Research Topics

# Coastal fisheries: Emerging initiatives toward the sustainability objectives

**Edited by**
Luca Bolognini, Pablo Pita and Sebastian Villasante

**Published in**
Frontiers in Marine Science

ISSN 1664-8714
ISBN 978-2-8325-3356-7
DOI 10.3389/978-2-8325-3356-7

## About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

## Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

## Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

## What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

# Coastal fisheries: Emerging initiatives toward the sustainability objectives

**Topic editors**
Luca Bolognini — National Research Council (CNR), Italy
Pablo Pita — University of Santiago de Compostela, Spain
Sebastian Villasante — University of Santiago de Compostela, Spain

**Citation**
Bolognini, L., Pita, P., Villasante, S., eds. (2023). *Coastal fisheries: Emerging initiatives toward the sustainability objectives*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-8325-3356-7

# Table of contents

Frontiers in Marine Science

TYPE Editorial
PUBLISHED 14 August 2023
DOI 10.3389/fmars.2023.1268711

Check for updates

OPEN ACCESS

EDITED AND REVIEWED BY
Stephen J. Newman,
Department of Primary Industries and Regional Development of Western Australia (DPIRD), Australia

*CORRESPONDENCE
Pablo Pita
pablo.pita@usc.es

RECEIVED 28 July 2023
ACCEPTED 02 August 2023
PUBLISHED 14 August 2023

CITATION
Pita P, Bolognini L and Villasante S (2023) Editorial: Coastal fisheries: emerging initiatives toward the sustainability objectives. *Front. Mar. Sci.* 10:1268711. doi: 10.3389/fmars.2023.1268711



# Editorial: Coastal fisheries: emerging initiatives toward the sustainability objectives

Pablo Pita[1]*, Luca Bolognini[2] and Sebastian Villasante[1]

[1]EqualSea Lab-CRETUS, Department of Applied Economics, University of Santiago de Compostela, A Coruña, Spain, [2]Institute for Biological Resources and Marine Biotechnologies, National Research Council (IRBIM-CNR), Ancona, Italy

KEYWORDS

**coastal seas, fisheries, aquaculture, leisure, impacts, blue economy, social-ecological systems, sustainability**

Editorial on the Research Topic
Coastal fisheries: emerging initiatives toward the sustainability objectives

Due to its location at the interface between terrestrial and marine domains, an increasing number of human activities are carried out in worldwide coastal seas. In addition to different fisheries, coastal seas are important for mariculture, but also for different recreational activities (Crossland et al., 2005). Despite growing anthropogenic impacts, coastal seas are key for the development of important ecological processes, sustaining much of the marine primary production due to nutrient inputs from rivers, enhancing complex food webs, and acting as nursery areas for many marine species, among others (Sherman and Duda, 1999).

Coastal fisheries, in particular Small-Scale Fisheries (SSF) such as commercial, including artisanal, and Marine Recreational Fisheries (MRF), are one of the most relevant coastal activities in terms of food provision, livelihoods, nutritional contribution, and cultural heritage. Therefore, in a context where different human activities are overlapping, understanding how different coastal fisheries interact and are effectively managed in accordance with sustainable principles is key to foster the resilience of these complex social-ecological systems (SES) (McClanahan et al., 2009) (Figure 1).

In this Research Topic we describe the results of 9 studies that contributed to moving coastal fisheries a step forward in their ecological, economical, and social sustainability.

The important role of MRF in the coastal areas was studied in 3 papers: Bachiller et al. analyzed the patterns of exploitation and impacts on marine living resources; Pita et al. analyzed the importance of MRF for regional economies; while its social relevance was addressed in Hamelin et al.

Bachiller et al. performed the first assessment MRF in the Basque Country (Eastern Cantabrian Sea), concluding that spearfishing population is the smallest (1 000 licenses), followed by boat fishers (5 000 licenses), with shore anglers more common (50 000 licenses). The main recreational fishery is carried out by boats operating during summer targeting albacore (*Thunnus alalunga*), which is also caught by commercial boats. The authors recommended developing an ecosystem management of fisheries, paying special

FIGURE 1
Image showing human activities in a coastal area created by using the Artificial Intelligence-based application *Photosonic* available at: https://app.writesonic.com/es/photosonic. The image was created by entering the keywords of this editorial: coastal seas, fisheries, aquaculture, leisure, impacts, blue economy, social-ecological systems, sustainability.

attention to the interactions between commercial SSF and recreational fisheries, and incorporating information from multiple species into the assessment models.

Pita et al. conducted an economic analysis of recreational fisheries developed by charter boats in the Eastern North Atlantic to assess their contribution to social welfare. The study described two case studies, one located in Galicia (NW Spain) and the other in the Madeira archipelago (Portugal). On average, the study showed that charter boats go fishing ~40 fishing journeys and take 2 500 anglers on board per year in Galicia, while in Madeira they fish about 64 journeys and take 3 200 anglers on board. The study also assessed the demand of recreational fishing trips showing that the visitor surplus mean value was € 1 385 per year in Galicia, and € 1 738 in Madeira. Furthermore, the study estimated that the social annual recreation value of Galician fishery was worth € 3.4 million, a value well below the annual economic impact generated by commercial fishing (€ 700 M). The recreation value of the charter boat fishery in Madeira, € 6.3 M, is comparable to the annual economic impact of commercial fishing that contributes to the local economy with € 12 M.

Hamelin et al. assessed the human dimensions of a Canadian recreational fishery targeting Atlantic mackerel (*Scomber scombrus*). The species has a high social and cultural value and traditionally has been under diverse fishing pressures exerted by commercial, bait, recreational, and indigenous fisheries. However, the current poor state of the stock only allows access to recreational fishers and indigenous harvest. The conclusions of the study highlighted that a greater involvement of recreational fishers in management models will promote local awareness and improve fisheries governance.

Different management measures for sustainable and resilient coastal SSF, including new perspectives, methods, and tools to allocate fishing opportunities were explored in a group of three papers.

Villaseñor-Derbez et al. quantified the operational costs of community-based MPA monitoring programs in nine SSF communities in Mexico. The authors found that the annual monitoring costs represent between 0.3% and 55% of the extractive use value of the biomass contained in the MPAs. Therefore, the direct monetary benefits of community-based marine conservation can more than out-weight the costs, providing further support for these types of management schemes. The study concluded that while further research should explore other mechanisms that would allow fishers to leverage the non-extractive use value of reserves (e.g., tourism) or the non-use value (i.e., existence value of biodiversity) to sustainably finance their conservation efforts, a stop-gap measure to ensuring long-term monitoring costs are covered might include limited extractive use of resources in the MPAs.

Ding et al. analyzed the performance of a new catch allocation scheme based in a weighted multi-criteria method that includes a relative deprivation coefficient in 11 Chinese coastal regions. The study demonstrated that the performance of the new allocation method performs better than previously used methods based in single-criterion and multi-criteria with equal weights. The authors concluded that the application of this method will contribute to reduce conflicts in the future allocation of fishing opportunities.

The historical patterns and current status of IUU fishing in the coastal and marine waters of Bangladesh was analyzed by Mozumder et al. The study demonstrated that because of the lack of appropriate and robust governmental regulations and manpower, IUU fishing led to the collapse of important fisheries, biodiversity loss, and increased poverty among fishers. To revert this situation, the study recommended raising the living conditions of poor fishers by improving the management of artisanal and industrial fisheries, and by motivating and training stakeholders.

In this Research Topic, attention was also paid to the development of new techniques that allow increasing the sustainability of mariculture (Loayza-Aguilar et al.), and reducing its negative interactions with other coastal activities like fisheries and tourism (Chor et al.).

Loayza-Aguilar et al. explored the implementation of new Integrated Multi-Trophic Aquaculture (IMTA) initiatives in Peru. The study proposed and validated a IMTA model for the scallop *Argopecten purpuratus*, after an analysis of the local conditions and specific cultivation needs of the species. The authors concluded that the IMTA on this species will minimize the negative environmental impacts of the culture, while keeping its profitability.

Chor et al. assessed the reallocation of intensive aquaculture facilities in Malaysia to improve the decline in water quality, associated to increasing fish mortality, and decreasing profitability. The authors developed a feasibility analysis of current and potential locations that assessed the benthic communities, substrate and water quality, hydrodynamics, and climate. The authors concluded that reallocation to offshore, more hydrodynamic waters by using fish cages made with high-density polyethylene would increase sustainability of the system and increase revenues for local fish farmers.

Finally, the impacts of climate change on the interaction between kelp forests and SSF was explored in Piñeiro-Corbeira et al. Kelps conform key habitats in temperate regions that have experienced severe declines in the last decades. However, the consequences of their decline for SSF have received little attention. In the study, it was found that in Galicia many fish, echinoderms, crustaceans, mollusks, and kelp species are exploited, showing high socioeconomic value. The study concluded that in the last two decades there has been an important reduction of the area where kelp forests used to occur, which was associated with decreases in the fisheries typically developed in these habitats.

## Author contributions

PP: Writing – original draft, Writing – review & editing. LB: Writing – review & editing. SV: Writing – review & editing.

## Funding

PP acknowledges funding by Xunta de Galicia research and innovation program (RECREGES II project under Grant ED481B2018/017). PP and SV acknowledge support by Grupo de Referencia Competitiva GI-2060 AEMI, under Grant ED431C2019/11 and of the project Grupo de Trabajo Sobre Pesca Marítima Recreativa en España, funded by the Fundación Biodiversidad of the Spanish Ministerio Para la Transición Ecológica y el Reto Demográfico, co-funded by the European Maritime and Fisheries Fund.

## Acknowledgments

We are grateful to the Editorial Board of the section of Marine Fisheries, Aquaculture and Living Resources of Frontiers in Marine Science for their valuable support and confidence. We also thank the different reviewers that made possible the publication of the different contributions. Finally, we appreciate the authors of the papers that were sent to this Research Topic.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The authors declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## References

Crossland, C. J., et al. (2005). The Coastal Zone — a Domain of Global Interactions. In: Crossland, C. J. , Kremer, H. H. , Lindeboom, H. J. , Marshall Crossland, J. I. , and Le Tissier, M. D. A. (eds) Coastal Fluxes in the Anthropocene , Global Change — The IGBP Series. Berlin, Heidelberg: Springer. doi: 10.1007/3-540-27851-6_1

McClanahan, T. R., Castilla, J. C., White, A. T., and Defeo, O. (2009). Healing small-scale fisheries by facilitating complex socio-ecological systems. *Rev. Fish Biol. Fish.* 19, 33–47. doi: 10.1007/s11160-008-9088-8

Sherman, K., and Duda, A. M. (1999). An ecosystem approach to global assessment and management of coastal waters. *Mar. Ecol. Prog. Ser.* 190, 271–287. doi: 10.3354/meps190271

frontiers | Frontiers in Marine Science

ORIGINAL RESEARCH
published: 20 May 2022
doi: 10.3389/fmars.2022.888662

# Spatial Analysis for Mariculture Site Selection: A Case Study of Kukup Aquaculture Zones in the Peninsula of Malaysia

*Wei-Kang Chor[1], Teng-Yun Lai[2], Melissa Mary Mathews[3], Tony Chiffings[3], Chi-Wei Cheng[3], Victor Charlie Andin[1], Kok-Song Lai[4] and Jiun-Yan Loh[2*]*

*[1] Marine Programme Conservation Department, World Wide Fund for Nature (WWF, Malaysia), Petaling Jaya, Malaysia, [2] Centre of Research for Advanced Aquaculture (CORAA), UCSI University, Kuala Lumpur, Malaysia, [3] DHI Water & Environment (M) Sdn. Bhd, Kota Kinabalu, Malaysia, [4] Health Sciences Division, Abu Dhabi Women's College, Higher College of Technology, Abu Dhabi, United Arab Emirates*

OPEN ACCESS

**Edited by:**
*Sebastian Villasante,
University of Santiago de Compostela,
Spain*

**Reviewed by:**
*Nor Azman Kasan,
University of Malaysia Terengganu,
Malaysia*
*J.German Rodriguez,
Technological Center Expert in Marine
and Food Innovation (AZTI), Spain*

***Correspondence:**
*Jiun-Yan Loh
loh.jiun.yan@gmail.com;
lohjy@ucsiuniversity.edu.my*

**Specialty section:**
*This article was submitted to
Marine Fisheries, Aquaculture and
Living Resources,
a section of the journal
Frontiers in Marine Science*

**Received:** 03 March 2022
**Accepted:** 20 April 2022
**Published:** 20 May 2022

**Citation:**
*Chor W-K, Lai T-Y, Mathews MM,
Chiffings T, Cheng C-W, Andin VC,
Lai K-S and Loh J-Y (2022) Spatial
Analysis for Mariculture Site Selection:
A Case Study of Kukup Aquaculture
Zones in the Peninsula of Malaysia.
Front. Mar. Sci. 9:888662.
doi: 10.3389/fmars.2022.888662*

Marine aquaculture sites at Kukup Strait in the peninsula of Malaysia are experiencing a decline in water quality in the last five years, resulting in high mortality rates (50 - 80%), seasonal massive fish mortalities and poor profitability. Currently, Kukup farmers are involved in intensive aquaculture within the existing aquaculture zone. This study explores the sustainability of a modern mariculture method, where fish farms are relocated to deeper waters with higher flushing rates, and high-density polyethylene (HDPE) are used to improve water quality. Several site selection criteria are utilised in identifying the proposed aquaculture industrial zone: 1) bathymetry depth (operational requirement: 10 m to 30 m), 2) located within the Kukup Port Limit, 3) does not interfere with the Kukup ferry navigation route, and 4) distance from Kukup mainland. Site feasibility analysis, including hydrodynamics, meteorology, water quality, sediment quality and macrobenthos assessment, was conducted to compare the proposed and existing aquaculture sites. It was found that the water quality at the existing site contained higher concentrations of fecal coliform and nutrients and salinity fluctuations. Tropical finfish can survive under these conditions with poorer fish health and higher fish mortality. Apart from that, the flushing capacity is higher in the proposed site, indicating the capacity to handle moderate-intensity aquaculture. Moderate-intensity aquaculture using HDPE cages could be profitable for the local fish farmers. Therefore, it is suggested that other locations within Kukup Straits with deeper waters (> 25 m) with possibly improved water quality and the ability for intensive aquaculture production should be explored for a larger depth and economics of scale.

**Keywords: aquaculture, Kukup Island, macrobenthos diversity, site selection, water quality**

# 1 INTRODUCTION

Kukup is a small fish-farming community consisting of two water villages (Kukup Laut and Ayer Masin) located at the start of Malacca Straits in Pontian District, Johor (Lai, 2014). The two villages initially developed in the sheltered waters of Kukup Strait, approximately 500 m offshore at the close point between the mainland and Kukup Island. However, urban growth has led to the halving of these villages. Since the establishment of water villages in the 1860s, the locals have profited from fishing and staked fish farms (*kelong*) in Kukup Strait. In the late 1970s, the fish farming activities were upgraded to the floating cage system, thus increasing production and contributing to the small-scale marine aquaculture (mariculture) industry in Malaysia (Hassan, 2010; Barau and Stringer, 2015; Michel and Zahler, 2015).

Fish farming at Kukup has grown in response to the rising demand for fresh seafood from the rapidly expanding neighbouring cities like Johor and Singapore. What began as a fishing village of only eight farms in 1984 (Lai, 2014) has grown into a town with an estimated population of 1400, with approximately 79 fish farmers and 8,000 cages. The aquaculture species found in Kukup Strait include groupers (*Epinephelus* sp.), snappers (*Lutjanus* sp.), trevallies (*Gnathanodon* sp.), pompano (*Trachinotus* sp.) and Asian sea bass (*Lates calcarifer*), which are sold mainly fresh at the Singaporean markets, about an hour by boat down the Malacca Straits to the south (Ismail et al., 2018). Furthermore, the flourishing tourism industry in Kukup since the 1980s has attracted local and international tourists from countries like Singapore. Nevertheless, the Kukup aquaculture community continue to face challenges in profiting solely from farming activities; thus, most of them have diversified their portfolio by venturing into the tourism industry, such as operating homestays and seafood restaurants (Hampton, 2010).

Throughout the years, Kukup fish farmers constantly experienced economic losses due to the seasonal disease outbreak associated with microbial infections due to declining water quality (Jaafar et al., 2014). Moreover, Manan et al. (2011) reported hydrocarbon pollution resulting from oil leakage by tourist boats and boat repair activities in Kukup waters. Apart from that, the high density of fish cages is a potential source of "auto pollution" caused by the accumulation of effluent from the two water villages, adjacent agricultural development in the hinterland from constructed drains to avoid flooding, and natural drainage from rivers and streams. In addition, earlier studies suggested that oil and grease, fecal coliforms (*Escherichia coli*), and heavy metals (As, Cu and Hg) levels have exceeded the recommended limit by Malaysia Marine Water Quality Criteria and Standard (MMWQS) for mariculture activities (Mohamed et al., 2015; Fadzil et al., 2017).

Several solutions can be considered to improve the deteriorating water quality and the consequent disease impacts on fish farm productivity. The World Wildlife Fund (WWF), in partnership with Kukup Fish Farmer Association, Malaysian Fish Farmers Association of Malaysia (MFFAM), UCSI university and Iskandar Regional Development Authority (IRDA) recommended fish farmers explore other potential farming sites south of Kukup Island (unpublished data). The newly proposed aquaculture development site is a 50 ha (500 m x 1 km) area, roughly 3.8 km from the Kukup Straits and 1.3 km from the Kukup Port Limit (**Figure 1**). Originally, the proposed aquaculture site was 200 ha, however, it was narrowed to 50 ha based on these selection criteria: (i) higher water depth (> 10m, as shown in **Figure 3**) with better turnover, (ii) short travelling distance from Kukup town, and (iii) enclosed within the port limit to avoid obstructing the shipping lane (**Figure 1**). WWF and MFFAM's proposed aquaculture development site is a preliminary assessment. The outcomes of this study will be submitted and discussed with the Department of Fisheries and local government authorities to assist with the state and federal Aquaculture Industrial Zone (AIZ) planning. The recently suggested aquaculture site sits on the edge of the main transit lane for international shipping through the Singapore – Melaka Straits and is immediate to the north of the Johor and Singapore outer port areas. Furthermore, the area is located within the Kukup Port Limit, Sector 6 of the Straits of Malacca and Singapore (SOMS) Vessel Traffic Information System (VTIS) and the Traffic Separation Scheme and Deepwater Route. Malacca Straits Sector 6 is narrow and act as an entry point to the Port of Tanjung Pelepas (PTP) and Singapore Straits, thus, subjected to heavy international shipping pressures. The Malaysian Marine Department governs the Kukup Port.

When selecting a new aquaculture site, conducting a technical assessment to ensure future business profitability is critical. One of the main criteria of the site evaluation is water quality. Therefore, this study aims to analyse the suitability of a new aquaculture site for sea cage farming offshore of Kukup within the Magellan Strait by assessing several key criteria: 1) hydrodynamic and meteorological conditions, 2) marine water quality, and 3) marine sediment quality of existing aquaculture site and the proposed site. In addition, several key factors are evaluated in this study, including bathymetry, wind, currents, waves, water temperature, pH, salinity, dissolved oxygen, turbidity, ammoniacal nitrogen, particles size distribution, redox potential, total organic carbon, hydrocarbons, heavy metals and benthic biodiversity (Szuster and Albasri, 2010; Radiarta et al., 2011; Leung et al., 2015; De Novaes Vianna and Bonetti Filho, 2018; Divu et al., 2021). The hydrodynamics and meteorology conditions (bathymetry, wind, currents and waves) are crucial in selecting a new aquaculture location (Radiarta et al., 2011; Gimpel et al., 2015; Mayerle et al., 2020). A better knowledge of the factors listed above can help in determining the physical impacts on the new infrastructure, structural integrity, cost, operating conditions and the associated costs for supporting infrastructure (vessel size, capital and operational costs). Additionally, higher energy environments like those anticipated further offshore offer potentially improved water quality due to high flushing rates enhanced operational conditions, and, most importantly, greater distances from land-based pollution sources.

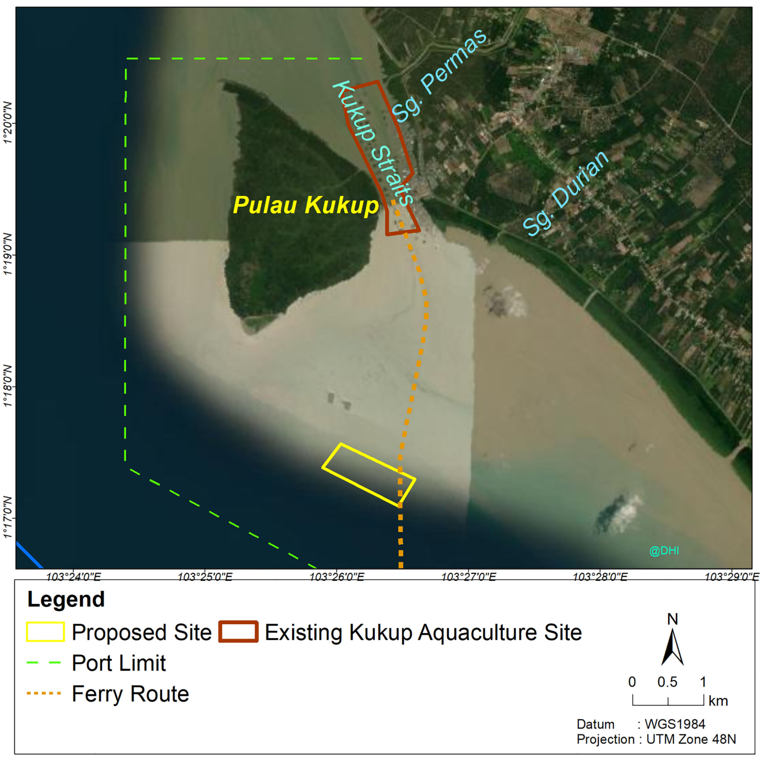



**FIGURE 1** | Satellite image of existing Kukup aquaculture site and new proposed site.

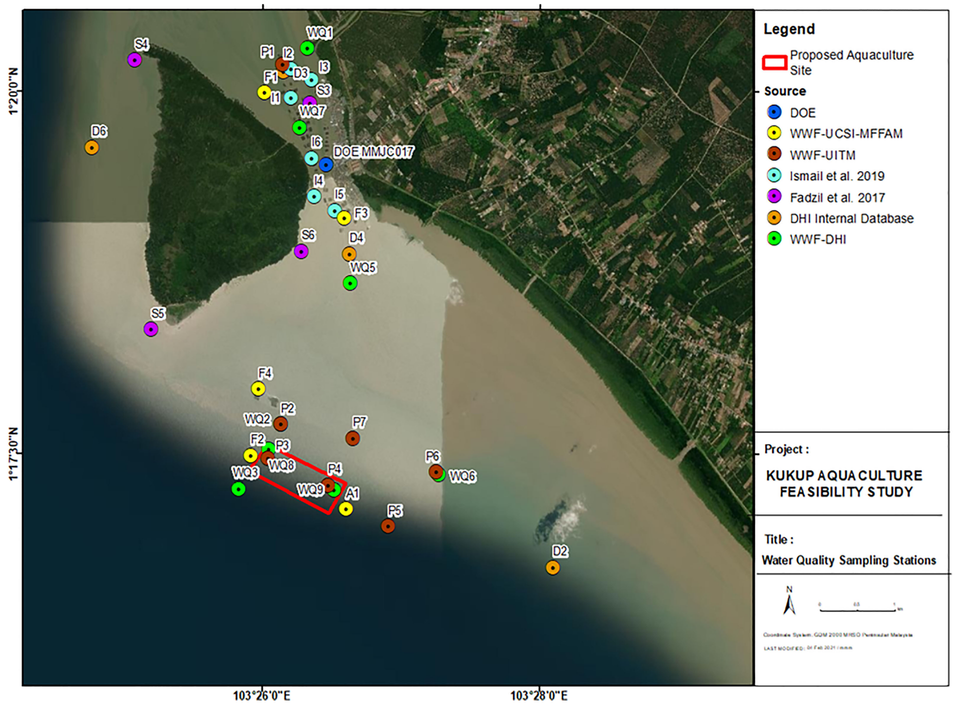



**FIGURE 2** | Water quality and marine sediments sampling stations from the respective sources within the existing Kukup aquaculture site, new proposed aquaculture site and surrounding waters.

