catching periods). The range of adaptation responses and implementation approaches that stakeholders revealed in the study reinforces the need for step-wise, structured and mixed-method techniques to support adaptation planning and coordination. The screening method demonstrated is not mutually exclusive of other established evaluative techniques as required by the complex and dynamic decision-making contexts confronted by fisheries management. For example, a semi-quantitative criteria-based assessment of a range of adaptation options could be used to select a smaller set of options for subsequent MSE, cost benefit analysis, impact assessment or equivalent evaluative analysis as required (e.g., Hobday et al., 2011).

Diversity of Adaptation Response Options and Adaptation Preferences

The options characterized for each fishery were found to vary in degree of adaptation (from autonomous to transformative), the lead and consequence period, and the type of stakeholder leading implementation (i.e., public, private and multi stakeholder). Implementation of a diversity of types of collective action at different levels and scales is more likely to engender a full array of climate adaptive properties necessary to sustain fisheries activity, notwithstanding potential maladaptation (Adger et al., 2005; Hobday et al., 2016; Ogier et al., 2016).

The study tested a method of screening a broad range of adaptation response options by characterizing options with reference to their attributes for addressing specific climate challenges, followed by semi-quantitative formative evaluation of options to enable comparison. However, comparison of the evaluation of all options was limited by the low levels of participation in the evaluation exercise by all groups. Only those options for which minimum required numbers of industry, management, and research stakeholders participated in the exercise are presented in this study. This limitation could be addressed in future applications to support more comprehensive comparison of the full range of options.

The sub-set of options evaluated were primarily those intended to adapt to changing productivity or availability of the stocks via a variety of mechanisms, inclusive of conventional fisheries input, and output controls applied to fishing catch and effort (such as TACC reductions, temporal or seasonal closures) through to quota system administration, early harvesting in the event of expected high heatwave-induced mortality, and stock enhancement. Reduction of the total annual commercial catch as well as reductions in both effort and catch through spatial and temporal closures were the options scored as having the highest level of expected benefit and of feasibility and the lowest level of risk of negative outcomes overall by management and research participants in the study. Industry participants scored these options lower in terms of level of feasibility and expected benefit overall in comparison to management and research participants, although the differences were low in degree. However, the limited range of scores for level of risk of negative outcomes across all groups and across all options indicates the need to increase the sensitivity of this evaluative criteria to support greater delineation and comparison of the level of risk posed by alternate options.

Participatory Evaluation and Its Limitations

Participation in the evaluation exercise by fisheries managers, research scientists, and representatives of industry allowed for *in situ* operational and local ecological knowledge of fishers to be considered alongside science-based evidence and model-based predictions. It further enabled measurement of the degree of consensus and level of potential conflict between stakeholders in the evaluation of adaptation options. For the majority of the adaptation options evaluated for the abalone fishery, industry members ranked benefit, and feasibility lower than management and research agency participants. This may have reflected industry members' skepticism of management agency-led adaptation options, or of the likelihood of any private benefit being generated. In contrast, industry members of the rock lobster fishery perceived higher levels of expected benefit arising from translocation and stock enhancement options, compared to management and research agency participants. These differences may highlight asymmetries in information, differences in risk tolerance or preferences for specific types of benefits (Nursey-Bray et al., 2012; Van Putten et al., 2015). In both fisheries, low levels of consensus highlight differences warranting further exploration and discussion. Analysis of the scores given for individual measurement criteria for feasibility, risk and expected benefit would support this.

The formative influence which participatory processes provide to participating stakeholders introduces a source of bias. The initial characterization of climate challenges and response options and the preferences and positions expressed in deliberative processes can determine the framing of adaptation possibilities (Haasnoot et al., 2013; Wise et al., 2014). In this study the small number of participants from each of the stakeholder groups (see **Table 4**) increased the likelihood of sample bias (Berk, 1983). In some cases, the small number of participants reflected the level of consolidation in the fishery – the blue grenadier fishery is managed under a single jurisdiction and the majority of catch is taken by a small number of large operators. In contrast, the snapper fishery is managed under multiple jurisdictions. The large numbers of commercial and recreational fishers that participate in this fishery would ideally necessitate a larger

TABLE 4 | Evaluation score classes and level of consensus within stakeholder group for selected adaptation options for abalone, blue grenadier, snapper, and southern rock lobster in south-eastern Australia.

Fishery	Climate challenge	Adaptation option	Stakeholder group	No. responses	Mean evaluation score classification			*Level of consensus within stakeholder group*		
					Feasibility	Risk	Benefit	*Feasibility*	*Risk*	*Benefit*
Abalone	1. Mortality event through thermal shock (extreme event)	1a. Reduce the TACC by up to 40%	Industry	3	Moderate	Moderate	Low	*High*	*High*	*Low*
			Management	3	Moderate	Low	Moderate	*Low*	*High*	*High*
			Research	3	High	Low	Low	*High*	*High*	*High*
			All (combined)	9	High	Low	Low	*High*	*High*	*High*
		1c. Bring harvest forward when forecast	Industry	4	Low	Moderate	Low	*Medium*	*Medium*	*High*
			Management	3	Moderate	Very low	Moderate	*Medium*	*High*	*Low*
			Research	3	Moderate	Low	Low	*Low*	*High*	*High*
			All (combined)	10	Moderate	Low	Low	*Low*	*Medium*	*High*
	7. Altered weather patterns	7a. Fleet mobilization – prioritizing fishing trips/areas	Industry	4	Low	Low	Low	*Medium*	*High*	*Medium*
			Management	3	Moderate	Low	Low	*High*	*High*	*High*
			Research	3	High	Very low	Moderate	*High*	*High*	*High*
			All (combined)	10	Moderate	Very low	Low	*High*	*High*	*High*
		7b. Increase use of mother boats	Industry	4	Very low	Low	Low	*Medium*	*High*	*Medium*
			Management	3	Moderate	Low	Low	*Low*	*High*	*High*
			Research	4	Moderate	Low	Low	*High*	*High*	*High*
			All (combined)	11	Low	Low	Low	*Low*	*High*	*High*
		7c. Change number of divers	Industry	4	Low	Low	Low	*High*	*High*	*Medium*
			Management	3	Low	Low	Low	*High*	*High*	*High*
			Research	3	Moderate	Very low	Low	*High*	*High*	*High*
			All (combined)	10	Low	Low	Low	*High*	*High*	*High*
		7d. Stop fishing to increase biomass & CPUE	Industry	3	Low	Moderate	Low	*High*	*High*	*High*
			Management	2	Very low	Low	Low	*High*	*Low*	*High*
			Research	2	Low	Low	Low	*High*	*High*	*High*
			All (combined)	7	Low	Low	Low	*High*	*High*	*High*
		7e. Carry quota across years	Industry	4	Low	Low	Low	*Low*	*High*	*Low*
			Management	3	Moderate	Low	Moderate	*High*	*High*	*High*
			Research	5	Moderate	Low	Moderate	*High*	*High*	*High*
			All (combined)	12	Moderate	Low	Low	*Medium*	*High*	*High*
		7f. Greater flexibility in quota transfers	Industry	3	Low	Low	Low	*High*	*Medium*	*High*
			Management	2	High	Very low	Low	*High*	*High*	*High*
			Research	2	Moderate	Low	Low	*High*	*High*	*High*
			All (combined)	7	Moderate	Low	Low	*High*	*High*	*High*
Blue grenadier	1. Reduced productivity/availability	1a. Reduce TACC by up to 40%	Industry	3	Moderate	Low	Moderate	*High*	*High*	*High*
			Management	2	High	Low	Moderate	*High*	*High*	*High*
			Research	7	High	Low	Moderate	*High*	*High*	*High*
			All (combined)	12	High	Low	Moderate	*High*	*High*	*High*

(Continued)

TABLE 4 | Continued

Fishery	Climate challenge	Adaptation option	Stakeholder group	No. responses	Mean evaluation score classification			*Level of consensus within stakeholder group*		
					Feasibility	Risk	Benefit	*Feasibility*	*Risk*	*Benefit*
		1f. Spatial or temporal closures for juveniles	Industry	3	Low	Low	Moderate	*High*	*High*	*High*
			Management	1	Moderate	Very low	Low	*High*	*High*	*High*
			Research	5	Low	Low	Moderate	*High*	*High*	*High*
			All (combined)	9	Moderate	Low	Moderate	*High*	*High*	*High*
		1g. 2 years quota period	Industry	3	Moderate	Low	Moderate	*High*	*High*	*High*
			Management	1	Moderate	Moderate	Very low	*High*	*High*	*High*
			Research	6	Moderate	Low	Low	*High*	*High*	*High*
			All (combined)	10	Moderate	Low	Low	*High*	*High*	*High*
Snapper	1. Reduced productivity and availability	1a. Reduce effort through spatial closures	Industry	3	Low	Moderate	Low	*High*	*Low*	*High*
			Management	2	Moderate	Low	Low	*High*	*High*	*Low*
			Research	4	Low	Moderate	Low	*Medium*	*Medium*	*Medium*
			All (combined)	9	Moderate	Moderate	Low	*Low*	*Low*	*Medium*
		1b. Reduce effort though temporal closures	Industry	3	Low	Moderate	Moderate	*Low*	*High*	*Medium*
			Management	2	Moderate	Low	Low	*Low*	*High*	*Low*
			Research	4	Moderate	Low	Moderate	*Medium*	*Medium*	*Medium*
			All (combined)	9	Moderate	Low	Low	*Low*	*Medium*	*Low*
		1d. Change seasonal fishing activities/ methods	Industry	3	Low	Low	Moderate	*High*	*High*	*High*
			Management	2	Low	Low	Moderate	*High*	*High*	*High*
			Research	4	Very low	Low	Low	*High*	*Medium*	*Medium*
			All (combined)	9	Low	Low	Moderate	*High*	*Medium*	*Medium*
		1e. Implement single cross-jurisdictional management arrangements across stock range	Industry	3	Very low	Low	Moderate	*High*	*Low*	*Low*
			Management	2	Very low	Low	High	*High*	*Low*	*High*
			Research	4	Very low	Very low	High	*Medium*	*High*	*Medium*
			All (combined)	9	Very low	Low	High	*High*	*Medium*	*Medium*
Southern rock lobster	1. Reduced productivity	1a. Reduce TACC by up to 40%	Industry	7	Moderate	Low	Low	*Medium*	*Medium*	*High*
			Management	4	Moderate	Low	Moderate	*High*	*High*	*High*
			Research	6	Low	Very low	Moderate	*High*	*Medium*	*High*
			All (combined)	17	Moderate	Low	Moderate	*High*	*Medium*	*Medium*
		1f. Translocation	Industry	3	Low	High	High	*High*	*High*	*Low*
			Management	1	Low	Low	Low	*High*	*High*	*High*
			Research	3	Low	Low	Low	*Medium*	*Medium*	*Low*
			All (combined)	7	Low	Moderate	Low	*Medium*	*High*	*Medium*

(Continued)

TABLE 4 | Continued

Fishery	Climate challenge	Adaptation option	Stakeholder group	No. responses	Mean evaluation score classification			Level of consensus within stakeholder group		
					Feasibility	Risk	Benefit	*Feasibility*	*Risk*	*Benefit*
		1e. Stock enhancement	Industry	5	Moderate	Very low	Moderate	*High*	*High*	*High*
			Management	4	Very low	Moderate	Low	*High*	*Medium*	*Medium*
			Research	6	Low	Low	Low	*Low*	*Low*	*Low*
			All (combined)	15	Low	Low	Moderate	*High*	*Medium*	*Medium*
	3. Altered ecosystem – Increased octopus predation	3a. Spatial and temporal closures	Industry	5	Moderate	Moderate	Moderate	*High*	*Low*	*High*
			Management	3	Moderate	Low	Moderate	*Low*	*High*	*High*
			Research	3	Moderate	Very low	Moderate	*High*	*High*	*High*
			All (combined)	11	Moderate	Low	Moderate	*High*	*High*	*High*
		3b. Increase take of octopus	Industry	0	N/a	N/a	N/a	*N/a*	*N/a*	*N/a*
			Management	4	Moderate	Low	Low	*High*	*Medium*	*Medium*
			Research	3	Moderate	Low	Moderate	*High*	*High*	*High*
			All (combined)	7	Moderate	Low	Low	*Medium*	*Medium*	*Medium*

number of survey respondents from the various jurisdictions, and also from the recreational sector, than the number who participated in this study.

Incorporation of Inter-Temporal Characteristics and Dynamic Adaptation Pathways

Temporal dimensions of the implementation and consequence of identified adaptation options were included in the characterization matrix. The extent to which an option also addressed other climate challenges facing that fishery was also included. However, together these characteristics did not address the inter-temporal properties of identified adaptation options, that is, the extent to which an option would affect what options would become available in the future (Wise et al., 2014). Examples of options which would have clear inter-temporal implications include options to change location of fishing operations or fishing gears used (snapper), or establishment of new managed fisheries (snapper) or of new products and markets (blue grenadier). Nor did the characterization matrix account for interactions between options if implemented at the same time, or for incorporating feedbacks which would require adjustment of both the characterization and comparative evaluation of options. These limitations together highlight the need for characterization and evaluation which supports dynamic adaptation pathways, or the sequencing of sets of possible adaptation actions "based on alternative external developments over time" (Haasnoot et al., 2013) in preference to the focus of this study on single options using static models of anticipated impact. However, the rapid assessment techniques applied in this study have the advantage of being repeatable with low resourcing requirements and so could be adapted to periodically re-evaluate the sequencing of sets of possible adaptations as the effects of previous adaptation responses are observed.

Integration Into Fisheries Planning and Management

The results of the evaluations have the potential to inform the further prioritization of options for more quantitative impact assessment, or MSE against management objectives, as required by public management agencies when considering changes to fisheries management settings (Grafton, 2010; Jennings et al., 2016). This potential would be strengthened by including further characteristics in the characterization matrix concerning the extent to which implementation of the adaptation option would be through existing or new management instruments. In addition, the specific evaluation criteria could be more closely aligned with any relevant management objectives or policy-based evaluative criteria.

The rapid assessment procedures and evaluative techniques applied in this study also have the potential to function as pre-feasibility assessments for industry stakeholders when prioritizing options for private sector adaptation strategies. The inclusive design of the study further supports improved awareness of industry-led adaptation responses and strategies and therefore, potentially, better coordination between public

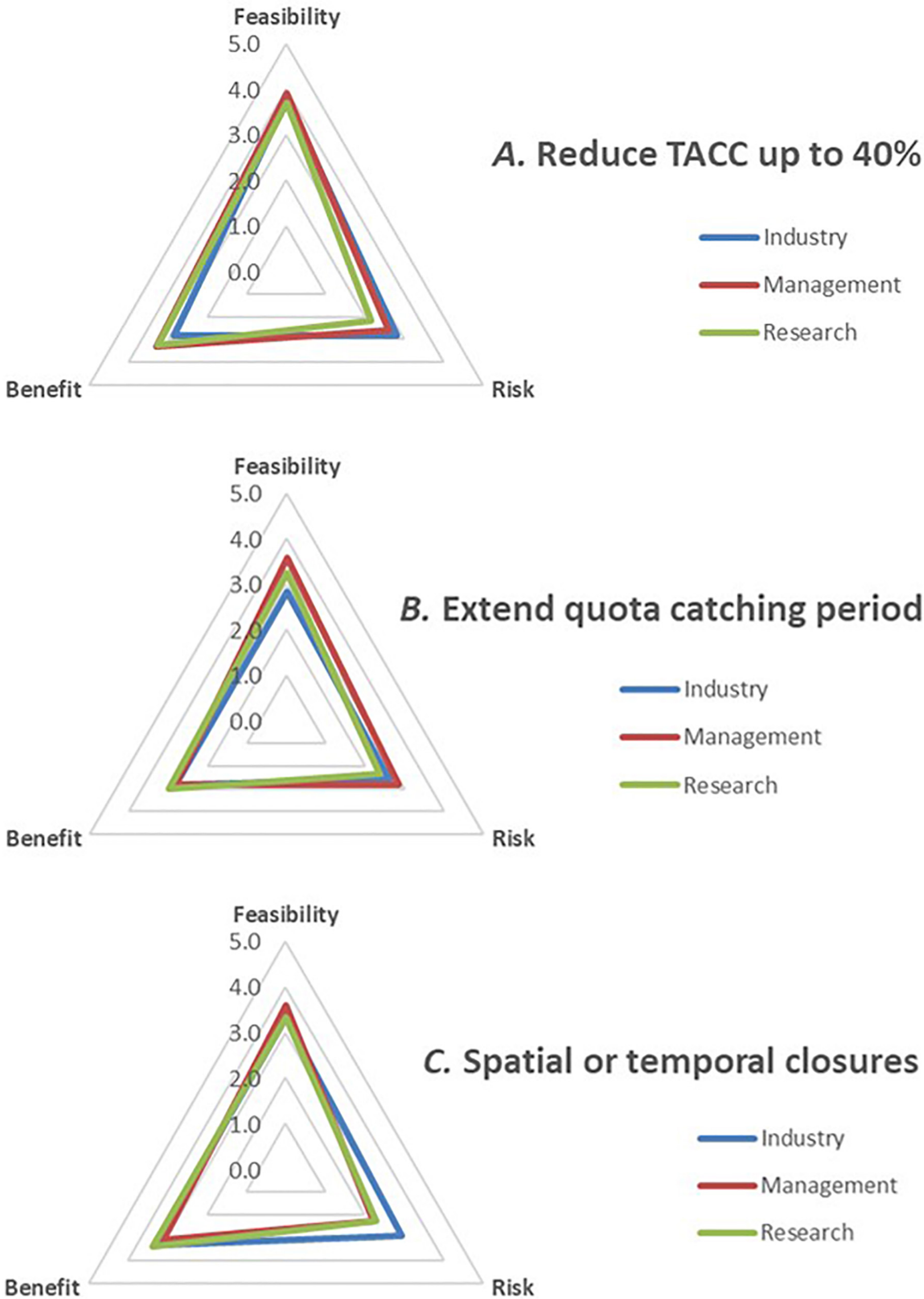

FIGURE 4 | Comparison of the evaluation by industry, management and research respondents of feasibility, risk, and benefit of three common adaptation options: Reduce TACC **(A)**; Extend quota catching period **(B)**; and Spatial or temporal closures **(C)**.

and private sector responses (Tompkins and Eakin, 2012; Gutiérrez and Morgan, 2017).

The additional planning sub-processes developed and tested in this study are directly relatable to existing fisheries adaptative management processes (Grafton, 2010; Lindegren and Brander, 2018) and could be incorporated into the initial impact pathway characterization and risk assessment stages of integrated ecosystem assessment exercises. Currently there is no formal requirement for public management agencies to undertake any type of climate adaptation planning (Creighton et al., 2015), so uptake of results or planning sub-processes is at the discretion of fisheries managers and industry representatives.

CONCLUSION

Adaptation planning in response to the increasing vulnerability of targeted fish stocks and affected communities to climate driven effects requires a range of analytical techniques to support decision making. Planning requires making choices between options that vary in degree of adaptation, level of private and public sector dependency, and inter-temporal effects in order to optimize outcomes. This study has demonstrated a two-step "first pass" rapid assessment screening technique in which 100 adaptation options for four fisheries in south-eastern Australia were characterized by the specific climate challenge they addressed, and the attributes of their implementation and consequence. Semi-quantitative evaluation of a selected sub-set options was effective in distinguishing between options on the basis of perceived level of feasibility, risk of negative effects, and expected benefit in responding to a specific climate challenge. Levels of consensus between scientists, fisheries managers, and industry representatives in evaluative scores was inversely related to the degree of adaptation proposed by an option. Managers and research staff preferred the significant reduction of total allowable commercial catches as an option as revealed by higher scores for the level of expected benefits compared with industry respondents. Benefits of this technique, therefore, include identification of – not only – differing preferences by stakeholder groups, but also of the basis of these differences. This function, in turn, supports identification and, potentially, resolution of points of conflict. While the techniques applied in this study were able to demonstrate the utility of "first pass" low-cost techniques, incorporation of further steps to identify and evaluate the implications of inter-temporal and distributional effects of implementing adaptation options is required.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

EO led the drafting of the manuscript. GP, SJ, PH, SF, SM, and AH contributed to the manuscript's development. EO, SJ, GP, AS, AH, and SF designed the characterization and evaluation methods. CM, PH, SM, TW, GT, AF, CG, AL, and AS contributed to the refinement of these methods. EO and AS undertook data collection and analysis. GP led the overall research project funded by the Fisheries Research and Development Organization (FRDC) on behalf of the Australian Government (grant number 2011/039), of which the results of this study are a part. GP led the project to assess key effects of climate change for the four species, results of which were used in this study. CM, PH, SM, TW, GT, AH, CG, SF, AF, and AL contributed to that assessment.

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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.2020.00097/full#supplementary-material

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Endogenous, Climate, and Fishing Influences on the Population Dynamics of Small Pelagic Fish in the Southern Humboldt Current Ecosystem

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There remains a lack of holistic approaches for analyzing how different density-independent and density-dependent (endogenous) mechanisms interact to drive the dynamics of the small pelagic fish populations of the southern Humboldt Current ecosystem. In this study, we analyzed the drivers of the small pelagic fishes (SPF) off the coast of Chile from the late 1980s until the early 2010s. We postulated that climate, fishing, and endogenous effects drove the biomass dynamics of these populations. Per capita growth rates (R models) were used to investigate how these factors regulated the dynamics of three anchovy populations and one population of common sardine (CS) off the Chilean coast. We found that the dynamics of the anchovy populations located off northern Chile were driven by endogenous components and by the effects of the climate, fishing, and the climate–fishing interaction. We proposed that during the study period, the climate conditions favored the population growth of the anchovies in the north; however, fishing had a negative effect on anchovy biomass, which was facilitated by the climate. The dynamics of the SPF off central-southern Chile showed weaker endogenous effects. Indeed, the anchovy population displayed the lowest density-dependent effect, and fishing played the most significant role. The endogenous effect on the CS was slightly higher in comparison to that on the anchovy; however, climate [sea surface temperature (SST)] seemed to be the main driver of the flourishment in the CS biomass following 2006, which supported the previous hypothesis regarding the effect of climate on the species. We discussed that the *R* models approach could be used to provide a holistic understanding of the drivers of the biomass dynamics of these populations. The approach provided a framework for integrating climate variability in the population dynamics of these species and moving toward an ecosystem approach to fisheries management. Further steps involve exploring the effects of competition and predation on the population dynamics of these species.

Keywords: Chile, anchovy, sardine, density dependence, temperature, effort, Southern Oscillation Index

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INTRODUCTION

Populations of small pelagic fishes (SPF) provide ∼25% of the total annual yield of fish capture worldwide and those of many coastal communities, particularly in developing countries (Alheit and Peck, 2019; Food and Agriculture Organisation [FAO], 2019). These populations experience extreme fluctuations in abundance and have a wide geographic distribution (Alheit et al., 2019).

The mechanisms causing fluctuations in SPF have received considerable attention worldwide (Alheit et al., 2009; MacCall, 2009; Alheit and Bakun, 2010). The general view is that the variations in population abundances are primarily steered by bottom–up controls, such as ocean temperature, upwelling, and plankton composition (Chavez et al., 2003; Alheit and Niquen, 2004; Ayón et al., 2008); top–down processes, such as intraguild predation and natural predators (Irigoien and de Roos, 2011; Checkley et al., 2017); and the intrinsic traits of the species (Checkley et al., 2017).

Small pelagic fishes support large-scale fisheries worldwide, and thus, the anthropogenic effect of fishing is also considered an important driver (Beverton, 1990; Essington et al., 2015). High exploitation rates have been associated with the decline in biomass production, accelerating the population collapses in SPF (Essington et al., 2015). Hence, maintaining high fishing rates at unfavorable climate phases may amplify the collapse of populations of SPF. In other words, fishing and climate act together in a synergistic manner. In addition, fishing exploitation is a highly selective process that produces the loss of older age classes (known as age truncation), which accelerates the collapse by decreasing the capacity of the population to adjust to climate variability (Anderson et al., 2008). In SPF, the effect is difficult to detect (Hay et al., 2019); however, a few examples exist. Cubillos et al. (2014) compared empirical observations and results from a simulation analysis and found that in *Strangomera bentincki*, mortality from fishing removes fast-growing fish or fish that recruit at younger ages. Therefore, the age structure is truncated, and as a consequence, slow-growing fish or late-recruiting fish are selected. In this way, fishing induces changes in the reproductive cycle, increasing the sensitivity of the population to climate variability, by either matching or mismatching the reproductive cycle with the favorable/unfavorable climate conditions for recruitment.

Density-dependent and density-independent factors are critical for the dynamics of wild populations (Lima et al., 2002; Stenseth et al., 2002; Belgrano et al., 2004), and a particular set of density-dependent factors is necessary to ensure the robust regulation of a population (Royama, 1992; Turchin and Taylor, 1992). Density-dependent processes also drive fish populations (Rose et al., 2001). This negative feedback control arises from the interaction between individuals competing for one or more resources, affecting population size through processes such as growth, survival, reproduction, movements (Rose et al., 2001; Berryman and Kindlmann, 2008), and cannibalism (Irigoien and de Roos, 2011). Hence, determining density dependence is an essential step in understanding population regulations and their responses to climate variability and exogenous perturbations (Royama, 1992). For instance, Lindegren et al. (2013) predicted that density-dependence regulation (competition) would be an essential factor during favorable sea surface temperature (SST) conditions with high levels of sardine spawning biomass. Similarly, Cahuin et al. (2009) found that density dependence was a component of the Peruvian anchovy dynamics during regimes that were unfavorable for anchovy (i.e., warm SST, weak upwelling, low zooplankton).

Two small pelagic fish species inhabit the southern Coast of Chile and Peru; anchovies (*Engraulis ringens*) and common sardine (CS; *S. bentincki*) are important species in regard of their ecological interactions and economic value. Both species accounted for 38.8% of all fish that landed in Chile in 2017 (SERNAPESCA, 2017). They are the dominant species in terms of biomass in the pelagic communities of the southern Humboldt Current ecosystem and vital species in the transfer of energy from plankton to higher trophic levels (Neira, 2008). In addition, these species aggregate into a small number of populations (Cubillos et al., 2007; Garcés et al., 2019). Several factors have been reported to influence the dynamics of SPF in the Humboldt Current system, such as ocean temperature, zooplankton, oxygen, plankton size structure, cannibalism, and fishing (Alheit, 1987; Chavez et al., 2003; Ayón et al., 2008; Bertrand et al., 2011; Essington et al., 2015; Canales et al., 2016). However, there is no holistic perspective on how different density-dependent and density-independent mechanisms interact to drive these populations. Understanding the underlying mechanisms controlling the biomass dynamics of anchovies and sardines involves disentangling the effects of interacting density-dependent/density-independent factors (Lindegren et al., 2013). Understanding such mechanisms is particularly useful in the context of an ecosystem approach to fisheries management (Link and Browman, 2014) and thus the sustainable exploitation of SPF in the southern Humboldt Current Ecosystem.

We examined key drivers of the biomass dynamics of a CS population and three anchovy populations off the Chilean coast from the late 1980s until the early 2010s. We hypothesized that the biomass dynamics of these populations over these decades were the result of the combined effects of density-dependent and density-independent factors, such as climate variability and fishing. We used a functional relationship between the realized per-capita rate of biomass change and the population biomass, which can be considered a general property of a dynamical system (Turchin, 2003), and we analyzed the effects of climate, fishing, and endogenous drivers in modulating the biomass dynamics of these species.

MATERIALS AND METHODS

Time Series

Small Pelagic Fish Data

The first anchovy population examined is distributed between southern Peru and northern Chile (APCH) between 16 and 24°S (**Figure 1**). The exploitation of this population expanded in the mid-1950s, with an average annual catch of approximately 1

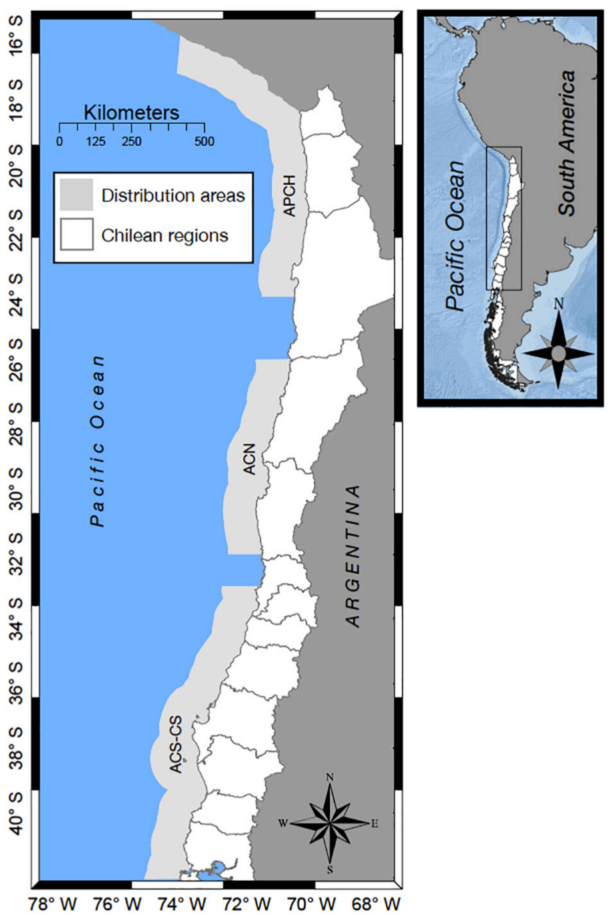

FIGURE 1 | Distribution of the small pelagic fish populations along the Chilean coast and the southern Peruvian coast. The first anchovy population (APCH) is shared between southern Peru and northern Chile (16–24° LS). The second anchovy population (ACN) is distributed along central-northern Chile (25–32° LS). The third anchovy population (ACS) and the common sardine (CS) population inhabit the area from 33 to 41° LS, which is known as central-southern Chile.

million tons (Canales, 2014). The second anchovy population studied was located off central-northern Chile (ACN) between 25 and 32°S (**Figure 1**), with annual catches of ∼30 thousand tons (Leal and Canales, 2014). The third anchovy population located between 33 and 41°S shared its habitat with the CS (**Figure 1**). Both species support a pelagic fishery in the area of 33–41°S with average annual catches of 700 thousand tons since 1990 (Zuñiga and Canales, 2014).