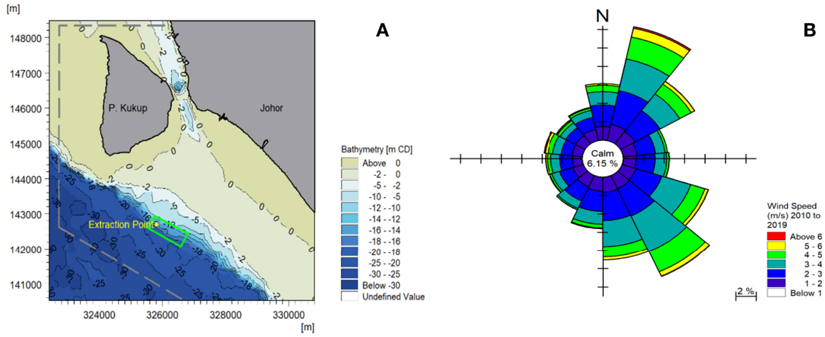


**FIGURE 3** | Hydrodynamic, meteorological conditions and ship density plot of the study area: **(A)** extraction point of wind time series, and **(B)** wind speed.

## 2 MATERIALS AND METHODS

### 2.1 Hydrodynamics and Meteorological Conditions

Bathymetry or seabed contour levels of the study areas were sourced from the navigation chart MAL5129 published in April 2008. Bathymetry levels were referenced to Chart Datum (CD), and areas with positive values or higher than 0 m CD were interpreted as the inter-tidal areas within a certain distance from the coastline. Wind data were obtained from a global high-resolution weather model along with meteorological and oceanographic information, sourced from the National Center for Environmental Prediction, USA (NCEP) (Saha et al., 2014). The spatial and temporal extent of currents and waves at the proposed site were derived using results from two-dimensional (2D) numerical models, namely, the MIKE 21 Hydrodynamic (HD) and Spectral Wave (SW) model (Uddin et al., 2014).

The Climate Forecast System Reanalysis (CFSR) wind forcing is applied in this assessment. It is a third-generation reanalysis product from a global, high resolution, coupled atmosphere-ocean-land surface-sea ice modelling system, sourced from the National Centers for Environmental Prediction (NCEP), USA. The data from 2010 to 2019 are supplied in one-hour intervals, at the height of 10 m above mean sea level. The spatial resolution of the CFSR was set in the order of 0.20° by 0.20°. Typical northeast (NE) monsoon, southwest (SW) monsoon and inter-monsoon current flow conditions of the study area were predicted using the MIKE 21 HD FM (flexible mesh) hydrodynamic model. Simulation periods were selected as February (NE monsoon), April (inter-monsoon) and July (SW monsoon) 2017 and each simulation includes 28 days for spring-neap tidal cycle. The model applied boundary conditions driven by a large regional domain, including seasonal variations and CFSR spatial wind maps as the key wind forcing. The ship wakes analysis and simulations for various vessels, sailing routes, and potential ship wakes generated are sourced from DHI in-house assessments (unpublished data).

### 2.2 Sampling Site Description

A field expedition was conducted on 9$^{th}$ August 2020 to sample ambient water at eight stations, while marine sediment was collected at seven sites from the 17th to 18th August 2020 at the locations shown in **Figure 2**. Ammoniacal nitrogen and nitrate were measured at seven sampling sites in 2013 and 2019. The coordinates of the water quality (WQ, D & F) sampling stations and marine sediment sampling site (P) are presented in **Table 1**.

### 2.3 Water Quality Assessment

*In situ* parameters were measured using an Aqua TROLL® 600 multiparameter sonde (*In-situ* Inc., USA) at each water quality sampling station (WQ1 - WQ9), and a YSI *in situ* multiparameter (ProQuatro, USA) was used in seven water sampling sites (P1 – P7) to quantify the water mass properties including temperature, salinity, pH, turbidity, dissolved oxygen (DO). Meanwhile, the physicochemical parameters such as the redox potential (Eh) were measured using Oxidation Reduction Potential (ORP) meter (HM Digital ORP-200, Culver City, USA) following methods of Praveena and Aris (2013). Turbidity was not sampled in WQ1, -5, -6, and -7, due to equipment error. pH was not sampled at WQ6, and dissolved oxygen (DO) was not sampled at WQ2 due to the unstable sea conditions. Ammoniacal nitrogen and nitrate at D-2, -3 and -4 were sourced from DHI's internal database (unpublished data), while F-1, -2 and -3 were measured using Horiba compact meters (LAQUAtwin, Japan).

### 2.4 Extraction of Seabed Sediment

Macrobenthos sampling was conducted at seven sites (P-1, -2, -3, -4, -5, -6, and -7) from 17$^{th}$ to 18$^{th}$ August 2020 by Universiti Teknologi MARA (UiTM) A&A Laboratory. Before the sampling process was conducted, the site coordinates were obtained using a Global Positioning System (GPS) application, while the water depth was recorded using a portable echo sounder (SM5, Laylin Associates, Unionville, VA). Then, samples for the quantitative determination of the chemical composition and macrobenthos were initiated using the sampling device known as a Petite Ponar Grabber (Wildco®, Yulee, FL), with a sampling area of 152 x 152 mm (6 x 6") (Wang et al., 2013). The water depth of sampling sites ranged from 2.3 m to 24.6 m. One sub-sample was extracted for chemical composition analysis, while sampling was done in triplicates (P1 - P7) to estimate the macrobenthos diversity. The

**TABLE 1 |** Coordinates of 16 sampling sites for water quality and marine sediments assessment in degrees-minutes-seconds (DMS).

| Sampling sites | Descriptions | Coordinates |
|---|---|---|
| WQ1 | Existing site (straits of Kukup) | N 1°20'17.934'' E 103°26'19.5144'' |
| WQ2 | At the edge of proposed site | N 1°17'42.4716'' E 103°26'8.034'' |
| WQ3 | Within proposed site | N 1°17'15.7632'' E 103°25'49.7676'' |
| WQ5 | Existing site (straits of Kukup) | N 1°18'40.8024'' E 103°26'38.166'' |
| WQ6 | At the edge of proposed site | N 1°17'21.462'' E 103°27'16.3836'' |
| WQ7 | Existing site (straits of Kukup) | N 1°19'45.2568'' E 103°26'16.098'' |
| WQ8 | Within proposed site | N 1°17'32.0136'' E 103°26'2.6952'' |
| WQ9 | Within proposed site | N 1°17'15.4248'' E 103°26'31.1244'' |
| P1 | Existing site (straits of Kukup) | N 1°20'11.4" E 103°26'08.6" |
| P2 | At the edge of proposed site | N 1°17'42.5" E 103°26'08.0" |
| P3 | Within proposed site | N 1°17'28.4" E 103°26'02.3" |
| P4 | Within proposed site | N 1°17'17.3" E 103°26'28.5" |
| P5 | At the edge of proposed site | N 1°16'57.0" E 103°26'54.4" |
| P6 | At the edge of proposed site | N 1°17'22.6" E 103°27'15.4" |
| P7 | At the edge of proposed site | N 1°17'36.6" E 103°26'39.1" |
| D2 | At the east of proposed site | N 1°16'46.7" E 103°28'05.3" |
| D3 | Existing site (straits of Kukup) | N 1°20'10.8" E 103°26'09.1" |
| D4 | Existing site (straits of Kukup) | N 1°19'06.7" E 103°26'31.2" |
| F1 | Existing site (straits of Kukup) | N 1°19'59.7" E 103°26'0.95" |
| F2 | At the edge of proposed site | N 1°17'29.45" E 103°25'54.93" |
| F3 | Existing site (straits of Kukup) | N 1°19'07.9" E 103°26'35.3" |
| F4 | At the edge of proposed site | N 1°17'57.05" E 103°25'58.47" |

weight of each sample is around 1 kg, and the extracted sediments were deposited in resealable plastic bags and preserved with 500 ml of 8% formalin. Then, the samples were transported to the laboratory in a sealed cooling box with ice packs for further analysis.

## 2.5 Marine Sediment Evaluation

### 2.5.1 Particle Size Distribution (PSD)

The particle size distribution was analyzed following the United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) Soil Taxonomy (United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS), 2018). First, approximately 20 g of air-dried sediment sample was filtered using a 2.0 mm sieve, weighed and recorded. Next, 30% hydrogen peroxide ($H_2O_2$) was added to the sample to remove organic matter and dispersing reagent. After that, 4% sodium hexametaphosphate was added to prevent the flocculation of sediment particles. The treated sample was then transferred to a 1 L measuring cylinder, and distilled water was added to make a total volume of 1 L.

The sample in the measuring cylinder was mixed vigorously with a plunger for 30 s. Then, clay and silt pipetted out after 46 s at a depth of 20 cm. A soil sedimentation chart was used to determine the time required to pipette out the clay and silt samples. Later, the weight of an empty beaker was recorded (W1) before pipetting the sample to be oven-dried overnight at 105°C. The sample was weighed and recorded (W2) the next day. In addition, the sample temperature was measured, and the depth for the second pipetting procedure was determined using the soil settling chart. After that, the empty beaker was weighed (W3), and the pipetted clay was placed in the beaker. The beaker was oven-dried overnight at 105°C and weighed (W4). A total of 200 ml of sample was kept while the remaining sample was discarded. Then, the collected sample was transferred into a weighed 1 L beaker (W5) and added with distilled water. The settling process was repeated several times until the sample solution became clear. Next, the sample solution was poured into the sink until 50-mL of the sample was left. The collected sample was oven-dried overnight at 105°C and weighed (W6). Lastly, the final percentage of silt, clay and sand were calculated, and the types of sediments were determined using the USDA soil texture pyramid and the following formulas (United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS), 2018).

$$\%\ silt\ clay = \frac{(W2) - (W1)}{sample\ \ weight} \times 100$$

$$\%\ clay = \frac{(W4) - (W3)}{sample\ \ weight} \times 100$$

$$\%\ sand = \frac{(W6) - (W5)}{sample\ \ weight} \times 100$$

$$\%\ silt = 100 - (\%\ \ sand + \%\ \ clay)$$

### 2.5.2 Total Organic Carbon (TOC)

The total organic carbon (TOC) measures the organic matter content *via* the Walkley and Black Titration method (Walkley and Black, 1934). First, the sample was dried at 35°C and filtered using a 0.15 mm mesh sieve. A total of 0.5 g sample was weighed and transferred to a 500 mL conical flask, and 10 mL of 0.1667 M potassium dichromate solution ($K_2Cr_2O_7$) was added to the sample. Then, 20 mL of concentrated sulphuric acid was cautiously added to the sample and swirled for 30 s, followed by 200 mL deionised water after the sample had cooled to room temperature. The sample was allowed to sit for 30 min before the suspension was filtered. Next, three to four drops of ferroin indicator were added to the filtrate. Finally, the excess dichromate was titrated using 0.5 M standard ferrous ammonium sulphate solution (FAS). The colour change at the endpoint was observed from blue-green to a reddish hue. Total organic carbon is calculated using the following formula (Walkley and Black, 1934):

$$TOC\,(\%) = \frac{(B - A)(0.3)(Ma)}{weight\ \ of\ \ dry\ \ sample}$$

Where, B = blank titre (mL), A = sample titre (mL) and Ma = concentration of FAS

### 2.5.3 Oil and Grease

The oil and grease (OG) content in sediment was analysed according to the American Public Health Association (APHA et al., 1912) -5520B (partition gravimetric) method (Baird et al., 2017). First, a wet sludge sample was taken from a 1 L wide mouth glass bottle, and 1 mL concentrated hydrochloric acid (1:1 HCL) per 80 g sample was added and acidified to pH 2.0 or lower. Approximately 20 ± 0.5 g of the acidified sample was weighed (W1) and placed into a beaker. Then, 25 g of magnesium sulphate monohydrate ($MgSO_4.H_2O$) was added to dry the sample. After the sample had solidified (15 to 30 min), the sample was ground into powder form using a porcelain mortar. A total of 100 mL n-hexane was added, and the sample was transferred to a separator funnel. The sample was shaken vigorously for 2 min to achieve layer separation. Next, the solvent layer was drained through a funnel containing a filter paper (Whatman No 40). Then, the extracts were filtered and combined into the same distilling flask. Later, the solvent from the flask was distilled in a water bath at 85°C for 15 min, cooled in a desiccator for at least 30 min and weighed (W2). Finally, the extracted oil and grease were calculated using the following formula (APHA et al., 1912):

$$O\ \ G(mg/kg) = \frac{(W2 - W1)x1000000}{Sample\ \ weight\ \ (g)}$$

Where W2 = final weight and W1 = initial weight.

### 2.5.4 Polynuclear Aromatic Hydrocarbon and Total Petroleum Hydrocarbon

Polynuclear aromatic hydrocarbon (PAH) and total petroleum hydrocarbon (TPH) of the marine sediment were extracted using the United States Environmental Protection Agency Soxhlet Extraction (USEPA) method 3540 (Solid) (Guerin, 1999). Before the drying process, the water layer in the sediment sample was decanted and discarded. In addition, foreign objects such as sticks, leaves, and rocks were removed, and the sample was mixed thoroughly. A total of 10 g sample was weighed and placed into a tared crucible and subjected to drying overnight at 105°C. The dried sample was weighed after cooling to room temperature. The dry weight (%) was calculated using the following formula (Guerin, 1999):

$$\%\ \ dry\ \ weigh\ \ samples = \frac{dry\ \ sample\ \ (g)}{sample\ \ weight\ \ (g)}\ \ \times 100$$

A total of 10 g of solid sample with 10 g of anhydrous sodium sulphate were blended and placed in an extraction thimble. Then, 1 ml of surrogate standard spiking solution and matrix spiking standard were added to the selected samples. Next, a 300 mL extraction solvent (Acetone/Hexane at 1:1) was added to a 500 ml round bottom flask containing two cleaning chips. The flask was attached to the Soxhlet extractor, and the samples were extracted for 16 h at 4 - 6 cycles/h. Then, the extracted samples were allowed to cool. A Kuderna-Danish (K-D) concentrator was assembled by attaching a 10 mL concentrator tube to a 500 ml evaporation flask. The solvent vapour-recovery glassware (condenser and collection device) was attached to the Snyder column of the K-D apparatus following the manufacturer's instructions. The extract was dried by passing it through a drying column containing about 10 cm of anhydrous sodium sulphate, and the dried extract was later collected. The concentrator flask and sodium sulphate column were washed with 100 to 125 ml extraction solvent to complete the quantitative transfer. Subsequently, two clean boiling chips were added to the flask, and a three-ball Synder column was attached. Methylene chloride (1 ml) was added to the top of the Synder column. The K-D apparatus was placed on a hot water bath, and the temperature was set to 15 – 20°C above the solvent boiling point. The concentrator tube was partially immersed in hot water, and the entire lower rounded surface of the flask was bathed with hot vapour. The vertical position was adjusted to complete the concentration within 10 - 20 min. In the end, the K-D apparatus was removed from the water bath when the clear liquid reached 1 and later drained and cooled for at least 10 min.

The PAH determination was done according to the USEPA 8100 method using the gas chromatography (GC) solvent flush technique. At the same time, compounds in the GC effluents were detected by the Flame Ionisation Detector (FID) (Agilent 7890A gas chromatography, Agilent Technologies, USA) (Adeniji et al., 2018). The column used for the analysis was a 30 m x 0.32 mm I.D. (inner diameter) SE-54 fused silica capillary column. The PAH separation *via* gas chromatography was as follows: oven temperature program was 40 °C held for 1 min, then increased at 15 °C $min^{-1}$ and 150 °C for 10 min. Meanwhile, the injector and detector temperature were 250 °C. The injection volume was 1 μL in the splitless mode, keeping the split valve closed for 1 min. Finally, the PAH was quantified using Agilent ChemStation software (HPLADD01.EXE ver. 4.03.016).

The determination of sample TPH *via* the separation method was conducted using the total petroleum hydrocarbon USEPA 8015D since the technique provides gas chromatographic conditions for detecting certain non-halogenated volatile and semi-volatile organic compounds (Cortes et al., 2012). The column was a 30 m x 0.32 mm I.D. SE-54 fused silica capillary column. Gas chromatographic conditions used for separating TPH was set at 40 °C for 2 min, then increased to 10 °C for 1 min and 300 °C for 10 min. The injector and detector temperature were set at 250 °C. The injection volume was 1 µL in the splitless mode, keeping the split valve closed for 1 min. Lastly, the TPH was quantified using the Agilent ChemStation software.

### 2.5.5 Heavy Metals

Heavy metals composition was measured using the USEPA method 1311 toxicity characteristic leaching procedure (TCLP) (US Environmental Protection Agency, 1992). Two different buffered acidic leaching extraction fluids were utilised for this procedure depending on the pH value of the sediment samples. As described in TCLP, extraction fluid 1 (± pH 4.93) was used for sediment samples with a pH < 5, while extraction fluid 2 (± pH 2.88) was used for sediment samples with a pH of > 5. First, extraction fluid 1 was prepared by adding 5.7 mL glacial acetic acid ($CH_3CH_2OOH$) to 500 mL reagent water. Then, 64.3 mL 1 N sodium hydroxide (NaOH) was added to the mixture and diluted with reagent water to a volume of 1 L. Meanwhile, extraction fluid 2 was prepared by diluting 5.7 mL of glacial acetic acid was diluted with reagent water to a volume of 1 L. The final pH of Solution 1 and 2 were 4.93 and 2.88, respectively. All reagents used in the TCLP test were made from ACS (American Chemical Society) reagent grade.

Extracts or portions of extracts for metallic analysis were acidified with nitric acid to a pH of < 2. An aliquot of 2 g of each sample and 40 mL extraction reagent was transferred into 100 mL plastic vessels and rotated for 18 h in a horizontal shaking mixer with a speed of 30 ± 2 rpm. The room temperature was maintained at 23 ± 2°C throughout the extraction process. After 18 h, the fluid in each vessel was separated from the solid phase by vacuum-filtration through 0.8 µm borosilicate glass fibre filter paper. Both primary and secondary extract fluids were used. The concentrations of heavy metals in extracts produced by TCLP were determined using flame atomic absorption spectrometry (FAAS) (Sun et al., 2006).

## 2.6 Benthic Biodiversity Analysis

Benthic biodiversity analysis was conducted according to Musale and Desai (2011). First, the sediment samples were sieved (mesh size: 0.25 mm) to separate the benthic organisms from the sediment and organisms before they were identified under the microscope (OMAX™ stereomicroscope, USA) at 10 – 40 × magnification. Next, the organisms were classified into taxonomic categories to the family level using six identification keys (Day, 1968; Sterrer, 1986; Blake, 1994; Miner, 2006; Eleftheriou and Moore, 2013; Gill, 2019). Then, these organisms were filtered from the sediment and placed on a white tray filled with water for the sorting process. Next, the organisms were stained with 200 mg/L rose bengal to achieve a light pink and preserved in formalin for more than 24 h to facilitate detritus sorting (Schönfeld et al., 2013). Finally, the number of taxa (S), total number of individuals (N), diversity index (H'), dominance index (D), richness index (DMg) and evenness index (J') were calculated using the following formula: Shannon-wiener index (H') (Shannon and Weaver, 1949), Dominance index (D) (Simpson, 1949), Margalef's richness index (DMg) (Margalef, 1958), and Pielou's evenness index (J') (Pielou, 1966).

$$\text{Shannon} - \text{Wiener index}\ (\mathrm{H}'): \mathrm{H}' = \sum s\ [(\frac{ni}{n})\ln(\frac{ni}{n})]$$

$$\text{Dominance index}\ (\mathrm{D} = 1 - \text{Simpson index}): \mathrm{D} = [1 - \frac{\sum n(n-1)}{N(N-1)}]$$

$$\text{Margalef's richness index}:\ DMg = \frac{(S-1)}{\ln(n)}$$

$$\text{Pielou's evenness index}: \mathrm{J}' = \frac{\mathrm{H}'}{\mathrm{H}\}\max}, \mathrm{H}'\max = \ln(\mathrm{S})$$

## 2.7 Statistical Analysis

Water quality data at different sampling sites were subjected to normality and homogeneity-of-variance tests, and analysed using the Kruskal Wallis non-parametric one-way ANOVA to compare each sample, while a difference in means was determined using Dunn's multiple comparisons *post hoc* test with Bonferroni adjustment to obtain significance difference of water quality parameters among sampling sites. In all cases, the significant difference is denoted when $p < 0.05$. The statistical analyses were conducted using the IBM Statistical Package for the Social Sciences (SPSS) software version 20.

# 3 RESULTS

## 3.1 Hydrodynamics and Meteorology Conditions

The bathymetry map shows that the proposed site has a depth between -10 and -20 m CD, with deeper contours toward the offshore. The proposed aquaculture site (in green) is located within the Kukup Port Limit (grey dash) (**Figure 1**). The data obtained from the navigation chart is useful to provide a preliminary estimate of the proposed area. The Kukup Strait is a narrow channel between Kukup Island and the mainland, where the existing aquaculture site is located. The depth of the approaching entrances of the strait is around -2 m CD with a particularly deep spot about -23 m CD at the narrowest part of the strait, resulting from the high-speed current that led to scouring.

A wind speed and direction time series from 2010 to 2019 (10 years) at a location within the proposed aquaculture study area were obtained from the CFSR database (103°26’3.52”E, 1°17’26.03”N) (**Figure 3A**). Meanwhile, the wind rose generated from the 10-year time series is presented in **Figure 3B**. The predominant wind directions were from the northeast (NE) and southeast (SE), and the highest predicted wind speed during the extraction period is 9.5 m/s. The ship density plot, Kukup Port Limit and the marine traffic separation scheme are shown in **Figure 1**.

The current flow at the proposed site is predominantly toward the northwest (NW) and SE, which are aligned with the mainland coastline. Generally, the current flows towards 300°N during ebb tide and 120°N during flood tide. The current speed increases as the tide move onshore to offshore into deeper waters. The mean and maximum currents calculated throughout the 28 days for each monsoon are shown in **Figure 4A** and **Figure 4B**, respectively. The predicted mean current speed at the new site are between 0.3 - 0.4 m/s (in deeper waters), while the maximum current speed ranges between 0.7 - 1.1 m/s. Nevertheless, it was noted that the values represent typical conditions and do not include extreme conditions that the latter will be required forinfrastructure design purposes.

The wave conditions at the new site are primarily wind-generated waves. Wind waves, also known as wind sea, is induced by immediate local wind blowing on the water surface. These waves are of a high frequency (2 – 7 s) and can present as short steep seas that rise quickly with increased wind speed. In contrast, swell waves are generated from remote weather systems with a longer frequency and are hardly affected by local winds. The significant wave heights and peak wave periods at the study area are less than 0.6 m and 4 s, respectively. Meanwhile, the highest significant wave heights are expected to be < 3.0 m.

## 3.2 Water Quality

The water temperature of the existing aquaculture site ranged from 29.3 to 30.2°C. This narrow range is considered typical of coastal waters, reflecting the tropical climate in Malaysia. Furthermore, the pH value ranged between 6.7 and 7.8, while the salinity ranged from 23.6 to 29.9 psu. The recorded DO values were between 5.5 and 6.0 mg/L (**Table 2**). The data collected between 2013 and 2019 demonstrated that ammoniacal nitrogen concentrations ranged between 3 and 179 μg/L, exceeding the MMWQS Class 2 limit of 50 μg/L. Similarly, nitrate concentrations were also high, with a maximum concentration of 383 μg/L.