The biomass of these species was estimated with the catch at age-/length-integrated stock assessment models that are updated yearly by the Instituto de Fomento Pesquero (IFOP[1]). Data derived from acoustic biomass surveys were available only for a few years for these populations (**Supplementary Table S1**). Therefore, these data are short time series (e.g., ACN had only six observations) for the type of analysis, and the estimation procedure applies here (see section "Statistical Analysis"). In addition, the discontinuity within the time series and the lack of a consistent sampling window for all years are typical restrictions of the survey data (**Supplementary Table S1**). We used biomass estimates from the stock assessments, which may be less precise than independent biomass surveys but represent a long time series that allows the representation of a more general pattern in the population dynamics of anchovy populations and the CS. We describe the main characteristics and assumptions of the stock assessment models of the anchovy populations and CS off the Chilean coast, and their data sources in the **Supplementary Material**.

Environmental Data

We used the Southern Oscillation Index (SOI) as covariable to explore the climate effect on the population growth rates. The index registers SST fluctuations in the tropical Pacific related to the occurrence of El Niño. Monthly standardized annual SOI values were obtained at https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/. Positive values of SOI indicate the presence of cold conditions, such as La Niña-type conditions to normal conditions, and the negative values are indicative of warm conditions, such as El Niño. In addition to the SOI, the SST (°C) was used to analyze the impact of the climate on the SPF populations. SST data were obtained for the habitat of each population using the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder dataset[2] at a spatial resolution of 4 km from 1990 until the first half of 2007. From the second half of 2007 until December 2014, the SST (daytime and nighttime) data were obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) at https://doi.org/10.5067/MODSA-MO4N4. To make the SST data comparable, we corrected the SST from the AVHRR using a linear correlation between SST-MODIS and SST-AVRR that was obtained for the period 2003–2009, during which the SSTs from both sources overlapped. Linear correlations of the SSTs from AVHRR and MODIS for the three habitats yielded $R^2 = 0.99$.

Annual or semester averaged values of both climate variables (SOI and SST) were used to study the influence of the climate on the biomass dynamics of each population. The SST anomaly was used and calculated by subtracting the mean of the SST by the observed value for each period of the study. The environmental variables SOI and SST were correlated for each population [APCH-S1: $r = -0.38$; APCH-S2: $r = -0.49$; ACN: $r = -0.47$; anchovy population of central-southern Chile (ACS): $r = -0.51$; CS: $r = -0.64$]; therefore, we avoided including both climate variables in a single model. Early explorations of both climate indexes on the R model of the anchovies and CS led to SOI for the anchovy populations and the SST for CS. The SOI explained more of the variance of the R_t data than the SST did for anchovy populations, and the SST performed better for the CS. Previous authors (Cubillos and Arcos, 2002; Gomez et al., 2012) also identified significant correlations between the SST and CS (recruitment), supporting our chosen climate variable.

[1]www.ifop.cl

[2]https://data.nodc.noaa.gov/pathfinder/Version5.0/Monthly/

Fishing Data

The number of fishing trips was used as the unit of effort for measuring the fishing effect on the biomass dynamics of the fish. Fishing trips were selected because there was robust measurement of the fishing effort (Aranis et al., 2017) when more detailed effort information, such as duration of the fishing trip, is fragmentary, such as in the Chileans anchovy and CS fisheries. In all populations, the chosen fishing variables were the number of fishing trips (E), catches (C), the ratio between the annual catch and the biomass (exploitation rate), and the ratio between the annual effort and the biomass. In addition, for the ACS and CS populations, we tested the total number of fishing trips (E^{A+S}) and the total catches (C^{A+S}) of anchovies and sardine together.

Density-Dependent Effect Diagnosis

We assume that the population dynamics of SPF are the result of the combined effects of ecological interactions within species (endogenous effect), climate influences, fishing, and stochastic forces. To understand the influences of these factors on biomass fluctuations, density-dependent and density-independent effects can be modeled using R functions (Lima et al., 2008; Lima and Naya, 2011). These functions represent the realized per capita population growth rates (R_t) that reflect the processes of individual survival and reproduction (Berryman, 1999). The population growth rate at time t is defined as $R_t = \ln(B_t) - \ln(B_{t-1})$ and can be expressed as:

$$R_t = \ln\left(\frac{B_t}{B_{t-1}}\right) = \mathrm{f}(B_{t-1},\ B_{t-2}, .., B_{t-i}) \quad (1)$$

where B is the total biomass, B_{t-i} is the biomass in year t, and i represents the time lags (with i = 1,2,3) (Berryman, 1999).

The first step in the development of the statistical model was to estimate the order of the dynamical process (Royama, 1977) by analyzing how many lags (B_{t-i}) should be included in the R model to represent the density dependence or the endogenous effects. We used the partial rate correlation function (PRCF) between R_t and $ln\,(B_{t-i}) = X_{t-i}$ to explore the relative strength of the different parts of the feedback structure regulating the population dynamics (Berryman, 2001; Lima and Naya, 2011). PRCF is a useful diagnostic tool for making inferences about the structure of the density-dependence feedback processes that govern the population trajectory, but it is not a modeling tool (Berryman and Turchin, 2001).

Equation 1 was rewritten in natural logarithmic form to calculate the partial correlations as follows:

$$R_t = ln\left(\frac{B_t}{B_{t-1}}\right) = A + B_1X_{t-1} + B_2X_{t-2} + \ldots + B_tX_{t-i} \quad (2)$$

where R_t is calculated from the data, and X_{t-i} is the lagged population biomass.

Theoretical Models

To understand the fluctuations of the SPF biomasses, we assumed that R_t was influenced by density-dependent and density-independent effects, such as climate and fishing. The general model consisted of a simple exponential logistic equation (Royama, 1992) as follows:

$$B_t = B_{t-1}e^{\left(R_\mathrm{m} + \mathrm{b}B_{t-i} + \mathrm{c}C_{t-i} + \mathrm{d}F_{t-i}\right)} \quad (3)$$

where B_t represents the population biomass of a Chilean SPF at time t, R_m is a positive constant representing the maximum per capita growth rate of each population, b is the constant of the endogenous effect (B_{t-i}), c is the constant of the climate variability effect (C_{t-i}), and d is the constant of the fishing effect (F_{t-i}). Taking the natural logarithmic form of Eq. 3 leads to the following general model:

$$R_t = \mathrm{R_m} + \mathrm{b}B_{t-i} + cC_{t-i} + dF_{t-i} \quad (4)$$

where all terms were as defined before.

Climate perturbations in the model were added as an additive effect on the R_t and followed the framework in Royama (1992). Two types of climate effects were studied: vertical and lateral. The vertical effect was additive and influenced R_m. This can be expressed as $\mathrm{R}_m{}' = R_m + c(C_{t-i})$, where c is a simple linear function (positive or negative) of the climate variable C_{t-i}. The lateral climate perturbations shift the R function along the x-axis and can be represented as $\mathrm{b}' = \left[\mathrm{b} + c(C_{t-i})B_{t-i}\right]$, where c was previously defined, and b' represents the constant of the lateral climate effect (Andreo et al., 2009). We also considered the potential effects that arose from the interaction between climate and fishing, which are indicated in this study as the climate–fishing interaction effects. This was represented as $\mathrm{d}' = \left[\mathrm{d} + \mathrm{c}(C_{t-i})\right]F_{t-i}$, where d' represents the constant of the interaction effect.

Statistical Analysis

Parameter Estimation

The estimation of the parameters in Eq. 4 is routinely performed with non-linear regression techniques (Lima and Estay, 2013). Such an approach assumes that the error is only in the observations but that the dynamics are known without error. Here, an alternative approach is suggested in which error can be assumed in both the dynamics (process error) and the observations. By introducing process error, we try to account for some aspects of the stock assessment data used in this study, such as the correlation between estimates (Brooks and Deroba, 2015).

When estimating the parameters of a time series as in Eq. 4, a popular method for incorporating processing and observation errors is known as the Kalman filter (Kalman, 1962). We used the Kalman filter algorithm to calculate the expected means and covariances of the observed values for the complete time series in the presence of observation and process errors (Bolker, 2008).

Following Kalman (1962), we considered an unobserved variable x_t that could be estimated through the observed trajectory from y_t. Therefore, there is a relationship between x_t and y_t with the following linear structure:

$$x_{t+1} = Wx_t + H\varepsilon_t \quad (5)$$

$$y_t = Gx_t + \varepsilon_t \quad (6)$$

where W is the state matrix with $t = 1, \ldots, N$; G is the observed matrix; H is a linear operator; and ε_t is the noise that is assumed to have a Gaussian distribution, with a mean of zero and a constant variance σ^2. Equation 5 is called the state equation, and Eq. 6 is the observed equation that is used to model the observed variable R_t. Therefore, the observed matrix G is $[1\ b\ c\ d\ e]$, and x_t includes the covariables as $[R_m B_{t-1} C_{t-i} F_t]$. It is clear that, depending on the models that are used, the dimensions of G and x_t could be reduced. For the state equation, Eq. 5, the absence of independence between the observations x_t and the high correlation between the covariables in matrix H are assumed. Indeed, it is assumed that x_t is an autoregressive model, AR(p) and that coefficients of H are non-zero (Hyndman and Khandakar, 2008).

Model selection was conducted using the Akaike information criterion for small sample sizes (AICc), and the differences in the AICc among models were assessed (ΔAICc). We also examined Akaike weights (w_i) and R-squared values (R^2; pseudo-R^2) as a measure of the variance explained by the model (Burnham and Anderson, 2004).

Time series cross-validation is used to measure the prediction performance of the selected models. Cross-validation consists of selecting a subsample with a size k ($k < N$) of ∼25% of the total sample size N, fitting the proposed model on this subsample and forecasting R_t, 1-year prediction ahead.

Biomass predictions and observations were compared using the root-mean-square error (RMSE) prediction. The smallest values represent the best prediction of biomass (Sheiner and Beal, 1981). The prediction uncertainty is computed with the 95% confidence interval of a standardized normal quantile. All models were implemented in R (R Core Team, 2017), and the "Forecast" package in R was used to apply the Kalman filter algorithm (Hyndman and Khandakar, 2008).

RESULTS

Biological Time Series and Diagnostics

The biomass time series of the APCH for both semesters (APCH-S1 and APCH-S2) spanned the period from 1986 to 2010 and showed almost identical dynamics (**Figures 2A,B**). Both presented a large second-order like oscillation of the biomass from 1986 to 1997 and more stable dynamics after 1998. The biomass time series of the ACN (**Figure 2C**) ranged from 1985 to 2013 with a maximum in 1994, which was followed by a sharp decline and a slow recovery after 2000. The time series of the ACS and CS spanned the period from 1990 to 2014 (**Figures 2D,E**). The former was characterized by two large second-order oscillations; on the other hand, the CS showed a different type of variability with irregular high-frequency oscillation and a "*U*" shaped long-term trend.

The diagnosis of the PRCF for all anchovy populations exhibited significant first-order processes (density-dependence effects). APCH-S1, APCH-S2, and ACN (**Figures 3A–C**) showed significant correlations between the R_t and biomass with a 1-year lag. The second-order processes in the APCH population in both semesters were identified in the limit of their significance. In the case of APCH-S2 (**Figure 3B**), a fifth-order process was detected but not included in the statistical model because the number of observations was short to estimate its correlation. The ACN population also displayed a second-order effect; however, a sensitivity analysis (not shown) indicated that the presence of this effect was conditional on the high maximum biomass estimated in the period from 1993 to 1995. The ACS showed a correlation with a second-year lag (**Figure 3D**) and the first-order effect within the limits of its significance compared to the APCH and ACN populations. Contrary to the anchovies, the CS only showed a first-order process (**Figure 3E**).

Population Dynamics Modeling

Anchovy Peru–Chile

APCH-S1. The first-order process of the APCH-S1 as occurred with the biomass with a 1-year lag (B_{t-1}), which explained 0.50 of the variance (**Table 1**, S1.m1). The SOI vertical climate effect with no lags displayed the lowest AICc (**Table 1**, S1.m2). The effect of fishing in models S1.m8 to S1.m10 (**Table 1**) showed that E_t was the predictor that best improved the fit (**Table 1**, S1.m8).

The combined effect of the previous factors on R_t showed an improvement in the fit (**Table 1**, S1.m11 and S1.m12). Model S1.m12, which considered the additive effect of climate and fishing rather than the climate–fishing interaction, showed a lower AICc value.

The predictability of the biomass of APCH-S1 was assessed with models S1.m2, S1.m8, S1.m11, and S1.m12. Model S1.m12 showed the best prediction of the APCH-S1 biomass (lowest RMSE value). **Figure 4A** indicates that the selected model was able to predict the trend starting with that for 1993, the maximum biomass for 1994, and the declining trend after 2005. The endogenous effects primarily drove the APCH-S1 biomass, which was secondarily driven by the climate and fishing. These last two factors had negative effects on the APCH-S1 growth rate.

APCH-S2. The first-order process explained 0.49 of the R_t variance (**Table 1**, S2.m1). As in the case of APCH-S1, the vertical climate effect (SOI) and fishing (E_t) with no lags showed the best fit with the R models, although in the APCH-S2 models, the climate effect performed better than fishing alone (**Table 1**). The combined influences of endogenous, vertical climate, and fishing factors (S2.m10 and S2.m11) showed an improvement in the fit of models with independent effects (S2.m1 to S2.m9). Cross-validation analyses were conducted with models S2.m2, S2.m8, S2.m10, and S2.m11. The lowest RMSE value was obtained with model S2.m10; thus, this model best predicted the APCH-S2 biomass (**Figure 4B**).

Anchovy central-northern Chile

The endogenous process in the ACN population explained a slightly higher variance compared to the APCH, with an $R^2 = 0.54$ (**Table 2**, m1). The climate effect was examined, and the best parsimonious model was obtained with a vertical effect and no lags (**Table 2**, m2). The fishing effect slightly improved the fit in comparison with model m1, whereas models m9 and m11 showed the lowest AICc values.

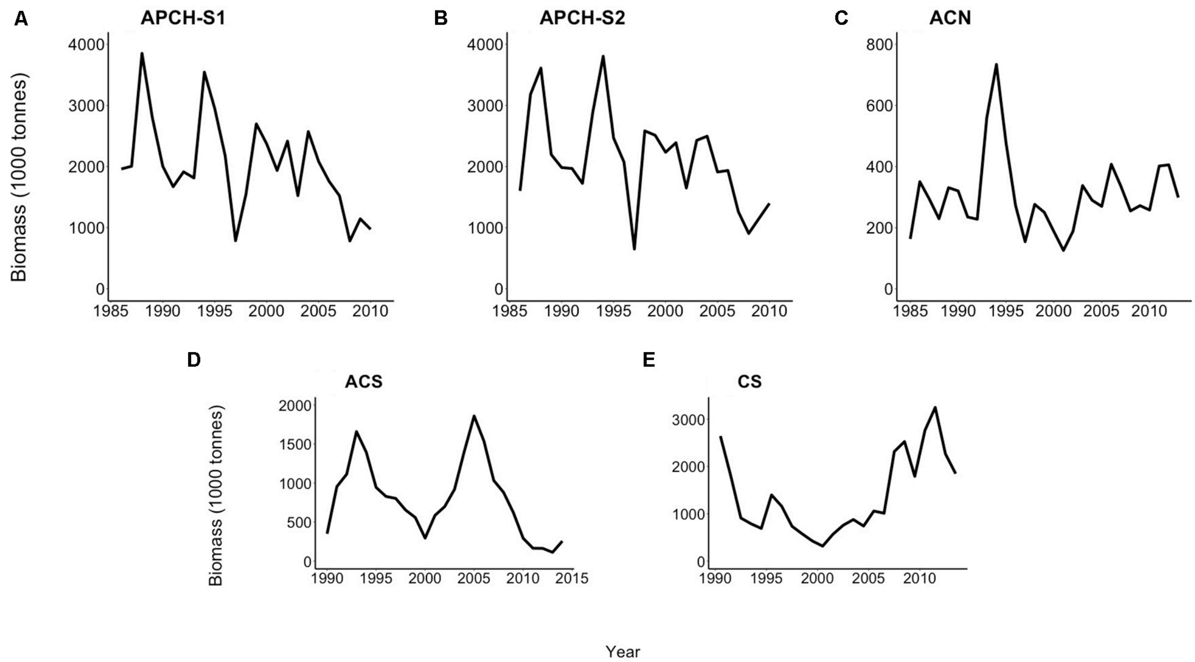

FIGURE 2 | Biomass (tonnes) time series of the Chilean small pelagic fish populations. Anchovy population of southern Peru and northern Chile (APCH) from 1986 to 2010. **(A)** APCH-S1, biomass semester January–June and **(B)** APCH-S2, anchovy biomass semester July to December. **(C)** Anchovy population off central-northern Chile (ACN) from 1985 to 2013. **(D)** The anchovy population (ACS) and **(E)** common sardine (CS) population off central-southern Chile includes estimates from 1990 to 2014.

Combining the density-dependent effect with climate and fishing (**Table 2**, m12 to m17) showed that the model with the climate–fishing interaction performed better. The best fit was obtained when the climate–fishing interaction was considered (**Table 2**, m12 and m13). Cross-validation analysis was conducted with models m12 and m13; however, the last model better predicted the biomass (smallest RMSE). The forecast of the ACN biomass by m13 (**Figure 4C**) predicted the observed decline in biomass in 1994 and the recovery and stability following 2005 as a function of an endogenous process and the climate–fishing interaction.

Anchovy central-southern Chile

The first-order process explained a low variance of 0.15 (**Table 2**, m1), which had a weak influence on the ACS dynamics compared to the northern anchovies. The climate effect, either vertical or lateral, performed better (lowest AICc) than the endogenous effect alone (**Table 2**, m3–m8). Adding the fishing effect to the R model showed the best results when the anchovy exploitation rate was added (**Table 2**, m11). Indeed, the anchovy exploitation rate increased the R^2 to 0.68 in the presence of the endogenous effect, thereby improving the fit.

The combination of the previous factors (endogenous process, climate, and fishing) in models m13–m20 (**Table 2**) did not improve the fit with model m11. Therefore, cross-validation analysis was performed only considering m11. **Figure 4D** shows that m11 closely predicted the fluctuation in the ACS biomass in the period from 1999 to 2013 as a function of the endogenous effect and fishing.

Common sardine central-southern chile (CS)

The endogenous effect in the CS population showed a low influence in R_t, as in the ACS (**Table 3**, m1). The vertical climate effects, SST_{t-1}, displayed the lowest AICc values, although no significant differences were found with the SST_{t-2} effect. The additive effects of the fishing or the climate–fishing interaction (m8 and m9) did not lead to a better fit. Hence, the effect of fishing was dismissed. One- and 2-year SST lag effects produced a significant improvement in model fit (**Table 3**, m10–m12).

Cross-validation analysis was conducted with models m10, m11, and m12. Small differences in the RMSE values of m11 and m12 were recorded. On the other hand, m10 showed the lowest RMSE values. Although model m12 did not record the lowest RMSE value, it was selected because it had the better fit and explained more of the variance. **Figure 4E** shows the predictions of the CS biomass from model m12. The biomass dynamics seemed to be mainly driven by the climate conditions signaled in the SST and, to a lesser extent, by a density-dependent effect. The model was able to predict the low biomass period observed from 2000 to 2006 and the sharp increase in biomass following 2006.

DISCUSSION

Density-dependent and density-independent (climate and fishing) effects were the drivers of the biomass dynamics of the anchovy and CS populations off the Chilean coast from the late 1980s to the early 2010s. The relative importance of these effects varied across the studied populations. The

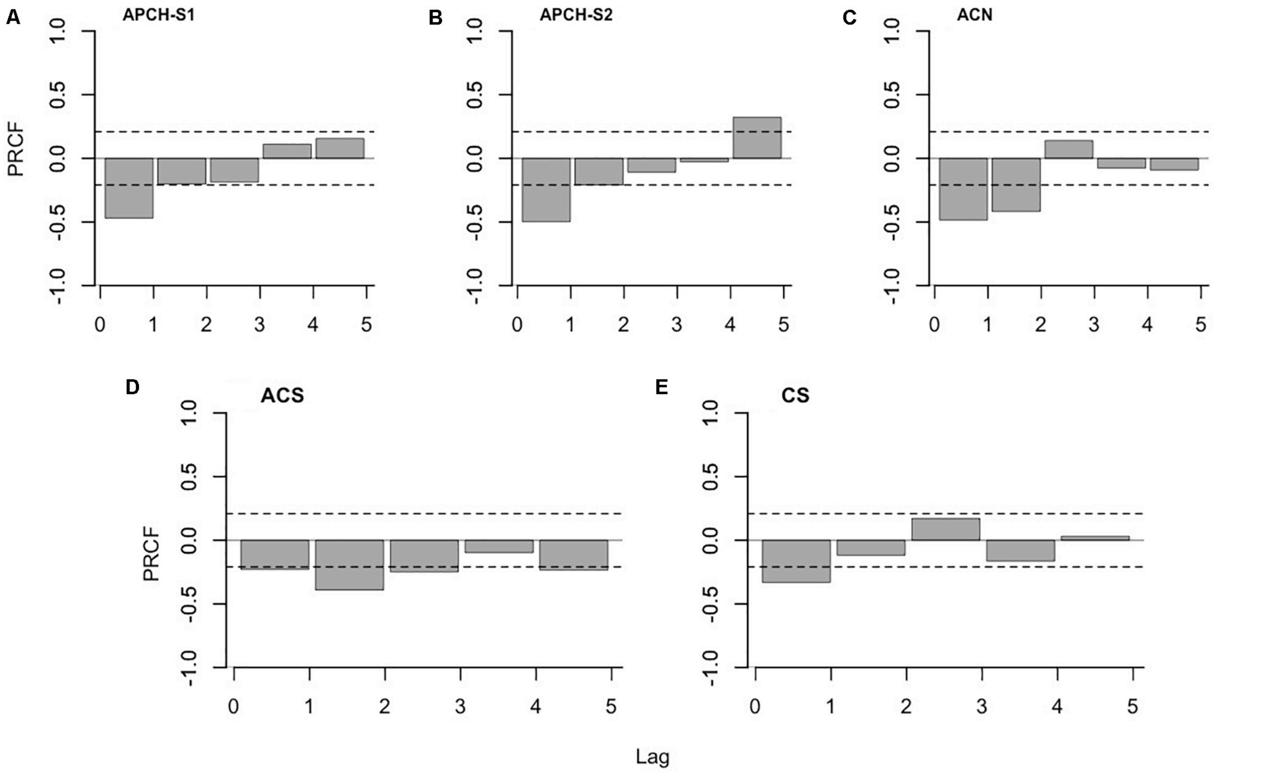

FIGURE 3 | Partial rate correlation function (PRCF) of the per capita population growth rate (R_t, *y*-axis) and the biomass at different time lags (*x*-axis). The analysis diagnoses the relative contribution of the population feedback at a lag of *i* (*i* = 0,1,2,3,4,5) (endogenous effect) for the determination of R_t. **(A)** Anchovy population of southern Peru and northern Chile (APCH-S1). **(B)** Anchovy population of southern Peru and northern Chile (APCH-S2). **(C)** Anchovy population of central-northern Chile (ACN). **(D)** Anchovy population of central-southern Chile (ACS), and **(E)** the common sardine (CS) population of central-southern Chile (the dashed line indicates significance at $p < 0.05$).

density-dependent, climate, and fishing effects were significant in the anchovy populations. Whereas climate was the main driver of the CS biomass, fishing had a non-significant effect in modulating its dynamics.

We also found differences in the anchovy populations, where northern anchovies showed the most important endogenous effect (higher explained variance) in comparison with the southern population. Pedraza and Cubillos (2008) proposed a similar modeling framework to assess density-dependent forcing on the anchovy and CS populations of central-southern Chile. Their results pointed to an endogenous effect in the anchovy of central-southern Chile with an explained variance of 23%, which was close to the value found in this study (15%) for the same anchovy population (ACS). However, the process effect of the same order shown by Pedraza and Cubillos (2008) was far lower than the importance of the endogenous components in the northern anchovy populations. Regarding the CS population, the density-dependent effect detected in Pedraza and Cubillos (2008) explained a variance of 42% of the changes in biomass compared to those found in this study, where the endogenous component only explained 27%. The differences between the studies could be related to the trends and the length of the time series used. The results in Pedraza and Cubillos (2008) used information from 1991 to 2002, which coincided with a low abundance period in CS. Our results extended the period used in Pedraza and Cubillos (2008) and included a relatively high abundance phase of CS after 2006; thus, comparison of our results and those in Pedraza and Cubillos (2008) should be conducted cautiously. Indeed, the sensitivity to climate changes of anchovy and probably other SPF seems to be dependent on the population size (Cahuin et al., 2009). These authors found that the density-dependent effects in anchovy could be more important when unfavorable habitat conditions prevailed in the system. We believe that the lower influence of the density-dependent effects on the CS found in this work may be associated with the increase in the population after 2006 due to the prevailing favorable SSTs in the habitat of the species. Therefore, the climate conditions did not favor high competition for food.

The studied populations showed a density-independent climate effect with the SOI and SST. In anchovy populations, the influence was through the climate–fishing interaction (APCH-S2 and ACN) or through direct effects on the population growth rate (APCH-S1). In the first scenario, the climate–fishing interaction indicated that, in addition to the negative effect of fishing on the population growth rate (high fishing effort after 2000, **Figure 5C**), climate mediated the negative influence of fishing on the anchovy biomass. Likewise, the SOI indicated the trend of the prevailing climate conditions toward a cool environment

TABLE 1 | Population models for the Chilean anchovy stocks (*Engraulis ringens*).

R models	*m*	logLike	AICc	ΔAICc	w_i	R^2	RMSE
APCH-S1 (*n* = 25)							
Endogenous effect							
$R_t = 0.57 - 2.84e^{-7}B_{t-1}$	S1.m1	−10.59	25.73	0.71	0.10	0.50	
Endogenous and environmental vertical effects							
$R_t = 0.57 - 2.81e^{-7}B_{t-1} - 0.22SOI_t$	S1.m2	−8.94	25.02	0.00	0.14	0.59	698.5
$R_t = 0.71 - 3.51e^{-7}B_{t-1} - 0.23SOI_{t-1}$	S1.m3	9.15	25.44	0.42	0.11	0.58	
$R_t = 0.46 - 2.32e^{-7}B_{t-1} + 0.14SOI_{t-2}$	S1.m4	−10.11	27.37	2.35	0.04	0.53	
Endogenous and environmental vertical effects							
$R_t = 0.53 + \left(-2.62e^{-7} - 8.20e^{-8}SOI_t\right)B_{t-1}$	S1.m5	−9.44	26.02	1.00	0.08	0.56	
$R_t = 0.70 + \left(-3.58e^{-7} - 9.62e^{-8}SOI_{t-1}\right)B_{t-1}$	S1.m6	−9.25	25.64	0.62	0.10	0.57	
$R_t = 0.50 + \left(-2.48e^{-7} + 4.14e^{-8}SOI_{t-2}\right)B_{t-1}$	S1.m7	−10.4	27.93	2.91	0.03	0.51	
Endogenous and fishing effects							
$R_t = 0.84 - 2.34e^{-7}B_{t-1} - 3.28e^{-5}E_t$	S1.m8	−8.94	25.02	0.00	0.14	0.59	747.8
$R_t = 0.63 - 2.73e^{-7}B_{t-1} - 9.51e^{-5}C_t$	S1.m9	−10.42	27.99	2.92	0.03	0.51	
$R_t = 0.78 - 3.35e^{-7}B_{t-1} - 17.16E_t/B_t$	S1.m10	10.36	27.85	2.83	0.03	0.51	
Endogenous and climate–fishing interaction effects							
$R_t = 0.85 - 2.41e^{-7}B_{t-1} + \left(-3.12e^{-5} - 1.32e^{-5}SOI_t\right)E_t$	S1.m11	−8.02	26.94	1.02	0.08	0.62	730.3
Endogenous, climate vertical and fishing effects							
$R_t = 0.79 - 2.40e^{-7}B_{t-1} - 0.18SOI_t - 2.72e^{-5}E_t$	S1.m12	−7.72	25.45	0.43	0.11	0.64	683.3
APCH-S2 (*n* = 25)							
Endogenous effect							
$R_t = 0.64 - 3.02e^{-7}B_{t-1}$	S2.m1	−12.69	29.92	1.40	0.11	0.49	
Endogenous and vertical climate effects							
$R_t = 0.62 - 2.88e^{-7}B_{t-1} - 0.21SOI_t$	S2.m2	−10.69	28.52	0.00	0.21	0.60	776.9
$R_t = 0.75 - 3.56e^{-7}B_{t-1} - 0.19SOI_{t-1}$	S2.m3	−11.54	30.22	1.70	0.09	0.56	
$R_t = 0.56 - 2.68e^{-7}B_{t-1} + 0.08SOI_{t-2}$	S2.m4	−12.51	32.16	3.64	0.03	0.50	
Endogenous and lateral climate effects							
$R_t = 0.63 + \left(-2.91e^{-7} - 5.81e^{-8}SOI_t\right)B_{t-1}$	S2.m5	−11.99	31.11	2.59	0.06	0.53	
$R_t = 0.77 + \left(-3.70e^{-7} - 9.59e^{-8}SOI_{t-1}\right)B_{t-1}$	S2.m6	−11.17	29.48	0.96	0.13	0.57	
$R_t = 0.61 + \left(-2.86e^{-7} + 1.60e^{-8}SOI_{t-1}\right)B_{t-1}$	S2.m7	−12.65	32.45	3.93	0.03	0.49	
Endogenous and fishing effects							
$R_t = 0.98 - 2.72e^{-7}B_{t-1} - 3.50e^{-5}E_t$	S2.m8	−11.48	30.11	1.59	0.10	0.56	802.6
$R_t = 0.89 - 3.59e^{-7}B_{t-1} - 20.68E_t/B_t$	S2.m9	−12.59	32.31	3.79	0.03	0.50	
Endogenous and climate–fishing interaction effects							
$R_t = 0.94 - 2.74e^{-7}B_{t-1} - (2.97e^{-5} - 1.38e^{-5}SOI_t)E_t$	S2.m10	−10.15	30.29	1.77	0.09	0.62	733.15
Endogenous, vertical climate and fishing effects							
$R_t = 0.89 - 2.65e^{-7}B_{t-1} - 0.18SOI_t - 2.75e^{-5}E_t$	S2.m11	−9.86	29.72	1.20	0.12	0.63	751.4

The APCH anchovy population is shared between southern Peru and northern Chile (16°–24°S). APCH-S1: first semester biomass (January–June) and APCH-S2: second semester biomass July–December. Note. The model notation is R_t = per capita population growth rate, B_{t-1} = population biomass with a 1-year lag; SOI, Southern Oscillation Index; C, catches; E, fishing effort. The parameter values of each model are given in the equations. m indicates model number, n = number of observations. Population dynamics models for each small pelagic fish species were compared using logLike = log-likelihood, the Akaike information criteria for small-sample size AIC_c, ΔAIC_c = model AIC_c = lower AIC_c, Akaike weights, w_i, the determination coefficient R^2, and RMSE = root-mean-squared prediction. The gray color indicates the selected model.

(**Figure 5A**), favoring the growth of the anchovy population. A lasting period of cold temperature anomalies due to the retreat of the warm subtropical oceanic waters off the coasts of Peru and Chile creates conditions for active upwelling (Cahuin et al., 2009; Swartzman et al., 2009; Bertrand et al., 2011). Such climate conditions also increase the vulnerability of anchovy to fishing by creating pools of cold water where anchovies gather to feed or spawn, thereby increasing the probability of being found by fishing boats (Alheit and Niquen, 2004; Bertrand et al., 2004, 2008; Alheit et al., 2009). Therefore, anchovy population growth is favored under cold conditions, but this also increases their vulnerability to fishing.

The anchovy population (APCH-S1) did not show a climate–fishing interaction but rather a negative effect of climate (SOI) on the population growth rate, signaling that prevailing warm conditions seemed to have a positive effect on the growth rate of APCH-S1. Previous knowledge of the anchovy and climate conditions favoring the population growth of the species in northern Chile indicated that cool conditions (i.e., cold SSTs, intense upwelling) favored the recruitment of anchovy in the

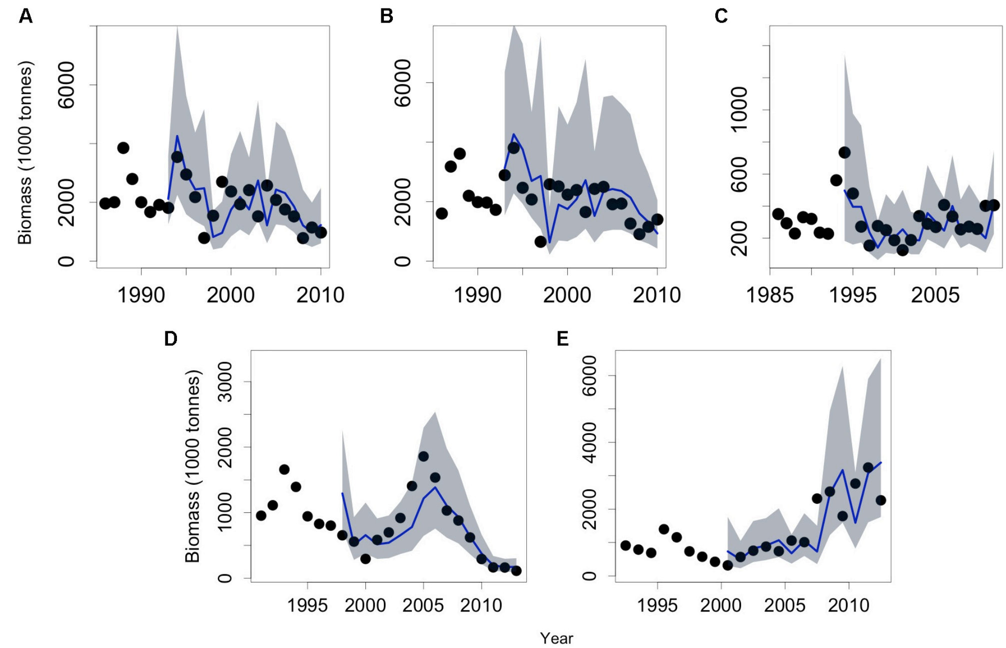

FIGURE 4 | Simulations of the anchovy and common sardine biomasses with the selected models in **Table 1**. **(A)** APCH-S1 population (**Table 1**, S1.m12). **(B)** APCH-S2 population (**Table 1**, S2.m10). **(C)** ACN population (**Table 2**, m13). **(D)** Anchovy population of central southern Chile (**Table 2**, m11), and **(E)** common sardine population of central-southern Chile (**Table 3**, m12) (points correspond to the observations, the blue line to the prediction, and gray area to the confidence interval of the predictions).

area (Cahuin et al., 2009) leading to a high level of biomass. We think that our results may be seen as a consequence of north–south migration during warm events rather than recruitment success. Salvatteci et al. (2018) found that anchovies persisted off Mejillones (northern Chile) for several decades from 1880 to 1905, when upwelling was dramatically reduced in the northern part of the Humboldt system due to warm conditions. Moreover, observations in this area during strong El Niño events showed that anchovies tended to move toward the coast and southward (Alheit and Niquen, 2004). Thus, warm events in northern Chile, such as those observed in the system before 2000, may trigger anchovy migration from areas beyond northern Chile, which may be seen through increases in the biomass in northern Chile.

The negative vertical climate effect on the population growth rate of the CS implied that a decrease in the local SSTs could have a positive effect on its population growth rate. **Figure 5B** shows that SSTs in the CS habitat from the early 1990s to early 2010 tended to have negative anomalies, particularly after 2005. The climate conditions occurred almost simultaneously with the significant increase of the CS biomass after 2006. The relationship between the CS and climate variables such as the SST and recruitment has been previously studied. For instance, Cubillos and Arcos (2002) found that the recruitment of the CS had a negative correlation with SST anomalies during the prerecruitment period and the upwelling index in the peak of spawning, signaling that negative anomalies might favor CS recruitment. Recently, Gomez et al. (2012) found that recruitment and the CS recruitment rate had a negative correlation with the SSTs in the El Niño 34 region, indicating that cold habitat conditions favor CS recruitment. Moreover, the authors proposed that chlorophyll (which is significantly correlated with SST) is a good proxy for the abundance of food for the CS population and that changes in this quantity can substantially affect the survival of CS prerecruits, which determine the strength of a population in late spring. Hence, we believe that the climate conditions after 2006 were predominantly cold years off central-southern Chile (Corredor-Acosta et al., 2015), favoring chlorophyll-a production in the austral spring–summer (Aguirre et al., 2018) and, therefore, the recruitment success and the population growth rate of CS.

Effect of fishing was found on all anchovy populations, although the effects were mostly relevant only in the ACS population due to the high exploitation rates after the year 2000 (**Figure 5D**). Two clear oscillations were present in the ACS population, where the second-order effect was more significant than the first-order effect. Thus, at an early stage, we hypothesized that fishing (or an alternative specialist predator) may have played a more significant role in the dynamics of the ACS population, causing the typical oscillations observed in a predator–prey relationship (Berryman and Turchin, 1997). Although no explicit effect of fishing on this anchovy population has been detected before, Pedraza and Cubillos (2008) discussed the presence of a second-order effect in the anchovy population off central-southern Chile, proposing the hypothesis of the effect of a specialist predator on the ACS. Currently, the ACS is a collapsed fishery off central-southern Chile that is characterized by low levels of recruitment and low spawning biomass (Zuñiga, 2017).

TABLE 2 | Population dynamics models for the anchovy stocks (*Engraulis ringens*).

R models	*m*	Like	AICc	ΔAICc	w_i	R^2	RMSE
ACN (*n* = 27)							
Endogenous effect							
$R_t = 0.58 - 1.89e^{-6}B_{t-1}$	m1	−7.24	21.53	3.71	0.050	0.54	
Endogenous and vertical environmental effects							
$R_t = 0.48 - 1.52e^{-6}B_{t-1} - 0.17\text{SOI}_t$	m2	−7.22	21.48	3.66	0.051	0.53	
$R_t = 0.49 - 1.54e^{-6}B_{t-1} - 0.13\text{SOI}_{t-1}$	m3	−7.86	22.77	4.95	0.027	0.49	
$R_t = 0.34 - 1.14e^{-6}B_{t-1} + 0.09\text{SOI}_{t-2}$	m4	−8.35	23.75	5.92	0.016	0.46	
Endogenous and lateral environmental effects							
$R_t = 0.53 + \left(-1.69e^{-6} - 4.84e^{-7}\text{SOI}_t\right)B_{t-1}$	m5	−7.47	21.98	4.16	0.040	0.52	
$R_t = 0.53 + \left(-1.64e^{-6} - 4.09e^{-7}\text{SOI}_{t-1}\right)B_{t-1}$	m6	−7.71	22.47	4.65	0.031	0.50	
$R_t = 0.40 + \left(-1.32e^{-6} + 4.22e^{-7}\text{SOI}_{t-2}\right)B_{t-1}$	m7	−8.65	24.34	6.52	0.012	0.45	
Endogenous and fishing effects							
$R_t = 0.45 - 1.16e^{-6}B_{t-1} - 9.21e^{-5}E_t$	m8	−8.34	23.72	5.90	0.017	0.47	
$R_t = 0.46 - 7.83e^{-7}B_{t-1} - 3.24e^{-6}C_t$	m9	−7.28	21.61	3.79	0.048	0.52	
$R_t = 0.48 - 1.36e^{-6}B_{t-1} - 16.59E_t/B_t$	m10	−8.54	24.13	6.31	0.014	0.45	
$R_t = 0.64 - 1.42e^{-6}B_{t-1} - 0.89C_t/B_t$	m11	−7.64	22.32	4.50	0.033	0.51	
Endogenous and climate–fishing interaction effects							
$R_t = 0.61 - 1.24e^{-6}B_{t-1} + \left(-3.24e^{-6} - 3.60e^{-6}\text{SOI}_t\right)C_t$	m12	−4.66	19.14	1.32	0.164	0.64	257.8
$R_t = 0.80 - 1.64e^{-6}B_{t-1} + \left(-1.20 - 1.14\text{SOI}_t\right)C_t/B_t$	m13	−4.00	17.82	0.00	0.317	0.66	239.2
Endogenous, vertical climate and fishing effects							
$R_t = 0.54 - 9.73e^{-7}B_{t-1} - 0.17\text{SOI}_t - 3.28e^{-6}C_t$	m14	−5.65	21.12	3.30	0.061	0.60	
$R_t = 0.74 - 1.63e^{-6}B_{t-1} - 0.18\text{SOI}_t - 0.97C_t/B_t$	m15	−5.88	21.59	3.77	0.048	0.59	
Endogenous, lateral climate and fishing effects							
$R_t = 0.57 + \left(-1.15e^{-6} - 4.66e^{-7}\text{SOI}_t\right)B_{t-1} - 3.14e^{-6}C_t$	m16	−6.07	21.96	4.14	0.040	0.58	
$R_t = 0.77 + \left(-1.80e^{-6} - 5.00e^{-7}\text{SOI}_t\right)B_{t-1} - 0.93C_t/B_t$	m17	−6.27	22.36	4.54	0.033	0.57	
ACS (*n* = 23)							
Endogenous effect							
$R_t^A = 0.05 - 1.27e^{-7}B_{t-1}^A$	m1	−11.36	24.91	8.64	0.008	0.15	
Endogenous and vertical climate effects							
$R_t^A = 0.20 - 2.77e^{-7}B_{t-1}^A - 0.19\text{SOI}_t$	m2	−10.63	28.52	12.25	0.001	0.28	
$R_t^A = 0.18 - 2.66e^{-7}B_{t-1}^A - 0.17\text{SOI}_{t-1}$	m3	−10.83	28.93	12.66	0.001	0.25	
$R_t^A = -0.09 + 1.41e^{-8}B_{t-1}^A + 0.18\text{SOI}_{t-2}$	m4	−10.67	28.60	12.33	0.001	0.28	
Endogenous and lateral climate effects							
$R_t^A = 0.14 - (2.57e^{-7} - 2.36e^{-7}\text{SOI}_t)B_{t-1}^A$	m5	−10.51	28.28	12.01	0.001	0.30	
$R_t^A = 0.12 - (2.30e^{-7} - 1.65e^{-7}\text{SOI}_{t-1})B_{t-1}^A$	m6	−11.03	29.32	13.05	0.001	0.22	
$R_t^A = -0.02 - (2.37e^{-8} - 1.95e^{-7}\text{SOI}_{t-2})B_{t-1}^A$	m7	−10.87	29.01	12.74	0.001	0.24	
Endogenous and fishing effects							
$R_t^A = 0.22 - 1.26e^{-7}B_{t-1}^A - 1.44e^{-5}E_t^{A+S}$	m8	−10.68	28.63	12.36	0.001	0.27	
$R_t^A = 0.53 - 1.13e^{-7}B_{t-1}^A - 6.52e^{-7}C_t^{A+S}$	m9	−8.72	24.71	8.44	0.008	0.47	
$R_t^A = 0.15 - 7.72e^{-8}B_{t-1}^A - 2.84e^{-5}E_t$	m10	−10.78	28.82	12.55	0.001	0.26	
$R_t^A = 0.82 - 3.66e^{-7}B_{t-1}^A - 1.50C_t/B_t$	m11	−4.50	16.27	0.00	0.464	0.68	339.9
Endogenous and climate–fishing interaction effects							
$R_t^A = 0.82 - 3.62e^{-7}B_{t-1}^A + \left(-1.52 - 0.02\text{SOI}_t\right)C_t^A/B_t^A$	m12	−4.50	19.23	2.96	0.130	0.68	
Endogenous, vertical climate and fishing effects							
$R_t^A = 0.82 - 3.64e^{-7}B_{t-1}^A + 2.72e^{-3}\text{SOI}_t - 1.51C_t^A/B_t^A$	m13	−4.50	19.23	2.96	0.130	0.68	
Endogenous, lateral climate and fishing effects							
$R_t^A = 0.82 - (3.96e^{-7} - 6.92e^{-8}\text{SOI}_t)B_{t-1}^A - 1.46C_t^A/B_t^A$	m14	−4.39	19.01	2.74	0.145	0.68	

ACN anchovy located off central-northern Chile (25–32° LS) and the anchovy (ACS) located from 33 to 41° LS.

Here, we used biomass estimates derived from the Chilean stock assessment of SPF as the input to infer population dynamics in our proposed models. Ideally, a more independent source for biomass observations (e.g., from fishery-independent surveys) should be used because the original population models (Berryman and Turchin, 2001; Lima and Naya, 2011) should be fed with empirical observations rather than estimates from models. However, fishery-independent biomass observations

TABLE 3 | Population dynamics models for the common sardine (*Strangomera bentincki*) off central-southern Chile (33–41° LS).

R models	*m*	Like	AICc	ΔAICc	w_i	R^2	RMSE
CS (*n* = 21)							
Endogenous effect							
$R_t^S = 0.58 - 1.49e^{-6}B_{t-1}$	m1	−7.80	23.02	3.98	0.04	0.27	
Endogenous and vertical environmental effects							
$R_t^S = 0.23 - 1.52e^{-7}B_{t-1}^S - 0.36\mathrm{SST}_t$	m2	−7.28	21.98	2.94	0.06	0.35	
$R_t^S = 0.25 - 1.64e^{-7}B_{t-1}^S - 0.33\mathrm{SST}_{t-1}$	m3	−5.82	19.04	0.00	0.28	0.48	
$R_t^S = 0.27 - 1.85e^{-7}B_{t-1}^S - 0.54\mathrm{SST}_{t-2}$	m4	−6.34	20.08	1.04	0.17	0.44	
Endogenous and vertical environmental effects							
$R_t^S = 0.26 + \left(-1.96e^{-7} - 3.66e^{-7}\mathrm{SST}_t\right) B_t^S$	m5	−7.86	23.13	4.09	0.04	0.27	
$R_t^S = 0.21 + \left(-1.39e^{-7} - 6.67e^{-8}\mathrm{SST}_{t-1}\right) B_t^S$	m6	−7.37	22.16	3.12	0.06	0.34	
$R_t^S = 0.23 + \left(-1.70e^{-6} - 2.23e^{-7}\mathrm{SST}_{t-2}\right) B_t^S$	m7	−7.75	22.91	3.87	0.04	0.28	
Endogenous and fishing effects							
$R_t^S = 0.24 - 1.31e^{-7}B_{t-1} - 5.24C_t^{A+S}/B_t^{A+S}$	m8	−7.89	23.19	4.15	0.04	0.26	
Endogenous and climate-fishing interaction effects							
$R_t^S = 0.29 - 1.51e^{-7}B_{t-1} + \left(-8.17 - 18.63\mathrm{SST}_{t-1}\right) C_t^{A+S}/B_t^{A+S}$	m9	−7.62	25.75	6.71	0.01	0.30	
Endogenous and vertical climate with different lags							
$R_t^S = 0.30 - 2.09e^{-7}B_{t-1} - 0.38\mathrm{SST}_t - 0.35\mathrm{SST}_{t-1}$	m10	−6.35	23.21	4.17	0.03	0.44	512.5
$R_t^S = 0.38 - 2.64e^{-7}B_{t-1} - 0.44\mathrm{SST}_{t-1} - 0.61\mathrm{SST}_{t-2}$	m11	−4.44	19.37	0.33	0.20	0.57	569.0
$R_t^S = 0.42 - 2.98e^{-7}B_{t-1} - 0.33\mathrm{SST}_t - 0.45\mathrm{SST}_{t-1} - 0.58\mathrm{SST}_{t-2}$	m12	−3.52	21.05	2.01	0.37	0.62	571.1

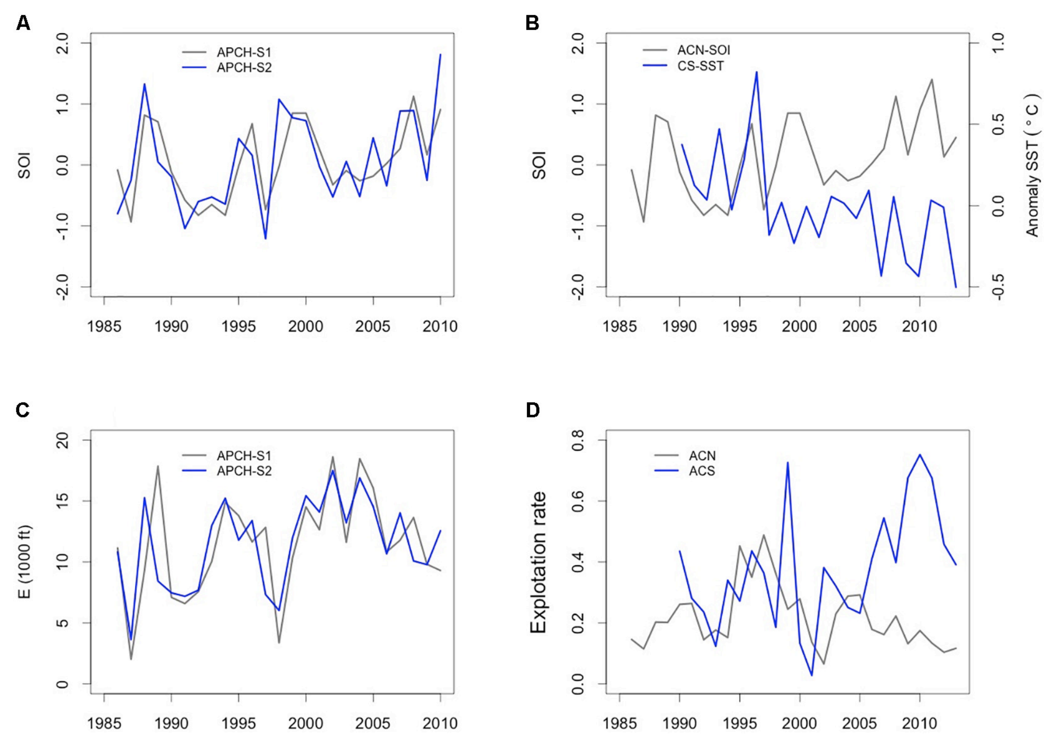

FIGURE 5 | Climate and fishing predictors of the anchovy and common sardine biomass dynamics off Chile. **(A)** Southern Oscillation Index (SOI) climate predictors for the anchovy population of southern Peru and northern Chile (APCH), **(B)** SOI for the anchovy population of central-northern Chile (ACN) and anomaly sea surface temperature (SST, °C) for the common sardine, **(C)** fishing effort as the number of fishing trips (ft) (*y*-axis has been/1000) for APCH. **(D)** Exploitation rates for the ACN and ACS populations.

are fragmented for the anchovy and CS fisheries in Chile because they span a short time window, show discontinuity, and do not always have a consistent sampling window (**Supplementary Table S1**). Therefore, these features preclude their incorporation into the population models proposed in this study for these species.

In addition, the biomass estimates from the stock assessment may overlook potential biases, correlation among estimates, and the structural assumptions of the original assessment model (Brooks and Deroba, 2015). We believe that we accounted for these aspects using Kalmar filter analysis (Hosack et al., 2013) rather than a non-linear regression (Lima and Naya, 2011 and similar). The Kalmar filter assumes both observation and process error, and thus, the estimates of biomass from the stock assessment were tractable as input in the proposed population model. In addition, the Kalmar filter accounts for potential correlation among estimates, which is a desirable property when working with possibly correlated data, such as the outputs from a stock assessment, or structural assumptions (e.g., the existence of fishing mortality). Because the Kalman filter accounts for both process and observation error, the overall uncertainty in the biomass estimates is higher compared to the estimates from the stock assessments (**Figure 4** and **Supplementary Figure S1**). Moreover, all unmeasured effects (exogenous effects) were included within the error (Eq. 6) as part of the uncertainty of the biomass. Therefore, the proposed statistical treatment of our data supported the hypothesis that fishing, climate, and density-dependent factors may influence the population dynamics of the anchovy and CS populations in Chile.

We used a simple logistic model with linear assumptions about the relationship between the per capita growth rate and their predictors (density dependence, climate, and fishing). The variability explained by the density-dependent and density-independent factors in the selected models fluctuated from 62 to 68%, depending on the population. The predictability of these models may improve with further explorations that focus on covariables, such as predators and competitor biomass, and that consider the trophic role of the species or even additional climate predictors. In addition, the assumption of linearity between the per capita growth rate and the predictors could be relaxed. In this context, Pedraza and Cubillos (2008) used generalized additive models (GAMs) to explore the endogenous effect on the CS and anchovy population dynamics, which explained the higher level of variance. In this study, to simplify the analysis, we used a simple linear assumption considering the numbers of predictors and populations.

The current management of the SPF in Chile is based on a single-species model approach that does not explicitly include climate variability. The failure to include climate variability may cause fisheries to be considered either underexploited during favorable regimes or overexploited during unfavorable climate conditions. On the other hand, not including density-dependent effects when modeling is equivalent to assuming an infinite compensatory effect (Hilborn and Walters, 1992) in which recruitment is unaffected by decreases of biomass, which increases the risk of overfishing (Rose et al., 2001). Our approach does not offer a straightforward solution for including climate and density-dependence effects in the management of these populations but rather identified critical drivers of the anchovy and CS populations in the southern Humboldt Current ecosystem. The approach used here and the identification of the underlying drivers of SPF biomass can be seen as a step forward in the ecosystem approach to fisheries management.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: www.ifop.cl, https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/, and https://modis.gsfc.nasa.gov/data/dataprod/mod28.php.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because we used public information.

AUTHOR CONTRIBUTIONS

TC wrote most of the manuscript, developed the ideas, interpreted the results, and created the tables and some figures. ML interpreted the results and reviewed the final manuscript. RW developed the ideas, interpreted the results, wrote some of the manuscript, and reviewed the final manuscript. JC-R performed and wrote the statistical analyses. UC contributed to collecting the climate time series. JM contributed to creating the figures.

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The Interaction Between Stock Dynamics, Fishing and Climate Caused the Collapse of the Jack Mackerel Stock at Humboldt Current Ecosystem

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The collapse of marine fisheries had caused a cascade of ecological, social and economic consequences. Recognizing the complex nature of the fisheries collapses is essential for understanding the impact of human activities on natural systems. The rapid and abrupt shifts in abundance exhibited by some marine fish populations can be driven by the fishing fleet behaving like generalist predators. Here, we propose that fishing fleet has a s-shaped functional predator function that, combined with economic factors and ENSO variability could cause rapid and abrupt transitions in the of jack mackerel (*Trachurus murphyi*) fishery in the south-eastern Pacific. Our results showed that fishing fleet predator functional response is well described by a s-shaped function, where ENSO variability (El Niño/La Niña years) appears to decrease/increase the fishing rate. Our model predictions were able to accurately forecast independent data of jack-mackerel acoustic survey estimates. We show that the population trend and collapse of jack mackerel stock at the Humboldt Current Ecosystem (HCE) can be explained by the changes in fishing effort, which seem to be driven by economic forces and El Niño climatic variability. Our simple model allows us to explore some management responses in a heuristic manner. The most critical element seems to be the combination of an n-shaped isocline for fish stock growth, modulated by ENSO variability, and a horizontal isocline of fishing effort which is highly sensitive to changes in the profitability of the fishery. Therefore, the implementation of management policies based on simple theoretical models will be increasingly required to harvest fish stocks in these times of growing demographic demands and climate change.

Keywords: population dynamics, ENSO, jack-mackerel, collapse, abrupt shifts

INTRODUCTION

Many global marine fisheries have collapsed during the last decades (Hutchings, 2000; Jackson et al., 2001), often causing severe ecological and socio-economic consequences (Hilborn, 2007). Although collapses of fish stocks are generally caused by overfishing (Myers et al., 1995; Hutchings, 2000), other factors may also interact with human exploitation, such as, the inherent climate variability of marine ecosystems (Alheit and Niquen, 2004; Ottersen et al., 2005) and the complex web of ecological interactions where the exploited stocks are embedded (Pitcher, 2001; Pikitch et al., 2004; Lindegren et al., 2009). Determining the relative effect of these factors is one of the major challenges for the sustainability of marine fisheries.

The jack mackerel (*Trachurus murphyi*) is one of the most important commercial species inhabiting the Humboldt Current Ecosystem (HCE) at the south-eastern Pacific Ocean. The stock biomass has declined abruptly after 2005 and still remains at historically low levels despite the reduction of fishing mortality (Quiroz, 2019). Some studies suggest that a combination of low recruitment, overfishing and climate may explain the collapse of the stock (Arcos et al., 2001; Gang et al., 2013; Quiroz, 2019), but the relative influence of these factors is still controversial. In fact, at HCE, the jack-mackerel fishery had been subjected to both factors, high fishing pressure (Quiroz, 2019) and ENSO driven inter-annual variability.

The jack-mackerel pelagic catches had been driven by the high demand for fishmeal directly related to the growth of the world population and the feed requirements of poultry, aquaculture and derivatives, triggering the acceleration in the prices during the last 10 years (**Figure 1A**). The determination of the harvest quotas determined by economic forces seem to have induced the abrupt change in the stock (**Figure 1A**). Changes in fishing effort not only depend on the stock abundance, but also they are largely determined by socio-economic factors, such as, the difference between the income and the costs of the fishery (Gordon, 1954; Grafton et al., 2007; Fryxell et al., 2010, 2017; Sethi et al., 2010). In fact, some studies showed how the sustained increases in consumer demand coupled with the dynamics of the fish stock can generate a rapid and surprising transition from high-yield/low-price to low-yield/high-price fisheries, generating severe disruptions in socio-economic and ecological systems (Fryxell et al., 2010, 2017).