The water temperature at the proposed site ranged between 29.4 and 30.2°C. The pH value ranged between 6.3 and 8.0, whereas the salinity was between 27.0 and 30.2 psu. The recorded DO ranged from 5.1 to 6.5 mg/L, while the turbidity ranged between 2.5 and 7.3 NTU (**Table 2**). Meanwhile, the ammoniacal nitrogen ranged between 2 - 79 μg/L, slightly exceeding MMWQS Class 2. Apart from that, ammoniacal nitrogen concentrations were much lower compared to the existing Kukup aquaculture site. However, the maximum nitrate concentration (330 μg/L) was approximately five times higher than the MMWQS Class 2 limit of 60 μg/L.

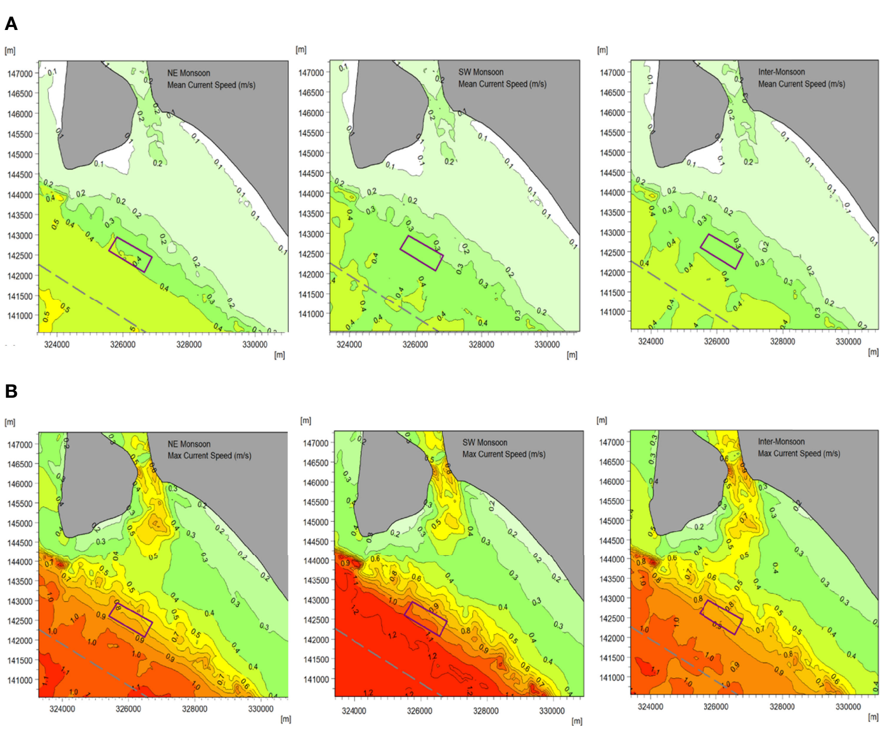



**FIGURE 4** | Mean **(A)** and maximum **(B)** current speeds calculated from 28-day simulation results of a typical NE monsoon (left), SW monsoon (middle), and inter-monsoon (right).

**TABLE 2** | Physio-chemical properties of water sampling sites (existing and proposed site) at Kukup Strait, Johor, Malaysia.

| Parameters | Sampling points | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **WQ1** | **WQ2** | **WQ3** | **WQ5** | **WQ6** | **WQ7** | **WQ8** | **WQ9** |
| Temperature (°C) | 30.2± 0.01$^{a}$ | 30.2± 0.01$^{a}$ | 29.7± 0.06$^{c}$ | 29.6± 0.09$^{c}$ | 30.2± 0.24$^{c}$ | 29.3± 0.05$^{d}$ | 29.8± 0.04$^{b}$ | 29.8± 0.07$^{b}$ |
| pH | 7.8± 0.00$^{de}$ | 7.9± 0.01$^{d}$ | 8.0± 0.02$^{b}$ | 7.8± 0.08$^{e}$ | NA | 7.8± 0.01$^{e}$ | 7.9± 0.02$^{c}$ | 8.0± 0.01$^{a}$ |
| Salinity (psu) | 29.9± 0.01$^{d}$ | 30.1± 0.02$^{b}$ | 30.1± 0.02$^{b}$ | 28.4± 1.95$^{d}$ | 30.2± 0.03$^{a}$ | 28.5± 0.04$^{d}$ | 30.1± 0.01$^{c}$ | 30.2± 0.01$^{a}$ |
| Dissolved oxygen (mg/L) | 6.0± 0.01$^{d}$ | NA | 6.5± 0.04$^{b}$ | 5.7± 0.38$^{d}$ | 6.2± 0.26$^{c}$ | 5.5± 0.05$^{d}$ | 6.5± 0.08$^{a}$ | 6.5± 0.46$^{b}$ |
| Turbidity (NTU) | NA | 7.3± 3.12$^{a}$ | 2.5± 0.30$^{d}$ | NA | NA | NA | 3.1± 0.65$^{b}$ | 2.7± 0.56$^{c}$ |
| | **P1** | **P2** | **P3** | **P4** | **P5** | **P6** | **P7** | |
| Temperature (°C) | 29.4 | 29.4 | 29.5 | 29.5 | 29.6 | 29.5 | 29.5 | |
| pH | 6.7 | 6.5 | 6.4 | 6.4 | 6.5 | 6.3 | 6.4 | |
| Salinity (psu) | 23.6 | 27.0 | 27.1 | 27.3 | 27.7 | 27.6 | 27.3 | |
| Dissolved oxygen (mg/L) | NA | 5.4 | 5.1 | 5.6 | 5.7 | 5.7 | 5.7 | |
| | **D2** | **D3** | **D4** | **F1** | **F2** | **F3** | **F4** | |
| Ammoniacal Nitrogen (µg/L) | <2 - 45 | 3 - 93 | 3 - 69 | 32 - 179 | 43 - 79 | 39 - 51 | NA | |
| Nitrate (µg/L) | 7 - 39 | 4 - 37 | 5 - 39 | 234 - 383 | 176 - 330 | 171 - 355 | 162 - 175 | |

*NA = Non-available. Superscripts indicate signification variation (P<0.05).*

## 3.3 Marine Sediments and Macrobenthos Diversity

At the existing aquaculture site, the marine sediment is categorised as silt, which consists of a high percentage of silt (95.13%) with low percentages of clay (0.49%) and sand (4.38%) (**Figure 5A**). The lowest redox potential was recorded at P1 (-196 mV); the shallowest sampling site (2.3 m). However, the TOC recorded was 1.9%, indicating that the sediment at P1 was not organically enriched. In contrast, the sediment structure at all sediment sampling sites is consistent. The metals recorded in this study were consisting of copper, nickel, lead, zinc, iron and manganese (**Table 3**)). Meanwhile, the hydrocarbons, cadmium, mercury, vanadium and barium levels were lower than the respective limit of detection (LOD), thus considered undetected in the sediments at the existing aquaculture site (**Table 3**). In terms of macrobenthos diversity, the number of *Lumbrineridae* polychaetes sampled at P1 was the highest compared to other sampling sites. The Shannon-wiener diversity index (H) recorded at P1 was 1.75 ± 0.15, while the number of individuals (N) was 12.67 ± 3.09. The evenness index (J') and richness index (DMg) of macrobenthos at the existing aquaculture site were 0.92 ± 0.03 and 2.13 ± 0.38, respectively (**Table 4**; **Figure 5B**).

Marine sediments at the proposed site are categorised as silt sediment with a high percentage of silt (95.07 – 96.48%), low percentage of clay (0.31 – 0.62%) and sand (3.21 – 4.31%) (**Figure 5A**). The redox potential recorded at the proposed site was between -138 to -135 mV. The result analysis clearly showed the absence of hydrocarbons, cadmium, mercury and vanadium at all sampling points in this study (**Table 3**). Meanwhile, copper, nickel, lead, zinc, iron and manganese are detected at all sampling points (**Table 3**). Barium was detected at four sampling points of the new proposed site, namely, P-4, -5, -6, and -7 (**Table 3**). The lowest concentration of total metals was detected at P2 (835.17 mg/kg), which consists of copper (0.47 mg/kg), nickel (2.49 mg/kg), lead (10.30 mg/kg), zinc (18.93 mg/kg), iron (688.99 mg/kg) and manganese (113.99 mg/kg). Macrobenthos in the proposed site and surrounding vicinity had the highest evenness index (J') was recorded at P5 (0.93 ± 0.02), while the greatest macrobenthos abundance (N) was recorded in station P7 with a mean density of 1884 ± 1220 (127 ind./m$^2$), followed by station P2 at 1623 ± 856 (111 ind./m$^2$) and the lowest mean density was recorded at station P3 with 318 ± 74 (22 ind./m$^2$) (**Table 5**). The lowest evenness index (J') was recorded in P7 at 0.54 ± 0.23. However, the highest Shannon-wiener (H') and richness indices (DMg) were recorded at the proposed site (P2). No sensitive environment species such as corals were present within the sediment samples (**Table 5**).

# 4 DISCUSSION

## 4.1 Hydrodynamics and Meteorology Conditions

Bathymetry or seabed contour should be considered during site selection because floating cages must be placed where the water is deep enough to maximise water exchange and ensure that cage bottoms do not come in contact with seabed substrates at low tide (Shih, 2017). As a rule of thumb, the operational depth of the fishnet should be one-third of the water column depth, preventing net abrasion on the seabed. The new proposed site is expected to support deep cages of 5 to 8 m based on the bathymetry map. Apart from that, the bathymetry of the new proposed site (around 10 to 20 m) is highly suitable for offshore mariculture, and it is economical to install the mooring system (Zikra et al., 2020). The dispersion of farm waste materials is limited if the site is too shallow (< 1 m), and the build-up of waste materials directly beneath cages is inevitable. Re-suspension of deposited materials in shallow sites will reduce visibility, thus, inducing stress in the fish and lower oxygen concentration in the cage. Moreover, large floating particles such as sediment slurries are abrasive to fish gills, eventually leading to secondary infection of the gill lamellae and increasing their susceptibility to diseases (Wong et al., 2013). However, deep sites with good currents will carry additional installation and infrastructure costs.

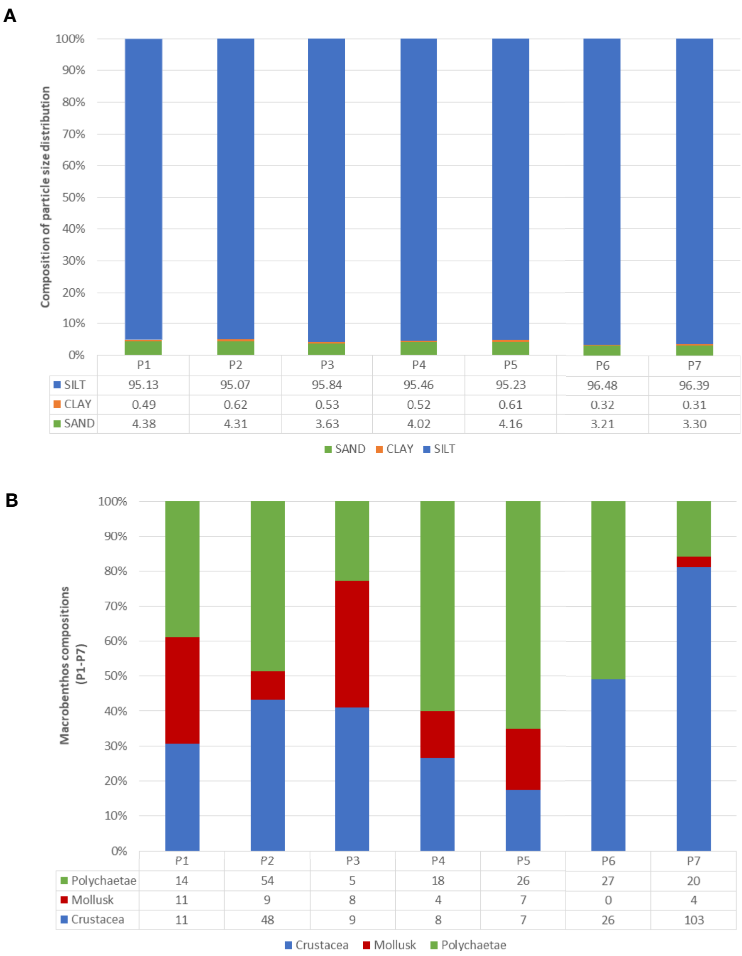



**FIGURE 5** | Composition of **(A)** particle size distribution, **(B)** polychaetae, mollusk and crustacean (P1-P7).

During the NE monsoon (usually in November to March), the average wind speed of the west coast of Peninsular Malaysia is around 2.57 – 5.14 m/s, reaching up to 12.86 m/sfor short periods. Conversely, the southwest (SW) monsoon (May-September) bring about intense solar heating, leading to high temperature over the Asian landmass as hot air expands and rises upward, creating a semi-permanent low-pressure area. Typically, the wind speed is 5.14 m/s but could reach up to 7.72 – 10.28 m/s in northern parts of the west coast (Binti Sa'adin et al., 2016). In the transition period between the monsoons, commonly known as the inter-monsoon (April and October), the winds are often mild and omnidirectional. However, the CFSR data are unlikely to fully resolve the Sumatra squalls (a phenomenon for high intensity, short duration winds in the region) with wind speeds reaching up to 30 m/s. The Sumatra Squall is characterised by intense, local, gusty surface winds, usually accompanied by heavy rain over Peninsular Malaysia that lasts for 1 to 2 h, occurring in June, July and August. In this study, meteorological results indicate that the average wind speed in the study area is maintained at the Beaufort wind scale of ≤ 5, where the is wind speed = 8 – 11 m/s, maximum wave height = 2.5 m/s. The exposed farming equipment is influenced by wind due to the increased abrasion between the net and its supporting structures. In addition, the wind may also damage the bird net protection and affect the stability of their supports.

Furthermore, operators are susceptible to accidents in rough weather conditions while moving on the vessel deck or net cage. Moreover, strong wind and high waves will increase the likelihood of fish escaping through structural damage or holes in the net (Yang et al., 2020). On the other hand, swell waves around the proposed site are expected to be minimal due to the relatively short fetch because of wind direction and low wind strengths (Abankwa et al., 2015). The ships reported in Sector 6 are government vessels, tug, ferry, fishing vessels, general cargo, tanker vessels, VLCC, bulk carrier, container vessel, and RoRo. A plot of ship density is shown in **Figure 3C** that reflects the movement of some 100 000 ship passages annually. Based on the previous assessment, the predicted maximum wake waves height generated by high-speed ferry transit at an average speed of 10.28 m/s from and to Kukup will generate wakes of up to 0.6 m and induce large waves of up to 1.0 m at the proposed site. Ship wakes are formed downstream of a moving object such as ships or vessels and can contribute to the small period waves at the proposed aquaculture site, although this needs further documentation.

TABLE 3 | Physical properties of marine sediment sampling sites (existing site and proposed site) at straits of Kukup Straits, Johor, Malaysia.

| Parameters | Marine sediment | | | | | | |
|---|---|---|---|---|---|---|---|
| | P1 | P2 | P3 | P4 | P5 | P6 | P7 |
| Depth (m) | 2.3 | 10.9 | 17.9 | 24.6 | 21.2 | 17.6 | 7.5 |
| Redox potential (mV) | -196 | -136 | -137 | -136 | -138 | -135 | -138 |
| Particle Size Distribution (Type of Sediment) | Silt | Silt | Silt | Silt | Silt | Silt | Silt |
| Silt (%) | 95.13 | 95.07 | 95.84 | 95.46 | 95.23 | 96.48 | 96.39 |
| Clay (%) | 0.49 | 0.62 | 0.53 | 0.52 | 0.61 | 0.32 | 0.31 |
| Sand (%) | 4.38 | 4.31 | 3.63 | 4.02 | 4.16 | 3.21 | 3.30 |
| Total Organic Carbon (%) | 1.9 | 1.0 | 5.2 | 1.2 | 4.4 | 2.2 | 9.6 |
| **Hydrocarbons** | | | | | | | |
| Oil & Grease (mg/kg) | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Total Petroleum Hydrocarbon (mg/kg) | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Aromatic Hydrocarbon (mg/kg) | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Aliphatic Hydrocarbon (mg/kg) | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Petrogenic Hydrocarbon (mg/kg) | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Non-Petrogenic Hydrocarbon (mg/kg) | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| **Heavy metals** | | | | | | | |
| Cadmium (mg/kg) | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 |
| Copper (mg/kg) | 0.73 | 0.47 | 0.31 | 0.68 | 1.04 | 1.18 | 1.69 |
| Mercury (mg/kg) | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Nickel (mg/kg) | 3.70 | 2.49 | 3.78 | 1.19 | 3.01 | 2.26 | 1.69 |
| Lead (mg/kg) | 10.64 | 10.30 | 13.78 | 14.65 | 16.73 | 14.41 | 15.71 |
| Zinc (mg/kg) | 29.82 | 18.93 | 21.37 | 20.77 | 15.75 | 26.67 | 26.63 |
| Iron (mg/kg) | 739.33 | 688.99 | 742.63 | 773.01 | 741.05 | 738.36 | 756.17 |
| Manganese (mg/kg) | 210.80 | 113.99 | 132.93 | 154.40 | 137.75 | 123.05 | 128.42 |
| Vanadium (mg/kg) | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Barium (mg/kg) | <0.01 | <0.01 | <0.01 | 2.08 | 0.52 | 1.03 | 0.51 |
| Total Heavy Metal (mg/kg) | 995.02 | 835.17 | 914.80 | 966.78 | 915.85 | 906.96 | 930.82 |

While the coastal currents are vital in driving the transport and dispersal of substances such as nutrients, pollutants, and sediments in the water, a significant net transport is more significant to the magnitude of the net current (Geyer et al., 2004). In general, the net current in the Malacca Straits tends to move towards the northern part of the Straits and is particularly strong during the NE monsoon and weaker in the SW monsoon and inter-monsoon. Ships wake due to heavy marine traffic in the marine traffic separation scheme, and ferries from the Kukup Port also generate waves (**Figure 3**). Water currents affect the load distribution and motion of offshore net cages. Apart from that, waves are the dominant factor causing structural failure of offshore net cages. Nonetheless, a slightly higher sea current speed (~20 cm $s^{-1}$) is considered beneficial for the welfare of farmed fish and the farm environment. On the other hand, higher current speeds (> 1.5 body lengths $s^{-1}$) can adversely affect fish health, farming equipment and operations (Oppedal et al., 2011; Xu and Qin, 2020; Hvas et al., 2021).

TABLE 4 | Comparison of present data with MMWQA class 2 limit and dutch sediment standards target value and intervention value.

| Water quality | MMWQS Class 2 | Proposed site |
|---|---|---|
| Temperature (°C) | ≤ 2°C increment | 29.7 – 30.2 |
| Salinity (psu) | NA | 27.0 – 30.2 |
| Dissolved oxygen (mg/L). | > 5.0 | 5.1 – 6.5 |
| pH | 6.5 – 9.0 | 6.3 – 8.0 |
| Ammoniacal Nitrogen (µg/L) | 50 | < 2 - 79 |
| Nitrate (µg/L) | 60 | 7-330 |
| **Sediment quality** | **Dutch sediment Standard** | **Proposed site** |
| PAH (mg/kg) | 40 | <0.01 |
| Cadmium (mg/kg) | 14 | <0.02 |
| Copper (mg/kg) | 190 | 0.31 – 1.69 |
| Lead (mg/kg) | 580 | 10.30 – 16.73 |
| Mercury (mg/kg) | 10 | <0.001 |
| Nickel (mg/kg) | 210 | 1.19 - 3.78 |
| Zinc (mg/kg) | 2000 | 15.75 – 26.67 |

*PAH, Polycyclic aromatic hydrocarbons.*
*NA, value is non-available.*
*MMWQS, Marine Water Quality Criteria and Standard (Department of Environment, 2011).*
*Dutch sediment Standard, (Dutch Ministry of Housing, Spatial Planning and Environment, VROM, 2010).*

**TABLE 5** | Summary of the biological parameters of the macrobenthos communities: mean number of taxa, individuals and Shannon Diversity Index

| Macrobenthos | P1 | P2 | P3 | P4 | P5 | P6 | P7 |
|---|---|---|---|---|---|---|---|
| **Polychaetae** | | | | | | | |
| Cirratulidae (S) | 0 | 6 | 0 | 0 | 0 | 0 | 0 |
| Ampharetidae (S) | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Terebellidae (S) | 0 | 2 | 0 | 0 | 1 | 1 | 1 |
| Trichobranchidae (S) | 0 | 1 | 0 | 0 | 4 | 3 | 0 |
| Spionidae (S) | 0 | 3 | 0 | 0 | 1 | 2 | 4 |
| Poecilochaetidae (S) | 0 | 2 | 0 | 0 | 0 | 0 | 0 |
| Aphroditidae (E) | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Glyceridae (E) | 0 | 0 | 0 | 0 | 2 | 0 | 0 |
| Goniadidae (E) | 0 | 3 | 2 | 1 | 0 | 0 | 0 |
| Nephtyidae (E) | 2 | 5 | 0 | 1 | 0 | 1 | 0 |
| Nereididae (E) | 0 | 8 | 1 | 0 | 2 | 2 | 1 |
| Hesionidae (E) | 0 | 4 | 0 | 0 | 0 | 1 | 1 |
| Pilargidae (E) | 0 | 3 | 0 | 0 | 0 | 0 | 0 |
| Lumbrineridae (E) | 8 | 0 | 1 | 0 | 3 | 1 | 1 |
| Onuphidae (E) | 0 | 0 | 0 | 0 | 2 | 0 | 0 |
| Capitellidae (S) | 2 | 11 | 0 | 15 | 7 | 9 | 7 |
| Ophellidae (S) | 0 | 0 | 0 | 0 | 2 | 4 | 1 |
| Scalibregmatidae (S) | 1 | 0 | 0 | 1 | 0 | 0 | 1 |
| Orbiniidae (S) | 0 | 2 | 0 | 0 | 0 | 1 | 1 |
| Paraonidae (S) | 0 | 4 | 1 | 0 | 0 | 2 | 1 |
| Cossuridae (S) | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| **Sub-total** | 14 | 54 | 5 | 18 | 26 | 27 | 20 |
| **Mollusk** | | | | | | | |
| Gastropodes | 8 | 2 | 3 | 3 | 2 | 0 | 0 |
| Bivalves | 3 | 7 | 5 | 1 | 5 | 0 | 4 |
| **Sub-total** | 11 | 9 | 8 | 4 | 7 | 0 | 4 |
| **Crustacea** | | | | | | | |
| Amphipods | 0 | 7 | 1 | 0 | 1 | 6 | 11 |
| Tanaidacae | 6 | 3 | 0 | 0 | 2 | 11 | 80 |
| Decapods | 0 | 2 | 1 | 1 | 0 | 2 | 0 |
| Isopoda | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| Euphasia/krill | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Roundworm | 4 | 17 | 2 | 2 | 0 | 3 | 5 |
| Peanutworm | 0 | 11 | 0 | 1 | 0 | 1 | 1 |
| Ophiuroidae (Brittle star) | 0 | 8 | 5 | 4 | 3 | 1 | 2 |
| Unknown | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| **Sub-total** | 11 | 48 | 9 | 8 | 7 | 26 | 10 |
| **Total no of individual** | 36 | 111 | 22 | 30 | 40 | 53 | 127 |
| **Grand total** | | | | 419 | | | |
| **Diversity index** | **P1** | **P2** | **P3** | **P4** | **P5** | **P6** | **P7** |
| Taxa (S) | 6.33 ± 0.94 | 14.00 ± 4.24 | 5.00 ± 1.63 | 5.33 ± 2.49 | 9.67 ± 3.09 | 10.00 ± 2.94 | 11.33 ± 2.49 |
| Individuals | 12.67 ± 3.09 | 37.33 ± 19.69 | 7.33 ± 1.70 | 10.00 ± 2.16 | 13.33 ± 3.30 | 17.67 ± 3.85 | 43.33 ± 28.05 |
| Density (ind/m$^2$) | 550 ± 134 | 1623 ± 856 | 318 ± 74 | 434 ± 94 | 580 ± 143 | 768 ± 168 | 1884 ± 1220 |
| Shannon-Wiener (H) | 1.75 ± 0.15 | 2.36 ± 0.39 | 1.44 ± 0.34 | 1.35 ± 0.58 | 2.15 ± 0.31 | 2.08 ± 0.31 | 1.67 ± 0.57 |
| Evenness Index (J) | 0.92 ± 0.03 | 0.80 ± 0.02 | 0.90 ± 0.07 | 0.84 ± 0.04 | 0.93 ± 0.02 | 0.84 ± 0.03 | 0.54 ± 0.23 |
| Richness index (DMg) | 2.13 ± 0.38 | 3.69 ± 0.64 | 1.97 ± 0.61 | 1.86 ± 1.00 | 3.31 ± 0.86 | 3.11 ± 0.81 | 2.94 ± 0.82 |

*For the polychaetes (E), errantia and (S), sedentaria groups.*

Currents act as additional drag force on the mooring system and simultaneously apply wave force on the anchor components. High current speeds will wash out the feed from the cages before fully- consumed, thus, increasing feed use and lowering the feed conversion ratio (FCR). The current force could be reduced by increasing the mooring lines at the cage centre and positioning the short side of the grid against the incoming current (Purnawanti et al., 2018). Overall, the degree of wind exposures, current speeds, water depths, wave heights and wave periods of the new proposed site is within the HDPE cages limit with a life span of around 15 – 20 years.