On the other hand, ENSO variability seems to influence the spatial distribution of jack-mackerel, hence, affecting the catchability to the fishery (Yañez et al., 1996; Arcos et al., 2001; Naranjo et al., 2015). A similar finding was described for another jack mackerel species at New Zealand coasts, where ENSO variability has strong effects on krill distribution at coastal waters and introduce changes in the jack mackerel school behavior leading to fishery failures (Harris et al., 1992). These lines of evidence suggest climatic effects on the spatial distribution of jack mackerel schools may have consequences on catchability which is a combination of fishing efficiency and availability. Such combination of economic and climatic forces on the fishery dynamics may cause rapid and abrupt shifts in abundance, sometimes in responses to small changes in external factors (Jones and Walters, 1976; May, 1977; Steele and Henderson, 1984; Scheffer and van Nes, 2004). The notion of abrupt shifts in the state of a dynamical system derives from catastrophe theory (Thom, 1972), which is a topological approach for analyzing complex dynamical systems (Thom, 1972; Zeeman, 1976). In fact, catastrophe theory was first applied to fisheries by Jones and Walters (1976) in a heuristic manner relating the stock dynamics, the fishing effort and technological efficiency. This idea was applied in the salmon fishery of British Columbia by Peterman (1977), who proposed that stable alternative states in the fish stock may emerge as a consequence of including mechanisms of depensatory predation mortality (Neave, 1953) in Ricker's production models (Peterman, 1977). The same author (Peterman, 1980) determined that the mortality of these salmon stocks emerges as a consequence of the operations of the fishery that behaves similarly to the functional responses of natural predators (Holling, 1959, 1965). In fact, processes such as fleet aggregation and changes in search efficiency in response to certain thresholds of stock sizes are similar to those observed in generalist predators.

Here, using time series data of fish biomass, fishing effort and climate, we develop a model of fishery dynamics based on the relationships between fish stock abundance, effort exerted by the fishing fleet and ENSO variability. Our model is based on a logistic population dynamic growth of fish stock combined with a functional predator response of the fishery (Jones and Walters, 1976). We assumed that the rate of change in effort from year to year is a positive function of fishery revenue, but is negatively influenced by fishing costs which are proportional to the fishing effort (Grafton et al., 2007; Fryxell et al., 2010). We use this model to test the effects of ENSO variability and consider how changes in the fishing effort can generate the observed large abrupt shifts in the abundance of the jack mackerel (*T. murphyi*) stock at south-eastern Pacific.

MATERIALS AND METHODS

Data

Jack Mackerel Biomass

We used model-based estimates of total biomass available in Canales et al. (2015). The model used corresponded to the one part of the assessment method for the Jack mackerel fishery adopted in the Scientific Committee of the South Pacific Regional Fishery Management Organization[1] in 2010 (JMSWG-Report, 2014). The model is an integrated statistical catch-at-age analysis implemented in AD Model Builder (ADMB) for the jack mackerel fisheries and population in the South Eastern Pacific area covering the period from 1970 to 2014 (Canales, 2014; JMSWG-Report, 2014). Several population-structure hypotheses have been proposed for jack mackerel in the South Pacific, the model used here corresponded to the one that assumes that jack mackerel conforms one single population in the South Eastern Pacific.

A detailed summary about the stock assessment of jack mackerel in the South Eastern Pacific is provide in the **Supplementary Material** as well as the sources of information (**Supplementary Table S1**) and the time series of biomass and their interval of confidence (**Supplementary Figure S1**).

Fishing Effort

Data were obtained from the logbooks of the Chilean purse seine commercial fleet requested to the Instituto de Fomento

[1] www.sprfmo.int

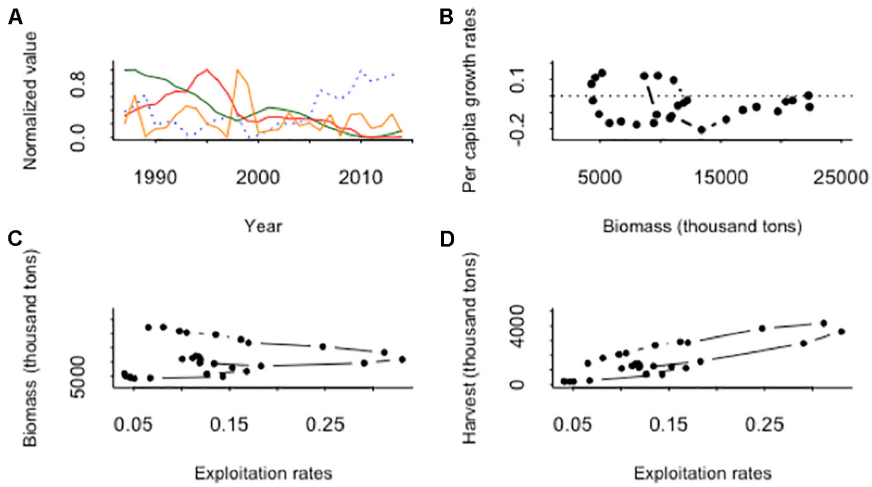

FIGURE 1 | (A) Observed dynamics of the jack-mackerel fish stock biomass (green solid line), harvest (red solid line) and inflation-corrected price (blue dotted line), and the Niño 3.4 anomalies (orange solid line) for the period 1986–2015. **(B)** The phase plot of the per capita population growth rates against biomass showed a low-frequency oscillatory pattern in the jack mackerel dynamics toward low biomass. **(C)** The relationship between stock biomass (thousand tons) and exploitation rates (fishing mortality) for the period 1986–2015, stock biomass declined with exploitation rates, but the reduction in exploitation rates did not caused a recovery of the stock, during the late period much lower stock biomass are observed for the same range of exploitation rates. **(D)** The observed relationship between stock yield and exploitation rates for the period 1986–2014.

Pesquero of Chile[2]. Fishing effort was estimated as the product of the annual number of trips with positives catches to jack mackerel and the proportion of days off port. We used the product of these two effort variables because as the jack mackerel stock declined in biomass, the days off port have increased significantly (**Supplementary Figure S2**). Thus, we accounted for the change in the availability of jack mackerel to the fishery by weighting the fishing trips with positive catches by the days off port. Although, jack mackerel is caught by different fleets such as the Far North fleet (Peru) and Offshore Trawl (China, European Union, Faroe Islands, South Korea, Japan, Russian Federation, Ukraine, and Vanuatu countries) the majority of the catches has been taken by the Chilean fleets and the largest fraction of the estimated total allowed catch is assigned to Chile. **Supplementary Figure S3** shows that the Chilean fleets (North and Central-South) accounted for an average of a 73% of the total annual catches of jack mackerel in the South Eastern Pacific over the period 1985–2014, and a 70% for the period 1970–2014. Therefore, we assume that the Chilean fishing effort is a good proxy of total fishing effort of the jack mackerel fishery in the South Eastern Pacific.

Climatic Data

Fluctuations in tropical Pacific Sea Surface Temperature (SST) are related to the occurrence of El Niño (EN), during which equatorial surface waters warm considerably from the International Date Line to the western coast of South America. The atmospheric phenomenon linked to EN is termed Southern Oscillation (SO), which involves exchanges of air between the eastern and western hemispheres mainly in tropical and subtropical latitudes. EN and SO are linked so closely that the term ENSO is used to describe the atmosphere ocean interactions throughout the tropical Pacific. Various EN indices exist, for example the El Niño 3.4 index (5N-5S, 170W-120W): The Niño 3.4 anomalies may be thought of as representing the average equatorial SSTs across the Pacific from about the dateline to the South American coast. The Niño 3.4 index typically uses a 5-month running mean, and El Niño or La Niña events are defined when the Niño 3.4 SSTs exceed ±0.4C for a period of 6 months or more. Annual average of the Niño 3.4 index was obtained from https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni, for the period 1986–2015.

The Model

We started modeling the stock biomass annual changes of the jack mackerel according a simple Ricker logistic function minus annual harvest as it had been proposed in recent studies (Fryxell et al., 2010, 2017);

$$B_t = B_{t-1} \cdot e^{\left[R_{\max}\cdot\left(1-\frac{B_{t-1}}{K}\right)\right]-b(B_{t-1})\cdot E_{t-1}}, \quad (1)$$

where $R_{\max}$ is the exponential rate of growth, K is the carrying capacity of the jack mackerel stock, b is the catchability function, B is the stock biomass and E is the fishing effort. Our first hypothesis was based in the basic type of functional responses of predators (Holling, 1959, 1965). Because any fishing operation imply at least two time-consuming activities, searching and handling the fish, the basic functional response equation of the catches is an asymptotic function of fish biomass (Holling, 1959). Therefore, we examined the type of functional response of the fishery by fitting the following equation;

$$y = w \cdot \frac{B}{h+B} \quad (2a)$$

[2]www.ifop.cl

where y is the harvested biomass per unit of fishing effort and B is the jack-mackerel biomass, parameters w is the maximum fishery catch rate and h is the fish biomass where the fishing rate is half saturated. Our second hypothesis was that the functional response of fishing was s-shaped as it has been proposed earlier in the literature (Jones and Walters, 1976);

$$y = w \cdot \frac{B^2}{h^2 + B^2} \tag{2b}$$

Dividing the behavioral fishing responses (density-dependent catchability functions) y by the fish biomass, we obtain the per capita (or per biomass unit) exploitation rates $z = y/B$, in the case of a type II behavioral response the fishing mortality rates are negatively related to fish biomass;

$$z = \frac{w}{h + B}, \tag{3a}$$

while in the case of the sigmoid behavioral response, per capita fishing mortality is a humped function of fish biomass;

$$z = w \cdot \frac{B}{h^2 + B^2}. \tag{3b}$$

Therefore, the function b (B_{t-1}) in Eq. 1 can be represented as the two types of functional responses of Eqs 2a,b as:

$$B_t = B_{t-1} \cdot e^{\left[R_{\max} \cdot \left(1 - \frac{B_{t-1}}{K}\right)\right] - w \cdot \frac{B_{t-1} \cdot E_{t-1}}{h + B_{t-1}}}, \tag{4a}$$

$$B_t = B_{t-1} \cdot e^{\left[R_{\max} \cdot \left(1 - \frac{B_{t-1}}{K}\right)\right] - w \cdot \frac{B_{t-1} \cdot E_{t-1}}{h^2 + B_{t-1}^2}}, \tag{4b}$$

where w and h are the same parameters that Eqs 2a,b.

The following step is to include climatic forces (ENSO-El Niño) to the model, we included the effects of ENSO variability on the carrying capacity of the fish biomass (K), and also on the maximum catch rate (w) and on the fish biomass where the fishing rate is half saturated (h).

On the other hand, because the jack-mackerel fishery is regulated by quotas, we assumed that fishing effort changes at a rate proportional to the difference between revenue, calculated by harvest quota (H), price (P), and cost per unit effort (c) multiplied by effort (E) (Bjørndal and Conrad, 1987; Fryxell et al., 2010).

$$E_t = E_{t-1} \cdot e^{[a \cdot (P_{t-1} \cdot H_{t-1} - c \cdot E_{t-1})]}, \tag{5}$$

where a is the scale parameter fort the response in effort and c is the cost per unit of effort.

Statistical Analyses

Parameters were estimated using maximum likelihood approach via nls library in the R program (R Core Team, 2015[3]) and ranked according to the corrected Akaike information criterion for small samples (AIC_c). For clarity, AIC_c weights also figure in the results. Minimum AIC_c was selected to determine the most parsimonious (best) model.

Simulations were conducted to elucidate the capacity of the models to describe real dynamics. Models were fitted with data from 1987 to 2015 jack-mackerel biomass estimated from the assessment model (Canales et al., 2015) and the simulations were conducted using independent data by using the acoustic biomass surveys (Canales et al., 2015) for the period 1997–2009. Uncertainty on biomass estimates was incorporated by resampling a joint multivariate normal distribution of the estimated parameters considering the asymptotic distribution of maximum likelihood estimates. 95% confidence intervals (CIs) of biomass time series were obtained by the percentile method (Efron and Tibshirani, 1993) based on 10,000 realizations. Furthermore, values of the root-mean-square prediction error (rmse; Sheiner and Beal, 1981) were calculated to evaluate the predictive performance of the models. Smallest rmse values represent better predictive performance.

[3]http://www.r-project.org

RESULTS

Jack-mackerel biomass, fishing effort and harvest showed a fivefold magnitude variation over time (**Figure 1A**). During the late 1980s population peaked, then declined severely along the 1990s, showed a small recovery during the first years of the 2000, and declined toward low biomass during the last 10 years (**Figure 1A**). On the other hand, fishing effort and catches showed an increasing trend until they peaked around the late 1990s and a subsequent decline (**Figure 1A**). Inflation-corrected price was unresponsive as jack-mackerel fishery went through the phase of increase, but after the collapse in catches around the year 2000 inflation-corrected prices started to increase (**Figure 1A**). In fact, the jack-mackerel stock experienced fourfold variations in total biomass, harvest and real price over time (**Figure 1A**). The phase plot of the per capita population growth rates against biomass showed a low-frequency oscillatory pattern in the jack mackerel dynamics toward low biomass (**Figure 1B**), suggesting the existence of population cycles in the declining trend of the stock. The relationship between stock biomass and fishing mortality, showed also a low-frequency oscillatory pattern, stock biomass declined with exploitation rates, but the reduction in exploitation rates did not cause a recovery of the stock (**Figure 1C**), during the late period much lower stock biomass are observed for the same range of exploitation rates. A similar trend is observed for the relationship between stock yield and exploitation rates (**Figure 1D**).

The functional response function is better described by a type III response (sigmoid or s-shaped) (**Table 1** and **Figure 2A**). A type III functional response model was 17 times more plausible than a type II response (w_2/w_1 = 17.03; **Table 1**). This response is typical of predators that switch from one prey to another (generalist) and/or concentrate in areas where preys are more abundant (spatial density-dependence). Dividing behavioral responses by fish stock biomass, we obtain an estimate of the per capita fishing death rate, sigmoid functional predator responses produces a humped-mortality rate function in its preys with higher mortality rates at intermediate stock abundances (**Figure 2B**). In fact, this model of fishing per capita mortality rates was almost 34 times better than a simple exponential negative model (w_2/w_1 = 33.74; **Table 1**).

TABLE 1 | The behavioral responses of the fishery to changes in jack-mackerel stock biomass.

	w	*h*	AICc	DAICc	Loglike	w_i	w_i/w_j	k
Functional response models								
$y = w \cdot \frac{B}{h+B}$	379.6	8101.4	281.62	5.67	−137.29	0.06	17.03	2
$\mathbf{y = w \cdot \frac{B^2}{h^2+B^2}}$	**281.9**	**−5284.2**	**275.95**	**0.00**	**−134.45**	**0.94**	**1.00**	**2**
Per capita mortality models								
$z = \frac{w}{h+B}$	510.80	14,489.1	−220.05	7.04	113.55	0.029	33.74	2
$\mathbf{z = w \cdot \frac{B}{h^2+B^2}}$	**295.14**	**5719.9**	**−227.09**	**0.00**	**117.07**	**0.97**	**1.00**	**2**

The parameter values given in the equations were estimated by non-linear regression analysis in R-program using the nls library. The best model was chosen by using the corrected Akaike information criteria (AIC_c). y is the harvest biomass per unit of fishing effort (harvest/fishing effort), B is population biomass of jack-mackerel stock, z = y/B is the per capita fishing mortality rates, k number of model parameters, $DAIC_c$ = model AIC_c − lowest AIC_c, w_i = Akaike weights. The best selected models are in bold face.

According to our results, the best model structure for the jack-mackerel dynamics is one including intraspecific competition and a functional predator response type III of the fishery as is described in Eq. 4b (**Table 2**; model 1).

Comparing the basic model versus the models that include ENSO effects on the carrying capacity of the jack-mackerel population (model 1 versus models 6 and 7), our results show that ENSO did not influence limiting factors of jack-mackerel dynamics ($w_1/w_6 = 3.25$; $w_1/w_7 = 3.25$; **Table 2**). In the same vein, our results did not account for the ENSO effects on the maximum fishery catch rate (model 1 versus models 2 and 3; $w_1/w_2 = 6.50$; $w_1/w_3 = 1.08$; **Table 2**). However, the best model was one including the 2-year lagged ENSO effects on the parameter *h*, the fish biomass where the fishing rate is half saturated (model 1 versus model 5; $w_5/w_1 = 48.46$; **Table 2**). In fact, our basic and best models (**Table 2**; models 1 and 5) were able to predict quite well independent data as the acoustic survey estimates from Chilean fishery (**Figure 3B**). An interesting result is that ENSO variability (El Niño/La Niña years) may decrease/increase the half-saturated fishing rate (**Figure 3C**).

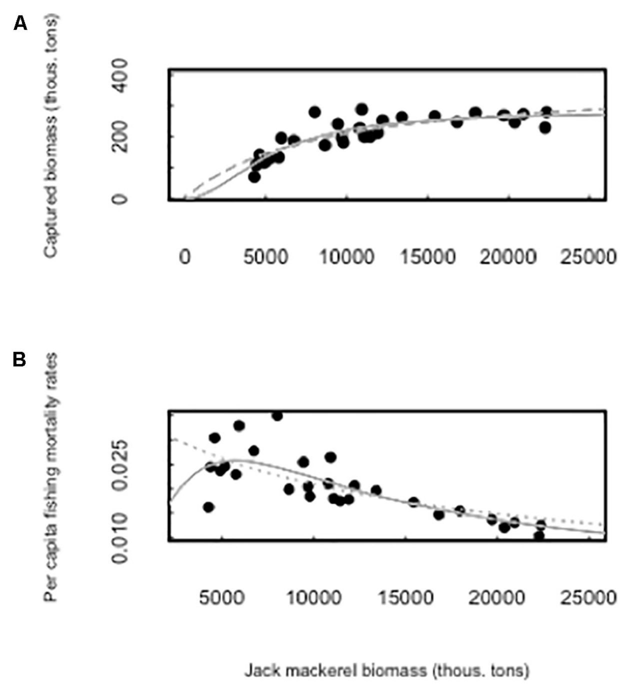

FIGURE 2 | (A) The behavioral responses of the fishery catch per effort unit to changes in jack-mackerel stock biomass, the gray dotted line is the type II behavioral response model while the gray solid line is the type III functional response model. **(B)** Resulting per capita fishing death rates from the type II (dotted line) and III (solid line) behavioral responses of the fishery.

The dynamics of the fishing effort was captured by the model from Eq. 5 (**Figure 4** and **Table 2**). In fact, the model where fishing costs are proportional to the fishing effort is a good description of fishing effort annual changes (**Figure 4** and **Table 2**). Setting the fish stock and the fishing effort at equilibrium in the Eqs 4 and 5 and solving these equations for B^* and E^*, we can obtain the fish stock and fishing effort isoclines and the phase space plot determining the system dynamics and equilibrium (**Figure 5**). In the case of a fish population exploited by a fleet with s-shaped behavioral responses, the stock isoclines are humped and the isoclines of the fishing effort are horizontal (**Figure 5**), because the fishing effort is determined by quotas. When the fishing fleet behave as a generalist predator with sigmoid functional responses, the fish stock isocline is now n-shaped with the possibility of multiple equilibrium points (**Figure 5**), the fishery can change from a situation from high fish biomass, low harvest toward an intermedium harvest scenario generating alternative stable states in the fish stock (**Figure 5**).

DISCUSSION

Our results provide evidence that the collapse of the jack-mackerel stock at the HCE can be explained by the changes in fishing effort, which seem to be driven by economic forces and El Niño climatic variability. Our model predict that jack-mackerel stock dynamics can have alternate stable states. In particular, the fishing dynamics is described by a harvest characterized as a generalist predator with a type III sigmoid functional response able to generate a complex n-shaped stock fish isocline, which is

TABLE 2 | Population dynamic models for the Jake mackerel biomass, the fishing effort and prices.

	Deviance	AICc	DAICc	Loglik	w_i	w_i/w_j	k
Fish stock models							
1. $B_t = B_{t-1} \cdot e^{\left[0.13 \cdot \left(1 - \frac{B_{t-1}}{23030}\right)\right] - 0.17 \cdot \frac{B_{t-1} \cdot E_{t-1}}{(1468)^2 + B_{t-1}^2}}$	0.205	−42.29	7.78	27.58	0.0013	48.46	5
2. $B_t = B_{t-1} \cdot e^{\left[0.16 \cdot \left(1 - \frac{B_{t-1}}{26830}\right)\right] - (1.19 - 0.04 \cdot EN_{t-1}) \cdot \frac{B_{t-1} \cdot E_{t-1}}{(-1470)^2 + B_{t-1}^2}}$	0.182	−38.96	11.11	27.57	0.0002	315.00	6
3. $B_t = B_{t-1} \cdot e^{\left[0.12 \cdot \left(1 - \frac{B_{t-1}}{2312}\right)\right] - (1.71 - 0.07 \cdot EN_{t-2}) \cdot \frac{B_{t-1} \cdot E_{t-1}}{(1684)^2 + B_{t-1}^2}}$	0.161	−42.11	7.96	29.15	0.0012	52.5	6
4. $B_t = B_{t-1} \cdot e^{\left[0.16 \cdot \left(1 - \frac{B_{t-1}}{32340}\right)\right] - 2.65 \cdot \frac{B_{t-1} \cdot E_{t-1}}{(-153500 + 6573 \cdot EN_{t-1})^2 + B_{t-1}^2}}$	0.164	−44.92	5.15	30.56	0.005	12.6	6
5. $\mathbf{B_t = B_{t-1} \cdot e^{\left[0.13 \cdot \left(1 - \frac{B_{t-1}}{36920}\right)\right] - 2.65 \cdot \frac{B_{t-1} \cdot E_{t-1}}{(-228100 + 9798 \cdot EN_{t-2})^2 + B_{t-1}^2}}}$	**0.135**	**−50.07**	**0.00**	**33.13**	**0.063**	**1.00**	**6**
6. $B_t = B_{t-1} \cdot e^{\left[0.14 \cdot \left(1 - \frac{B_{t-1}}{(-93890 + 5022 \cdot EN_{t-1})}\right)\right] - 0.18 \cdot \frac{B_{t-1} \cdot E_{t-1}}{(-960)^2 + B_{t-1}^2}}$	0.199	−39.71	15.71	27.96	0.0004	157.5	6
7. $B_t = B_{t-1} \cdot e^{\left[0.14 \cdot \left(1 - \frac{B_{t-1}}{(-92160 + 4922 \cdot EN_{t-2})}\right)\right] - 0.17 \cdot \frac{B_{t-1} \cdot E_{t-1}}{(-930.4)^2 + B_{t-1}^2}}$	0.198	−39.84	15.57	28.02	0.0004	**1.00**	**7**
Fishing effort model							
1. $\mathbf{E_t = E_{t-1} \cdot e^{\left[2.01^{e-07} \cdot (P_{t-1} \cdot H_{t-1} - 228.2 \cdot E_{t-1})\right]}}$	**1.08**	**−3.16**		**5.10**			**3**

The parameter values given in the equations were estimated by non-linear regression analysis in R-program using the nls library. The best model was chosen by using the corrected Akaike information criteria (AIC_C). B_t population biomass of jack-mackerel stock, E_t is the fishing effort, P_t is the inflation-corrected price, H_t is the harvest of the jack-mackerel, EN_t is the El Niño 3.4 climatic index, k number of model parameters, ΔAIC_C = model AIC_C - lowest AIC_C, w_i = Akaike weights, goodness of fit of the models were evaluated using the deviance values. The best selected models are in bold face.

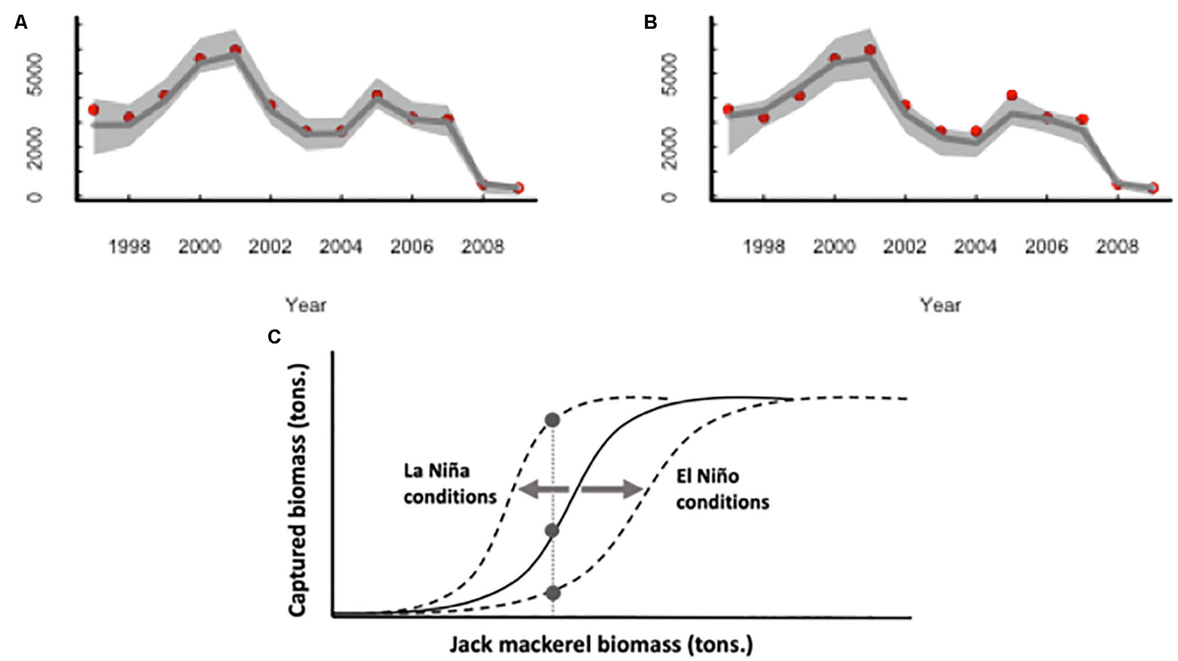

FIGURE 3 | Comparison of the observed jack-mackerel biomass extracted from the acoustic estimates (red dots) for the period 1997–2009 with predictions from models fit to the 1986–2014 estimated biomass from the stock assessment model (gray lines) and the 95% confidence band. **(A)** predictions from model 1, **(B)** model 5 from **Table 2**, **(C)** hypothesized ENSO effects on the parameter *h* (the fish biomass where the fishing rate is half saturated) of the functional response of fishing suggesting that ENSO variability (El Niño/La Niña years) decrease/increase the half-saturated fishing rate. For the same jack-mackerel biomass during the El Niño years the captures biomass is lower than La Niña or normal conditions.

modulated by the presence of ENSO variability. The combination of these ecological, economic, and climatic factors has the potential to explain the large and abrupt changes exhibited by the jack-mackerel stock size at the Humboldt current ecosystem during the last decades.

Abrupt and persistent changes in the size of the populations can be caused by the existence of multiple points of equilibrium or meta-stability (Berryman, 1999). It is well established that generalist predators with a sigmoid (s-shaped) functional responses are capable of generate a prey per capita mortality function that increases to intermediate prey abundances generating three equilibrium points, a low and high abundance stable equilibrium points an unstable equilibrium at intermediate abundances (Holling, 1965; Berryman, 1999). In fact, sigmoid

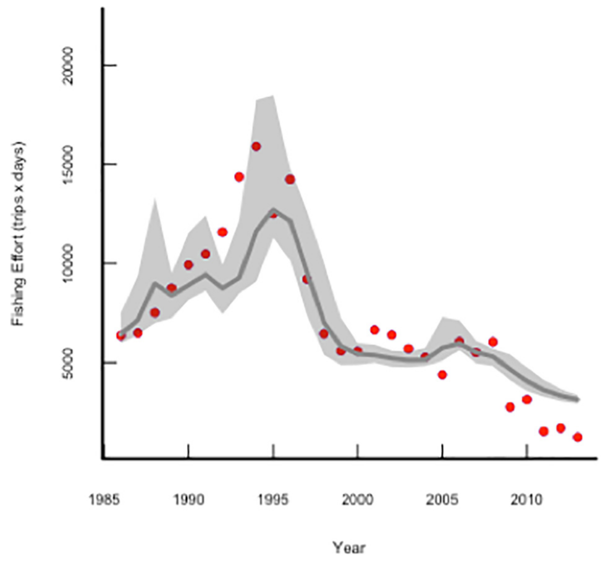

FIGURE 4 | Comparison of the observed changes in fishing effort (number of trips × days out of port, red dots) with the predictions from models (gray line) (**Table 2**).

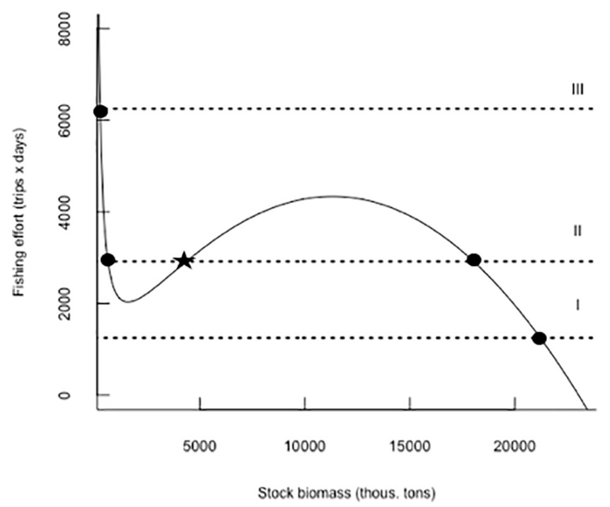

FIGURE 5 | Equilibrium isoclines from model 1 (**Table 2**) for fish stock (solid line) and model 1 for fishing effort dynamics (**Table 2**), the system can be stabilized toward a high fish biomass equilibrium (Isocline I), but increases in harvest or fish prices can lead the system rapidly toward a low fish biomass equilibrium with complex oscillatory transient dynamics (Isocline II) (Berryman, 1999). Closed dots are stable equilibrium points and the star represents an unstable equilibrium point.

behavioral responses of predators usually result from the action of generalist predators that switch to and/or aggregate on dense prey populations (Holling, 1965; Murdoch, 1969). This theory has been previously applied for explaining the fishery development and collapse (Jones and Walters, 1976).