## 4.2 Water Quality

The existing aquaculture site in Kukup Straits showed the lowest salinity recorded in this study (P1) at 23.6 psu. Sampling sites (WQ7 and P1) are located adjacent to the mouth of the Permas river; thus, lower salinity is expected at these sites. Even though the turbidity at the existing site was not measured in the present study, the National Coastal Erosion Study in 2015 reported a high coastal erosion rate (18.32 m/year) at the western and southern shores of Kukup Island (DID, 2015). In addition, Philipose et al. (2012) reported that weight gain of sea bass (*Lates calcarifer*) - one of the fish species cultured in Kukup

Straits, is optimal when the ambient water temperature is 32.5°C. The low DO values in this site indicated the high biochemical oxygen demand (BOD) of cultured fish in the aquaculture farms and the bacterial nitrification processes of fish faeces. Healthy fish require high DO, and the recommended threshold is > 5 mg/L as per MMWQS Class 2 Fisheries in mariculture. Factors contributing to ammoniacal nitrogen and nitrate peaks are nutrient runoffs from agriculture activities upstream of the rivers, nutrient waste from aquaculture faeces and feed, and sewage and resuspension of surface sediments into the water column that increases the decomposition rate. These factors increase the risk of phytoplankton blooms and potentially ammonia poisoning of the fish.

The temperature at the existing aquaculture site does not vary significantly compared to the study by Isa et al. (2020), where the temperature of the Malacca Straits ranged between 28 and 30°C. Isa et al. (2020) suggested that the temperature is lowest during NE monsoon and highest during SW monsoon. Besides, Bermudes et al. (2010) reported that the ideal temperature for rearing seabass (*L. calcarifer*) for the maximum growth and feed intake is within the range of 29.1 - 34.9°C, while the optimal feed efficiency is achieved between 26.2 - 34.9°C. At station WQ5, DO fluctuations were found between 3.5 - 4.0 m. Similarly, salinity fluctuation was evident at 3.5 - 4.0 m compared to the surface water, contributed by the influx of river water and resulting turbulence during the water mixing activity.

The DO concentrations recorded at the proposed site exceeded the 5 mg/L MMWQS Class 2 limits. The positive finding might result from the increased exposure to the ocean, higher current velocities and distance from aquaculture site (Johansson et al., 2007). However, abiotic factors such as high water temperature and salinity also affect the liberation of an oxygen molecule from water; hence, the reduced DO concentration (Jack et al., 2009). Asian seabass is a hardy fish that can tolerate 0 to 56 ppt salinity (Food and Agriculture Organization (FAO), 2017), and thus, highly suitable to be reared at the proposed site. Additionally, pompano can tolerate a wide range of salinity (10 ppt to 15 ppt salinity) (Pathak et al., 2019), and is suitable for culture at the proposed site. The overall test temperatures applied across the different life stages of the aquaculture groupers (Serranidae) ranged from 13°C to 35°C, with a mean optimum rearing temperature of 26°C (Das et al., 2021), thus, ideal to be cultured at the proposed site. Ammoniacal nitrogen concentrations were much lower compared to the existing Kukup aquaculture site. However, the F2 station located close to the boundary of the proposed site recorded high ammoniacal nitrogen concentration, exceeding the MMWQS Class 2 limits. Meanwhile, the nitrate concentrations were high at stations F2 and F4. The high nutrient load could lead to eutrophication and, subsequently, phytoplankton blooms.

## 4.3 Marine Sediments and Macrobenthos Diversity

Silt sediment is categorised as lithogenous sediment derived from continental rock erosion. Shaari et al. (2017) reported that the seafloor around Kukup Island consists mainly of quartz and kaolinite in sediments, while the highest oxide element in sediments is silicon dioxide ($SiO_2$). The redox potential of marine systems is a measure of electrochemical potential or electron availability within the systems. Electrons are essential to all inorganic and organic chemical reactions. Redox potential measurements allow rapid characterisation of the degree of reduction and predict various compound stability that regulates nutrients and metal availability in soil and sediment (Eggleton and Thomas, 2004; Pereira et al., 2004). Wong and Yang (1997) found that high redox potential and low pH are associated with chemical equilibrium disruption and the release of heavy metals from marine sediments. Negative Eh values are characteristic of bottom deposits rich in organic matter and consist mainly of fine sediments. Reimers et al. (2013) suggested that the reducing condition is generally caused by decomposable organic matter, bacteria and allied microorganisms. The lowest redox potential value was recorded at the existing aquaculture site, indicating that such conditions are maintained by certain organic compounds, ferrous iron, reduced manganese, hydrogen sulphide, and other inorganic constituents of sediments.

TOC was remarkably high (9.63%) at P7, which may be contributed by the proximity to the shipping lane and estuarine area prone to anthropogenic pollution from the mainland (sewage, surface runoff, heavy sedimentation). Generally, organic carbon represents < 5% of marine sediment even when the PSD findings of fine silt/clay particles are high. Martinez-Garcia et al. (2015) suggested that the organic carbon found in muddy sediment with polychaete and fecal pellets could account for ≥ 30% of the sediment dry weight. Organically enriched sediment is an aerobic environment that does not facilitate nitrification and phosphate release from the iron-bound pool. Unfortunately, phosphate concentration in the water column was not measured. The anaerobic environment of benthic sediment promotes the sulphate reduction process, which leads to a high concentration of dissolved sulphide in the sediment (Holmer et al., 2003). Sulphate depletion is the main factor contributing to microbial methanogenesis. The accumulation of sulphides and methane are harmful to benthic macrofauna. Naturally, muddy sediment has higher organic matter and sulphate reduction rates than sandy sediment (Martinez-Garcia et al., 2015). In this study, decomposable organic matter content may result from debris and waste from existing aquaculture sites adjacent to sampling stations. Organic matter characteristics may be seasonal in quantity and quality (Gremare et al., 1997). No hydrocarbons were detected (< 0.01 mg/kg) at all sampling points, although the new proposed site is in the vicinity of the shipping lane. Hydrocarbons are introduced into the surface water of the marine environment from surface runoff and erosion, effluent discharge, debris of virgin polystyrene, and biological sources. Despite the association of hydrophobic compounds with particles, the deposition in the underlying sediments is variable (Liu et al., 2012; Rochman et al., 2013). At the global scale, the storage of organic matter as TOC mirrors the distribution pattern of phytoplankton biomass (Seiter et al., 2004). However, diverse biogeochemical and sediment processes can modify such patterns at the regional level (Zabel et al., 1998).

The quantity and nature of the deposited organic matter are intimately related to the environmental conditions of deposition, depending on multiple factors, many of which are interdependent. The three main factors include 1) supply of organic matter in the overlying water, 2) the rate of decomposition of the organic substances in water or after accumulation in the sediments, and 3) water movement where the materials are deposited (Wakeham and Canuel, 2006). The supply of organic matter in typical marine deposits is primarily influenced by the growth of the phytoplankton in the water, sunlight exposure and mineral nutrients. Water movement or circulation influences the supply of nutrients, while organic matter decomposition is regulated by several factors, mainly oxygen supply. The oxygen supply is determined by the decomposition of organic matter and water circulation. In addition, horizontal advection and compound selective degradation can affect the distribution and composition of the settling particles. Therefore, the material deposited at the sediment-water interface is not a good representation of hydrocarbon transported through the water column.

Copper, nickel, lead, zinc, iron and manganese are detected at all sampling points. The trace elements potentially originated from wastewater discharge or soil erosion (Hosono et al., 2011). Furthermore, studies have suggested that heavy metals could be derived from fish food at existing aquaculture sites (Liang et al., 2016). Moreover, earlier studies found that the source of heavy metals could leach from the fish food at existing aquaculture sites (Kundu et al., 2017; Sabbir et al., 2018). Meanwhile, Hayat et al. (2017) suggested that 10 mg/kg of heavy metals such as lead, silver, chromium, copper, cobalt, nickel and zinc can significantly affect *L. calcarifer's* kidney by inhibiting cholinesterases (ChE) activity at various percentages. Apart from that, heavy metals weaken their immune system and induce pathological changes. The consumption of finfish polluted by heavy metals can adversely affect human health (Kumar et al., 2021). As the heavy metals become more concentrated in the environment, these elements enter the biogeochemical cycle, leading to toxicity.

The polychaete fauna of the study area is dominated by sedentaria and errantia orders commonly found in the tropical Indo-Malayan sub-region of the Indo-West-Pacific province (Shin, 1982). The Shannon diversity index (H') values of the study site were relatively high, indicating well distribution of macrobenthos fauna. Nonetheless, these values were higher than those reported by Quek and Chua (1990) for Sungei Buloh and Chung and Goh (1990) in Tekong Island. A high variation in the evenness index (J') value was evident, ranging from 0.54 ± 0.23 at P7 to 0.93 ± 0.02 at P5. A good distribution of organisms in a pristine environment would typically have a score of ≥ 0.9 (Sokołowski et al., 2012). The evenness index (J') values were relatively high, stipulating that the macrobenthos were equally distributed throughout the habitats except for P7. Meanwhile, studies in Tg. Pulai has reported the abundance of macrobenthos mean density, ranging between 320 ± 114 (range: 126 - 535) ind./m2 during the NE monsoon and 267 ± 247 (range: 56-1,343) ind./$m^2$ during the SW monsoon (DHI Water and Environment, 2013). Capitellids are regular inhabitants of the soft marine sediments found in all sampling sites except P3. They are among the many keystone species essential in the energy budgets due to their feeding habits and abundance (García-Garza and De León-González, 2011). In addition, they are benthic burrowers and feed on organic matter adhering to sediments and are regarded as non-selective deposit feeders (Dean, 2001). Microscopic images of bivalve, capitellid, hesionid, peanut worm, scalibregmatid are shown in **Figure 6**.

Capitellids are distributed from the intertidal zone to the deep sea and are often dominant components of the infaunal community, especially in organically enriched sediments. Therefore, they act as pollution indicators of man-induced, organically enriched areas such as organic-rich sediments and benthic habitats defaunated by artificial disasters such as oil spills, red tide blooms and tropical storms (Sivadas et al., 2010; Washburn et al., 2016; Hilliard, 2020). However, polychaete under the *Lumbrineridae* family is commonly found within the organically enriched sediment and sediment with a low degree of metal contamination (D'Alessandro et al., 2014). Similarly, Spionids are opportunistic surface deposit feeders and thrive in organically enriched sediments. Water with a heavy suspended sediment load could be significantly filtered when it passes over dense populations of spionid polychaetes. Spionids accumulate particles from water column and sediment as part of their tubes or in interstices between the tubes (Taghon et al., 1980). Studies have suggested that smaller particles collected by spionids are consumed while bigger particles are utilised as building materials for their tubes (Frithsen and Doering, 1986). The ecological role of spionids is to remove particles from the water during the high particle flux, which is an active sedimentation process in coastal ecosystems (Blake et al., 2020). Gillet et al. (2012) suggested that Nereididae is a significant link in benthic food webs and through sediment reworking by bioturbation activity. Nereidae also enhances the oxygen transport into sediments through irrigation and increases the surface area of oxygenated sediments through the burrow construction. Overall, the water quality data of all sampling sites are within the MMWQS Class 2 Fisheries and mariculture threshold limits. Similarly, the sediment hydrocarbons and heavy metals composition values are within the intervention value compared to the Dutch Intervention values for aquatic sediment (Dutch Ministry of Housing, Spatial Planning and Environment, VROM, 2010).

## 5 CONCLUSION

Water quality at the existing aquaculture site is subjected to higher concentrations of nutrient loading and salinity fluctuations. Aquaculture tropical finfish will still grow in these conditions but with poorer fish health and higher mortality. Due to lower flushing rates and high nutrient measurements, the existing site should move toward moderate to low-intensity farming instead of the current high-intensity farming to maintain optimal fish health. The spatial analysis indicates that the water quality during the normal hydrodynamic and meteorological conditions at the

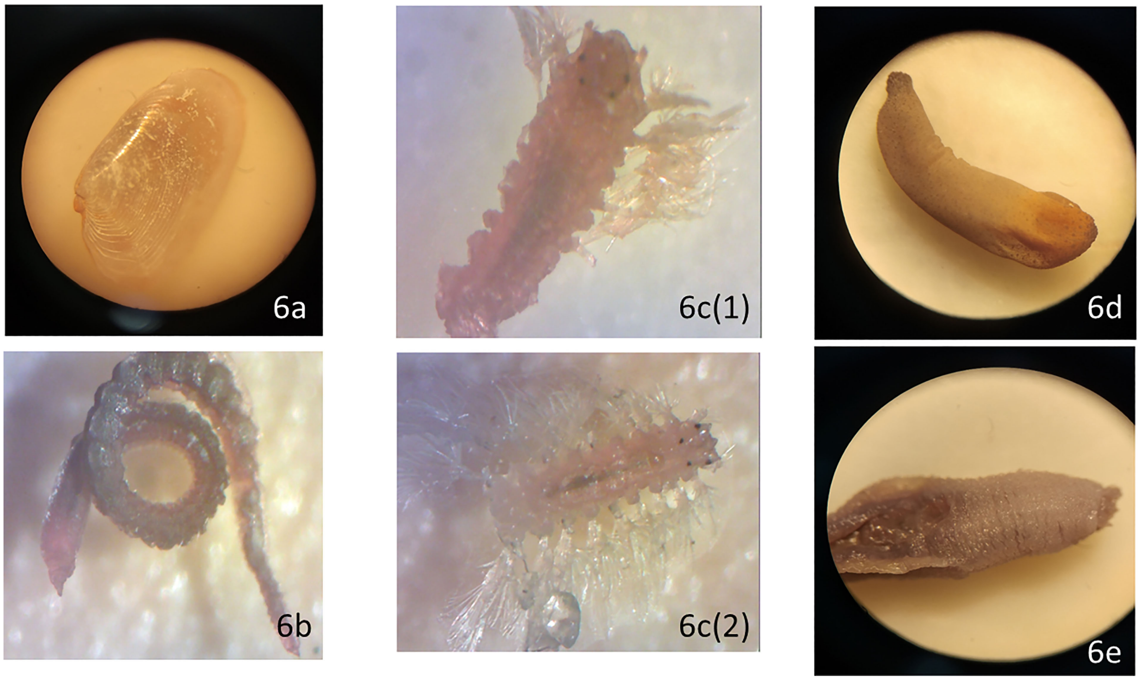



**FIGURE 6** | Microscopic images of macrobenthos: **(A)** bivalve, **(B)** capitellid, **(C)** hesionid, **(D)** peanut worm, and **(E)** scalibregmatid.

proposed aquaculture site has potential for aquaculture operations. Furthermore, the flushing capacity is higher in the proposed site, indicating the capacity to handle moderate-intensity aquaculture. It is recommended that additional data, especially on nutrient cycling, water quality model, and carrying capacity evaluation, be collected to determine the optimal stocking density for mariculture to ensure sustainable aquaculture production. Moreover, further studies with longer duration are highly recommended to understand periodic monsoonal variations, storms, and algal blooms to prevent operational failures and economic losses. Given the low flushing rates and high nutrient loading from river mouths, relocating the existing fish farms offshore with moderate to low-intensity farming is recommended. Alternatively, the proposed aquaculture site could also be established into deeper waters. Intensive aquaculture could have had significant social and economic impacts *via* chemicals, waste deposition, and fish stock migration. Thus, it is crucial to engage wider community stakeholders for the rigorous application of cost-benefit analysis. Finally, the critical understanding of the social and ecosystem services must be integrated into the new aquaculture industrial development value chains.

## DATA AVAILABILITY STATEMENT

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

## AUTHOR CONTRIBUTIONS

W-KC, T-YL, and J-YL wrote the manuscript. MM, TC, C-WC, and VA conceptualized the flow and technical aspects of the manuscript. K-SL and J-YL contributed specialized sections. All authors have read and agreed to the published version of the manuscript.

## FUNDING

This work was supported by WWF Singapore and Malaysia (Grant No.: MA021123911INTL) and a WWF-Conservation Partnership Scheme (CPS) (Grant No. CPS-FAS-2021/001), and partly financed by UCSI University Research Excellence & Innovation Grant (Grant No.: REIG-FAS-2020/067).

## ACKNOWLEDGMENTS

The authors would like to thank the Department of Fisheries Johor, Iskandar Regional Development Authority, Marine Fish Farmers Association of Malaysia, Mr Lim Hong Peng and other fish farmers from Kukup for their support in completing this research.

## REFERENCES


Abankwa, N. O., Johnston, S. J., Scott, M., and Cox, S. J. (2015). "Ship Motion Measurement Using an Inertial Measurement Unit" in *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT), Conference paper*. Milan, Italy.

Adeniji, A. O., Okoh, O. O., and Okoh, A. I. (2018). Analytical Methods for Polycyclic Aromatic Hydrocarbons and Their Global Trend of Distribution in Water and Sediment: A Review. *Recent Insights Petroleu. Sci. Eng.* 10, 393–420. doi: 10.5772/intechopen.71163

APHA, American Public Health Association, American Water Works Association and Water Pollution Control Federation, & Water Environment Federation (1912). *Standard Methods for the Examination of Water and Wastewater* Vol. Vol. 2) (Washington DC: American Public Health Association).

Baird, R. B., Eaton, A. D., Rice, E. W., and Bridgewater, L. (2017). *Standard Methods for the Examination of Water and Wastewater* Vol. 23 (Washington, DC: American Public Health Association).

Barau, A. S., and Stringer, L. C. (2015). Access to and Allocation of Ecosystem Services in Malaysia's Pulau Kukup Ramsar Site. *Ecosyst. Serv.* 16, 167–173. doi: 10.1016/j.ecoser.2015.10.021

Bermudes, M., Glencross, B. D., Austen, K., and Hawkins, W. (2010). Effect of High Water Temperatures on Nutrient and Energy Retention in Barramundi (*Lates Calcarifer*). *Aquaculture* 306, 160–166. doi: 10.1016/j.aquaculture.2010.05.031

Binti Sa'adin, S. L., Kaewunruen, S., and Jaroszweski, D. (2016). Risks of Climate Change With Respect to the Singapore-Malaysia High Speed Rail System. *Climate* 4 (4), 65. doi: 10.3390/cli4040065

Blake, J. A. (1994). "Family Phyllodocidae. Taxonomic Atlas of the Benthic Fauna of the Santa Maria Basin and Western Santa Barbara Channel," in *Oligochaeta and Polychaeta: Phyllodocida (Phyllodocidae to Paralacydoniidae)*, vol. 4. (Santa Barbara, California: Santa Barbara Museum of Natural History), 115–186.

Blake, J., Maciolek, N., and Meißner, K. (2020). "7.4 Sedentaria: Sabellida/Spionida," in *Volume 2 Pleistoannelida, Sedentaria II: Band 2: Pleistoannelida, Sedentaria Ii*. Eds. G. Purschke, W. Westheide and M. Böggemann (Berlin, Boston: De Gruyter), 1–103.

Chung, D. S., and Goh, B. P. (1990). A Survey of the Soft-Bottom Benthic Fauna of Pulau Tekong. *Coast. Livin. Resour. Singap.* (Singapore: Department of Zoology, National University of Singapore), 53–62.

Cortes, J. E., Suspes, A., Roa, S., GonzÃ¡ Lez, C., and Castro, H. E. (2012). Total Petroleum Hydrocarbons by Gas Chromatography in Colombian Waters and Soils. *Am. J. Environ. Sci.* 8 (4), 396. doi: 10.3844/ajessp.2012.396.402

D'Alessandro, M., Cosentino, A., Giacobbe, S., Andaloro, F., and Romeo, T. (2014). Description of a New Species of Abyssoninoe (Polychaeta: Lumbrineridae) From North-East Sicily (Central Mediterranean Sea). *J. Mar. Biol. Assoc. Unite. Kingd.* 94 (4), 747–752. doi: 10.1017/S0025315414000095

Das, S. K., Xiang, T. W., Noor, N. M., De, M., Mazumder, S. K., and Goutham-Bharathi, M. P. (2021). Temperature Physiology in Grouper (Epinephelinae: Serranidae) Aquaculture: A Brief Review. *Aquacult. Rep.* 20, 100682. doi: 10.1016/j.aqrep.2021.100682

Day, J. H. (1968). A Monograph on the Polychaeta of Southern Africa Part 1, Errantia: Part 2, Sedentaria Published by the Trustees of the British Museum (Natural History), London 1967 Publication No. 656. Pp. Viii+ 878. Price£ 15. *J. Mar. Biol. Assoc. Unite. Kingd.* 48 (3), 836–836.

Dean, H. K. (2001). Capitellidae (Annelida: Polychaeta) from the Pacific Coast of Costa Rica. *Rev Biol Trop* 49: 69–84

De Novaes Vianna, L. F., and Bonetti Filho, J. (2018). Spatial Analysis for Site Selection in Marine Aquaculture: An Ecosystem Approach Applied to Baía Sul, Santa Catarina, Brazil. *Aquaculture* 489, 162–174. doi: 10.1016/j.aquaculture.2017.12.039

Department of Environment (2011) *Malaysia Marine Water Quality Criteria and Standard*. Available at: https://www.doe.gov.my/portalv1/wp-content/uploads/2019/04/BOOKLET-BI.pdf (Accessed 1 October 2021).

DHI Water and Environment (2013). *Tanjung Piai Reclamation DEIA (Johor)*, Kota Kinabalu: DHI Water and Environment (Malaysia).

DID (2015). *National Coastal Erosion Study (NCES2015) Report* Vol. 2015 (Kuala Lumpur, Malaysia: Department of Drainage and Irrigation), 467.

Divu, D. N., Mojjada, S. K., Pokkathappada, A. A., Sukhdhane, K., Menon, M., Mojjada, R. K., et al. (2021). Decision-Making Framework for Identifying Best Suitable Mariculture Sites Along North East Coast of Arabian Sea, India: A Preliminary GIS-MCE Based Modelling Approach. *J. Cleane. Prod.* 284, 124760. doi: 10.1016/j.jclepro.2020.124760

Dutch Ministry of Housing, Spatial Planning and Environment, VROM (2010) *Intervention and Target Values-Soil Quality Standards*. Available at: https://sednet.org/download/guidance_document_for_sediment_assessment.pdf.

Eggleton, J., and Thomas, K. V. (2004). A Review of Factors Affecting the Release and Bioavailability of Contaminants During Sediment Disturbance Events. *Environ. Int.* 30 (7), 973–980. doi: 10.1016/j.envint.2004.03.001

Eleftheriou, A., and Moore, D. C. (2013). Macrofauna Techniques. *Methods Stud. Mar. Benth.*, 175–251. doi: 10.1002/9781118542392.ch5

Fadzil, M. F., Yun, P. S., Razal, A. R., Chee, P. S., Suratman, S., Dagang, N. S., et al (2017). Oil and Grease and Total Petroleum Hydrocarbons in the Waters of Ramsar Gazetted Mangrove Area, Johor. *J Sustain Sci Manag* 12(1), 30–39.

Food and Agriculture Organization (FAO) (2017) *Fishstat Plus Version 2.30. FAO Fisheries Department, Fishery Information, Data and Statistics Unit*. Available at: http://www.fao.org./fi/statist/FISOFT/FISHPLUS (Accessed 28 March 2022).

Frithsen, J. B., and Doering, P. H. (1986). Active Enhancement of Particle Removal From the Water Column by Tentaculate Benthic Polychaetes. *Ophelia* 25 (3), 169–182. doi: 10.1080/00785326.1986.10429748

García-Garza, M. E., and De León-González, J. A. (2011). Review of the Capitellidae (Annelida, Polychaeta) From the Eastern Tropical Pacific Region, With Notes on Selected Species. *ZooKeys* 151), 17–52. doi: 10.3897/zookeys.151.1964

Geyer, W. R., Hill, P. S., and Kineke, G. C. (2004). The Transport, Transformation and Dispersal of Sediment by Buoyant Coastal Flows. *Continent. Shelf. Res.* 24 (7-8), 927–949. doi: 10.1016/j.csr.2004.02.006

Gill, K. (2019). *Identification Guide to Freshwater Macroinvertebrates* (Stroud Water Research Center).

Gillet, P., Mouloud, M., Mouneyrac, C., Simo, P., and Gilbert, F. (2012). Preliminary Data on the Bioturbation Activity of Hediste Diversicolor (Polychaeta, Nereididae) From the Loire Estuary, France. *Open Mar. Biol. J.* 6, 53. doi: 10.2174/1874450801206010053

Gimpel, A., Stelzenmüller, V., Grote, B., Buck, B. H., Floeter, J., Núñez-Riboni, I., et al. (2015). A GIS Modelling Framework to Evaluate Marine Spatial Planning Scenarios: Co-Location of Offshore Wind Farms and Aquaculture in the German EEZ. *Mar. Policy* 55, 102–115. doi: 10.1016/j.marpol.2015.01.012

Gremare, A., Amouroux, J. M., Charles, F., Dinet, A., Riaux-Gobin, C., Baudart, J., et al. (1997). Temporal Changes in the Biochemical Composition and Nutritional Value of the Particulate Organic Matter Available to Surface Deposit-Feeders: A Two-Year Study. *Mar. Ecol. Prog. Ser.* 150, 195–206. doi: 10.3354/meps150195

Guerin, T. (1999). The Extraction of Aged Polycyclic Aromatic Hydrocarbon (PAH) Residues From a Clay Soil Using Sonication and a Soxhlet Procedure: A Comparative Study. *J. Environ. Monitor.* 1 (1), 63–67. doi: 10.1039/a807307d

Hampton, M. P. (2010). Enclaves and Ethnic Ties: The Local Impacts of Singaporean Cross-Border Tourism in Malaysia and Indonesia. *Singap. J. Trop. Geograph.* 31 (2), 239–253. doi: 10.1111/j.1467-9493.2010.00393.x

Hassan, A. S. (2010). Fishing Villages: Resemblance to the Pre-Colonial City Landscape at the Straits of Malacca in Peninsular Malaysia. *Arab. World Geograph.* 13 (2), 93–107. doi: 10.5555/arwg.13.2.02567244g400867u

Hayat, N. M., Ahmad, S. A., Shamaan, N. A., Sabullah, M. K., Shukor, M. Y. A., Syed, M. A., et al. (2017). Characterisation of Cholinesterase From Kidney Tissue of Asian Seabass (Lates Calcarifer) and its Inhibition in Presence of Metal Ions. *J. Environ. Biol.* 38 (3), 383. doi: 10.22438/jeb/38/3/MRN-987

Hilliard, J. L. (2020). *The Evolution and Ecology of Capitella (Annelida, Capitellidae) in the Gulf of Mexico (Doctoral Dissertation)*, Texas: Texas A&M University.

Holmer, M., Duarte, C. M., Heilskov, A., Olesen, B., and Terrados, J. (2003). Biogeochemical Conditions in Sediments Enriched by Organic Matter From Net-Pen Fish Farms in the Bolinao Area, Philippines. *Mar. Poll. Bull.* 46 (11), 1470–1479. doi: 10.1016/S0025-326X(03)00281-9

Hosono, T., Su, C. C., Delinom, R., Umezawa, Y., Toyota, T., Kaneko, S., et al. (2011). Decline in Heavy Metal Contamination in Marine Sediments in Jakarta Bay, Indonesia Due to Increasing Environmental Regulations. *Estua. Coast. Shelf. Sci.* 92 (2), 297–306. doi: 10.1016/j.ecss.2011.01.010

Hvas, M., Folkedal, O., and Oppedal, F. (2021). Fish Welfare in Offshore Salmon Aquaculture. *Rev. Aquacult.* 13, 836–852. doi: 10.1111/raq.12501

Isa, N. S., Akhir, M. F., Khalil, I., Kok, P. H., and Roseli, N. H. (2020). Seasonal Characteristics of the Sea Surface Temperature and Sea Surface Currents of the Strait of Malacca and Andaman Sea. *J. Sustain. Sci. Manage.* 15 (4), 66–77. doi: 10.46754/jssm.2020.06.007

Ismail, N. A. H., Wee, S. Y., and Aris, A. Z. (2018). Bisphenol A and Alkylphenols Concentrations in Selected Mariculture Fish Species From Pulau Kukup, Johor, Malaysia. *Mar. Poll. Bull.* 127, 536–540. doi: 10.1016/j.marpolbul.2017.12.043

Jaafar, S. A., Latif, M. T., Chian, C. W., Han, W. S., Abd Wahid, N. B., Razak, I. S., et al. (2014). Surfactants in the Sea-Surface Microlayer and Atmospheric Aerosol Around the Southern Region of Peninsular Malaysia. *Mar. Poll. Bull.* 84 (1-2), 35–43. doi: 10.1016/j.marpolbul.2014.05.047

Jack, J. P., Abdsalam, A. T., and Khalifa, N. S. (2009). Assessment of Dissolved Oxygen in Coastal Waters of Benghazi, Libya. *J. Black. Sea/Mediterr. Environ.* 15 (3), 135–56.

Johansson, D., Juell, J. E., Oppedal, F., Stiansen, J. E., and Ruohonen, K. (2007). The Influence of the Pycnocline and Cage Resistance on Current Flow, Oxygen Flux and Swimming Behaviour of Atlantic Salmon (*Salmo Salar* L.) in Production Cages. *Aquaculture* 265 (1-4), 271–287. doi: 10.1016/j.aquaculture.2006.12.047

Kumar, P., Sivaperumal, P., Manigandan, V., Rajaram, R., and Hussain, M. (2021). Assessment of Potential Human Health Risk Due to Heavy Metal Contamination in Edible Finfish and Shellfish Collected Around Ennore Coast, India. *Environ. Sci. Poll. Res.* 28 (7), 8151–8167. doi: 10.1007/s11356-020-10764-6

Kundu, G. K., Alauddin, M., Akter, M. S., Khan, M. S., Islam, M. M., Mondal, G., et al. (2017). Metal Contamination of Commercial Fish Feed and Quality Aspects of Farmed Tilapia (*Oreochromis Niloticus*) in Bangladesh. *Biores. Communicat.-(BRC)* 3 (1), 345–353.

Lai, J. Y.. (2014). Spatial Development of Kukup Water Settlement in Adapting Coastal Environment. [Master's thesis, National Cheng Kung University] Available at: http://repository.ncku.edu.tw/retrieve/188600/5010217001-000002.pdf

Leung, H. M., Leung, S. K. S., Au, C. K., Cheung, K. C., Wong, Y. K., Leung, A. O. W., et al. (2015). Comparative Assessment of Water Quality Parameters of Mariculture for Fish Production in Hong Kong Waters. *Mar. Poll. Bull.* 94 (1-2), 318–322. doi: 10.1016/j.marpolbul.2015.01.028

Liang, P., Wu, S. C., Zhang, J., Cao, Y., Yu, S., and Wong, M. H. (2016). The Effects of Mariculture on Heavy Metal Distribution in Sediments and Cultured Fish Around the Pearl River Delta Region, South China. *Chemosphere* 148, 171–177. doi: 10.1016/j.chemosphere.2015.10.110

Liu, L. Y., Wang, J. Z., Wei, G. L., Guan, Y. F., and Zeng, E. Y. (2012). Polycyclic Aromatic Hydrocarbons (PAHs) in Continental Shelf Sediment of China: Implications for Anthropogenic Influences on Coastal Marine Environment. *Environ. Poll.* 167, 155–162. doi: 10.1016/j.envpol.2012.03.038

Manan, N., Raza, M., Yuh, Y. S., Theng, L. W., and Zakaria, M. P. (2011). Distribution of Petroleum Hydrocarbons in Aquaculture Fish From Selected Locations in the Straits of Malacca, Malaysia. *World Appl. Sci. J.* 14, 14–21.

Margalef, R. (1958). Information Theory in Ecology. *Gen. Syst.* 3, 36–71.

Marine Environment Protection Committee (2017)Identification and Protection of Special Areas and PSSAs. In: *Protection of Pulau Kukup (Kukup Island) and Tanjung Piai (Cape Piai)* (Accessed 05 October 2021).

Martinez-Garcia, E., Carlsson, M. S., Sanchez-Jerez, P., Sánchez-Lizaso, J. L., Sanz-Lazaro, C., and Holmer, M. (2015). Effect of Sediment Grain Size and Bioturbation on Decomposition of Organic Matter From Aquaculture. *Biogeochemistry* 125 (1), 133–148. doi: 10.1007/s10533-015-0119-y

Mayerle, R., Niederndorfer, K. R., Jaramillo, J. M. F., and Runte, K. H. (2020). Hydrodynamic Method for Estimating Production Carrying Capacity of Coastal Finfish Cage Aquaculture in Southeast Asia. *Aquacult. Eng.* 88, 102038. doi: 10.1016/j.aquaeng.2019.102038

Michel, S., and Zahler, A.-K. (2015). *Cultivated Sea – Fishing and Aquaculture in the Metropolitan Region* (Zurich: ETH Zurich).

Miner, G. (2006). Standard Methods for the Examination of Water and Wastewater. *Am. Water Work. Assoc. J.* 98 (1), 130.

Mohamed, K. N., May, M. S. Y., and Zainuddin, N. (2015). Water Quality Assessment of Marine Park Islands in Johor, Malaysia. *Bulletin of Environmental Science and Management* 3 (2), 19–27.

Musale, A. S., and Desai, D. V. (2011). Distribution and Abundance of Macrobenthic Polychaetes Along the South Indian Coast. *Environ. Monitor. Assess.* 178 (1), 423–436. doi: 10.1007/s10661-010-1701-3

Oppedal, F., Dempster, T., and Stien, L. H. (2011). Environmental Drivers of Atlantic Salmon Behaviour in Sea-Cages: A Review. *Aquaculture* 311 (1-4), 1–18. doi: 10.1016/j.aquaculture.2010.11.020

Pathak, S. M., Lakra, S. W., Reddy, A. K., Chadha, N. K., Tiwari, V. K., and Srivastava, P. P. (2019). Growth and Survival of Silver Pompano *Trachinotus Blochii* (Lacepede 1801) at Different Salinities in Inland Saline Ground Water. *Indian J. Anim. Sci.* 89 (5), 581–587.

Pereira, P. M., Black, K. D., McLusky, D. S., and Nickell, T. D. (2004). Recovery of Sediments After Cessation of Marine Fish Farm Production. *Aquaculture* 235 (1-4), 315–330. doi: 10.1016/j.aquaculture.2003.12.023

Philipose, K. K., Sharma, S. R., Loka, J., Damodaran, D., Rao, G. S., Vaidya, N. G., et al. (2012). Observations on Variations in Physico-Chemical Water Parameters of Marine Fish Cage Farm Off Karwar. *Indian J. Fish.* 59 (1), 83–88.

Pielou, E. C. (1966). The Measurement of Diversity in Different Types of Biological Collections. *J. Theor. Biol.* 13, 131–144. doi: 10.1016/0022-5193(66)90013-0

Praveena, S. M., and Aris, A. Z. (2013). A Baseline Study of Tropical Coastal Water Quality in Port Dickson, Strait of Malacca, Malaysia. *Mar. Poll. Bull.* 67 (1-2), 196–199. doi: 10.1016/j.marpolbul.2012.11.037

Purnawanti, Y., Syahroni, N., and Mulyadi, Y. (2018). "Analysis of Static Structural of Ocean FARMITS Offshore Cage Due to Environmental Load," in *MATEC Web of Conferences*, 177 (EDP Sciences), 01023).

Quek, S. T., and Chua, C. Y. Y. (1990). A Study of the Benthic Soft-Bottom and Pelagic Communities of Sungei Buloh. *Coast. Livin. Resour. Singap.*, 1–8.

Radiarta, I. N., Albasri, H., and Sudradjat, A. (2011). Geographic Information System-Based Modeling and Analysis for Site Selection of Green Mussel, Perna Viridis, Mariculture in Lada Bay, Pandeglang, Banten Province. *Indon. Aquacult. J.* 6 (1), 83–90. doi: 10.15578/iaj.6.1.2011.83-90

Reimers, C. E., Alleau, Y., Bauer, J. E., Delaney, J., Girguis, P. R., Schrader, P. S., et al. (2013). Redox Effects on the Microbial Degradation of Refractory Organic Matter in Marine Sediments. *Geochim. Cosmochim. Acta* 121, 582–598. doi: 10.1016/j.gca.2013.08.004

Rochman, C. M., Manzano, C., Hentschel, B. T., Simonich, S. L. M., and Hoh, E. (2013). Polystyrene Plastic: A Source and Sink for Polycyclic Aromatic Hydrocarbons in the Marine Environment. *Environ. Sci. Technol.* 47 (24), 13976–13984. doi: 10.1021/es403605f

Sabbir, W., Rahman, M. Z., Halder, T., Khan, M. N., and Ray, S. (2018). Assessment of Heavy Metal Contamination in Fish Feed Available in Three Districts of South Western Region of Bangladesh. *Int. J. Fish. Aquat. Stud.* 6, 100–104.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., et al. (2014). The NCEP Climate Forecast System Version 2 *J. Clim.* 27 (6), 2185–2208. doi: 10.1175/JCLI-D-12-00823.1

Schönfeld, J., Golikova, E., Korsun, S., and Spezzaferri, S. (2013). The Helgoland Experiment–assessing the Influence of Methodologies on Recent Benthic Foraminiferal Assemblage Composition. *J. Micropalaeontol.* 32 (2), 161–182. doi: 10.1144/jmpaleo2012-022

Seiter, K., Hensen, C., Schröter, J., and Zabel, M. (2004). Organic Carbon Content in Surface Sediments—Defining Regional Provinces. *Deep. Sea. Res. Part I.: Oceanogr. Res. Paper.* 51 (12), 2001–2026. doi: 10.1016/j.dsr.2004.06.014

Shaari, H., Shazili, N. A. M., Abdullah, L. I., Abdullah, N. A., Husain, M. L., and Tahir, N. M. (2017). Geochemistry and Clay Minerals of Surface Sediments of Southwestern Johor, Malaysia. *Malays. J. Analytic. Sci.* 21, 312–322. doi: 10.17576/mjas-2017-2102-06

Shannon, C. E., and Weaver, W. (1949). The Mathematical Theory of Communication. vol. 1949. (Urbana: University of Illinois Press), 125p.

Shin, P. K. S. (1982). "Some Polychaetous Annelids From Hong Kong Waters," in *Proceedings of the first international marine biological workshop: the marine flora and fauna of Hong Kong and Southern China, Hong Kong.* 161–172.

Simpson, E. H. (1949). Measurement of Diversity. *Nature* 163, 688. doi: 10.1038/163688a0

Sivadas, S., Ingole, B., and Nanajkar, M. (2010). Benthic Polychaetes as Good Indicators of Anthropogenic Impact. *Indian J. Mar. Sci.* 39 (2), 201–211.

Sokołowski, A., Wołowicz, M., Asmus, H., Asmus, R., Carlier, A., Gasiunaité, Z., et al. (2012). Is Benthic Food Web Structure Related to Diversity of Marine Macrobenthic Communities? *Estua. Coast. Shelf. Sci.* 108, 76–86. doi: 10.1016/j.ecss.2011.11.011

Sterrer, W. (1986). Marine Fauna and Flora of Bermuda. A Systematic Guide to the Identification of Marine Organisms. New York: Wiley-Interscience.

Sun, Y., Xie, Z., Li, J., Xu, J., Chen, Z., and Naidu, R. (2006). Assessment of Toxicity of Heavy Metal Contaminated Soils by the Toxicity Characteristic Leaching Procedure. *Environ. Geochem. Health* 28 (1-2), 73–78. doi: 10.1007/s10653-005-9014-0

Szuster, W. B., and Albasri, H. (2010). Site Selection for Grouper Mariculture in Indonesia. *Int. J. Fish. Aquacult.* 2 (3), 87–92.

Taghon, G. L., Nowell, A. R., and Jumars, P. A. (1980). Induction of Suspension Feeding in Spionid Polychaetes by High Particulate Fluxes. *Science* 210 (4469), 562–564. doi: 10.1126/science.210.4469.562

Uddin, M., Alam, J. B., Khan, Z. H., Hasan, G. J., and Rahman, T. (2014). Two Dimensional Hydrodynamic Modelling of Northern Bay of Bengal Coastal Waters. *Comput. Wat. Energ. Environ. Eng.* 3, 140–51. doi: 10.4236/cweee.2014.34015

United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) (2018) *National Soil Survey Handbook, Title 430-VI* (Washington, D.C: United States Department of Agriculture-Natural Resources Conservation Service). Available at: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054242 (Accessed 22 October 2021).

US Environmental Protection Agency (1992). Method 1311, in *Toxicity Characteristic Leaching Procedure*, Washington, DC; US Environmental Protection Agency vol. 1311. , 1 – 35.

Wakeham, S. G., and Canuel, E. A. (2006). Degradation and Preservation of Organic Matter in Marine Sediments. *Mar. Organ. Matter.: Biomarke. Isotope. DNA*, 295–321. doi: 10.1007/698_2_009

Walkley, A., and Black, I. A. (1934). An Examination of the Degtjareff Method for Determining Soil Organic Matter, and a Proposed Modification of the Chromic Acid Titration Method. *Soil Sci.* 37 (1), 29–38. doi: 10.1097/00010694-193401000-00003

Wang, B., Waters, A. L., Sims, J. W., Fullmer, A., Ellison, S., and Hamann, M. T. (2013). Complex Marine Natural Products as Potential Epigenetic and Production Regulators of Antibiotics From a Marine Pseudomonas Aeruginosa. *Microbial. Ecol.* 65 (4), 1068–1075. doi: 10.1007/s00248-013-0213-4

Washburn, T., Rhodes, A. C., and Montagna, P. A. (2016). Benthic Taxa as Potential Indicators of a Deep-Sea Oil Spill. *Ecol. Indic.* 71, 587–597. doi: 10.1016/j.ecolind.2016.07.045

Wong, C. K., Pak, I. A. P., and Jiang Liu, X. (2013). Gill Damage to Juvenile Orange-Spotted Grouper E Pinephelus Coioides (H Amilton 1822) Following Exposure to Suspended Sediments. *Aquacult. Res.* 44 (11), 1685–1695. doi: 10.1111/j.1365-2109.2012.03173.x

Wong, J. W. C., and Yang, C. L. (1997). The Effect of pH and Redox Potential on the Release of Nutrients and Heavy Metals From a Contaminated Marine Sediment. *Toxicolog. Environ. Chem.* 62 (1-4), 1–10. doi: 10.1080/02772249709358493

Xu, Z., and Qin, H. (2020). Fluid-Structure Interactions of Cage Based Aquaculture: From Structures to Organisms. *Ocean. Eng.* 217, 107961. doi: 10.1016/j.oceaneng.2020.107961

Yang, X., Ramezani, R., Utne, I. B., Mosleh, A., and Lader, P. F. (2020). Operational Limits for Aquaculture Operations From a Risk and Safety Perspective. *Reliabil. Eng. Syst. Saf.* 204, 107208. doi: 10.1016/j.ress.2020.107208

Zabel, M., Dahmke, A., and Schulz, H. D. (1998). Regional Distribution of Diffusive Phosphate and Silicate Fluxes Through the Sediment–Water Interface: The Eastern South Atlantic. *Deep. Sea. Res. Part I.: Oceanogr. Res. Paper.* 45 (2-3), 277–300. doi: 10.1016/S0967-0637(97)00073-3

Zikra, M., Armono, H. D., and Pratama, F. (2020). Wave Modeling for the Establishment Potential Area of Offshore Aquaculture in Indonesia. *Fluids* 5 (4), 229. doi: 10.3390/fluids5040229

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Publisher's Note:** All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 28 July 2022
DOI 10.3389/fmars.2022.939533

Check for updates

OPEN ACCESS

EDITED BY
Francois Bastardie,
Technical University of Denmark,
Denmark

REVIEWED BY
Andrew M. Scheld,
College of William &Mary,
United States
Fikret Öndes,
Izmir Kâtip Çelebi University, Turkey

*CORRESPONDENCE
Pablo Pita,
pablo.pita@usc.es

SPECIALTY SECTION
This article was submitted to
Marine Fisheries, Aquaculture and
Living Resources,
a section of the journal
Frontiers in Marine Science

RECEIVED 09 May 2022
ACCEPTED 04 July 2022
PUBLISHED 28 July 2022

CITATION
Pita P, Ainsworth GB, Antelo M,
Gouveia L, Martínez-Escauriaza R,
Tubío A and Villasante S (2022)
Economic contribution and social
welfare of recreational charter boat
fisheries in the northeast Atlantic: The
cases of Galicia (Spain) and Madeira
archipelago (Portugal).
*Front. Mar. Sci.* 9:939533.
doi: 10.3389/fmars.2022.939533



# Economic contribution and social welfare of recreational charter boat fisheries in the northeast Atlantic: The cases of Galicia (Spain) and Madeira archipelago (Portugal)

Pablo Pita[1,2]*, Gillian B. Ainsworth[1], Manel Antelo[3], Lidia Gouveia[4], Roi Martínez-Escauriaza[5], Ana Tubío[1] and Sebastián Villasante[1,2]

[1]Cross-disciplinary Research Center in Environmental Technologies (CRETUS), Department of Applied Economics, University of Santiago de Compostela, Santiago de Compostela, Spain, [2]Faculty of Economics and Business Administration, University of Santiago de Compostela, Santiago de Compostela, Spain, [3]Faculty of Economics, University of Santiago de Compostela, Santiago de Compostela, Spain, [4]Direção de Serviços de Investigação – DSI, Direção Regional das Pescas (DRP-RAM), Funchal, Portugal, [5]OOM - Oceanic Observatory of Madeira, Agência Regional para o Desenvolvimento da Investigação Tecnologia e Inovação (ARDITI), Edifício Madeira Tecnopolo, Funchal, Portugal

Recreational charter boat fisheries provide alternative economic development to traditional commercial fisheries, especially to coastal communities in warm seas. Charter boat fishing has been little studied in temperate regions, and the factors that trigger its development and social contribution to fishing communities are unknown. We performed an economic analysis of recreational charter boat fisheries in the Eastern North Atlantic to assess their contribution to social welfare. We selected two case studies located in Galicia (NW Spain) and Madeira archipelago (Portugal). The two cases differ in the socioecological attributes in which recreational charter boat fishing is developed (e.g., relevance of commercial fishing, tourism, or targeted species), that were included in the assessment. Up to 7 charter fishing companies were identified in Galicia (10 boats) and 14 in Madeira (18 boats), and information on the costs and benefits of the activity were collected by a questionnaire answered by company managers and skippers. Charter boats in Galicia are operating throughout the year, and anglers mostly engage in bottom fishing targeting demersal predators like ballan wrasse (*Labrus bergylta*) and European seabass (*Dicentrarchus labrax*) that they retain. Despite the strong seasonality of the fishery in Madeira, focused on summers, the fishing effort is higher than in Galicia. On average, charter boats go fishing for 39.3 ± 41.5 (SD) fishing journeys and take 2 500 anglers on board per year in Galicia, while in Madeira they fish 63.7 ± 32.7 journeys and take 3 200 anglers on board. Anglers target in Madeira pelagic top predators like blue marlin (*Makaira nigricans*), or some tuna species, e.g., bigeye (*Thunnus* *obesus*), by trolling in a catch and release fishery. The economic balance of companies was more favorable in Madeira, with an average gross annual profit of € 28 883 ± 30 755, while economic yield in Galicia was € 4 444 ± 7 916. We also applied a travel cost method to assess the recreation demand of recreational fishing trips based on a questionnaire answered by 150 clients in Galicia and 55 in Madeira. We estimated the visitor surplus mean value to be € 1 385 per year in Galicia (95% confidence interval, $CI_{95\%}$= € 1 219 – € 1 550), and € 1 738 in Madeira ($CI_{95\%}$= € 1 433 – 2 043). The social annual recreation value of Galician fishery was worth € 3.4 Million, ranging between € 3.0 M and € 3.8 M, a value well below the annual economic impact generated by commercial fishing (€ 700 M). The recreation value of the charter boat fishery in Madeira, € 6.3 M, ranging between € 5.2 M and € 7.5 M, is comparable to the annual economic impact of commercial fishing, that contributes to the local economy with € 12 M.