Pelagic fishing operations may behave as generalist predators by searching the high-densities fish schools. This pattern may be the result of density-dependent catchability because at low school densities, the CPUE and the economic revenues are also very low in pelagic fisheries. As a consequence, there is a non-linear increase in catch per unit of effort with fish biomass, a process described as hyperstability of CPUE (Harley et al., 2001). Therefore, the sigmoid generalist of functional response of the jack-mackerel fishery may be consequence of density-dependent catchability. In the jack-mackerel, we determined a type III functional response of the fishery where the per capita fishing mortality is a humped function of the fish abundance, generating negative feedbacks in sparse fish populations (Berryman, 1999). This property give rise to n-shaped isocline for the fish stock suggesting that meta-stable dynamics can arise depending on the shape of the fishing effort isoclines (Jones and Walters, 1976). Horizontal fishing effort isoclines generate important changes in the dynamics of the system (**Figure 5**), because the determination of the harvest quotas can generate alternative states in the dynamic of the system. Therefore, under low harvest scenarios, the system can be stabilized toward a high fish biomass equilibrium (Isocline I, **Figure 5**) but increases in harvest can led the system toward a low fish biomass equilibrium (Isocline III, **Figure 5**; Berryman, 1999). The most interesting situation occurs at intermediate harvest quotas, under these conditions the isoclines can cross at three locations giving rise to a metastable dynamic with a high and low biomass stable equilibriums and intermediate unstable equilibrium or threshold at intermediate fish stock biomass. In fact, a severe reduction in quotas during the last years seem to be necessary for the recovery of the stock biomass.

Our analyses highlight that ENSO variability may have important effects on the availability of fish in the fishing grounds and the efficiency of the fishing gear to catch the available fish (catchability). This is to our knowledge the first study that included the effects of the ENSO variability in a predator response function model of fishing (**Figure 3**) and its consequences on catchability. Although, catchability is associated with fish availability, is also influenced by fish behavioral responses to the fishing gear and environmental factors (Arreguín-Sánchez, 1996). Climate variability could affect the spatial and depth distribution of fishes and hence their availability to a particular fishing fleet (Rijnsdorp et al., 2009). In theHCE, the pattern of ENSO variability modifies the range of the favorable habitat conditions of pelagic species such as, anchovy, sardine, mackerel, and jack mackerel (Alheit and Niquen, 2004). Migrations inshore, shallow or bottom waters, can increase or decrease fish availability and therefore catchability to the purse seine fleets (Bertrand et al., 2004). The jack mackerel population at HCE is characterized by large horizontal/vertical displacements due to change in ENSO variability (Arcos et al., 2001; Bertrand et al., 2004). Strong changes in acoustic biomass were observed at the end of El Niño event because the jack-mackerel followed the offshore flow of oceanic water when the warm waters (El Niño) started to disappearing (Bertrand et al., 2004). Our predator functional response model seems to capture the ENSO effects on the jack-mackerel catchability proposing a mechanism for the interaction between climate variability and fishing (**Figure 3C**).

The hypothesis that climatic variability influence catchability has not been formally tested on fish stocks. Indeed, Yañez et al. (1996) reported that strong thermal gradients associated with the intrusion of oceanic waters off the Chilean coast increases the probability of catching jack mackerel, hence, influencing the operations of fishing vessels. For example, Chilean fishing fleet increased it capacity (larger vessels), the duration of the fishing trips and number of hauls per trip in response to changes in jack mackerel spatial distribution (Naranjo et al., 2015).

Management Implications

In the case of jack mackerel, the high demand for fishmeal is directly related to the growth of the world population and the feed requirements of poultry, aquaculture, and derivatives, triggering the acceleration in the prices during the last 10 years. The determination of the harvest quotas over time seems to have induced the abrupt change in the stock, but mediated by a sigmoid functional response of the fishing fleet. These two elements seem to be key to explaining the abrupt decline of the stock in the south-eastern Pacific.

Our simple model allows us to explore some management responses in a heuristic manner. The most critical element seems to be the combination of an n-shaped isocline for fish stock growth, modulated by ENSO variability, and a horizontal isocline of fishing effort which is highly sensitive to changes in the profitability of the fishery (harvest quotas and fishing costs). This complex dynamic system can take the stock from a situation of high abundance and stability to a metastable dynamic at intermediate fishing effort levels (**Figure 5**). Using this approach for management purposes, some counter-intuitive policies from an economic point of view may be applied. For example, given that the annual changes in fishing effort are driven by the difference between harvest (H) and fishing costs $c \times (E)$, in order to apply tariffs to increase fishing costs in situations of high abundance (B), high harvests (H) could be used as a measure capable of keeping the fishery away from equilibrium point II (**Figure 5**). Undoubtedly, the current challenges related to the management of fisheries require a more integrated view of the growing demand for marine food products and the dynamic changes that fishing induces in the exploited stocks. Therefore, the implementation of management policies based on simple theoretical models, such as those applied in this article, will be increasingly required to restore the feedback processes that maintain natural systems in these times of growing demographic demands and climate change.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because we used fishery data.

AUTHOR CONTRIBUTIONS

ML, TC, RW, and JM: conceptualization, investigation, validation, and writing – original draft. ML and JM: formal analysis and visualization. ML: methodology, and writing – review and editing.

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SUPPLEMENTARY MATERIAL

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Adaptive Capacity Level Shapes Social Vulnerability to Climate Change of Fishing Communities in the South Brazil Bight

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Understanding the social vulnerabilities and community strategies to adapt to environmental changes are crucial for the development of actions to enhance both community conservation and survival. With the aim to identify the drivers of vulnerability to climate change among different coastal communities a comprehensive multi-scale vulnerability framework was here adopted. Eight selected fishing communities representative of the South Brazil Bight (SBB) area were surveyed at the household level. A total of 151 fishers were interviewed. Quantitative indicators were calculated at the community-level, and their drivers identified, allowing for comparisons of the overall vulnerability score. Findings revealed that remoteness and the lack of climate change-related institutional support increase vulnerability among fishing communities in the region. On the other hand, community organization, leadership, research partnerships, community-based co-management, and livelihood diversification reduce vulnerability. Our analysis focused on social vulnerability to climate change in regional fishing communities and provides a better understanding of these effects in coastal zones, the factors explaining vulnerability and some perspectives on resilient and adaptable systems. Learning from comparisons at the ecosystem level may be applied to coastal regions elsewhere.

Keywords: small-scale, fishing community, climate change, vulnerability, adaptation

INTRODUCTION

Climate change causes a progressive loss of productive capacity in some coastal and oceanic regions, with changes in the distribution, availability and production of marine food resources (Booth et al., 2018). The impacts of climate change in marine ecosystems and coastal zones are predominantly felt by small-scale fishers, especially in developing countries (Badjeck et al., 2010; Martins and Gasalla, 2018). The limited spatial context and the small scale of some fisheries, as well as the complex socioeconomic and policy trends associated with the activity, make them highly susceptible to environmental changes, reducing their adaptive capacity (Morton, 2007). Assessing fishing communities effects of anthropogenic stressors and their capacity to adapt is a necessary and important step to inform management initiatives, to assist decision makers in weighing trade-offs and to promote and increase resiliency of coastal communities (Perry et al., 2010; Cinner et al., 2012; Mozaria-Luna et al., 2015). A set of different research frameworks has been developed to examine the vulnerability of small-scale fishers to environmental change (Badjeck et al., 2010; Cinner et al., 2012; Béné, 2009; Jacob et al., 2013; Aswani et al., 2018), proposing general definitions of vulnerability as the susceptibility of a system to cope with the adverse effects of a disturbance (Adger, 2006; Cinner et al., 2013) and resilience as the ability of the system to recover the functional state after a disturbance (Buckle, 2000). These concepts have been considered as complementary, considering the high vulnerable communities are expected to be less resilient and demand additional resources to retrieve from a disturbance (Jacob et al., 2013). In this study an recent framework proposed by Aswani et al. (2018) was applied to address the social vulnerability of coastal communities in Brazil seeking to raise innovative data on a local scale to support more effective management actions.

In the environmental change context, vulnerability is typically measured as a component of sensitivity, exposure, and adaptive capacity (Cinner et al., 2013). Sensitivity is the state of susceptibility to harm from perturbations or long-term trends (Adger, 2006; Allison et al., 2009). The sensitivity of socio-ecological system is usually defined as the intrinsic degree to which economic, political, cultural, and institutional factors are likely to be influenced by extrinsic stresses or hazards (Allison et al., 2009). Exposure is the degree to which a climatic event can stress a specific region (Adger, 2006; Allison et al., 2009). In other words, exposure can be defined as the scale to which a region, resource, or community experiences change (Cinner et al., 2012). In the fisheries context, exposure is the extend to which the resource will be affected by an climatic event (Cinner et al., 2013). Adaptive capacity is the ability of individuals to anticipate and respond to changes, or to cope, reduce and recover from the effects of the climatic stressor (Gallopin, 2006). Which means, those with low adaptive capacity are expected to have difficulty adapting to change or seeing opportunities that climate change may create in the availability of resources and services (Cinner et al., 2012, 2013).

There are no single measures of exposure, sensitivity, or adaptive capacity and because of that the interpretation and analysis is linked to the scale of the study and available data (Mozaria-Luna et al., 2015). However, understanding the vulnerabilities of fishing communities and their strategies to cope with and adapt to climate change is extremely important to the development of policies that seek to preserve the communities livelihoods (Kalikoski et al., 2010). Actions with the aim of reducing vulnerability to climate change should generally be focused on reducing sensitivity and exposure, and at the same time increase local adaptive capacity Cinner et al., 2012). Another key step in addressing the effects of climate change will be to develop clear management objectives that reconcile competing goals and consider multiple objectives, such as conservation-based, biological, economic, social, cultural, and political objectives of marine social-ecological systems (Perry et al., 2010; Mozaria-Luna et al., 2015).

Moreover, understanding the vulnerabilities of fishing communities to climate change and their capacity to adapt is urgently needed (Allison et al., 2009). Nevertheless, fishing communities vulnerability to climate change has not been properly identified and evaluated in coastal Brazil. A few studies focusing on coastal fishing communities in southern Brazil found that vulnerability varies among communities and households, mainly due to the differences in their dependence on fishing, the distribution of assets and the level of participation in community organizations (Faraco, 2012), and vulnerability varies because the knowledge of small-scale fishers contributes to reducing that vulnerability and adapting to changes (Silva et al., 2014; Martins and Gasalla, 2018). Both of these previous studies helped to understand some effects of climate change on fishing communities, although, they do not provide an understanding of which are the positive and negative drivers behind regional social vulnerability. Addressing these drivers should be useful to collaboratively build on the adaptation pathways that increase coastal community resilience.

Within this context, the present study aims to explore social vulnerability and adaptation patterns among distinct traditional fishing communities in the South Brazil Bight (SBB) with a goal of understanding how climatic changes are impacting their vulnerability and informing adaptation pathways and policy responses.

MATERIALS AND METHODS

Study Area

The SBB is the area of the continental shelf of southeastern Brazil extending from Cabo Frio (23°S; 42°W) to Cabo Santa Marta (28.5°S; 48.6°W). The SBB region has a coastline with multiple features and a diversity of ecosystems and social characteristics, sustaining a diversity of economic activities such as small- and large-scale fishing, tourism, shipping, and oil and gas exploration. Fishing communities are diverse and abundant, provide seafood and employment opportunities to the country and have been impacted by recent development as well as climate issues (Martins and Gasalla, 2018). Considering the diversity of the communities along the SBB, eight small-scale fishing communities with different socioeconomic context were selected to represent the different communities of the region in terms of population size, proportion of households with fishers, fishing gear, target species, isolation, and inclusion in protected areas. The communities were: Itaipu, Ilha do Araújo, Enseada, Bonete, Mandira, Boqueirão Sul, Pontal de Leste and Praia do Porto (**Figure 1** and **Supplementary Appendix 2**).

Social Vulnerability Framework

The framework used to evaluate coastal fishing community vulnerability to climate change has been developed to address different marine-dependent coastal communities in an internationally comparative effort across Southern Hemisphere coastal zones (Aswani et al., 2018; Martins et al., 2019). The framework was proposed by a multilateral scientific team from different countries and disciplines aiming at improving fishing

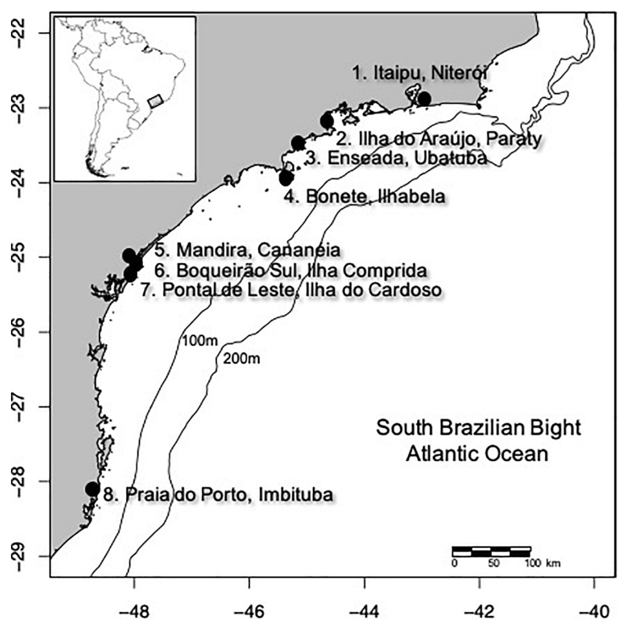

FIGURE 1 | Map of the study area and location of surveyed sites. In dark gray, from 1 to 8. Itaipu, Ilha do Araujo, Enseada, Bonete, Mandira, Boqueirao Sul, Pontal de Leste, and Praia do Porto fishing communities.

community adaptive capacity by characterizing, assessing and predicting the future of coastal-marine resources and by co-developing adaptation options through the provision and sharing of knowledge across fast-warming marine hotspot regions (Hobday et al., 2016; Popova et al., 2016). A key component of the vulnerability framework is to collect rich, local-level, social vulnerability data to provide a detailed understanding of the local-scale processes influencing community vulnerabilities while allowing for the data to be scaled up to regional, country, and global levels (Aswani et al., 2018). Here, the framework was used to understand the local process influencing the social vulnerability of coastal areas at a community level, but the same framework is also being used to scale up to regional and global analyses (Aswani et al., 2018; Martins et al., 2019). The framework consists of a four-step process that is described in the sections below (**Figure 2**).

The indicators that make up the framework used here were built in the context of the GULLS project, which sought to have a flexible structure to allow comparison between different cultural, social, and economic contexts. This meant that the same framework could be used in this in-country assessment. As the survey used had a wide range of questions (**Supplementary Appendix 3**) with redundancy in the structuring of the indicators (**Supplementary Appendix 1**), it meant that the survey could be customized to the local context of the SBB region. The indicators were used to measure the separate categories of vulnerability. The individual components of sensitivity, exposure and adaptive capacity categories were then divided in subcomponents to provide more detailed descriptors. The original framework has a total of 255 indicators categorized into 90 subcomponents and 20 components (Aswani et al., 2018). For the present study, a total of 160 indicators, 67 subcomponents and 20 components were selected and are described in **Supplementary Appendix 1**. The selected indicators are those that best applied to the Brazilian coastal fishing communities and those that had quality data after sampling.

After defining the indicators, the survey instrument was carefully constructed to translate the indicators into the questionnaire. The survey had previously been field tested in two other communities in the region. As proposed by the framework (Aswani et al., 2018) the questions that did not produce reliable data were identified during the field testing and subsequently improved or omitted. The final survey instrument has a mix of Likert scale, open, closed, binary (yes/no), and multiple-choice questions. The full survey can be accessed at **Supplementary Appendix 3**. Sampling occurred during two field periods, with the first in November and December 2014 and the second in September and November 2015. Sampling was done at household level using a systematic approach, which means one house with fisher was sampled and the next not until it reached 50% of fishers. In some cases the planned number of sampling was not

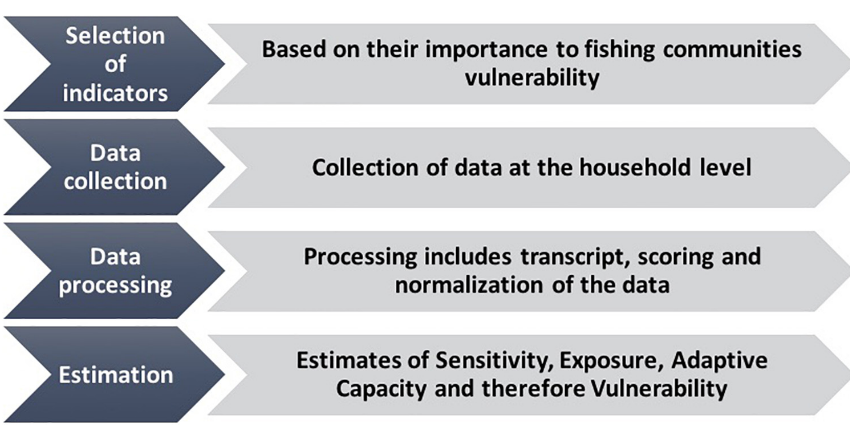

FIGURE 2 | Methodological steps taken in this study (based on Aswani et al., 2018).

reached due to refusal to participate in the research. Communities with up to 30 fishers were all invited to participate in the survey. Each survey was followed by the signed informed consent of the interviewed. A total of 151 households that had regular interaction with the ocean were sampled face-to-face in the eight selected communities. The average length of the interview was 1.08 h (0.35–2.35 h).

The answers were coded and scored for each of the indicators according to the rationale, as describe in **Supplementary Appendix 1**. As the survey included questions with different structures, the indicators resulted on measures of different scales, and to allow comparison the indicators were normalized to a value between 1 and 4 by dividing the number of alternatives by four (e.g., a question with 8 alternatives each would score 0.5, a question with 5 alternatives each would score 0.8).

The vulnerability score was derived from the indicators and the metrics of the following equation (IPCC, 2007): Vulnerability = (Exposure + Sensitivity) – Adaptive capacity. This approach assumes that each index is equally important for overall vulnerability (Mozaria-Luna et al., 2015). A balanced weighted average approach was used in a way that each sub-component contributes equally to the overall index (Hahn et al., 2009). No weight was used because of the complexity of weights assignment due to subjectivity and bias (Becker et al., 2017). The complexity lies in the fact that communities may assign different weights, which would make the comparison goal of the study infeasible in the first phase of the GULLS project, which aimed at comparing communities and countries. On the other hand, the non-weighting approach allowed evaluating equally the strength of each indicator in each component of vulnerability.

With the objective of both assessing the vulnerability of the selected communities representative of the region and comparing them, the individual household level data were considered within communities but the comparisons were undertaken at the community level. With this approach, the internal variability of each community was considered by using the household data when running the analysis comparing the communities. A bubble plot containing the scores for sensitivity, exposure, and adaptive capacity were used to visualize the differences among the three key components of vulnerability. The normality of the sensitivity, adaptive capacity, exposure and vulnerability index were tested using a Shapiro-Wilk test. As a consequence of the data eventually violating the criteria for normality, the non-parametric Kruskal-Wallis test was used to test if there was a difference among communities. To determine which community was significantly different from the average a *post hoc* pairwise comparison test was applied. All tests were considered at a 0.05 level of statistical significance. The analyses and plots were performed using *devtools*, *pgirmess*, *plotly*, and *ggbiplot* packages for the R program.

RESULTS

Sensitivity

The sensitivity category ended with a total of 36 indicators divided into four components that made up the final sensitivity category score, showing the communities with the highest overall sensitivity as being Pontal de Leste and Ilha do Araújo, while the community with the lowest was Enseada. The Kruskal Wallis test ($p = 0.0033$) indicated that there was a difference in the sensitivity between communities (**Figure 3**). The pairwise comparison test showed that the Enseada sensitivity index was significantly lower ($p < 0.05$) compared to Ilha do Araújo, Mandira and Pontal de Leste (**Table 1**). It was observed that the sensitivity of Pontal de Leste and Bonete are mainly influenced by the economic dependence on other resources index, Itaipu by the economic dependence on fishing index and Mandira by the historical and cultural dependence on fishing index.

Considering the social dependence on fishing component containing nine indicators, the community with the highest score was Itaipu, and the one with the lowest score was Enseada. For the historical and cultural dependence on fishing component, fifteen indicators were used; the community with the highest score was Ilha do Araújo, and the community with the lowest score was Boqueirão Sul. The economic dependence on fishing component was based on eight indicators; the community with the highest score was Itaipu, and the community with the lowest score was Bonete. For the economic dependence on other resources component, four indicators were used; the community with the highest score was Pontal de Leste, and the community with the lowest score was Enseada.

Exposure

For the exposure category, a total of 35 indicators were divided into four components. The environmental change component was based on eight indicators; the community with the highest score was Boqueirão Sul, and the community with the lowest score was Mandira. Two indicators were used for the institutional support component, and all communities had high scores. For the personal exposure component, twenty-one indicators were used; the community with highest exposure score was Pontal de Leste, and the community with the lowest score was Itaipu. For the attitude and perception component, four indicators were used; the community with the highest score was Itaipu, and the community with the lowest score was Pontal de Leste.

Itaipu and Enseada had a distinct pattern from the other communities due to the low scores of the personal exposure index, while Pontal de Leste had the highest scores. Boqueirão Sul was also influenced by the personal exposure and the environmental change indexes.

The community with the highest exposure was Boqueirão Sul, and the community with the lowest score was Enseada. The Kruskal Wallis test ($p < 0.0001$) indicates that there is a difference in the exposure between communities (**Figure 3B**). The pairwise comparison test showed that the Boqueirão Sul exposure index was significantly higher ($p < 0.05$) than that of Enseada, Praia do Porto, Itaipu and Mandira (**Table 1**). The Ilha do Araújo exposure index was also significantly higher ($p < 0.05$) than that of Praia do Porto and Itaipu.

Adaptive Capacity

A total of 89 indicators categorized into 12 components made up the adaptive capacity category. From the analysis, it is evident that

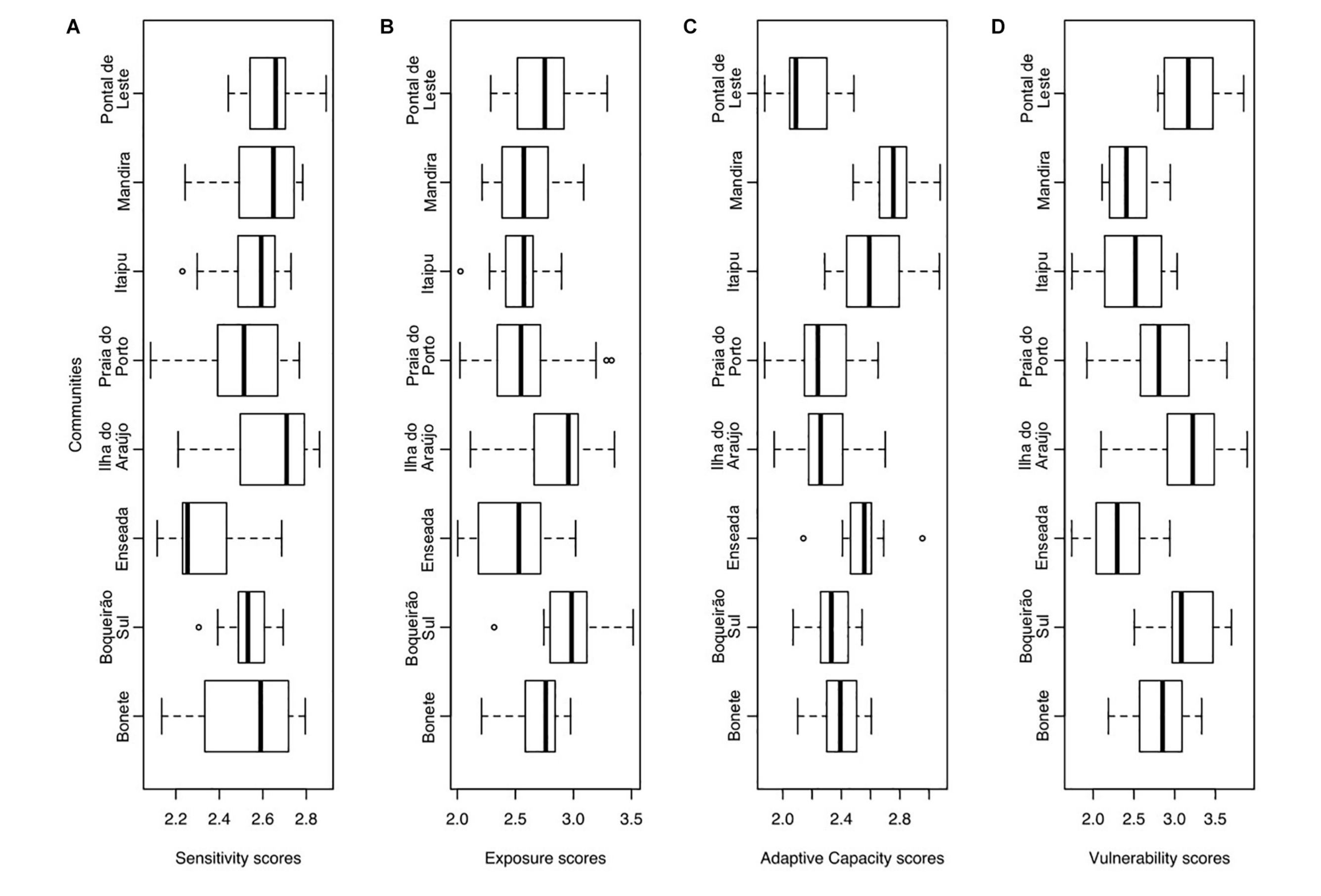

FIGURE 3 | Scores of sensitivity **(A)**, exposure **(B)**, adaptive capacity **(C)**, and vulnerability **(D)** per community. The solid black line represents medians; open boxes are 25 and 75% of the observations, bars indicate the range of durations, and dots the outliers.

Pontal de Leste differentiated from other communities mainly influenced by the lowest scores in the social dependence in fishing and occupational flexibility indexes. Whilest Ilha do Araújo, Bonete, Boqueirão Sul and Praia do Porto and was influenced by the low scores in the overall indexes. Mandira, Itaipu, and Enseada had the highest adaptive capacity in the overall indexes.

The final adaptive capacity score contained the twelve components; the community with the highest adaptive capacity was Mandira, and the community with the lowest overall adaptive capacity was Pontal de Leste. The Kruskal Wallis test ($p < 0.0001$) indicated that there was a difference in the adaptive capacity between communities (**Figure 3C**). The pairwise comparison test shows that the Mandira adaptive capacity index was significantly higher ($p < 0.05$) than those of Bonete, Boqueirão Sul, Ilha do Araújo, Praia do Porto and Pontal de Leste (**Table 1**). The Pontal de Leste adaptive capacity was also significantly higher ($p < 0.05$)

TABLE 1 | Pairwase comparison test for the vulnerability categories between communities, where the differences were significant ($p < 0.05$).

	IT	IA	ES	BN	MD	BS	PL	PP
IT								
IA	AC, E, V							
ES		S, AC, V						
BN								
MD		AC, V	S	AC				
BS	E, V		E, V		AC, E, V			
PL	AC, V		S, AC, V		AC, V			
PP	AC	E	AC, V		AC	E		

IT, Itaipu; IA, Ilha do Araújo; ES, Enseada; BN, Bonete; MD, Mandira; BS, Boqueirão Sul; PL, Pontal de Leste; PP, Praia do Porto; S, sensitivity; AC, adaptive capacity; E, exposure; V, vulnerability.

than the adaptive capacity of Itaipu and Enseada, while Ilha do Araújo and Praia do Porto had adaptive capacities that were significantly lower ($p < 0.05$) than Enseada and Itaipu.

Vulnerability

The vulnerability score was based on 160 indicators split into sensitivity, exposure and adaptive capacity categories. The Kruskal Wallis test ($p < 0.0001$) indicated that there is a difference in the vulnerability between communities (**Figure 3D**). The pairwise comparison test showed that the vulnerability of Boqueirão Sul was significantly higher ($p < 0.05$) than Enseada, Itaipu and Mandira (**Table 1**). The vulnerability of Enseada was also significantly lower ($p < 0.05$) than that of Ilha do Araújo, Praia do Porto and Pontal de Leste. The vulnerability of Ilha do Araújo was also significantly higher ($p < 0.05$) than that of Itaipu and Mandira. The vulnerability of Pontal de Leste was also significantly higher ($p < 0.05$) than that of Itaipu and Mandira.

The most vulnerable community was Pontal de Leste, followed by Ilha do Araújo, Boqueirão Sul, Bonete, Itaipu, Mandira and Enseada, and the least vulnerable was Praia do Porto. Pontal de Leste, Ilha do Araújo and Boqueirão Sul were the most vulnerable due to their highest scores in all three categories: sensitivity, exposure, and adaptive capacity. Bonete obtained intermediate values in the three categories and thus a moderate vulnerability score. Itaipu and Mandira had high sensitivity scores, but the highest adaptive capacity and low exposure, were determined to have low vulnerability. Enseada had the lowest vulnerability score due its low sensitivity and exposure, and intermediate adaptive capacity score (**Figure 4** and **Table 2**).