KEYWORDS

**travel cost method (TCM), marine recreational fisheries, economic contribution, big game fishing, blue economy**

## Introduction

Marine recreational fishing is defined as an activity aimed at the capture of aquatic resources for leisure and/or personal consumption (Pawson et al., 2008; ICES, 2013). Marine recreational fisheries are very important worldwide, with millions of practitioners and involving a considerable economic contribution to the global economy (Cisneros-Montemayor and Sumaila, 2010; FAO, 2012; Arlinghaus et al., 2014). In Europe there are about 9 million recreational fishers operating along the coastlines that each year generate around 6 € billion in direct expenditures (Hyder et al., 2018).

Fishing for commercial purposes is rarely considered as a traditional component of marine recreational fishing (FAO, 2012). However, recreational charter boat fishing (where clients pay for the transfer on board to a suitable fishing spot, among other potential services, like fishing guides), is a thriving business widely distributed in warm coastal waters worldwide (Ditton and Stoll, 2000; Ditton and Stoll, 2003; Shiffman and Hammerschlag, 2014). There are also some relevant charter boat fisheries in temperate waters, e.g., in Australia (Lynch et al., 2020) and North America (Steinback, 1999; Lew and Larson, 2015). In Europe, charter boat fishing is a relatively important economic activity in the Mediterranean (Öndes et al., 2020) and in the Atlantic archipelagos of Canary, Madeira, and Azores islands (León et al., 2003; Vieira and Antunes, 2017; Diogo et al., 2020; Martinez-Escauriaza et al., 2021). However, in the Atlantic continental coast of Southern Europe there are relatively few companies dedicated to charter boat fishing.

Since marine recreational fisheries can have a significant impact on European fish stocks (Radford et al., 2018), recreational charter boat fishing in Europe is under some management restrictions designed to ensure the sustainability of fish stocks (Council of the European Union, 2008), and to a control regime aimed to reduce conflicts arising from the concurrent use of the same fishing areas and fish stocks with commercial fishing vessels (Council of the European Union, 2009).

On the other hand, the Parliament of the European Union (EU) encourages further development of recreational charter boat fishing initiatives to improve local economic development, particularly in rural areas and in outer regions of the EU (European Parliament, 2018). To facilitate this process, it is necessary to understand the mechanisms that encourage the creation of charter boat fishing opportunities and their resilience over time. However, and despite its socioeconomic importance, to date, charter boat fishing has been little studied in Europe, and the factors that trigger its potential business development are unknown for the most part.

The basic characterization of this activity is essential to understand the public policies necessary to favor its sustainable development, including support for the development of ancillary services needed for implementing new charter operations (Williams et al., 2020). To obtain key information on this activity in Europe, especially in areas where its development is most necessary due to a high dependence on marine resources and the scarcity of economic alternatives, we selected two recreational charter boat fisheries located in rural and outer European regions, namely in Galicia (Spain) and Madeira archipelago (Portugal) (Figure 1).

Galicia, located in the Atlantic coast of Spain, has a long and strong tradition in marine recreational fisheries, with 60 000 fishers and 4 000 boats engaged in this activity in coastal waters (Pita et al., 2018). The high primary productivity of its waters, enriched by a coastal upwelling (Bode et al., 2009), the great importance of its commercial fishing sector, with the largest European fleet and one of the largest in the world (STECF, 2017), and the concurrence of many other maritime activities, including maritime transport (Suárez de Vivero and Rodríguez Mateos, 2012), aquaculture (Pérez-Camacho et al., 1991) and growing tourism (Cortés-Jiménez, 2008), make up a very complex socio-ecological system. Many Galician coastal towns and villages are highly dependent on marine resources, especially commercial fisheries due to the lack of alternative jobs, this sector being of key relevance in terms of the Galician Gross Domestic Product (GDP) (Freire and García-Allut, 2000; Villasante et al., 2013; Villasante et al., 2016). Despite the multiple human impacts exerted on coastal ecosystems, there is potential for the development of sustainable charter boat fishing, which is currently little developed (Pita et al., 2017; Pita and Villasante, 2019).

The case of Madeira archipelago, in the Macaronesia region, is very different in terms of charter boat fishing, since it is one of the best-known places in the world to practice big game fishing (Martinez-Escauriaza et al., 2021). The Madeira archipelago consists of two main inhabited islands (Madeira, and Porto Santo), and two other uninhabited islands (Desertas and Selvagens islands), with some adjacent islets. The local population also shows a relevant participation in recreational angling (Martínez-Escauriaza et al., 2020). The main threat to the continuity of recreational charter boat fishing companies comes from the high tourist pressure that can reduce the benefits derived from the stay for visitors who value natural environments the most (Oliveira and Pereira, 2008; Almeida et al., 2014; Almeida, 2016), and the impacts of different fisheries along the wide distribution ranges of the targeted fish stocks, mostly large and vulnerable oceanic top predators (Martinez-Escauriaza et al., 2021).

In this study we characterized for the first time, and compared, the main attributes of recreational charter boat fisheries of Galicia and Madeira archipelago, including an estimation of their direct economic contribution by assessing the financial performance of the companies operating in the two studied regions. We also evaluated the recreation demand of both recreational charter fisheries by characterizing recreation fishing use as a benefit generating social welfare.

# Methods

## Interviews with company owners and skippers

In January 2019 we interviewed owners and skippers of recreational fishing charter boat companies of Spain (Galicia) and Portugal (Madeira archipelago) to collect key economic, social, and ecological information. To identify the charter boat companies operating in the two areas we followed a snowball model (Goodman, 1961), starting with a small group of initial informants, and expanding through their contacts and social

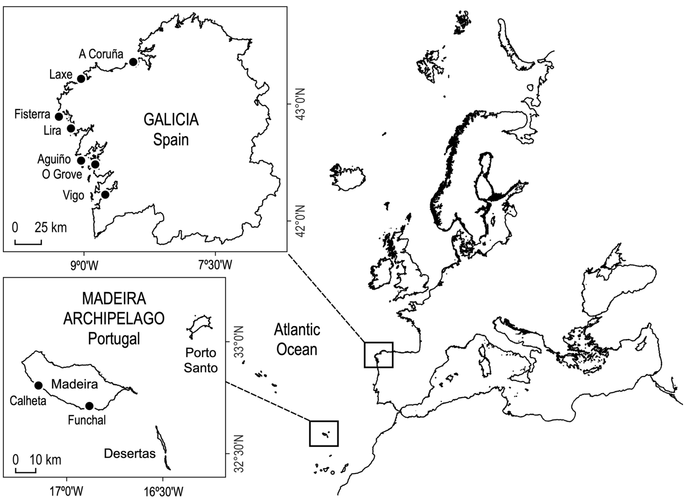



FIGURE 1
Map showing the location of Galicia (NW Spain) and Madeira archipelago (Portugal). We also show the marinas harboring recreational fishing charter boats.

networks. Although the supply of charter boat companies was simple to identify in Madeira, with the boats concentrated in a few marinas, in Galicia the offer was much more dispersed and less accessible to the uninitiated. For this reason, in our interviews we specifically asked respondents for the name and location of other companies, or contacts that could provide further references.

In-depth interviews were carried out to obtain information on the characteristics of the fishing boats (i.e., length, power, and onboard crew and clients), used fishing gears, seasonality, fishing effort (i.e., number of fishing journeys per year, number of hours per journey, and number of anglers per year), targeted species (including the ratio of retained and released fish), and on the economic performance of the companies, including costs and investments (i.e., in boat mooring, fuel and maintenance, fishing gears, food and drinks served onboard, insurances, licenses and taxes, staff salaries, publicity, and other), and also gross annual revenue. Company owners and boat skippers also reported the percentage of dedication of their boats to fishing in relation to other recreational activities with clients (e.g., tourist visits, wildlife watch, etc.) that was used to weigh the economic balance of the companies. To prevent recall bias in the responses, the company owners and skippers were asked to provide averages in their responses for the last three years.

## Client survey

Between February 2019 and October 2020, we performed interviews with clients of recreational fishing charter boat companies in Galicia and Madeira by using a structured questionnaire (Appendix 1). In Galicia, due to the dispersion of the companies along the coast, we provided the owners and skippers of the companies with paper copies of the questionnaire so that they could deliver them to the anglers. To facilitate responses, we also enabled an online form with the same questionnaire so that it could be answered by mobile phone, or computer. In Madeira, the owners and skippers preferred that the surveys be carried out by the researchers involved in this study. Thus, researchers visited the ports on a temporary random basis, including working and non-working days, through the annual fishing cycle.

Our survey aimed at collecting information on 1) visiting profile and frequency (number of fishing journeys during the current trip, number of fishing journeys during the previous year in the same, and in other locations, group size, type of accommodation, and daily expenses including accommodation, fishing fee and travel allowances); 2) characteristics of the fishing experience influencing the trip decision, e.g., reasonable cost, fish abundance or diversity, presence of particular fish species, natural or cultural values of the area, uncrowded, or close to my home, among other set of response options (the respondents could write their own option if it was not available in the list); 3) travel distance from home and transport modality; 4) other recreational activities practiced during the trip (number of days during the current trip); and 5) socioeconomic and demographic characteristics (age, gender, civil status, education level, number of people living in the household, number of underage people living in the household, job, working hours per month, revenue per month, residence country, and if they belonged to any fishing association or club). We also included an open-ended question about the Willingness To Pay of a tax ($WTP_t$) to support the ecological sustainability of the local environment.

The margin of error of the client survey, with a 95% confidence ($ME_{95\%}$), was obtained by following the equation:

$$ME_{95\,\%} = 1.96 \times \frac{\sigma}{\sqrt{n}} \quad [1]$$

Where σ represented the population standard deviation, and $n$ the sample size.

## Travel cost calculation

We estimated recreation value with the Travel Cost Method (TCM) (Clawson, 1959), a widely used revealed preference method of non-market valuation. Recreation value was estimated based on anglers' WTP obtained in an on-site survey, from which we estimated the Consumer Surplus (CS), i.e., the excess of social value for consumers over the price actually paid.

The Combined Travel Cost (CTC) was calculated as the sum of the individual travel cost ($t$C), the Opportunity Cost of Time (OCT), and Other Costs (OC) like fishing fee, accommodation, and food. The information on OC was provided by the anglers in the questionnaires. We then calculated $t$C as the product between the travelled distance in kilometers, also reported by the anglers, and the cost per kilometer, separately for anglers that arrived at the boat by walking (set to 0), by car or motorbike, and by national, European, and international flights. We multiplied by 2 the travelled distance to account for forward and return travels. In the case of cars and motorbikes, we estimated the cost per kilometer by using the official fiscal value. The travel cost both for Spain and Portugal was 0.19 € per km (Agencia Tributaria, 2022). In the case of flights, we used the information provided by one of the most popular flight search engines in Europe (Kayak España, 2017). For both Spanish and Portuguese national flights, we used 0.08 € per km, and for European and international flights we used 0.05 €/km, as estimated for flight searches conducted for round flights departing from Madrid and Barcelona in economic class between 2016 and 2017. In the case of multi-mode trips (e.g., anglers who traveled by plane and then by car, or other vehicle), we only considered the distance traveled by plane.

We finally used the product between the round trip time and 1/3 of the wage rate to estimate the OCT (Martínez-Espiñeira and Amoako-Tuffour, 2008; Roussel et al., 2016). The wage rate was approximated by the monthly income divided by the monthly hours of work (information that was provided in the questionnaires answered by the anglers). We calculated the trip time from the reported travel distance and assuming a driving average speed of 80 $km \cdot h^{-1}$ and a flying average speed of 600 $km \cdot h^{-1}$.

CS was derived from a recreation demand function obtained from the relationship between the number of fishing journeys undertaken to the site per year (outcome), and the price (the travel cost), among a set of other predictors, including the avidity for substitute sites, the number of days dedicated to practicing other leisure alternatives during the current fishing trip, group size, and visitors' socio-economic characteristics collected in the survey. We finally estimated the social annual value of fishing trips for the overall anglers' population to provide a first valuable reference.

## Econometric models

In the econometric models (fitted separately for each geographic area), $Y_i$ was the outcome representing the number of fishing journeys made by the respondent to the same destination during the past year (including the current trip) as a function of the Combined Travel Cost (CTC) and other independent predictors (see equation 2). Since the outcome is a nonnegative integer variable, linear models are unsuitable to estimate the recreation demand function (Shaw, 1988). We kept zero-truncation and potential overdispersion controlled by using more flexible negative binomial Generalized Additive Models (GAMs) (Hastie and Tibshirani, 1990). We used the maximum possible flexibility in the smoothed terms (i.e., the basis dimension) allowed by the available amount of data for each predictor, and cubic regression splines to avoid erratic behaviors of the fitted values at the extremes (Ferrini and Fezzi, 2012).

The demand function for the $_i$th visitor was:

$$Y_i = f[CTC_i, \quad p_i(N_i, \quad G_i, \quad A_i, \quad S_i)] \qquad [2]$$

Where $p_i(\cdot)$ represents the vector of other visitor-specific independent predictors. These predictors included $N_i$, which accounted for the number of days devoted to the practice of alternative leisure activities during the current fishing trip (following Roussel et al., 2016). $G_i$ included group size, i.e., the number of people traveling with the angler, in the fitted GAMs (including non-angling travelers). $A_i$ accounted for the willingness to choose alternative trips by including a factor variable (*avidity*) with 3 levels (*Low*, *Medium*, and *High*), based in the fishing days during the past year (that ranged between 0 and 80), and the country in which the fishing took place (national or foreign). Thus, *Low* included visitors that fished <40 days in their own country, *Medium* included visitors that fished ≥40 days in their own country, or <15 days in a foreign country, and *High* included visitors that fished ≥15 days in a foreign country. $S_i$ represents a set of visitors' socio-economic and demographic characteristics, including age, gender, civil status, education level, number of people living in the household, number of underage people living in the household, job, working hours per month, revenue per month, residence country, and level of associativism (i.e., membership to fishing associations or clubs) to account for fishing avidity.

Unadjusted GAMs were fitted first (i.e., considering the effect of only one predictor), whereas a backward stepwise selection procedure was followed to fit adjusted models (i.e., from saturated models to final models, removing non-significant variables at each step). The best models were selected based on the Akaike's information criterion (Akaike, 1973), deviance explained, and appropriate residual structure. Models with highly dispersed and anomalous distribution of residuals were discarded. All calculations were performed with the statistical software R ver. 4.0.2 (R Core Team, 2019).

We used the parameters of the final models to calculate recreation benefit, or welfare in terms of the CS anglers derive from trips to Galicia and Madeira. We calculated the average individual CS for access by computing the area under the demand curve (Haab and McConnell, 1996) by adaptive quadrature methods and obtained confidence intervals following a Monte Carlo simulation to solve the numerical integrals. We then multiplied the results by the predicted number of persons by trip to obtain the predicted annual CS for the average visitor group.

Finally, we used the expected number of anglers in Galicia and Madeira to obtain the overall social welfare for the two recreational charter boat fisheries. Since in our study we also assessed the economic performance of the charter boat companies operating in both recreational fisheries we did not consider their benefits as part of total social welfare. We computed the overall CS for the whole population of potential clients (P). Following Parsons (2003), the Population Surplus (PS) can be estimated as follows:

$$PS = CS \times P \qquad [3]$$

# Results

## Interviews with company owners and skippers

In Galicia we interviewed owners and skippers of 10 charter fishing boats belonging to 7 companies, which represents all the recreational fishing companies based in Galicia. In Madeira, we interviewed owners and skippers of 18 boats of a total of 20 currently operating in Madeira, belonging to the 14 companies, mainly based in Funchal and Calheta (Martinez-Escauriaza et al., 2021).

The average length of Galician charter fishing boats was 8.63 ± 2.96 (SD) m, while the boats operating in Madeira were bigger (9.57 ± 2.46 m on average). Average engine power and crew size were also higher in Madeira (465.0 ± 298.43 HP, and 2.06 ± 0.24 crew members, respectively) than in Galicia (246.0 ± 214.53 HP, and 1.2 ± 0.42 crew members) (Table 1).

The most popular fishing gear of recreational fishing onboard Galician boats was bottom fishing (65.2% of total annual fishing time), followed by spinning (29.2%), jigging (3.2%), and trolling (2.3%). In Madeira, fishing charter boats mainly engaged in trolling (74.4%), and to a lesser extent in bottom fishing (16.9%), and jigging (5.2%) (Table 1).

Recreational fishing charter boat companies in Galicia maintained their activity throughout most of the year, while in Madeira the activity showed a very strong seasonality, since fishing charter boats mainly operated during the summer months (Figure 2).

In Galicia, charter boat companies performed an average of 39.30 ± 41.45 fishing journeys per year, while charter boats in Madeira sailed out 63.69 ± 32.71 journeys. Average duration of the fishing trips was also lower in Galicia (5.0 ± 2.21 hours) than in Madeira (5.89 ± 1.02 hours). On average, Galician charter boat companies reported 246.0 ± 444.73 clients per year. Portuguese skippers and owners did not report the number of clients per year. Instead, they reported the number of clients per trip (3.18 ± 0.75). Therefore, since the annual number of fishing journeys performed in Madeira by the 18 charter boats was 1 019 trips, the total number of clients per year was estimated at 3 242 anglers (2 460 in Galicia).

Main targeted species in Galicia were ballan wrasse (*Labrus bergylta*), black seabream (*Spondyliosoma cantharus*), European seabass (*Dicentrarchus labrax*), pouting (*Trisopterus luscus*), and white seabream (*Diplodus sargus*). Other relevant species reported were Atlantic horse mackerel (*Trachurus trachurus*), Atlantic mackerel (*Scomber scombrus*), blackspot seabream (*Pagellus bogaraveo*), comber (*Serranus cabrilla*), common two-banded seabream (*D. vulgaris*), European conger (*Conger conger*), John dory (*Zeus faber*), Mediterranean rainbow wrasse (*Coris julis*), and pollack (*Pollachius pollachius*). Company managers also mentioned some catches of blue shark (*Prionace glauca*), and squids *Loligo* spp.

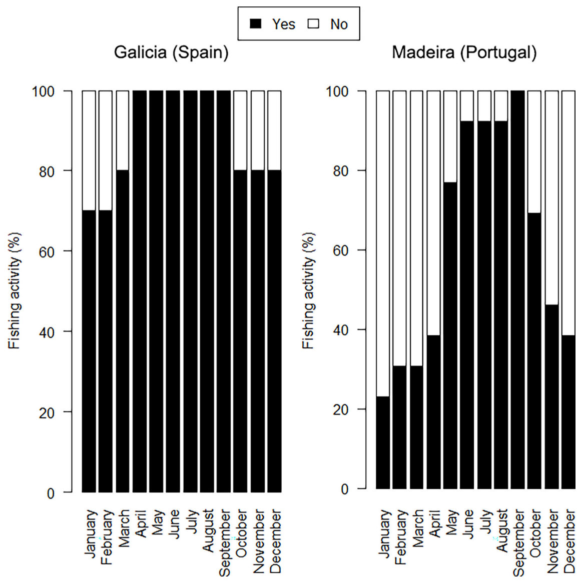



FIGURE 2
Annual cycle of activity of recreational fishing charter boat companies in Spain (Galicia) and Portugal (Madeira archipelago). The percentage of active boats in each month is shown.

In the archipelago of Madeira recreational anglers mainly targeted Atlantic white marlin (*Kajikia albida*), bigeye tuna (*Thunnus obesus*), blue marlin (*Makaira nigricans*), and wahoo (*Acanthocybium solandri*). Also, anglers onboard charter boats caught amberjacks (*Seriola* spp.), barred hogfish (*Bodianus scrofa*), barracudas (*Sphyraena* spp.), bluefish (*Pomatomus saltatrix*), dolphinfish (*Coryphaena* spp.), grey triggerfish (*Balistes capriscus*), island grouper (*Mycteroperca*

TABLE 1 Mean (and SD) characteristics of recreational fishing charter boats and percentage of annual fishing time using each gear in Spain (Galicia) and Portugal (Madeira archipelago).

| Attributes | | Spain (Galicia) | Portugal (Madeira) |
|---|---|---|---|
| Boat | | | |
| | Length (m) | 8.63 ± 2.99 | 9.57 ± 2.46 |
| | Power (HP) | 246.0 ± 214.53 | 465.0 ± 298.43 |
| | Crew (N) | 1.20 ± 0.42 | 2.06 ± 0.24 |
| Fishing gear | | | |
| | Bottom (%) | 65.20 ± 44.43 | 16.94 ± 19.64 |
| | Jigging (%) | 3.20 ± 7.83 | 5.17 ± 11.45 |
| | Spinning (%) | 29.20 ± 46.64 | 0.0 ± 0.0 |
| | Trawling (%) | 2.30 ± 3.09 | 74.44 ± 24.25 |
| | Other (%) | 0.10 ± 0.32 | 3.44 ± 9.67 |

*fusca*), pink dentex (*Dentex gibbosus*), red scorpionfish (*Scorpaena scrofa*), skipjack tuna (*Katsuwonus pelamis*), white seabream, and zebra seabream (*D. cervinus*). Portuguese skippers and company owners also reported some catches on pelagic sharks. Notably, while almost all catches were released in Madeira, only 25.8% ± 22.8% of the catches were released in Galicia.