A scheme with the key drivers affecting the vulnerability of fishing communities to climate change was established, showing the effects of each driver on the final adaptive capacity of the group (**Figure 5**).

DISCUSSION

Sensitivity Drivers

Economic dependence on fishing is usually considered in isolation to express the sensitivity category in many vulnerability assessments, but in the framework used in this study the level of social, historical and cultural dependence were also considered, giving a broad understanding of the sensitivities associated with climate change issues. The results show almost equal sensitivity scores for seven of the eight fishing communities surveyed, with the Enseada community being the only different one. The low sensitivity score for Enseada is due to livelihoods diversification. In this community, households have diversified their livelihoods with mussel and seaweed farming and activities related to tourism supported by their own means and by the local community organization. Finding other profitable activities and creating other sources of employment for the fishing communities under scenarios of collapsed fisheries and climate change are becoming a global challenge (Pauly, 2006). In our analysis, we indeed observed that livelihood diversification was an important factor driving a reduction in vulnerability. Although there is diversification and a non-exclusive dependence on

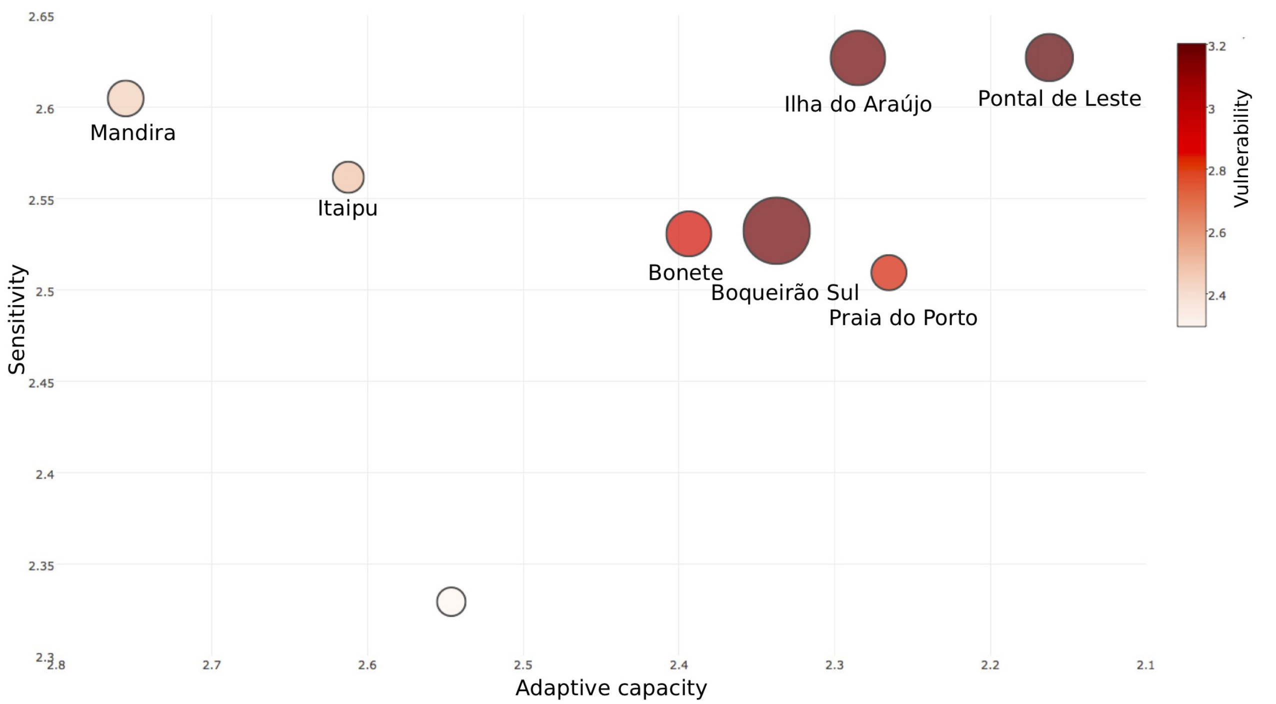

FIGURE 4 | Vulnerability of fishing communities in South Brazil Bight to climate change. Adaptive capacity (*x*-axis) is plotted against Sensitivity (*y*-axis). The size of the bubble shows exposure. The colors represent the vulnerability score.

TABLE 2 | Scores of each index and the cumulative score of sensitivity, exposure, adaptive capacity, and vulnerability.

Categories	Component	PL	IA	BS	BN	PP	IT	MD	ES
Sensitivity	Social dependence on fishing	2,88	2,84	2,79	2,81	2.86	3,02	2,78	2,64
	Historical and cultural dependence on fishing	2,13	2,25	2,01	2,12	2.13	2,06	2,21	2,13
	Economic dependence on fishing	2,33	2,69	2,71	2,17	2.56	2,87	2,69	2,29
	Economic dependence on other resources	3,16	2,72	2,61	3,03	2.49	2,29	2,74	2,25
		2,63	**2,63**	**2,53**	**2,53**	**2.51**	**2,56**	**2,60**	**2,33**
Adaptive capacity	Natural capital	2,37	2,09	2,29	2,38	2.63	2,32	2,99	2,11
	Human capital	2,09	2,53	2,48	2,82	2.09	2,97	2,90	2,70
	Social capital	3,50	2,39	2,34	2,71	2.74	3,01	3,88	2,84
	Bridging social capital	1	1,30	1,25	1,10	1.42	2,02	1,81	1,79
	Physical capital	2,90	3,10	3,00	2,97	3.02	3,42	2,95	3,39
	Financial capital	2,59	2,60	2,75	2,78	2.7	2,77	2,73	2,62
	Personal flexibility	2,08	2,19	2,26	2,28	2.16	2,52	2,47	2,31
	Attitude and perception	2,68	3,04	3,37	3,15	2.86	3,22	3,10	3,02
	Occupational flexibility	1,76	1,92	1,79	2,37	1.9	2,05	2,02	2,38
	Institutional support	1,91	1,97	2,27	1,81	1.85	2,42	3,21	2,08
	Institutional flexibility	1,89	2,01	2,04	2,11	2.11	2,63	2,16	2,62
	Social dependence on fishing	1,18	2,28	2,21	2,25	1.69	1,97	2,83	2,67
		2,16	**2,28**	**2,34**	**2,39**	**2.26**	**2,61**	**2,76**	**2,55**
Exposure	Environmental change	2,06	2,54	2,78	2,39	1.76	2,29	1,85	1,94
	Institutional support	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00
	Personal exposure	2,75	2,20	2,43	2,05	1.93	1,20	2,15	1,43
	Attitude and perception	2,17	2,56	2,67	2,40	2.66	2,67	2,39	2,67
		2,74	**2,82**	**2,97**	**2,71**	**2.59**	**2,54**	**2,60**	**2,51**
Vulnerability		**3,20**	**3,17**	**3,17**	**2,85**	**2.83**	**2,49**	**2,45**	**2,29**
Vulnerability ranking		1	2	3	4	5	6	7	8

Communities are ranked according to their cumulative vulnerability (1, most vulnerable; 7, least vulnerable). Scores are colored according to their value: green 1.00 – 1.74; yellow 1.75 – 2.49; orange 2.50 – 3.24; red 3.25 – 4.00). IT, Itaipu; IA, Ilha do Araújo; ES, Enseada; BN, Bonete; MD, Mandira; BS, Boqueirão Sul; PL, Pontal de Leste; PP, Praia do Porto. The bold values are the total scores of each category.

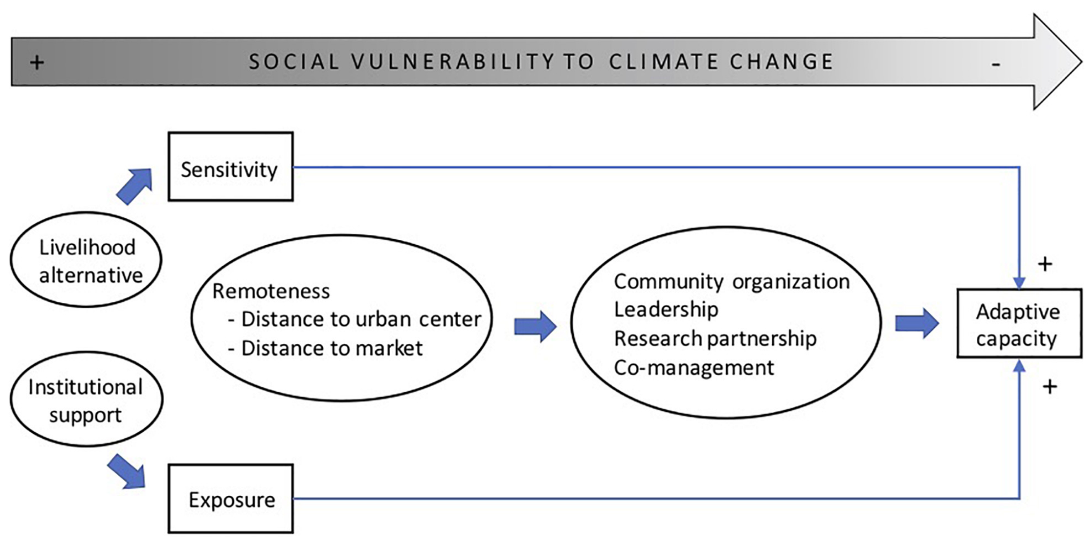

FIGURE 5 | Key factors affecting the vulnerability to climate change in fishing communities of South Brazil Bight. Main drivers, in circles and vulnerability categories, in rectangles.

fishing, the Enseada community still has a strong link with the fishing tradition, with it being practiced daily by all the interviewees.

The strong social, economic, and cultural dependencies on fishing were an important drive to increase sensitivity in Ilha do Araújo, Mandira and Pontal de Leste. The index of economic dependence on other resources is the main factor affecting the sensitivity of Pontal de Leste and Bonete, the most isolated communities and accessed only by the sea. The index considered the distance to the market to buy and sell goods, methods to obtain food, importance of food source, and level of farming. The distance to market, which can express remoteness, is the factor that increases the sensitivity of the communities (Cinner and Aswani, 2007) as it limits their ability to negotiate prices and avoid the use of middlemen to sell their catches (Merlijn, 1989). In Pontal de Leste, the situation is worse, as it is a subsistence community and reliant on income from selling the fish. The strong dependence of these communities implies a concern in relation to food security, since their main source of income and food is threatened by climate change (Gasalla et al., 2018) and their access to markets, in addition to involving greater spending on transit, may also be impacted by the increase in storm surges predicted by climate change scenarios (von Storch, 2014). A similar situation is expected to be found in other isolated communities that also depend on the external market to buy and sell goods.

For the Itaipu community the high economic dependence on fishing leads to its high sensitivity score, as changes in fishery resource availability are expected to have proportionally negative effects on the turnover of the activity. To ensure the survival of fishing and the maintenance of income related to fishing, the community fought for over 20 years for the creation of the Itaipu MER, established in 2013. The MER ensured community participation in the (in progress) construction of the management plan and the exclusive right to explore the area, which is facing the speculation from the real estate and the oil and gas industries.

Exposure Drivers

Fisher personal exposure plays an important role in community exposure, with the shoreline change subcomponent playing the main influence on the most exposed communities. The erosion process has been well documented in the communities exposed (Angulo et al., 2009) and has a direct effect on the livelihoods of local fishers, by jeopardizing their homes and their access to the sea (Martins and Gasalla, 2018). Other associated impacts of personal exposure are related to large storms, such as damage on roof and on fishing gear, and occasionally shipwrecks. Shipwrecks occur with some frequency in the south and southeastern regions (Fuentes et al., 2013), and was reported by the Itaipu, Araujo Island and Bonete fishers over the past 5 years.

Another important driver of exposure that also affects the adaptive capacity of the communities is the distance to an urban center, with the closest communities being the less exposed, as they typically have better infrastructure and access to public services. The communities most exposed are those that have poor infrastructure and that use the ocean as the main mode of transport. Due to the lack of infrastructure in these communities, they must use the ocean to go the close town to sell their fish catches and to buy food and basics needs. Using the ocean as the main mode of transport also means that good ocean and weather conditions are not only important to fishing activities but also to community mobility and survival. An increase in the frequency and intensity of the storms are predicted by climatic models (Pezza and Simmonds, 2005; von Storch, 2014), which may increase communities vulnerability.

The analysis has drawn attention to the lack of institutional support related to climate change. None of the localities have institutions or government departments working with the community on climate change issues. There are universities undertaking climate change research in the region, but communities are not aware of such research. In addition to the need for clear government action on climate change mitigation, focusing on the fishing communities, the institutions and universities that are already researching the climate change issues need to improve communication and knowledge exchange with local communities (Cvitanovic et al., 2015). The institutions also needs to better engage the social component of the ecosystem by using an interdisciplinary approach combining innovative frameworks and data (Osterblom et al., 2013; Bennett et al., 2017), and encourage the participation of local communities in climate research to increase the capacity of these populations to cope and adapt to changes (Nop, 2015). These actions are mandatory to improve the knowledge of the climate change issues and therefore to contribute toward effective implementation of adaptation policies (Makinde, 2005).

Adaptive Capacity Drivers

Adaptive capacity depends upon the availability of natural, human, social, physical, financial and institutional resources, as can be measured as the ability people have to convert these resources into useful adaptation strategies (Brooks and Adger, 2004; Folke et al., 2005; Smit and Wandel, 2006). The flexibility component (personal, occupational, and institutional) were also explored in the used framework to refine the measure of the potential of people and institutions to overcome their present situation and deal to future conditions (Marshall, 2010). Therefore, the community with the highest adaptive capacity was Mandira. The high adaptive capacity of the community was driven by well-established community organization, proper management of the oyster resulting from a partnership between government, university and local knowledge (Machado et al., 2015), control of commercialization through a community cooperative (Kefalás, 2016), and the search for local income alternatives such as handcrafts and community-based tourism. On the other hand, Pontal de Leste had the lowest adaptive capacity, mainly due to its high dependence on fishing, inability to negotiate fish price due to its distance to the market and lack of electricity to freeze and store the fish, and absence of livelihood alternatives not related to fishing. The community has tried to diversify its income by having a community restaurant and renting rooms for tourism, but these activities are not yet making significant economic contribution to the families as they are not yet part of the regional tourism route. The engagement of the community members into regional tourism councils is necessary to bring the community new employment opportunities even as local communities are faced with increasing responsibilities to provide for their own well-being and development (Flora and Flora, 1993). Reducing community vulnerability requires adopting similar approaches to those used in Mandira, including collective sales of fish, community-based tourism, a representative community organization, and strong leadership (Haque et al., 2009; Gutierrez et al., 2011).

Communities within a MER, as is the case for Mandira and Itaipu, have the highest adaptive capacity. MER is a type of community-based marine protected area in Brazil, with management decisions being taken at a local level (Diegues, 2006; Santos and Schiavetti, 2018). The marine MER in Brazil has been successful in ensuring rights for fisheries to small-scale fisher organizations and to preserve marine resources, despite some implementation problems (Santos and Brannstrom, 2015). These characteristics increase the ability of a community to adapt to hazards, as well as reduce vulnerability. The combination of community organization, representative leadership, scientific support, and bottom-up decision-making was the key for a higher adaptive capacity. The infrastructure and income alternatives are aspects that still need to be worked on in all sampled communities, resulting in an overall low adaptive capacity. The diversification of livelihoods is expected to increase income and reduce the overall vulnerability of the community (Brugere et al., 2008). The diversification of livelihoods is usually dependent on external investments in community enterprises and microcredit interventions (Torell et al., 2017). However, Mandira proved that a strong leadership and community commitment can play an important role in the development of alternative livelihood options without dependence on external factors.

Overall Vulnerability

From a global aspect, developing countries, such as Brazil, are in the top half of the countries' most vulnerable to climate change in relation of marine resources (Blasiak et al., 2017). At the national level, Brazil is predicted to have high exposure and moderate sensitivity, adaptive capacity and vulnerability to the impacts of climate change on fisheries (Allison et al., 2009). At the local level, our findings were similar to those of a study conducted in Parana, southern Brazil, where infrastructure, household assets and level of participation in community organizations were also found to be key drivers of vulnerability (Angulo et al., 2009). A study carried out by Silva et al. (2014) in Praia da Almada, Ubatuba, southern Brazil, shows that fishers are looking for alternative source of income and diversifying their fishing grounds as means to reduce their vulnerability. This indicates that in the absence of policies addressing vulnerability, fishers in SBB are trying to reduce vulnerability by their own means drawing on local knowledge and collective action. A global analysis shows that strong leadership and community cohesion is beneficial for fisheries management (Gutierrez et al., 2011). Here, we showed that these factors are also contributing to reduce the vulnerability to climate change by increasing the community adaptive capacity.

The socioeconomic vulnerabilities of coastal communities to climate change are typically related to the ongoing challenges of managing urbanization, pollution, sanitation, and marginalization (Cinner et al., 2012). These factors are also influencing the communities of SBB, but we found that the remoteness, in terms of the distance to urban center and to market, as the main drivers negatively affecting the vulnerability in the region. Remote communities tend to have limited or disadvantaged access to markets, and also poor access to basics services as health and education (FAO, 2015). In addition to these factors, communities located on islands have geophysical characteristics, as low average altitude of Pontal de Leste and Boqueirão Sul (Angulo et al., 2009) that create inherent physical vulnerabilities to those locations. These findings bring new elements to support policies to mitigate the effects of climate change in communities dependent on marine resources. The factors that guide the vulnerability of communities and the elements used by those that have managed to reduce them must be used to build local adaptation strategies. The use of these elements is important for implementing adaptation actions, but to become effective, it should involve the stakeholders, strenghten participatory processes and articulate them with local leaderships (Gasalla and Martins, 2019).

Lastly, the vulnerability framework used in this study (Aswani et al., 2018) was initially developed to ultimately allow cross-country comparisons, but as it was based on a wide and refined survey assessed on the very local scale, allowing a strong enough vulnerability comparison of local communities. The criteria for selecting the communities that were designed to represent the diversity of characteristics in the region were also useful, since the criteria allow the extrapolation of the data found here to communities with similar combination of factors founded in this study.

CONCLUSION

The study provided an important contribution to the understanding of the differences and similarities in the social vulnerability to climate change among coastal communities, bringing a rich interpretation of the local processes affecting the exposure, sensitivity, adaptive capacity and vulnerability of small-scale fishing communities of the SBB. Findings shows that those communities are highly affected by climatic events as fishers have a strong dependence on marine resources for maintaining their livelihoods. This dependence makes all the communities in SBB vulnerable to climate change.

The main factors affecting the vulnerability of the small-scale fishing communities of the SBB to climate change were: community remoteness, lack of institutional support related to climate change, livelihood diversification, well-established community organization, strong leadership, partnership with research institutions, and resources community-based co-management. Moreover, their particular ranking in the vulnerability framework should allow policy-makers to prioritize much needed actions.

The strengths of the method were highlighted, yet the use of indicators which appeared useful for cross-community (and future cross-country) comparisons deserves an in-depth outlook of the different drivers at the very local scale if lower-resolution policies are proposed. This is intended to be presented in the following series of contributions for each of the local commmunities studied here. Also, the replicability potential of this approach seems to be high since similar studies were conducted in Northern Brazil and showed a clear and useful ranking within the different vulnerability componentes and impacts. Future research should build on and improve this approach especially in the qualitative analysis of the narratives from local fishers that were also accessed through this study.

Overall, our results allow a comprehensive understanding of social vulnerability to climate change in the SBB seeking to find the main drivers affecting the small-scale fishing communities elsewhere. This approach should be particularly important in a post-Covid19 setback scenario.

DATA AVAILABILITY STATEMENT

The datasets generated for this study will not be made publicly available because of the Ethics Commission requirement in Brazil.

ETHICS STATEMENT

The project was reviewed and approved by the Committee for Human Research Ethics of the University of São Paulo. All participants were informed about the research purposes and consented to participate.

AUTHOR CONTRIBUTIONS

IM conducted all the field trips for data collection, calculated the scores for each indicator, and wrote the first draft. MG was the research's supervisor, brought ideas for methodology and analysis made, revised all the data and scoring analysis with suggestions, took care of the submission process, and was the PI of the research grant. Both 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.2020.00481/full#supplementary-material

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The Melting Snowball Effect: A Heuristic for Sustainable Arctic Governance Under Climate Change

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Climate change in the Arctic is occurring at a rapid rate. In Longyearbyen, Svalbard, the world's northernmost city, deadly avalanches and permafrost thaw-induced architectural destruction has disrupted local governance norms and responsibilities. In the North Atlantic, the warming ocean temperatures have contributed to a rapid expansion of the mackerel stock which has spurred both geo-political tensions but also tensions at the science-policy interface of fish quota setting. These local climate-induced changes have created a domino-like chain reaction that intensifies through time as a warming Arctic penetrates deeper into responsibilities of governing institutions and science institutions. In face with the increasing uncertain futures of climate-induced changes, policy choices also increase revealing a type of "snowballing" of possible futures facing decision-makers. We introduce a portmanteau-inspired concept called "The Melting Snowball Effect" that encompasses the chain reaction ("domino effect") that increases the number of plausible scenarios ("snowball effect") with climate change (melting snow, ice and thawing permafrost). We demonstrate the use of "The Melting Snowball Effect" as a heuristic within a Responsible Research and Innovation (RRI) framework of anticipation, engagement and reflection. To do this, we developed plausible scenarios based on participatory stakeholder workshops and narratives from in-depth interviews for deliberative discussions among academics, citizens and policymakers, designed for informed decision-making in response to climate change complexities. We observe generational differences in discussing future climate scenarios, particularly that the mixed group where three generations were represented had the most diverse and thorough deliberations.

Keywords: climate change, governance, geopolitics, Arctic, social sustainability, responsible research and innovation

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INTRODUCTION

How can the different social, economic, political and ecological aspects of climate change be useful for achieving sustainable governance of fisheries in the Arctic and beyond? Can the natural and social sciences integrate their methods to address inherent interdependencies and complexities of climate change? Is it possible for these insights to be discussed among the public, and do decision-makers have the capacity to be responsive to public deliberations about climate change? The inherent interrelations and complexities of climate-induced changes to fisheries pose huge challenges to the science—society dialogue. There is as such a knowledge gap in how to design a practical and digestible interdisciplinary framework to discuss plausible future scenarios with society and the implications of environmental change to human communities and political structures governing environmental issues globally.

This need is among others seen in the fishing industry, with the observed changes in the distribution trend of the Northeast Atlantic mackerel stock as a current example.

Specifically, the Northeast Atlantic mackerel stock has been growing since 2007 (Nøttestad et al., 2015; Nøttestad, 2016), often attributed to warming waters and increased available prey habitats because of climatic stressors (Gattuso et al., 2015). This increase of the stock has given great returns to the industry in the form of valuable catches. It has however, also led to quota allocation disputes between Norway, the European Union, the Faroes Islands on the one side and Iceland, Greenland and Russia on the other (Hotvedt, 2010; Spijkers and Boonstra, 2017). It has also led to an on-going disagreement between Norwegian pelagic fishers of the Pelagic Fishers' Association (Pelagisk Forening) and the scientific stock assessment teams of the Institute of Marine Research and the International Council for the Exploration of the Sea (ICES) in regard to the officially reported scientific assessment of the size of the stock. In addition, we a see that there are both possible and real geopolitical repercussions to changing fish stocks such as that of the herring as well (Tiller and Nyman, 2017; Harte et al., 2019; Tiller and Dankel, 2019; Tiller et al., 2019).

In this paper, we synthesize relevant insights from the Norwegian nationally funded project REGIMES and develop a portmanteau-inspired concept called "The Melting Snowball Effect." The Melting Snowball Effect encompasses the chain reaction ("domino effect") that increases the number of plausible scenarios ("snowball effect") associated with the possible effects of a number of climatic stressors, including snow melting, and thawing ice and permafrost in the Arctic. This concept emerged from the observations of the effects the warming Arctic climate have had on local governance situations for Longyearbyen, the largest settlement in the archipelago of Svalbard in the High North (**Figure 1**). In light of this, we look at heuristics, or practical but imperfect mental models for the purpose of decision-making, and how these can be helpful in arenas where interdependencies can be complex. As the Arctic warms, more plausible scenarios are revealed leading to more complexity and more uncertainty in decision-making. We hypothesize that the use of heuristics can be convenient and helpful for citizens and policy- and decision-makers who are faced with urgent decisions in highly uncertain scenarios in order to build capacity for inclusive democratic deliberation regarding climate plans at different levels of governance.

We already understand that marine fisheries are being affected by climate change, and it is projected that Arctic areas of the Ocean could be more productive in the future, thereby positively affecting the world's northernmost fisheries (Cheung et al., 2009; Gattuso et al., 2015; Lam et al., 2016a). We therefore begin our transdisciplinary analysis of Arctic climate change and how Arctic governance could respond by first applying the Dynamic Bioclimate Envelope Model (DBEM) to the Northeast Atlantic and areas around Svalbard under different IPCC climate scenarios (Cheung et al., 2009). We then couple these fisheries model projections with a fisheries economic model that incorporates costs and revenues of future fisheries scenarios. We then apply results from qualitative in-depth interviews of stakeholder perceptions from a selection of representative respondents living in Longyearbyen, Svalbard, about the economic potentials that they consider of interest under a changing climate. We finally make some conclusions as to how the Melting Snowball Effect can be used as an organizing heuristic to (1) demonstrate the additive effect of climate-induced complexity in decision-making, and (2) provide a space for deliberation of plausible scenarios among local citizens, academics and governing bodies. Taken together, we argue that these two points can contribute to reduce the inherent interrelations and complexities of climate-induced changes to fisheries that we see pose these substantial challenges to the science-society dialogue.

Social, Economic, Political, Ecological and Governance Aspects of Climate Change

Anthropogenic-induced climate change is altering the relationship humans and societies have with nature. Unsustainable practices of using non-renewable fossil fuels as the main source of energy for industries has become a causal agent of a warming climate and a warming Ocean for most parts of the world. According to the IPCC and other experts (IPCC, 2014), large-scale transitions to renewable, non-greenhouse gas emitting energy sources are needed as fast as possible to prevent CO_2 emissions into the atmosphere and further increases of global warming. These large-scale transitions, however, cannot occur without coordination of reliable renewable energy technologies and products, infrastructure investments, and regulations to guide climate-smart policies. There is little doubt that the regional and local scales will be critical areas for the success of climate mitigation and adaptation. But how can the regional and local levels of governance and policymaking in a given socio-geographical area have sustainable impacts?

Governance, and the related norms of societal structure and societal decision-making and control, is usually supported by institutions that are also shaped by society and politics by formal and informal processes (Krasner, 1983; Lawrence and Suddaby, 2006). Many societies have started to come to terms with climate change by incorporating climate plans in local, regional and national policies as measures to adapt to climate change. However, in certain parts of the world, like the Arctic, climate change has occurred so rapidly, that local governors and bureaucrats have already had to deal with dire consequences of a warming climate. In addition, the Arctic Council for the first time did not have a joint declaration signed at the end of

FIGURE 1 | Map of the Arctic Region. The Svalbard archipelago is outlined in the pink hashed circle, and Longyearbyen (Longyear City) indicated. Public domain source: https://commons.wikimedia.org/wiki/File:Arctic_circle.svg.

its 11th Ministerial Meeting – because of disagreements over climate change, with the United States wanting to remove all reference from the declaration if it were to sign the declaration (Tømmerbakke and Breum, 2019).

Svalbardi fundinn

In Longyearbyen, Svalbard, however, there is less discussion about whether there are effects of climate change – and more about how to adapt to it. This was the area in the High North where we explored the concepts of future fisheries and the role of institutional and community adaptive capacities. The case was chosen because it is located in an area where climate change is having an effect faster than most places in the world, but also because its governance structure is complex. This gave us the opportunity to assess the effects of institutional capacity on a case where governance is not straightforward, and where adapting to future scenarios involves not only institutional changes but also geopolitical considerations. This does not make it a representative area of the Arctic populations in general, given the diversity of its peoples and geographical realities, but it gives a snapshot of what one group of Arctic residents envision in terms of future scenarios around fishing. It also exemplifies some of the challenges to governance that the Arctic is faced with under a changing climate.

Svalbard is an administered territory of the Kingdom of Norway, though this is not without some controversy. Several nations, including Iceland, Norway, Russia and the United Kingdom, have all claimed that their people discovered Svalbard first with its first mention being from 1194 with *"Svalbardi fundinn"* written into the "Islandske Annaler." In a different text, dating from around 1230, geographical descriptions to this insert are given, upon which Fridtjof Nansen commented that the land found was likely what we do know as Svalbard and not Greenland, though the discoverer(s) remained unknown (Nansen, 1926). What is known for certain, though, is that in 1596, the Dutchman Willem Barents did discover the archipelago, and that in 1899, the first commercial exchange of coal from Svalbard took place in Tromsø as well as in Trondheim. It was not until the American John Munroe Longyear visited the archipelago in 1901 and 1903 and founded the Arctic Coal Company in 1906 that investments were made into coal extraction at a serious level. Longyear City (today known as Longyearbyen) as a community was as such founded by the Arctic Coal Company and was from its early beginning known as a "company town" where the only economic activity centered on coal extraction.

At this time, the Svalbard Treaty was not signed yet, and as such, Svalbard was still considered terra nullius, a de facto no-man's land owned by no-one. In 1918, however, the Norwegian government voted that it should attempt to take possession of Svalbard, and in a letter dated 10 April 1919, Norway relayed this request for sovereignty to the Supreme Council of the Peace Conference in Paris. This was re-emphasized by the Norwegian Ambassador in Paris, F. Wedel Jarlsberg under the peace negotiations. He claimed Svalbard for Norway, as war compensation for the losses of almost half the fleet tonnage of the Norwegian merchant fleet under WWI, as well as the lives of 2,000 sailors that were providing transport of supplies to the Entente nations (Ulfstein, 1995; Berg, 2012; Czarny, 2015; Rossi, 2016). The Svalbard Treaty was signed by the Treaty parties on February 9, 1920, and when Norway, under Article 1 of the Treaty, was granted territorial sovereignty, it effectively meant that it is free to regulate all activities on the islands, including fisheries and other non-coal related industries, current and future. After years of institutional adaptation to new realities, both socio-political and economic, in the autumn of 1993, political parties were allowed in Longyear City, and democratic elections were held for the 15 representatives of the city council (Utnes, 1999) and the town was no longer a coal company town.

A move toward new industries in Svalbard is important for the Norwegian population on Svalbard. Fisheries have not had a strong role as employment in Svalbard though. The cornerstone industry and de facto "district politics" tool, or "social contract" has consistently through the history of the community been the coal mining industry, which was decommissioned recently (Hagen et al., 2018). As such, there is a new horizon awaiting the community of Longyearbyen where new industry options must materialize sooner rather than later to ensure the sustainability of the community structure, and where fisheries and a fish processing industry is one of those options considered.

The Melting Snowball Effect in Light of Responsible Research and Innovation

The interconnectedness of natural phenomena like climate change and its relations to governance is critical for the management of the Arctic since this area is a literal hotspot for governance research, due to the warming Arctic climate and melting sea ice and permafrost (Tiller et al., 2019). The dynamics of the community of Longyearbyen is also changing, seen in the trend of the increase of non-permanent residents which reflects the shift of work from coal and hunting to research and tourism (Statistics Norway, 2017). This community has given us the opportunity to observe and assess the local governance challenges climate change has incurred on a specific Arctic group of people. In this paper, we explore this case study where the world's northernmost non-indigenous community is located. Although Svalbard is a world center for Arctic natural science research, there are significantly less efforts in linking the natural science research to social, economic and political science research and theories. We explored this interdisciplinary (linking different fields of research) and transdisciplinary (linking research to the social, economic and geopolitical realities of local communities) research in the 3-year project *REGIMES "An interdisciplinary investigation into scenarios of national and international conflicts of ecosystem services in the Svalbard zone under a changing climate in the Arctic."*

Climate change governance is a relatively new research front and the integration of ecological, social, economic and political insights are complex. Our overall methodological framework is "Responsible Research and Innovation" commonly known as

RRI (von Schomberg, 2013). von Schomberg (2013) lists two questions responsible research must attune to:

1. Can we define the right outcomes and impacts of research and innovation?
2. Can we subsequently be successful in directing innovation toward these outcomes if we would agree upon them?

The complexity of future climate change scenarios in the Arctic is confusing. Scientists use numerical models both to make predictions about climate change and to understand how climate change affects different sectors and society. But the underlying complexity and uncertainty of future climate-affected scenarios can be used as a stalling tactic for decision-makers and businessmen who prefer business as usual, and the need for anticipation, reflection and engagement. Participatory practices at the science-policy interface is a typical RRI tactic, and facilitated our use of plausible, interconnected future scenarios driven by climate. We have been most concerned with developing specific insights with pragmatic solutions, for example, heuristics.

MATERIALS AND METHODS

When applying RRI as a research frame, we induced the following four qualities of deliberation between science and society: *reflection/engagement (during workshops)*, *anticipation (scenarios)*, and *responsiveness (choices and decision-making under climate change)*.

As the basis for our anticipation intervention, we created a bio-social-economic-geopolitical plausible narrative of the future. To do this, we first applied the Dynamic Bioclimate Envelope Model (DBEM) to predict the ecological and economic effects of climate change in the Norwegian exclusive economic zones, with Atlantic cod as example. We then conducted in-depth interviews and participatory stakeholder driven workshops [see for example Tiller and Hansen (2013) for details on workshop methodology] as methods to elucidate current stakeholder perceptions and attitudes about climate change. These included in-person interviews in Longyearbyen (August 2017), as well as inter-generational pilot focus groups carried out in Bergen, Norway in November 2016 and September 2017 and the final workshop, on which we report here, in June 2019. The following subsections describe each of these methodologies in detail. The interviews were done in accordance with local regulations in terms of personal data through permits from NSD, Data Protection Services, Norway.

The next subsections describe the DBEM modeling and interviews conducted in Longyearbyen and workshops in Bergen.

Dynamic Bioclimate Envelope Model for the Northeast Atlantic and Svalbard Zone

The Dynamic Bioclimate Envelope Model (DBEM) is a simulation model that combines statistical and mechanistic approaches in projecting the changes in distribution, relative abundance and maximum catch potential (MCP) of the fishes, especially commercially important species such as Atlantic cod (*Gadus morhua*). DBEM has been applied at different scales and various regions globally (e.g., Fulton et al., 2005; Cheung et al., 2011; Lam et al., 2012; Jones et al., 2013; Leitão et al., 2018; Marushka et al., 2019). It (detailed description of DBEM, see Cheung et al., 2011). Here we use Atlantic cod as an example to project its population changes and its associated economic consequences. Based on the current distribution of Atlantic cod, the DBEM simulates changes in the distribution of abundance, biomass and MCP of Atlantic cod over time and space driven by projected changes in ocean conditions, with consideration of physiological and ecological effects of changes in ocean properties and density-dependent population growth and movement (Cheung et al., 2009, 2010).

To understand the impact of climate change on economics, DBEM has been built into economic models to examine the potential economic impact of climate change, and these studies focus on modeling the effects of climate change on the profits through changes in the catches (Lam et al., 2014, 2016b). We incorporate specific fishing effort dynamics into the DBEM. This model is a more holistic approach than the previous biological model such as DBEM and size spectrum model, which do not include how the change in socio-economic factors on the catch and biomass of marine species. Our model projects the future impact of climate change on economics of fisheries by incorporating the change in fishing effort, which is determined based on the change in catch, profit and fisheries regulations, into the biological model that projects the potential catch under climate scenarios.

The fishing effort dynamic model (EDM) simulates the change in fishing effort through the profit obtained from fishing in each year. The profitability is the driving force for fishing activity the following year. The fishers decide whether to go fishing, invest more on fishing activity, stay or exit fisheries. The potential fishing profits in each fishing year is projected using the bioeconomic model incorporating fish biology and economics of fishing operation (e.g., maximum carrying capacity, biomass, fishing cost, fish prices, subsidies, etc.). The resulting annual fishing effort in term of fishing mortality is integrated into the DBEM. Therefore, this entire model (DBEM-EDM-DBEM) (**Figure 2**) is an iterative process and allows us to investigate how the change in fish abundance and MCP may affect fishers' behavior and sequentially how fishers' action (i.e., change in fishing effort) may affect the fish abundance and MCP on top of the effect of climate change. The results from this simulation model will be used for formatting scenarios later for workshops conducted in Bergen with three generations.

In-Depth Interviews in Longyearbyen

We acknowledge that the use of case studies as a method in political science in the theory building process can help readers understand social problems in general (Stake, 1978; Eckstein, 2000), such as that of adaptive capacity to climatic stressors, including that of moving fish stocks. Following Stake's (1978) list of features of a case study in the social sciences, we emphasize that a given case study may include "*...descriptions that are complex, holistic, and involving a myriad of not highly isolated variables; data that are likely*

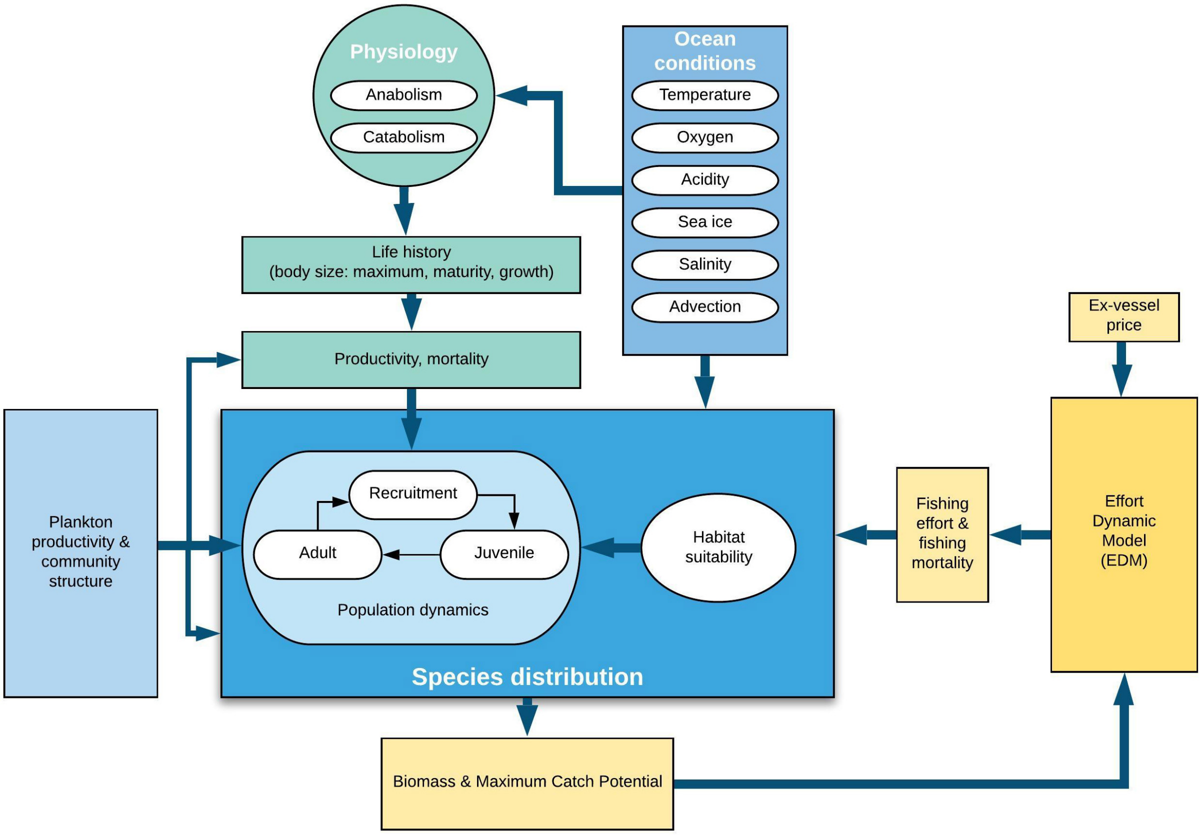

FIGURE 2 | Structure of the coupled Dynamic Bioclimate Envelope Model (DBEM) – Effort Dynamic Model (EDM) in this study.

to be gathered at least partly by personalistic observation; and a writing style that is informal, perhaps narrative, possibly with verbatim quotation, illustration and even allusion and metaphor."

On this note, our analysis therefore includes data gathered in August of 2017 from in-depth interviews of Longyearbyen residents. The interviews were semi-structured and in-depth, where the selected respondents were presented with a number of open-ended questions that were within the realm of the research question of the interviewer. The conceptual basis for the interview guide was based on literature studies, previous knowledge about the topic and the preliminary results from the DBEM. Based on this, and our research question, we formulated a first-draft interview guide (see **Supplementary Appendix** for Interview Guide) or list of questions, that would direct the interview with the informant. We wanted the questions to inspire the respondents to give frank, in-depth, and spontaneous answers and reflect their personal feelings – not just politically correct answers. We encouraged answers to be descriptive and thorough by leading with "who" or "where" or "what," and even "why" at times, for both the main questions and the follow-up questions, where the respondent would be asked to expand on the main topic. We then tested the interview guide on the research group to evaluate it in terms of its internal logic, lack of leading questions and interviewer bias, and that it gave us the answers we were looking to elicit. Though we used expert-testing, we could also have used in-field testing, having a potential interviewee test the guide. However, given our limited time of field work, we chose to test it within the research group itself. This exercise also helped determine the time frame of each interview.

The interviews lasted between 30 min and 1.5 h depending on the interest and needs of the respondents. To ensure that the interview respondents came from diverse backgrounds, we intentionally targeted participants that varied in their: years of residence in Svalbard, trade, family composition, gender, and age. We used the snowball method to contact individuals (Biernacki and Waldorf, 1981), and we had 17 interviews. Though this may seem like a small-N from a natural science and quantitative research perspective, samples in qualitative research tend to be smaller than one would expect in the more numerical sciences. This is to support the depth of case-oriented analysis that is fundamental to this mode of inquiry. The samples also tend to be purposive in that they were selected by virtue of the respondent's capacity to provide richly textured information, relevant to the phenomenon under investigation, in this case effects on fisheries potentials in the Arctic – specifically Longyearbyen. As such, this purposive sampling (as opposed to probability sampling that is customarily employed in quantitative research) selects "information-rich" cases or respondents, and the more useful the data sampled from each respondent is, the fewer respondents are needed. Research on this has shown for example that after 20 responses, there is seldom any new information to be gained that is analytically relevant (Green and Thorogood, 2004). We experienced this as well in our study and chose to end our inquiries after 17 responses.

These interviewees were represented by both men (6) and women (11), representing different sectors including tourism (6), research and education (5), public employees and governance (3), industry (2) and other (1). Five were in their 20s, four were in the bracket 30–40, two in the 40–50 age bracket, and six were more than 50 years old. They furthermore represented Norwegians (10), Europeans (5) and Russians (2). While the sample is small, we maintain that the sample size is relative to the information power a sample has and the value this presents for the advancement of the research toward a specific goal (Sandelowski, 1995; Malterud et al., 2015).

The emergent narratives from these interviews were later analyzed. Narratives are popularly described as "*discourses with a clear sequential order that connect events in a meaningful way for a definite audience and thus offer insights about the world and/or people's experiences of it*" (Hinchman and Hinchman, 1997). We interpreted the narratives and focused on pulling from the notes specific quotes that illustrate the emergent themes (Czarniawska, 2004), like that of a future of having Longyearbyen as a landing site for fish and other marine resources. The most important quality of the narrative in this case was the richness of the knowledge and experiences. This is in line with Elliott's (2005) account of narratives as being instrumental in that "*…internal validity is…thought to be improved by the use of narrative because participants are empowered to provide more concrete and specific details about the topics discussed and to use their own vocabulary and conceptual framework to describe life experiences*."

Workshops With Three Generations of People in Bergen, Norway (June 2019)

The focus groups were conducted over the span of 2 days, since the initial day only had 1 participant in the youngest category. This was remedied by recruiting young people in the local chapter of the activist group Natur og Ungdom (Nature and Youth) at their local meeting the following day. It is important to note that for both these workshops, we were not looking for a random sample of citizens, but instead people who were willing to discuss these issues. Therefore, many, but not all, of our workshop participants were currently well-versed in many aspects of climate politics and several considered themselves climate activists.

In order to demonstrate the "Melting Snowball Effect" to stimulate discussions in the workshops, we integrated plausible scenarios from four knowledge bases: (1) biology, climate and ecology, (2) economics, (3) political science (national and geopolitical), and (4) social science and community. Based on the DBEM and economic modeling and the community studies and interviews in Longyearbyen, we developed three scenarios, A, B, and C, that all take place in 2039, 20 years in the future. The scenarios in their entirety are in **Supplementary Appendix**. **Table 1** summarizes the excepts from each scenario related to fisheries and climate change.

TABLE 1 | The scenarios and questions used in the citizens' workshop in Bergen, Norway (June 2019).

Scenario	Excerpt related to climate change and fishing	Group question
A	Cod go to Russia Because of the warming Ocean, Norwegian cod seem to have stopped spawning in Lofoten, and now are exclusively located in the Russian zone. Russia has dropped out of the Joint Norwegian-Russian Fisheries Commission and does not let Norway fish any cod in their waters.	Should Norway do something to get back cod fishing?
B	Fish more popular It is more common to eat herring and mackerel, which have become more abundant along the coast of Norway. However, Norwegian fishermen has recently declined to follow the recommended scientific advice from the European fisheries scientists to reduce quota of these species, in order to meet the consumer demand for mackerel and herring. Environmentalists warn that this overfishing increases the risk that the fish stocks collapse.	Is it more important to provide healthy fish to reduce CO_2 emissions and increase public health, or to reduce fishing pressure to prevent overfishing? Why?

The scenarios are inspired by Round 1 of workshops with these three generations (each scenario topic is from specific areas of concern that came from the Bayesian Belief Networks conducted in November 2016 and September 2017). A first draft of the three scenarios that came out of the three generational groups' BBNs was peer-reviewed and discussed with two colleagues at the Centre for Climate and Energy Transformation (CET) in the Department of Geography at the University of Bergen. The second draft was reviewed by the REGIMES consortium. The third draft is what was used for the workshops (**Supplementary Appendix**).

The protocol is as follows:

1. Participants are welcomed and register their name, date of birth, education level and if they are currently active in any organizations (yes/no).
2. Participants split in generational groups in separate rooms (3).
3. Each generation gets a scenario/questions and 15 min to answer the questions as a group.
4. Refreshments break.
5. Random mixing of groups and repeat the scenarios/questions.
6. Plenary de-brief.

We audio recorded 15 min × 5 discussions (2 rounds of 2 discussions on Day 1 and 1 discussion the following day), transcribed each discussion and then performed a discourse analysis to analyze the discussion regarding future Arctic fisheries and their perceived strengths or vulnerabilities.

We demonstrate the use of "The Melting Snowball Effect" as a heuristic to create plausible scenarios (**Figure 3**) for deliberative discussions among academics, citizens and policy-makers and also a way to summarize these deliberative discussions.

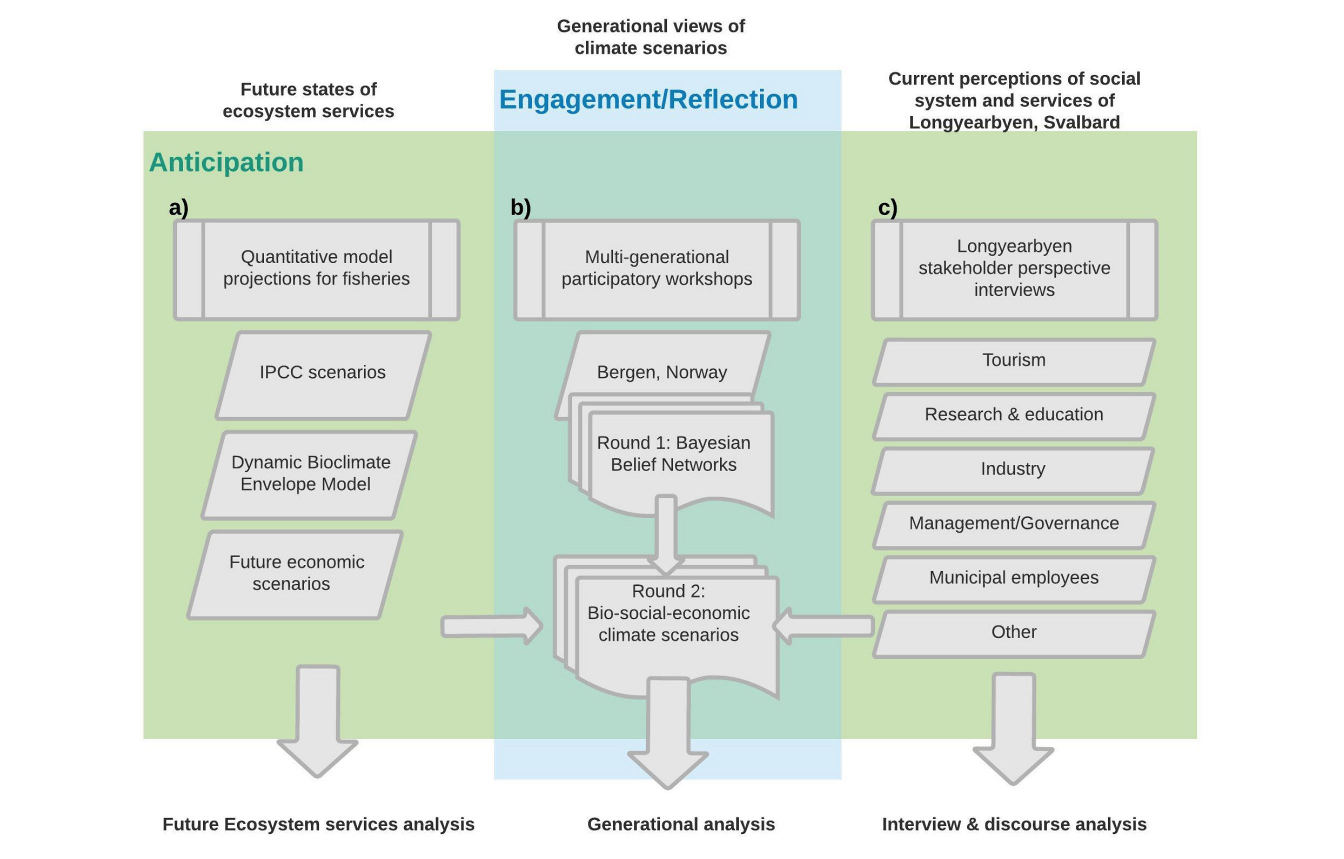

FIGURE 3 | A schematic of the interdisciplinary methodology developed for this paper. The three columns **(a,b,c)** represent the **(a)** modeling work, **(b)** workshops and **(c)** interviews. The arrows pointing to "Round 2" in **(b)** workshops show how the DBEM modeling and interviews were used to create the scenarios used in the second round of workshops.

RESULTS

In order to create plausible scenarios to use for our stakeholder workshops, we first analyzed our interviews from the different stakeholders in Longyearbyen. Then we applied the coupled *DBEM-EDM* and derived model projections of the future state of cod fisheries. Finally, as sketched in **Figure 3**, we created three plausible scenarios that we used as the basis for our stakeholder workshops in June 2019 (**Supplementary Appendix**). We now present the results as three parts: (1) Longyearbyen stakeholder interview results; (2) bio-physical-climate-economic model (*DBEM-EDM*) results; and (3) Bergen stakeholder workshop results.

Results 1/3 – Implications for Svalbard – Longyearbyen Interview Results (Excerpts Focus on Economic Opportunities and Fisheries)

Longyearbyen is in an international area, under Norwegian sovereignty. It follows some Norwegian rules and regulations, yet others cannot be implemented because of the international setting. You are not allowed to be born or to grow old in Svalbard, for example, and a popular phrase on tourist items is "Do not come here to die." This regulation has natural reasons, linking in on the institutional capacity of the area, in that social benefits from the mainland are not extended fully to Svalbard because of its international status. That is also the reason why women are not allowed to give birth on the archipelago but are sent to the mainland and their main address some weeks before the due date. Births still occasionally happen though, but that is usually with premature births, and they are rare (Dørmænen, 2007; Hansen, 2012). Nevertheless, as stated by another informant, "*there may one day be roots in the permafrost as well.*" Building resilience will be a requirement for these roots to gain traction, and more permanency of the population of Longyearbyen is a need. More work is therefore needed. However, in light of the geopolitically uncertainties around the Svalbard Treaty and the surrounding marine areas, climatic stressors, changes in fish distribution patterns and the closing of the coal mines in Longyearbyen in 2017 are still issues that may have a large effect in the future. One of the questions we asked the informants was whether – in their opinion – new industries could be able to attract a more stable population to the area, whereby social capital could build, and in turn enable the community to be more resilient to more climatic stressors. We also asked, more specific, what industries they considered as having future opportunities.

The sector which is seen as having the most potential for the future is the tourist sector, which is not surprising given the strong emphasis this industry has on the archipelago (**Figure 4**). However, there were multiple interviewees that mentioned the negative effects of tourism as well. They did see tourism as important to Svalbard, but said that it should not get too big, since this could cause more damage to the local environment and could affect the local community.

More than half the respondents, nine interviewees in total, discussed the topics of fish, fisheries and how these may become affected by climate change and affect Svalbard in turn. One respondent from the tourism industry, on this topic, said that *"The important thing with fish is that they are food for the seals. If climate change leads to warmer waters and more fish coming up here, that could also mean more seals come up here – which in turn means more food for the polar bear."* Another respondent, also from the tourism industry, expressed enthusiasm for the prospect of being able to land fish in Longyearbyen, but did not elaborate much beyond that, but a third tourism respondent was also enthusiastic, specifying how the community needed more industry legs to stand on, stating that *"This could definitely be a great opportunity to diversity the industries of Longyearbyen beyond tourism and research – and we hope it will be possible."*

A government employee furthermore emphasized that there already were new species of fish that had come up to Svalbard, but that only time could tell if they were there to stay or not. A researcher echoed this but specified it by stating that *"A lot of people like that the fish is coming up here now. Right now, they can't make any money off of it though since it is landed elsewhere. There is a possibility for a fishing industry here though."*

This was also reiterated by another researcher who said that "*They should be ready – the fish is coming – and maybe this will be the new Lofoten. Things will stabilize in about 50–100 years though, I think. There used to be a landing site in Ny Ålesund in the 1940s, you know...Maybe fisheries landing sites can happen again – but maybe only for a short while – there are no guarantees that the fisheries – if there is one in the future – will be stable."*

One of the respondents considered the issue more broadly though, bringing in the cost of investments for there to be a landing site for fish in Longyearbyen. In addition, he brought in the quota challenges because of the Svalbard Treaty, as opposed to Svalbard being considered Norway. He talked about how it would be a challenge if the quota for fish that were to be landed in Longyearbyen was considered part of the full Norwegian fish quota. *"It's a long way to go still, in other words"* he said somberly.

Results 2/3 – Arctic Change in Fish Abundance Under Climate Change Using the Bio-Physical-Climate-Economic Model (DBEM-EDM)

Our model showed that the total relative abundance of cod in the Northeast Atlantic is projected to increase under the high greenhouse gas emission scenario (RPC 8.5), however, the spatial distribution of cod is projected to shift from the southwestern coastal zone of the Norwegian EEZ to the Barents Sea by the 2100s (**Figure 5**). The increase in the biomass is because of the change in the suitability of the habitat such as the change in sea temperature and primary productivity under climate change (**Figure 6**), which leads to the shift in distribution of marine species. The model also predicts that other commercially important species, especially boreal species will be expanded northward (Manuscript in preparation). These results are consistent with findings from other research (e.g., Christiansen et al., 2014; Haug et al., 2017; Andrews et al., 2019).

Climate driven northward expansion of existing fish species may create potential opportunity for commercial fishing, especially the newly coming species for costal fishing vessels that can fish around the fjord of the Longyearbyen. However, the opportunities for feasible commercial fisheries are ambiguous, partially due to anticipated costs and benefits associated with Arctic ocean fishes (Christiansen, 2017). In the Svalbard Zone, the most important fisheries are Northeast Arctic cod, Northern shrimp, capelin and Northeast Arctic haddock, Iceland scallop and Greenland halibut (Misund et al., 2016; Statistics Norway), red king crab and snow crab have recently becoming important. The fishing cost in the Arctic zone is higher than in other fishing grounds due to its long transit time to the landing sites (Misund et al., 2016; Pettersson et al., 2020). Discussions of building a processing plant in the Longyearbyen for snow crab have been ongoing since 2016. Such a realization would boost employment and the local economy. However, a decision has not be made.

Results 3/3 – Scenario Workshop: Discussions Around the Melting Snowball Effect Scenarios

We now present how three different generations in our stakeholder workshops in Bergen in June 2019 discussed the scenarios. For this paper, we only present our analysis of scenarios A and C, which had themes related to fish and fishing. Scenario B contained topics that did not directly relate to those of A and C, so we omitted them from this analysis for brevity.

Youngest Generation

"We would have to have some compromises or something."

In Scenario A, NEA cod retreat more to the Russian zone and Russia pulls out of the quota sharing agreement with Norway. Should Norway do something to get cod back from Russia?

There were eight participants in this discussion who were all female. Their ages ranged from 16 to 19 years old. Each of these participants were members of the Norwegian Nature and Youth association (Natur og Ungdom).

The first aspect of the discussion was that Norway would become a poorer country if they lost the right to fish cod. These participants also discussed that it was very likely that Norway had stopped producing oil, thus making Norway even more vulnerable in the situation of losing cod. The main emphasis the youngest generation of participants was two-part: because Norway has become a poorer country due to loss of both oil and cod, a compromise with Russia to restore access to NEA cod was needed.