## Economic performance of recreational fishing charter boat companies

Galician fishing charter boat companies spent on average € 9 799 ± 18 793 per year to carry out their activities, and in Madeira € 21 299 ± 5 216 (Figure 3). Although in general more costly in Madeira, the breakdown of the main company expenses was similar between the two regions. Expenses on publicity and mandatory operational licenses were the only costs that were higher in Galicia than in Madeira. The highest annual expenses and investments were made in the fishing boats, especially in fuel, but also in equipment and maintenance, and in moorings. Staff salaries were also a relevant cost for charter boat companies, followed by the purchase of fishing gears, different insurances, and food and beverages served on board (Table 2).

Average annual income was higher in Madeiran companies (€ 50 182 ± 35 971) than in Galician ones (€ 14 243 ± 26 709) (Figure 3). Therefore, and despite their higher costs, the economic balance of charter fishing companies was more favorable in Madeira, with an average gross annual profit of € 28 883 ± 30 755, while economic yield in Galicia was € 4 444 ± 7 916.

## Client survey

We performed 150 interviews with clients of Galician recreational fishing charter boat companies and 55 interviews with clients of Madeiran companies. Most clients fishing in Galician companies were from Spain (94.7% of total), although some anglers also traveled from other European countries (France, Germany, the Netherlands, Russia, and Switzerland), and from the USA (Table 3). On the contrary, only 16.3% of total clients of Madeiran companies were from Portugal. In fact, the UK was the most relevant country of origin (38.2%), although many anglers also arrived from other European countries (Finland, France, Germany, Hungary, Italy, Latvia, Luxembourg, Russia, Spain, Sweden, and Switzerland), and from Canada, Costa Rica, and the USA (Table 3).

Almost half of the anglers in both destinations (43.9%, and 45.5% in Galicia and Madeira, respectively) were between 35 and 49 years old. Most anglers were men (85.4% in Galicia, and 89.1% in Madeira), married or living with a partner (58.3% in Galicia, and 79.6% in Madeira), and did not belong to any fishing association or club (80.3% in Galicia, and 70.2% in Madeira). Most anglers in Madeira finished university studies (85.7%), while in Galicia they mostly finished vocational training (36.9%), or university studies (36.2%) (Table 3).

Mean household size was up to 3.04 ± 1.22 persons in the case of Galicia, and 2.16 ± 1.19 persons in the case of clients of Madeiran companies, while on average 0.79 ± 0.84 and 0.68 ± 0.87 were minors, respectively. Mean monthly income of visitors to Galicia was € 1 692 ± 492, while € 2 071 ± 646 in the case of the visitors to Madeira. Almost half of the anglers of the two countries were employees (48.6% in Galicia, and 50.0% in

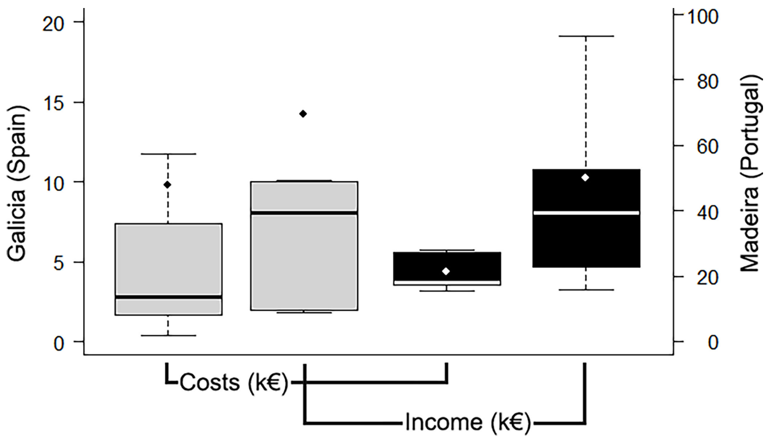



FIGURE 3
Annual expenses and income of companies engaged in commercial MRF in Spain (Galicia, in grey; left y-axis) and Portugal (Madeira archipelago, in black; right y-axis). The top and bottom sides of the boxes correspond to the first and third quartiles of the values, the vertical lines extend up to 1.5 times the interquartile range, the median is indicated with a horizontal line, and the mean with a black dot. Outliers are not shown for visualization purposes.

TABLE 2 Mean (and SD) annual expenses and investments (€) of recreational fishing charter boat companies operating in Spain (Galicia) and Portugal (Madeira archipelago).

| Expenses | Spain (Galicia) | Portugal (Madeira) |
|---|---|---|
| Boat equipment and maintenance | 539 ± 898 | 4 650 ± 5 111 |
| Boat fuel | 2 776 ± 6 492 | 5 194 ± 2 967 |
| Boat mooring | 517 ± 990 | 2 994 ± 2 320 |
| Fishing gears | 1 800 ± 1 568 | 708 ± 1 211 |
| Food and beverages | 92 ± 206 | 850 ± 961 |
| Insurances | 415 ± 429 | 1 396 ± 715 |
| Licenses | 280 ± 492 | 189 ± 6 |
| Publicity | 2 870 ± 8 717 | 965 ± 1 330 |
| Salaries | 4 947.53 ± 3 615.48 | 12 500.0 ± 0.0 |

Madeira), who on average worked 8.0 ± 1.26 hours per day in the case of Galicia, and 8.3 ± 0.44 hours per day in the case of Madeira. Self-employed and businessmen were the other occupations of fishers of working age, while the access of students and retirees was much lower (Table 3).

The natural value of the environment was the most valuable attribute of the fishing trip in the case of clients of Galician companies (45.0% of respondents), followed by the price (28.6%), and the presence of certain fish species (23.6%). Clients of Madeiran boats primarily valued the complete experience (36.5%), followed by the presence of certain fish species (23.1%) (Table 3).

Mean number of fishing journeys while on their current trip was 1.81 ± 2.71 days in Galicia, and 1.91 ± 1.69 days in Madeira. The previous year, these anglers fishing in Galicia spent another 0.84 ± 3.12 days in the same location, 1.11 ± 2.90 days in the case of Madeira. The anglers interviewed in Galicia spent another 3.39 ± 8.94 days in other fishing places, 7.38 ± 12.76 days in the case of clients of Madeiran companies. Moreover, the visitors also spent on average 0.52 ± 1.27 days in Galicia, and 2.73 ± 3.31 days in Madeira in alternative recreational activities (Table 3).

Mean group size was similar in both locations (2.69 ± 0.93 in Galicia, and 2.36 ± 1.09 in Madeira). Visitors to Galicia traveled on average 335.55 ± 566.19 km to arrive at the fishing location, while visitors to Madeira traveled 2 800 ± 1 880 km. According to the distances and the isolated nature of the Madeira archipelago, cars were the main transport in the case of Galicia (93.3% of total), while plane (87.3%) was the main transport used to arrive in Madeira. In the same way, most clients of Galician companies did not sleep away from home (59.3%), while up to 76.4% of anglers traveling to Madeira stayed in a hotel or in a vacation rental (Table 3).

All travel costs were higher in Madeira than in Galicia: mean individual travel cost (*t*C) was € 100.42 ± 140.38 in Galicia and € 282.63 ± 185.56 in Madeira; mean Opportunity Cost of Time (OCT) was € 21.39 ± 33.54 and € 36.20 ± 25.47, respectively; and mean daily costs (OC), that included fishing fees, accommodation, and food was € 127.97 ± 128.01 and € 156.18 ± 101.11, respectively. Consequently, mean individual CTC in Madeira, i.e., the sum of *t*C, OCT, and OC (€ 475.01 ± 247.66), almost doubled the CTC in Galicia (€ 249.77 ± 214.83). However, Willingness To Pay of an ecological tax ($WTP_t$) to support the local environment was a bit higher in the case of visitors to Galicia (€ 7.40 ± 12.72), than that of visitors of Madeira (€ 3.05 ± 6.88) (Table 3).

## Association between fishing journeys, willingness to pay and other predictors

In the econometric models the outcome was the number of fishing journeys performed by the respondent angler to the same location during the past year (including the current trip). Although the main predictor was expected to be the CTC (as a proxy of the WTP), we included other independent variables, like the number of days practicing alternative leisure activities, the willingness to choose alternative trips, the group size, and socio-economic characteristics.

The CTC had a significative effect in the number of fishing journeys in Galicia and Madeira, both in the unadjusted (p= 0.024; $R^2$ = 0.005, and p= 0.041; $R^2$ = 0.047, respectively), and in the adjusted GAMs (p= 0.024; $R^2$ = 0.005, and p= 0.025; $R^2$ = 0.230, respectively) (Table 4). The CTC had a clearer negative effect on the number of fishing journeys in Galicia than in Madeira, where the demand function was not decreasing at the right tail of the CTC values (Figure 4).

The different relative importance given by the anglers to the journeys dedicated to alternative recreational activities could partly explain the differences in the demand functions of Galicia and Madeira, affecting the expected negative slope of the demand function in the case of Madeira. To assess this, we fitted GAMs that modeled the association between the journeys devoted to fishing and alternative activities on the full duration of the trips, i.e., including days not dedicated to angling (Table 4). We found that although fishing journeys always exceed those dedicated to other activities in Galicia, after 10

TABLE 3 Descriptive characteristics of the fishing activity valued by clients of recreational fishing charter boat companies in Spain (Galicia) and Portugal (Madeira archipelago).

| Attributes | | Spain (Galicia) | Portugal (Madeira) |
|---|---|---|---|
| **Selected features** | | **% (N=140)** | **% (N=52)** |
| | Companionship | 2.9 | 0.0 |
| | Crew friendliness | 3.6 | 7.7 |
| | Cultural values of the area | 15.0 | 0.0 |
| | Fish abundance | 18.6 | 0.0 |
| | Fish diversity | 20.0 | 0.0 |
| | Low crowding | 5.7 | 0.0 |
| | Natural values of the area | 45.0 | 7.7 |
| | Presence of particular fish species | 23.6 | 23.1 |
| | Price | 28.6 | 0.0 |
| | Proximity | 19.3 | 7.7 |
| | Trophy fish | 0.0 | 1.9 |
| | Whole experience | 4.3 | 36.5 |
| Fishing journeys | | Mean (N=150) | Mean (N=55) |
| | | 1.8 ± 2.7 | 1.9 ± 1.7 |
| Past fishing journeys | | Mean (N=150) | Mean (N=55) |
| | | 3.4 ± 9.0 | 7.38 ± 12.8 |
| Past fishing journeys same place | | Mean (N=150) | Mean (N=55) |
| | | 0.8 ± 3.1 | 1.1 ± 2.9 |
| Activity journeys | | Mean (N=150) | Mean (N=55) |
| | | 0.5 ± 1.3 | 2.7 ± 3.3 |
| Travel distance (km) | | Mean (N=150) | Mean (N=55) |
| | | 335.6 ± 566.2 | 2 800.2 ± 1 880.0 |
| Transport | | % (N=150) | % (N=55) |
| | Walking | 0.0 | 3.6 |
| | Motorbike | 0.7 | 0.0 |
| | Car | 93.3 | 9.1 |
| | National plane | 2.0 | 3.6 |
| | European plane | 3.3 | 76.4 |
| | International plane | 0.7 | 7.3 |
| Group size | | Mean (N=150) | Mean (N=55) |
| | | 2.7 ± 0.9 | 2.4 ± 1.1 |
| Accommodation | | % (N=150) | % (N=55) |
| | Home | 59.3 | 12.7 |
| | Family/friend | 2.0 | 10.9 |
| | Car | 1.3 | 0.0 |
| | Motorhome | 0.7 | 0.0 |
| | Camping | 1.3 | 0.0 |
| | Vacation rental | 12.7 | 14.5 |
| | Hotel | 22.7 | 61.8 |
| Daily expenses (€) | | Mean (N=150) | Mean (N=55) |
| | | 128.0 ± 128.0 | 156.2 ± 101.1 |
| $WTP_t$ (€) | | Mean (N=93) | Mean (N=22) |
| | | 7.4 ± 12.7 | 3.1 ± 6.9 |
| Age | | % (N=148) | % (N=55) |
| | 18-24 | 4.1 | 0.0 |

*(Continued)*

TABLE 3 Continued

| Attributes | | Spain (Galicia) | Portugal (Madeira) |
|---|---|---|---|
| **Selected features** | | **% (N=140)** | **% (N=52)** |
| | 25-34 | 25.0 | 7.3 |
| | 35-49 | 43.9 | 45.5 |
| | 50-64 | 23.0 | 34.5 |
| | >65 | 4.1 | 12.7 |
| Gender | | % (N=144) | % (N=55) |
| | Men | 85.4 | 89.1 |
| | Women | 14.6 | 10.9 |
| Civil status | | % (N=148) | % (N=54) |
| | Single | 34.0 | 13.0 |
| | Married or living with a partner | 58.3 | 79.6 |
| | Divorced or separated | 7.6 | 7.4 |
| Education | | % (N=141) | % (N=49) |
| | Primary | 6.4 | 4.1 |
| | Secondary | 20.6 | 4.1 |
| | Vocational training | 36.9 | 6.1 |
| | University | 36.2 | 85.7 |
| Household members | | Mean (N=150) | Mean (N=55) |
| | | 3.0 ± 1.2 | 2.2 ± 1.2 |
| Underage | | Mean (N=150) | Mean (N=55) |
| | | 0.8 ± 0.9 | 0.7 ± 0.9 |
| Occupation | | % (N=146) | % (N=48) |
| | Student | 4.8 | 0.0 |
| | Employee | 48.6 | 50.0 |
| | Public employee | 0.7 | 6.3 |
| | Self-employed | 23.3 | 10.4 |
| | Businessman | 13.7 | 18.8 |
| | Retired | 8.9 | 14.6 |
| Working hours per day | | Mean (N=150) | Mean (N=55) |
| | | 8.0 ± 1.3 | 8.3 ± 0.4 |
| Monthly family income (€) | | Mean (N=150) | Mean (N=55) |
| | | 1 692.0 ± 491.6 | 2 070.9 ± 645.7 |
| Association | | % (N=142) | % (N=47) |
| | No | 80.3 | 70.2 |
| | Yes | 19.7 | 29.8 |
| Country | | % (N=149) | % (N=55) |
| | Canada | 0.0 | 1.8 |
| | Costa Rica | 0.0 | 1.8 |
| | Finland | 0.0 | 7.3 |
| | France | 0.7 | 10.9 |
| | Germany | 2.0 | 3.6 |
| | Hungary | 0.0 | 1.8 |
| | Italy | 0.0 | 3.6 |
| | Latvia | 0.0 | 1.8 |
| | Luxembourg | 0.0 | 1.8 |
| | Netherlands | 0.7 | 0.0 |
| | Portugal | 0.0 | 16.4 |

*(Continued)*

TABLE 3 Continued

| Attributes | | Spain (Galicia) | Portugal (Madeira) |
|---|---|---|---|
| **Selected features** | | **% (N=140)** | **% (N=52)** |
| | Russia | 0.7 | 1.8 |
| | Spain | 94.6 | 1.8 |
| | Sweden | 0.0 | 1.8 |
| | Switzerland | 0.7 | 1.8 |
| | UK | 0.0 | 38.2 |
| | USA | 0.7 | 3.6 |

We also show the mean (and SD) number of fishing journeys performed during the current recreational trip, the mean number of fishing journeys performed during the past year, the mean number of fishing journeys performed during the past year in the same location, the mean number of journeys devoted to alternative recreational activities during the current recreational trip, the mean distance traveled from home, the main transport used, the mean total group size, the type of accommodation during the stay, the mean daily expenses, and mean Willingness To Pay of an ecological tax ($WTP_t$) to support the local environment. In addition, we show basic demographics.

days of vacation the time dedicated to alternatives to angling was greatly reduced. On the contrary, in Madeira, after 8 days of vacation, alternative recreational activities became more important than fishing (Figure 5). These results suggest that trips to Madeira have a higher multi-purpose character than in the Galician case, which could have affected the expected negative relationship between the CTC and the fishing days estimated by the demand function in Madeira, especially in the case of higher travel costs (as shown in the Figure 4).

In the case of Galicia, an increase in the number of minors living in the visitor household (p= 0.002; $R^2 = 0.030$), and membership to a fishing association or club (p< 0.001; $R^2 = 0.050$) had a positive effect on the number of fishing journeys predicted in the unadjusted models. In the adjusted model only the number of underage members of the family was retained (p< 0.001) (Table 4).

In Madeira, the bigger the visitor group size (p= 0.034; $R^2 = 0.026$) the lower the number of fishing journeys predicted in the unadjusted model, while membership of a fishing association or club (p= 0.001; $R^2 = 0.186$) had a positive effect. Only membership of a fishing association or club (p= 0.004) was retained in the adjusted model (Table 4).

## Consumers' surplus

We estimated the individual CS mean value (as a reliable proxy for individual value) to be € 1 385 per year in Galicia (95% confidence interval, $CI_{95\%}$= € 1 219 – € 1 550), and € 1 738 in Madeira ($CI_{95\%}$= € 1 433 – € 2 043) (Figure 6).

The yearly mean CS per visit in Galicia could then be set to € 3 729, ranging from € 3 103 to € 4 404, since the observed size of the average group was 2.69 people ($CI_{95\%}$= 2.55 people – 2.84 people). In Madeira, the average fishing group was 2.36 people ($CI_{95\%}$= 2.07 – 2.65), for what the yearly mean CS per visit was € 4 108, ranging from € 2 973 to € 5 420.

To estimate the yearly social welfare of the recreational charter fishery in Galicia, i.e., the Population Surplus (PS), we

TABLE 4 Outputs of the GAMs fitted on the number of angling days and number of vacation days (including non-angling days, devoted to alternative recreational activities).

| Country | Outcome | Predictor | P value | Deviance explained (%) | AIC |
|---|---|---|---|---|---|
| Spain | Angling days | CTC (WTP) | 0.0242 | 3.5 | 636 |
| | Angling days | Underage | 0.0020 | 11.0 | 460 |
| | Angling days | Association: No *vs.* Yes | <0.0001 | 13.3 | 624 |
| | Angling days | CTC (WTP) | 0.0051 | 21.6 | 453 |
| | | Underage | 0.0004 | | |
| | Vacation days | Angling days*Non-angling days | <0.0001 | 98.8 | 392 |
| Portugal | Angling days | CTC (WTP) | 0.0408 | 10.6 | 245 |
| | Angling days | Group size | 0.0344 | 9.7 | 245 |
| | Angling days | Association: No *vs.* Yes | <0.0001 | 32.8 | 232 |
| | Angling days | CTC (WTP) | 0.0245 | 42.1 | 229 |
| | | Association: No *vs.* Yes | 0.0040 | | |
| | Vacation days | Angling days*Non-angling days | <0.0001 | 98.9 | 192 |

We show the p-values for the different significant predictors of unadjusted (i.e., considering the effect of only one predictor) and of final adjusted models (i.e., including more than one predictor), and the values of deviance explained, and Akaike's information criterion (AIC) (*stands for interaction term; CTC stands for Combined Travel Cost; WTP stands for Willingness To Pay; and "association" indicate anglers' membership to a recreational fishing association).

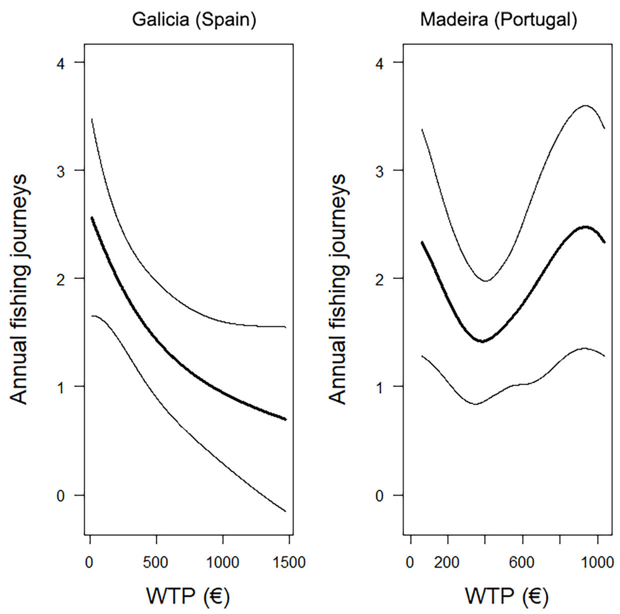



FIGURE 4
Partial effect of the WTP (as a function of the travel cost) on the number of fishing journeys to Spain (Galicia) and Portugal (Madeira). It is shown the prediction (dark lines), and their 95% confidence interval (thin lines) estimated by the adjusted GAMs.

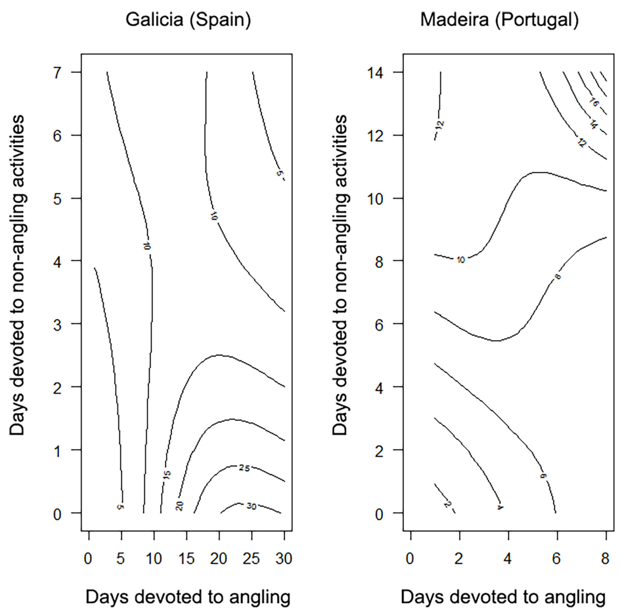



FIGURE 5
Partial effect of the interaction between the days devoted to angling and the days devoted to other recreational activities on the total days of the vacation in Spain (Galicia) and Portugal (Madeira). It shows the predictions of the total vacation duration estimated by a GAM.

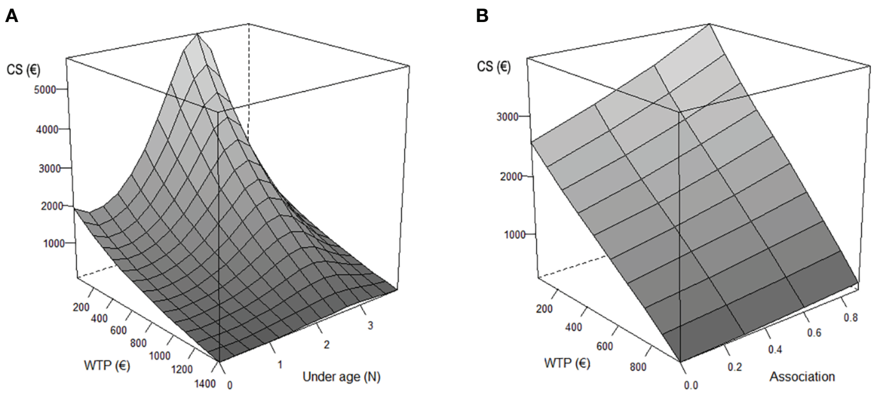



FIGURE 6
Consumer surplus (CS) per person and year estimated from fishing charter boat trips to Spain (Galicia; **A**) and Portugal (Madeira archipelago; **B**) by bidimensional GAMs. The covariate Willingness To Pay (WTP) was a function of the full individual travel cost. In the case of Galicia, the other covariate was the number of underage people in the household, while in Madeira we used a dummy numeric variable to include the membership (1) or not (0) to a recreational fishing association (see in Table 4 the outputs of the GAMs fitted on the fishing journeys).

used equation [3]. Since Spanish managers and boat skippers reported the number of clients per year in each of the charter boats, we obtained an estimate of total clients per year in Galicia (P = 2 460 anglers). This figure was then multiplied by the mean CS, to obtain a yearly recreation social welfare of € 3.41 Million in Galicia, ranging between € 3.0 M and € 3.81 M.