> *"So by reducing the cod I think we would be very poor, after a while. Because what should we base our economics on if we don't have the fish or the oil."*
>
> *"Yeah, and oil will be gone one day."*

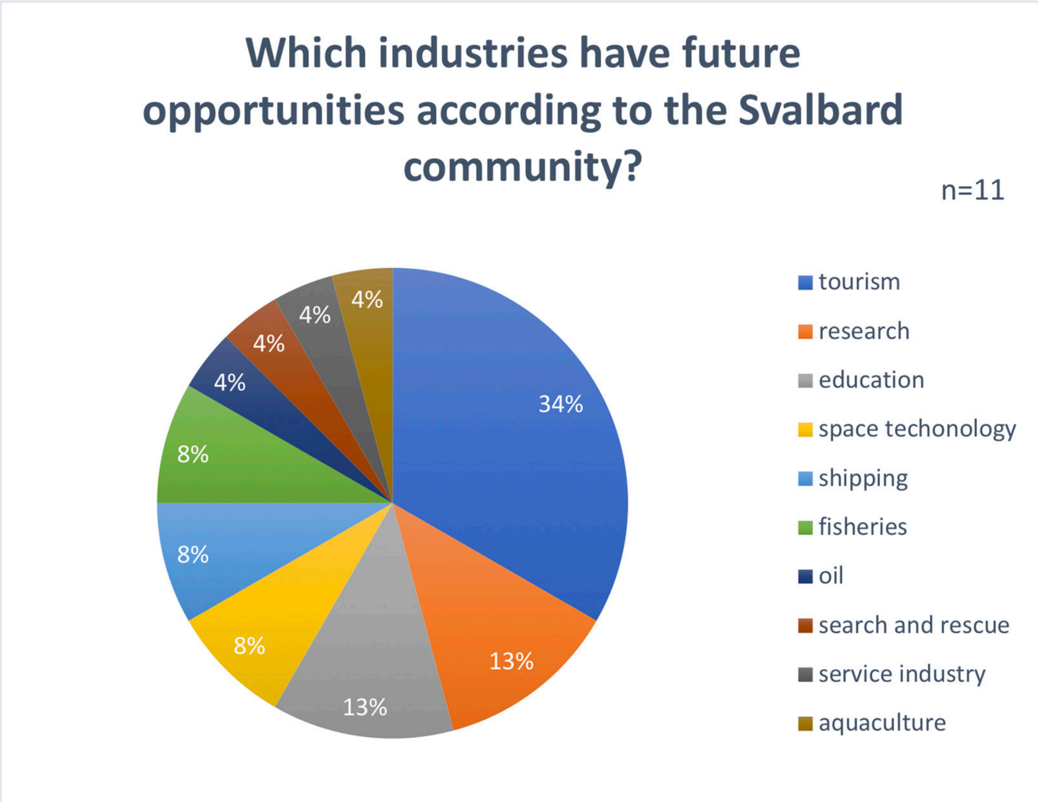

FIGURE 4 | Question posed to interviewees in Longyearbyen, Svalbard. Tourism was what was considered as having most potential, and fisheries only was discussed in 8% of the cases.

"And maybe it already is in this scenario."

"What I believe is problematic with this is that Russia is a strong opponent. So, if Russia isn't willing to come back to us, it would be really dangerous for us to just demand Russia to give the fish to us. So, I don't quite know how we would do that. We would have to have some compromises or something."

Oldest Generation

"We need limits on stocks but that might imply both fishing down and or reducing fishing based on what's needed for the total ecosystem."

In Scenario C, herring and mackerel are more abundant along the coast of Norway. We asked the participants if it is more important to increase fishing pressure to provide local, healthy fish to reduce CO_2 emissions (that would result from alternative imported protein sources) with the added benefit of increasing public health (due to Omega 3 that is abundant in herring and mackerel) or to reduce fishing pressure to prevent overfishing?

In this discussion, there were four participants between the ages of 47–71 years. All were male. The discussion revolved around the idea of an ecosystem approach to fisheries and an idea of considering the stocks as part of a protein system, and not as separate systems. Another point in this discussion was the migratory aspect of NEA mackerel, and that the sharing of this resource is currently problematic, and likely more so in the future.

One striking mention in this short discussion was that of the work of Johannes Hamre, and his theory, explained in the Introduction, that a large NEA mackerel stock is a threat to the Atlanto-Scandian herring:

"Right. (Johannes) Hamre is a person who is very into that theory. So his idea is that we should actually reduce the amount mackerel in order to get the balance on the other stocks."

"This is also the theory that Jens Christian Holst[1] has come out in the media in the later years. Overgrazing."

The mention of Hamre, and his protégé Jens Christian Holst, shows that theories about holistic views of the ecosystem are seen, by this group, as helpful and necessary to preserve fish stocks for the future.

Mixed Generations

Scenario A, was also discussed in a group that contained all three generations (N = 5, ages 19–66 years). The discussion commenced with an agreement that Norway didn't have a legal

[1] Jens Christian Holst is a former scientist who worked 23 years in the Pelagic Department at the Institute of Marine Research who now works as an independent scientific advisor.

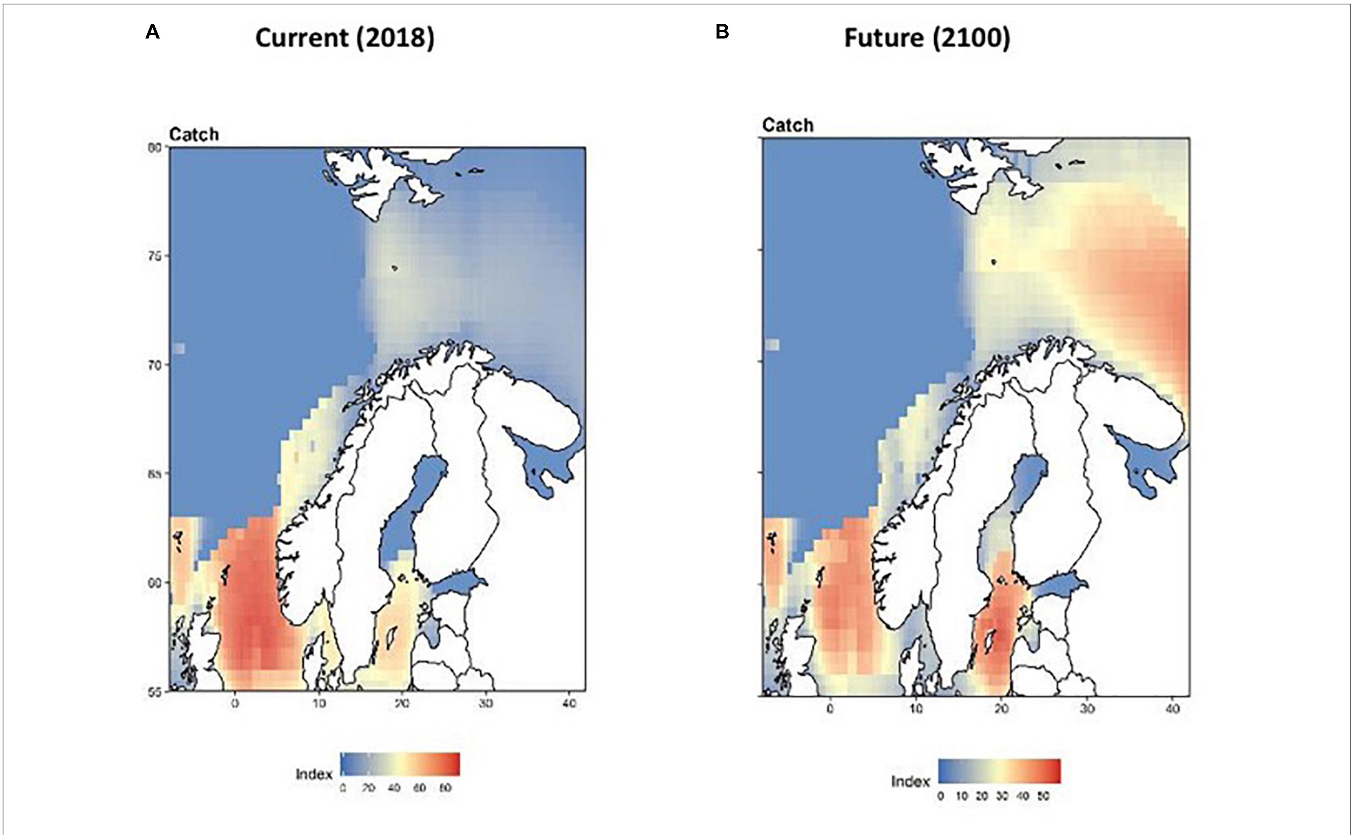

FIGURE 5 | The relative abundance of cod in the Northeast Atlantic region under **(A)** the current status **(B)** high greenhouse gas emission scenario (RCP8.5).

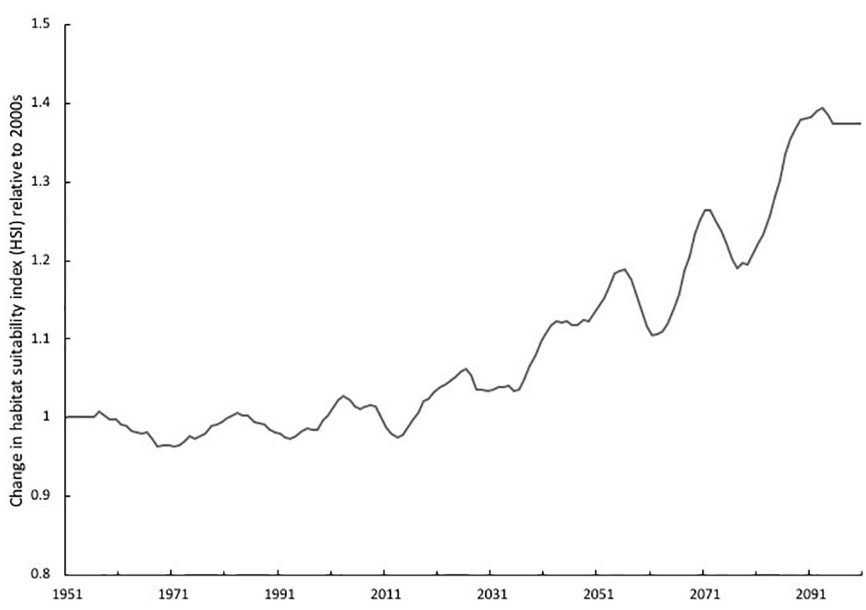

FIGURE 6 | Results from the DBEM-EDM model on the change in Habitat Suitability Index (HSI) in Norwegian EEZ.

right to fish in Russia's Economic Exclusive Zone, and that negotiations with Russia could be strained. One participant pointed out that Norway has "been lucky" with large fish stocks all these years, and if climate change leads to a major change in the location of the fish stocks to the Russian zone, then "that is not Russia's fault." The discussion then developed into an

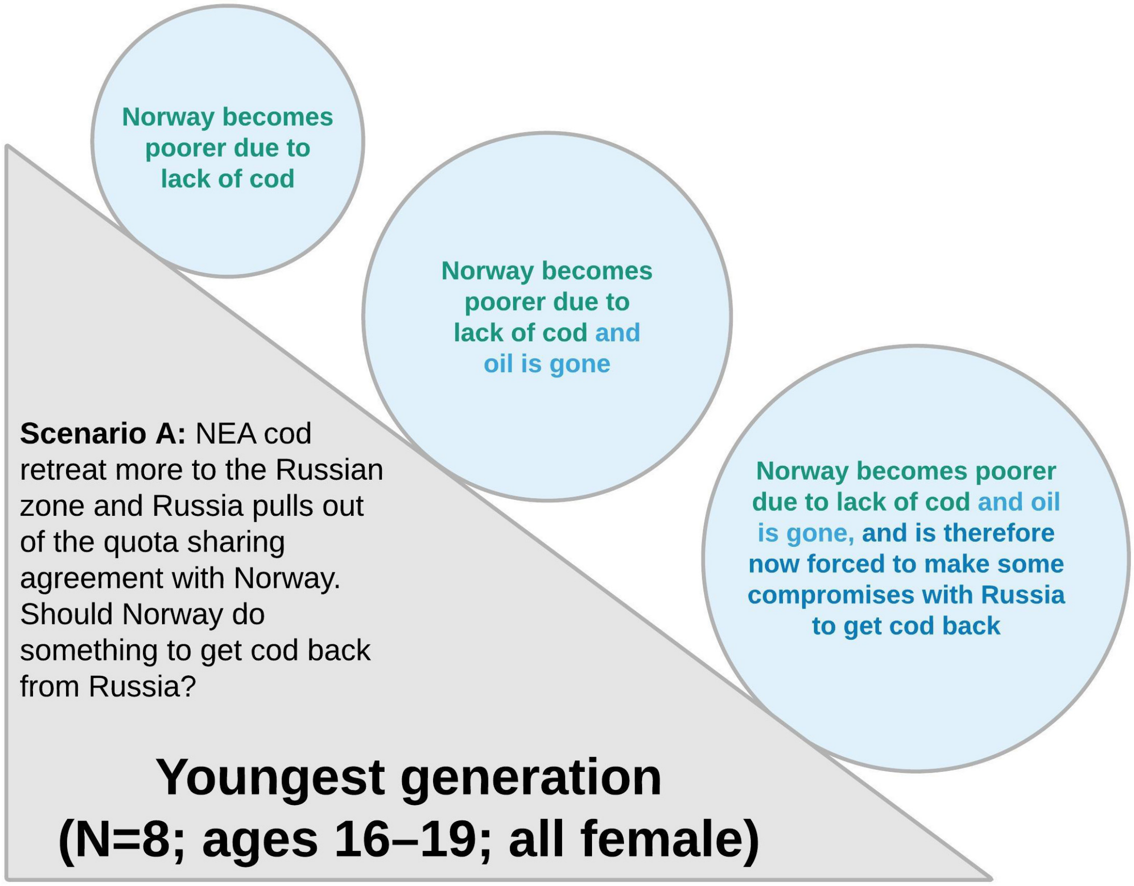

FIGURE 7 | A schematic summarizing the discussion among youths in Bergen, Norway in June 2019.

implicit argumentation for national food security. In the last part of the discussion, aquaculture was seen as a safer choice for fish production than wild caught fish shared with other countries. And finally, on the question "Should Norway do something to get cod back from Russia?" land-based aquaculture was mentioned as the safest and most reliable answer for producing fish protein, due to independence form uncertain geo-political and ecological Ocean states:

> *"Nah, that (negotiating with Russia to get more cod quota) will all be very hard, you know. . ."*
>
> *"We should increase fish farming."*
>
> *"On land."*
>
> *"That's the better way to grow fish."*

In summary, we illustrate the differences in the depth of dialogue that can occur when people of different generations are involved in discussions. This may be seen by the sheer amount of words needed to describe the discussions among three different groupings, where the mixed generational group (**Figure 9**) developed a future climate action narrative that was much more diverse than those of the youngest generation (**Figure 7**) and the oldest generation (**Figure 8**).

DISCUSSION: MELTING SNOWBALL EFFECT AND FUTURE FISHERIES IN THE ARCTIC

For centuries, we have observed that fisheries have an effect on ecology, social situations, local, regional and national economics and geopolitics. Depending on the severity of climate change, which in turn is dependent on how society mitigates future CO_2 emissions and adapts to the changing climate, the probable boost in Arctic fisheries due to a warming Ocean cold be negated by the Melting Snowball Effect if the geopolitical situation prevents an ecologically sustainable sharing of fish stocks.

In this sense, we see the vulnerability of fisheries to climate change in the Arctic around Svalbard as not a primary vulnerability, but a secondary or tertiary social, economic or geopolitical threat. This is because we see valuable fisheries like NEA mackerel and snow crab expanding, but the real tensions only precipitate when the expansions run into institutional deadlocks, such as the lack of the quota agreement with Iceland, Greenland for NEA mackerel (Spijkers and Boonstra, 2017; Harte et al., 2019), or the lack of precedent of sharing resources in the Svalbard Protection Zone (Tiller et al., 2019). The stock sharing regime and scientific collaborations between Norway and Russia

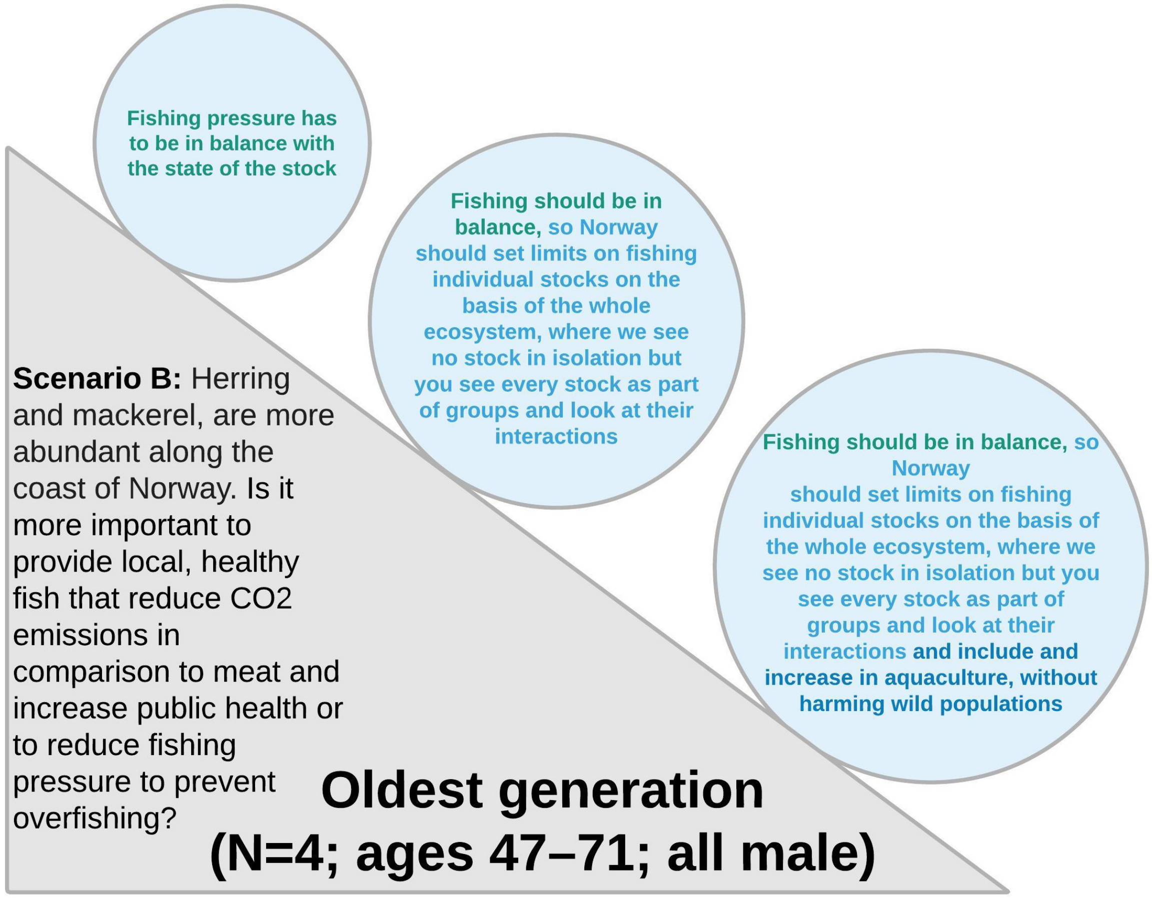

FIGURE 8 | A schematic summarizing the discussion among the group of the oldest participants in the workshop in Bergen, Norway, June 2019.

have been on-going for over 60 years, and is a very deserved celebration of successful sustainable management of the shared fish stocks (Hammer and Hoel, 2012). However, in the event of a shift in distribution or migration of NEA cod, for example, we postulate ripple effects that could strain this relationship as we illustrate in Scenario A. While the youngest generation focused on compromise, the mixed generation focus more on national security, turning to aquaculture rather than haggle with Russia to regain lost cod. It is obvious from the responses to Scenario A that there is a generational affect as to how to position the geopolitics between Russia and Norway. The Melting Snowball Effect heuristic makes these interdependencies and consequences an explicit part of model results.

And there are always unknowns. One of these is the ecological vulnerability of certain ecosystems to large increases in single stocks. Simple ecological theory says that if NEA mackerel population grows too big, the resulting predation on Atlanto-Scandian herring can be ecologically catastrophic. This theory was mentioned by the oldest generational group in section " Oldest generation."

The rapidly warming Ocean and Arctic regions is a game-changer for science-based policies and governance, due to the inherent complexities across disciplines, interdependencies across borders and uncertainties of predictions. Model projections help us understand the parameter space of aspects of ecosystem services and how these can change in the future, but we argue that these projections need to be put into plausible scenarios, or narratives, in order to be fully useful for society.

For those living in the High North, they general consensus of those that considered a local fishery and landing site a potential future industry for the archipelago of Svalbard, the future was bright, though complex. Many wanted population stability, and the chance to lay down roots in the Arctic. To do so, there had to be a shift in the employment pattern of especially Longyearbyen. In a city where the majority of the population is completely changed every 4 years, stability is rare, and goodbyes are plenty. For the small percentage of the population that is stable and that has been there for more than a decade, an opportunity for a stable employment sector that will ensure that more people choose to stay, longer, climate impacts pushing fisheries further north presents such an opportunity.

This methodological framework has provided an interactive platform or dialogue integrating inter- and intra-disciplinary sciences and various levels of stakeholders to discuss climate issues. We applied a RRI framework and designed a methodology based on anticipation, reflection and engagement in order to

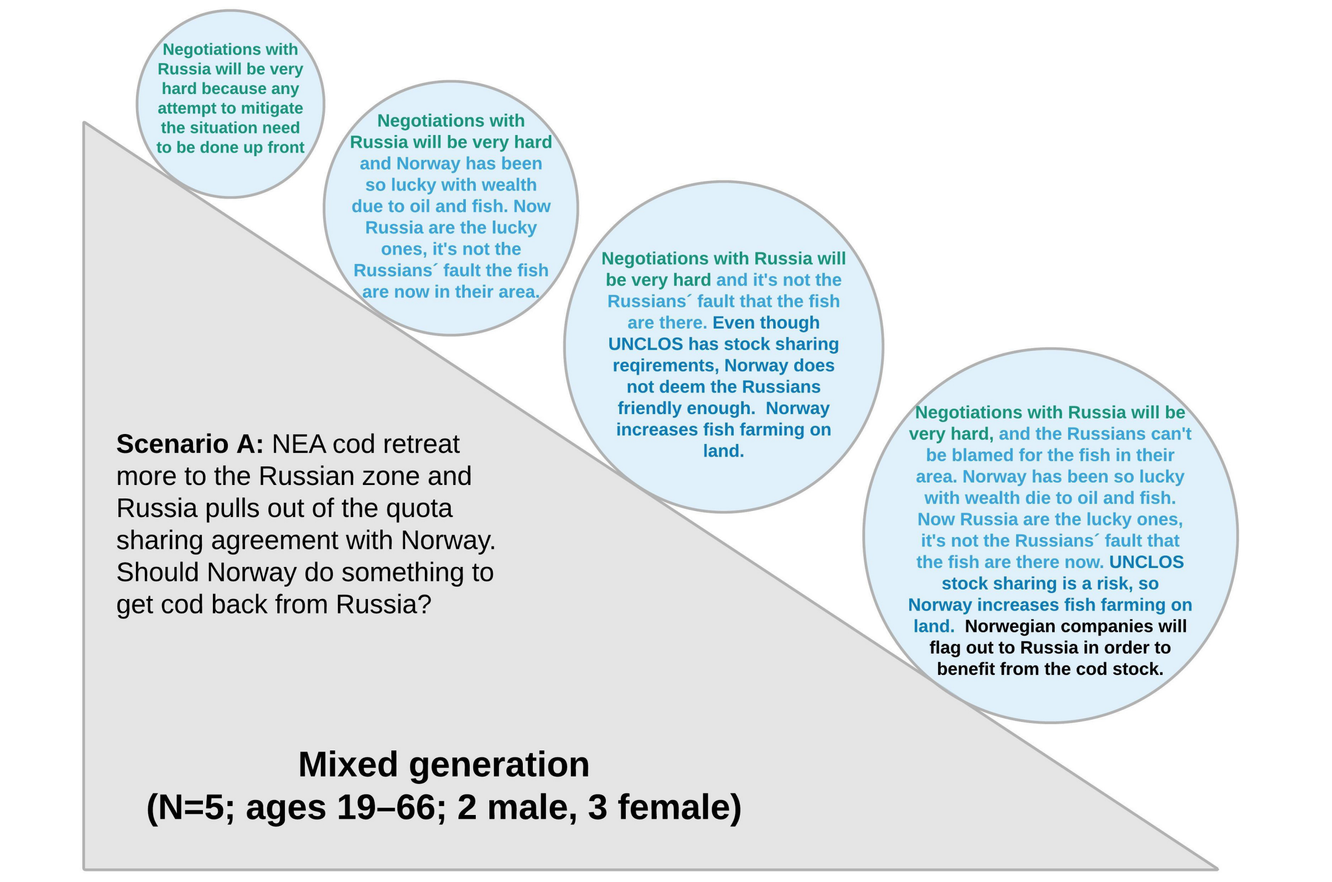

FIGURE 9 | A schematic of the results of a discussion among a mix of ages in Bergen, Norway, June 2019.

package the inherent complexity that we describe with the "Melting Snowball Effect" heuristic into plausible and realistic narratives of the future. We then designed an experimental set-up with three different generations in a workshop-setting to observe how publics responded to the narratives. There are two caveats we think are important to realize when interpreting the results of the Bergen workshop: (1) all participants were volunteers recruited from an unpaid advertisement on Facebook and flyers handed out at a climate strike in Bergen, and (2) all participants (except for two) all had been involved, or were currently involved in environmental NGOs. So, there is little doubt that the majority of our participants were concerned about climate change before their participation in the workshop. This being said, the discussions reflected the fact that the situations incorporated in our scenarios were unique narratives of the future that sometimes caught the participants off-guard. We feel this underscores the need for capacity-building in democratic deliberation, since even well-versed environmentalists were not used to being confronted with such dramatic, somewhat likely, vignettes.

Our goal was to design and test a heuristic that is able to encompass the complexity of cascading uncertainties that swell from the changing climate to the ecological and into the economic, social and geopolitical. Of course, we are not able to generate conclusions for decision-makers based on the views and discussions in the Bergen workshops, due to small example of participants and volunteer-based participation. Our focus in this paper is our approach, which we designed to be useful for different levels of decision-makers who are forced to related to the realities of climate change. Our approach can be used to map the interdependencies of climate-related effects on governance issues at the local, regional or even national, levels.

In this paper, we postulated that our workshops would aid in capacity-building for future climate plan discussions at a local level. But how could we measure this effect? We are encouraged that after the 15-min discussion for each scenario iteration, each group continued their discussions. In particular the oldest group who discussed for over 20 min and had to be reminded three times to please vacate the room in order to join the others for refreshments. In the de-briefing following the workshops, most of the participants continued to mingle, casually discussing with each other. At the very least, we feel that our workshops were an effective and lively way to disseminate interdisciplinary results that, in our opinion, are all too often hidden in distant and inaccessible reports.

Finally, the differences in the depth of dialogue that occurred in the mixed generational group (**Figure 9**) underscore a vital aspect of democratic deliberation: inclusive participation. We think that governance that includes perspectives from all generations in society is crucial for credible and salient future climate policies.

CONCLUSION

Climate change is affecting the Northeast Atlantic, one of the most studied parts of the Ocean, in different ways that affect different sectors and different ecosystem services. Scientists have attributed the increase in sea temperature as a contributor to the rapid expansion of the mackerel stock further north of the Arctic Circle and into the southern part of the Svalbard Fisheries Protection Zone. As a result, nations not originally included in the quota sharing scheme are now catching mackerel causing an on-going geopolitical havoc. This expansion of the distribution and increase in the biomass of the stock has made an already difficult scientific assessment of the stock even more difficult, leading to new benchmarks and revised quota advice (ICES, 2017, 2018, 2019a,b,c).

Many scholars agree that climate change has an effect on inherent synergies that encompass different parts of our societal interconnections with nature (Holtermann and Nandalal, 2015; Hoolohan et al., 2018). But interdisciplinary framings themselves, for example, the popular Water-Energy-Food Nexus scientific framing (Holtermann and Nandalal, 2015; Simpson and Jewitt, 2019) do not automatically produce good governance (Weitz et al., 2017). Scientists produce models to extrapolate climatic effects into the future, but it is not straight-forward how to translate these plausible futures into governance actions. This is why we designed and tested a conceptual modeling approach, based on a RRI framework, for deliberative democratic decision-making. We used our Melting Snowball Effect heuristic to bridge the complex coupled DBEM-economic model and its "snowball" effects on society into understandable narratives. We show through our results from the deliberations of different generations how society is able to grasp these narrative vignettes and make informed deliberations about the potential effects of climate change.

In 2019, the annual Arctic Frontiers science and policy conference in Tromsø, Norway had the theme "Smart Arctic." The theme was chosen as part of a pan-Arctic perspective "build new partnerships across nations, generations and ethnic groups." We agree to this perspective, but caution that these important process of inclusion and dialogue should be guided by credible and legitimate methods of engagement. In this paper, we demonstrated how our interdisciplinary team described the current climate and governance situation of Svalbard from the view of social science, ecosystem science, economics and political science. We created the heuristic, the "Melting Snowball Effect" to guide our scenario building and to examine the discussions and deliberations of different generations of citizens about futures affected by climate. We feel that the Melting Snowball Effect scenarios produced by an interdisciplinary team and deliberated on in by local citizens in our workshops present an example of filling a transdisciplinary void by engaging stakeholders across generations in ecological-social-economic-geopolitical moral narratives of a future Arctic. Only through these interdisciplinary and contextual scenarios can we come closer to a "Smart Arctic." Ultimately, though, it will be the local governors and citizens who will judge of the Melting Snowball Effect heuristic is helpful to design and implement appropriate responses for sustainable climate governance.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by NSD Norwegian Data Protection Services. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

DD initiated the manuscript idea, performed the analyses, wrote the first draft of the manuscript, and co-designed and co-conducted the workshops. RT held all the interviews, and presented results from these, reported on methodology as well as presented background on Svalbard and Longyearbyen for the article, and co-designed and co-conducted the workshops. EK transcribed the Longyearbyen interviews and summarized the results and co-conducted one workshop. YL and VL co-designed the manuscript, conducted model results, and wrote the methodology and results. 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.2020.00537/full#supplementary-material

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