In Madeira we estimated that the 18 charter boats had 3 242 clients per year. However, the total number of fishing boats in Madeira was 20 (Martinez-Escauriaza et al., 2021). Therefore, we assumed that the two charter boats that were not included in our survey carried out the same average number of clients per trip that the assessed 18 boats (3.18 ± 0.75), so the total number of clients per year in Madeira was estimated at 3 648 anglers. Applying the equation [3], the yearly social welfare of the recreational charter fishery of Madeira was € 6.34 M, ranging between € 5.23 M and € 7.45 M.

## Discussion

In our study we showed that the direct contribution to local economies derived from the operation of the recreational fishing charter boat companies is important, especially in Madeira. We believe that our results provide a first useful baseline, e.g., for the formulation of public policies aimed at increasing the resilience of coastal populations highly dependent on marine resources in remote and rural areas, as demanded by the EU Parliament (European Parliament, 2018). Managed in a sustainable way, we demonstrated that recreational charter boat fisheries can provide viable economic alternatives to commercial fishing, being possible to further increase its development in the European continental coasts.

As a general reference, commercial fishing generates some € 700 M annually in Galicia, which represents just over 1% of GDP (Surís-Regueiro and Santiago, 2014), while in Madeira, commercial fishing accounts for 0.7% of the GDP, which is about € 12 M annually (Vallerani et al., 2017). Gross output, representing the annual revenue from charter boats, estimated by extrapolating the mean annual turnover by company to the total number of companies, was of € 99 700 in Galicia and € 702 550 in Madeira. The relatively low figure that we obtained in Galicia, compared to gross outputs exceeding one million euros in similar charter boat fisheries (in terms of covered area, ambient conditions, visitation, and targeted species) of Southern England (Williams et al., 2020), indicates that it is possible to increase the economic contribution of this sector, helped by the low seasonality of the fishery. The similarity between the social welfare we derived from the charter boat fisheries in Galicia and Madeira (€ 3 M, and € 6 M, respectively) also points in this direction.

In our client survey we sampled up to 6.1% of the anglers fishing from charter boat companies operating each year in Galicia. Therefore, applying the equation [1] our survey had a potential margin of error of 7.8%. The margin of error was 13.1% in the case of the Madeiran survey (we interviewed 1.5% of charter boat anglers). Although our sampling error was moderate, we cannot rule out problems of representativeness of our sample with respect to the total population of anglers, that may ultimately affect the estimates of aggregated social welfare of the two recreational fisheries. It is possible, for example, that we have interviewed avid anglers more frequently (i.e., those who use the services of the companies the most), and that their answers differ in some way from those of other groups of anglers. On the other hand, we expect that the broad temporal and spatial coverage of our sampling has contributed to moderating this bias. Moreover, some sample biases (i.e., recall, non-response, and declaration) inherent to recreation data and on-site surveys could also affect our estimates (see Pollock et al., 1994) for an overview of bias affecting recreational fishing surveys). Also, the relatively low values of explained deviation in the GAMs could indicate that part of the variability has not been fully explained by the predictors evaluated. Furthermore, in our client survey we did not obtain disaggregated information on the expenses of the anglers. Although fishing fees are relatively small compared with the full cost of the trip, these should have been excluded from the calculation of CS. Therefore, the obtained welfare measures should be seen as a reasonable estimate for the full benefit derived by anglers.

We have not found significant differences according to the gender of the anglers in the models we used to estimate recreation value with the TCM. However, it would be possible to increase the social benefits provided by recreational fishing charter boat companies by reducing the important gender gap in this activity (Pita et al., 2020a). Companies exploring this possibility should highlight the social aspect of the activity, little valued by the anglers in our survey, which included mostly men. Increased female participation in angling would be especially feasible in Madeira, due to the multi-purpose nature of the trip (in fact, anglers visiting Madeira valued above all the overall experience of their trip), its longer duration, and the larger size of the visiting group. The development of marketing strategies that promote trips combining angling experiences and other family leisure activities could be good to increase trips to Madeira.

The contribution of companies to nature conservation could strategically increase the value and participation of anglers, especially in the case of Galician companies, since this was one of the best valued attributes in our survey, as well as in other recreational fisheries in the Northeast Atlantic (González et al., 2021). Indeed, the anglers in Galician companies showed higher $WTP_t$ to help conservation measures. Furthermore, the carbon footprint of the trips made to Galicia was lower than that of those made to Madeira, both because of the shorter distance traveled by the anglers and because of the use of less polluting means of transport, mainly private cars, instead of airplanes. The development of green strategies by charter boat companies and/or public institutions, which include the ecological restoration of the impacts produced during angling, could be well received by clients.

Another strategy that could increase numbers and length of anglers' trips to Galicia could be developed around promoting accommodation in the towns near the base port of the boat, since many of the clients spent the night back in their homes. For this, the support of public and private institutions is necessary to improve the infrastructure of basic tourist services in some of the areas of Galicia, with important deficiencies derived mainly from the high seasonality of tourism to Galicia, mainly focused on the summer (Garín-Muñoz, 2009). The high importance of the cost of the trip for the clients of the Galician charter boat companies suggests that economically adjusted packages would need to be offered.

The high dependence of the Madeiran charter boat fishery on big game fishing is a potential weakness in the face of the effects of environmental changes on the abundance and catchability of these species, e.g., because of the impact of climate change that could alter distribution ranges and/or affect the environmental conditions that anglers need to fish (Martinez-Escauriaza et al., 2021). In fact, the presence of "billfish" and other big predators was highly valued by the interviewed anglers in Madeira, which was found to be a key component of satisfaction, closely linked to loyalty to the fishing site in another recreational fishery in Macaronesia (González et al., 2021). Therefore, basing this fishery on catch and release seems a correct strategy in the long term. However, concerns about the impacts of both commercial and recreational fisheries on main targeted stocks (Restrepo et al., 2003; Maguire et al., 2006; Ehrhardt and Fitchett, 2016), make it necessary to assess the impacts of this charter boat fishery, specifically on post-release mortality. Increasing the percentage of released fish in the case of Galicia should be contemplated, especially if there is an increase in recreational fishing mortality, due to the current high human pressures on Galician marine ecosystems and fish stocks (Pita and Freire, 2014; Pita et al., 2020b), and the concerning state of conservation of some stocks of the most targeted species, such as European seabass (Council of the European Union, 2018).

## Conclusions

The social and economic importance of charter fisheries, both in Galicia and Madeira, demonstrated in our study, should be duly recognized by public European administrations and economic, coastal and resource management at different levels. The development of programs and agreements with private companies to provide the basic services necessary to promote sustainable angling tourism is key to meet public directives aiming to foster economic and social development in rural areas and in outer regions of the EU (European Parliament, 2018). For instance, while Funchal, the capital of Madeira, offers different recreational alternatives to visitors, in Calheta (the other port in the islands harboring recreational charter boats) visitors' main attraction is the marina with recreational fishing operators, fueling the arrival of tourists to this island and improving the local economy.

It would also be necessary to review the current EU fishing regulations, which contemplates the allocation of quotas to recreational fishing in a very limited way, leaving to the power of the member states the possibility of allocating part of the assigned quota to the recreational sector, including recreational charter boat operators. Current EU legislation only requires countries to provide data on the catches obtained in recreational fisheries (e.g., European Commission, 2016), but does not explicitly recognize the right of access by citizens or recreational charter boats.

This acknowledgment of fishing opportunities, in similar terms to that of commercial fishing fleets, should not necessarily drive an increase in total fishing mortality. In this sense, the further development of catch and release in charter boat fishing (Holland et al., 1998) could favor the socioeconomic development of this activity and avoid conflicts over access to resources with commercial fisheries. This is particularly important for regions, such as Galicia, highly dependent on fishing, and in general to avoid undesired local shortages of fishery products and the provision of other ecosystem services (see, e.g., Brown, 2016; Voyer et al., 2017).

## Data availability statement

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

## Ethics Statement

Ethical review and approval were not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## Author contributions

All co-authors contributed to the elaboration of the manuscript. All authors contributed to the article and approved the submitted version.

## Funding

This work was funded by the Xunta de Galicia (RECREGES II project under Grant ED481B2018/017) 2020 research and innovation program (grant agreement No 101002784). PP, GA, MA, AT, and SV acknowledge support by Grupo de Referencia Competitiva GI-2060 AEMI, under Grant ED431C2019/11. PP, MA, and SV acknowledge support of the project Grupo de Trabajo Sobre Pesca Marítima Recreativa en España, funded by the Fundación Biodiversidad of the Spanish Ministerio Para la Transición Ecológica y el Reto Demográfico, co-funded by the European Maritime and Fisheries Fund. RM-E was financially supported by the Oceanic Observatory of Madeira Project (M1420-01-0145-FEDER-000001-Observatório Oceânico da Madeira-OOM).

## Acknowledgments

We appreciate the involvement of the owners, skippers, and clients of recreational charter fishing companies in Portugal and Spain who voluntarily shared their knowledge during this study.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.939533/full#supplementary-material

## References

Agencia Tributaria (2022) *Asignaciones para gastos de locomoción*. Available at: https://sede.agenciatributaria.gob.es/Sede/manuales/ejercicio-2018/modelo-100/7-cumplimentacion-irpf/7_2-rendimientos-trabajo-personal/7_2_1-rendimientos-integros/7_2_1_2-dietas-gastos-viaje/asignaciones-gastos-locomocion.html (Accessed May 22, 2022).

Akaike, H. (1973). Information theory and an extension of the maximum likelihood principle. In *Second International Symposium of Information Theory* B. N. Petrov and F. Csaki ed. (Tsahkadsor, Armenia, USSR: Akademiai Kiado), 267–81.

Almeida, A. (2016). Modelling tourism demand in Madeira since 1946: and historical overview based on a time series approach. *J. Spat. Organ. Dyn.* 4, 145–156. doi: 10.1016/j.scitotenv.2016.03.035

Almeida, A., Correia, A., and Pimpão, A. (2014). Segmentation by benefits sought: the case of rural tourism in Madeira. *Curr. Issues Tour.* 17, 813–831. doi: 10.1080/13683500.2013.768605

Arlinghaus, R., Tillner, R., and Bork, M. (2014). Explaining participation rates in recreational fishing across industrialised countries. *Fish. Manage. Ecol.* 22, 45–55. doi: 10.1111/fme.12075

Bode, A., Alvarez-Ossorio, M. T., Cabanas, J. M., Miranda, A., and Varela, M. (2009). Recent trends in plankton and upwelling intensity off Galicia (NW Spain). *Prog. Oceanogr.* 83, 342–350. doi: 10.1016/j.pocean.2009.07.025

Brown, C. J. (2016). Social, economic and environmental effects of closing commercial fisheries to enhance recreational fishing. *Mar. Policy* 73, 204–209. doi: 10.1016/j.marpol.2016.08.010

Cisneros-Montemayor, A. M., and Sumaila, U. R. (2010). A global estimate of benefits from ecosystem-based marine recreation: potential impacts and implications for management. *J. Bioeconomics.* 12, 245–268. doi: 10.1007/s10818-010-9092-7

Clawson, M. (1959). Methods of measuring the demand for and value of outdoor recreation. *Res. Future* 10.

Cortés-Jiménez, I. (2008). Which type of tourism matters to the regional economic growth? the cases of Spain and Italy. *Int. J. Tour. Res.* 10, 127–139. doi: 10.1002/jtr.646

Council of the European Union (2008). *Council regulation (EC) no 199/2008 of 25 February 2008 concerning the establishment of a community framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the common fisheries policy* (Brussels, Belgium: Official Journal of the European Union).

Council of the European Union (2009). *Council regulation (EC) no 1224/2009 establishing a community control system for ensuring compliance with the rules of the common fisheries policy* (Brussels, Belgium: Official Journal of the European Union).

Council of the European Union (2018). *Council regulation (EU) 2018/1308 of 28 September 2018 amending regulation (EU) 2018/120 as regards fishing opportunities for European seabass* (Brussels, Belgium: Official Journal of the European Union).

Diogo, H., Veiga, P., Pita, C., Sousa, A., Lima, D., Pereira, J. G., et al. (2020). Marine recreational fishing in Portugal: Current knowledge, challenges, and future perspectives. *Rev. Fish. Sci. Aquac.* 28, 536–60. doi: 10.1080/23308249.2020.1777083

Ditton, R. B., and Stoll, J. R. (2000). A socio-economic review of recreational billfish fisheries. In *Proceedings of the 51 st Gulf and Caribbean Fisheries Institute* L. R. Creswell ed. (US Virgin Islands: St. Croix), 666–81.

Ditton, R. B., and Stoll, J. R. (2003). Social and economic perspective on recreational billfish fisheries. *Mar. Freshw. Res.* 54, 545–554. doi: 10.1071/MF01279

Ehrhardt, N., and Fitchett, M. (2016). *Status of billfish resources and billfish fisheries in the western central Atlantic* (Bridgetown, Barbados: Food and Agriculture Organization of the United Nations).

European Commission (2016). "Commission implementing decision (EU) 2016/1251 of 12 July 2016 adopting a multiannual union programme for the collection, management and use of data in the fisheries and aquaculture sectors for the period 2017-2019," (Brussels, Belgium: Official Journal of the European Union).

European Parliament (2018). *European Parliament resolution of 12 June 2018 on the state of play of recreational fisheries in the European union* (Brussels, Belgium: Official Journal of the European Union).

FAO (2012). *Recreational fisheries* (Rome: FAO).

Ferrini, S., and Fezzi, C. (2012). Generalized additive models for nonmarket valuation *via* revealed or stated preference methods. *Land. Econ.* 88, 782–802. doi: 10.3368/le.88.4.782

Freire, J., and García-Allut, A. (2000). Socioeconomic and biological causes of management failures in European artisanal fisheries: the case of Galicia (NW Spain). *Mar. Policy* 24, 375–384. doi: 10.1016/S0308-597X(00)00013-0

Garín-Muñoz, T. (2009). Tourism in Galicia: domestic and foreign demand. *Tour. Econ.* 15, 753–769. doi: 10.5367/000000009789955107

González, L., Leon, C. J., Gonzalez Hernandez, M. M., and De Leon, J. (2021). The structural relationships of destination image, satisfaction, expenditure and loyalty in the context of fishing tourism. *Scand. J. Hosp. Tour.* 21, 422–441. doi: 10.1080/15022250.2021.1884596

Goodman, L. A. (1961). Snowball sampling. *Ann. Math. Stat.* 32, 148–170. doi: 10.1214/aoms/1177705148

Haab, T. C., and McConnell, K. E. (1996). Count data models and the problem of zeros in recreation demand analysis. *Am. J. Agric. Econ.* 78, 89–102. doi: 10.2307/1243781

Hastie, T., and Tibshirani, R. J. (1990). *Generalized additive models* (London: Chapman and Hall).

Holland, S. M., Ditton, R. B., and Graefe, A. R. (1998). An ecotourism perspective on billfish fisheries. *J. Sustain. Tour.* 6, 97–116. doi: 10.1080/09669589808667305

Hyder, K., Weltersbach, M. S., Armstrong, M., Ferter, K., Townhill, B., Ahvonen, A., et al. (2018). Recreational sea fishing in Europe in a global context–participation rates, fishing effort, expenditure, and implications for monitoring and assessment. *Fish. Fish.* 19, 225–243. doi: 10.1111/faf.12251

ICES (2013). *Report of the ICES working group on recreational fisheries surveys (WGRFS)* (Esporles, Spain: ICES).

Kayak España (2017) *Las rutas más caras según el precio por km*. Available at: https://www.kayak.es/news/vuelos-precio-por-km/#:~:text=VuelosenEuropa,esde0%2C03€ (Accessed April 24, 2022).

León, C. J., Araña, J. E., and Melián, A. (2003). Tourist use and preservation benefits from big-game fishing in the canary islands. *Tour. Econ.* 9, 53–65. doi: 10.5367/000000003101298268

Lew, D. K., and Larson, D. M. (2015). Stated preferences for size and bag limits of Alaska charter boat anglers. *Mar. Policy* 61, 66–76. doi: 10.1016/j.marpol.2015.07.007

Lynch, T. P., Smallwood, C., Williams, J., Ochwada-Doyle, F., and Devine, C. (2020). *A cross continental scale comparison of Australian offshore charter boat recreational fisheries research and its applications to marine park and fisheries management*. Report to the National Environmental Science Program, Marine Biodiversity Hub. Hobart, Tasmania, Australia: CSIRO.

Maguire, J.-J., Sissenwine, M., Csirke, J., Garcia, S., and Grainger, R. (2006). *The state of world highly migratory, straddling and other high seas fishery resources and associated species* (Rome: Food and Agriculture Organization of the United Nations).

Martínez-Escauriaza, R., Hermida, M., Villasante, S., Gouveia, L., and Pita, P. (2020). Importance of recreational shore angling in the archipelago of Madeira, Portugal (northeast Atlantic). *Sci. Mar.* 84, 331–341. doi: 10.3989/scimar.05046.30A

Martinez-Escauriaza, R., Pita, P., de Gouveia, M. L., Gouveia, N. M., Teixeira, E., de Freitas, M., et al. (2021). Analysis of big game fishing catches of blue marlin (Makaira nigricans) in the Madeira archipelago (Eastern Atlantic) and factors that affect its presence. *Sustainability* 13:8975. doi: 10.3390/su13168975

Martínez-Espiñeira, R., and Amoako-Tuffour, J. (2008). Recreation demand analysis under truncation, overdispersion, and endogenous stratification: An application to gros morne national park. *J. Environ. Manage.* 88, 1320–1332. doi: 10.1016/j.jenvman.2007.07.006

Oliveira, P., and Pereira, P. T. (2008). Who values what in a tourism destination? the case of Madeira island. *Tour. Econ.* 14, 155–168. doi: 10.5367/000000008783554758

Öndes, F., Ünal, V., Öndes, H., and Gordoa, A. (2020). Charter fishing in the Aegean Sea (Turkey), eastern Mediterranean: The missing point of fisheries management. *Fish. Res.* 224, 105457. doi: 10.1016/j.fishres.2019.105457

Parsons, G. R. (2003). "The travel cost model BT - a primer on nonmarket valuation," Eds. P. A. Champ, K. J. Boyle and T. C. Brown (Dordrecht: Springer Netherlands), 269–329. doi: 10.1007/978-94-007-0826-6_9

Pawson, M. G., Glenn, H., and Padda, G. (2008). The definition of marine recreational fishing in Europe. *Mar. Policy* 32, 339–350. doi: 10.1016/j.marpol.2007.07.001

Pérez-Camacho, A., González, R., and Fuentes, J. (1991). Mussel culture in Galicia (NW Spain). *Aquaculture* 94, 263–278. doi: 10.1016/0044-8486(91)90122-N

Pita, P., Alos, J., Antelo, M., Artetxe, I., Biton-Porsmoguer, S., Carreño, A., et al. (2020a). Assessing knowledge gaps and management needs to cope with barriers for environmental, economic and social sustainability of marine recreational fisheries: the case of Spain. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00023Assessing

Pita, P., Antelo, M., Hyder, K., Vingada, J., and Villasante, S. (2020b). The use of recreational fishers' ecological knowledge to assess the conservation status of marine ecosystems. *Front. Mar. Sci.* 7, 242. doi: 10.3389/fmars.2020.00242

Pita, P., Artetxe, I., Diogo, H., Gomes, P., Gordoa, A., Hyder, K., et al. (2017). Research and management priorities for Atlantic marine recreational fisheries in southern Europe. *Mar. Policy* 86, 1–8. doi: 10.1016/j.marpol.2017.08.030

Pita, P., and Freire, J. (2014). The use of spearfishing competition data in fisheries management: evidence for a hidden near collapse of a coastal fish community of Galicia (NE Atlantic ocean). *Fish. Manage. Ecol.* 21, 454–469. doi: 10.1111/fme.12095

Pita, P., Hyder, K., Gomes, P., Pita, C., Rangel, M., Veiga, P., et al. (2018). Economic, social and ecological attributes of marine recreational fisheries in Galicia, Spain. *Fish. Res.* 208, 58–69. doi: 10.1016/j.fishres.2018.07.014

Pita, P., and Villasante, S. (2019). The building of a management system for marine recreational fisheries in Galicia (NW Spain). *Ocean. Coast. Manage.* 169, 191–200. doi: 10.1016/j.ocecoaman.2018.12.027

Pollock, K. H., Jones, C. M., and Brown, T. L. (1994). *Angler survey methods and their application in fisheries management* (Bethesda, Maryland: American Fisheries Society Special Publication), 25.

Radford, Z., Hyder, K., Zarauz, L., Mugerza, E., Ferter, K., Prellezo, R., et al. (2018). The impact of marine recreational fishing on key fish stocks in European waters. *PloS One* 13, e0201666. doi: 10.1371/journal.pone.0201666

R Core Team (2019). *R: A language and environment for statistical computing.* Vienna, Austria.

Restrepo, V., Prince, E. D., Scott, G. P., and Uozumi, Y. (2003). ICCAT stock assessments of Atlantic billfish. *Mar. Freshw. Res.* 54, 361–367. doi: 10.1071/MF02057

Roussel, S., Salles, J.-M., and Tardieu, L. (2016). Recreation demand analysis of sensitive natural areas from an on-site survey. *Rev. dEconomie. Reg. Urbaine.* 2, 355–384. doi: 10.3917/reru.162.0355

Shaw, D. (1988). On-site samples' regression: Problems of non-negative integers, truncation, and endogenous stratification. *J. Econom.* 37, 211–223. doi: 10.1016/0304-4076(88)90003-6

Shiffman, D. S., and Hammerschlag, N. (2014). An assessment of the scale, practices, and conservation implications of florida's charter boat–based recreational shark fishery. *Fisheries* 39, 395–407. doi: 10.1080/03632415.2014.941439

STECF (2017). *The 2017 annual economic report on the EU fishing fleet (STECF-17-12)* (Luxembourg: Publications Office of the European Union). doi: 10.2760/36154

Steinback, S. R. (1999). Regional economic impact assessments of recreational fisheries: an application of the IMPLAN modeling system to marine party and charter boat fishing in Maine. *North Am. J. Fish. Manage.* 19, 724–736. doi: 10.1577/1548-8675(1999)019<0724:REIAOR>2.0.CO;2

Suárez de Vivero, J. L., and Rodríguez Mateos, J. C. (2012). The Spanish approach to marine spatial planning. marine strategy framework directive vs. EU integrated maritime policy. *Mar. Policy* 36, 18–27. doi: 10.1016/j.marpol.2011.03.002

Surís-Regueiro, J. C., and Santiago, J. L. (2014). Characterization of fisheries dependence in Galicia (Spain). *Mar. Policy* 47, 99–109. doi: 10.1016/j.marpol.2014.02.006

Vallerani, M., Martí, C.-P., and Ojamaa, P. (2017). *Fisheries in Madeira* (Brussels: European Parliament).

Vieira, J. C., and Antunes, M. C. (2017). Touristic big-game fishing in saint Michael island (Azores) evaluating anglers' profiles, perceptions about the destination and business revenues. *Tour. Econ.* 23, 1362–1368. doi: 10.1177/1354816616686414

Villasante, S., Pierce, G., Pita, C., Guimeráns, C., Garcia Rodrigues, J., Antelo, M., et al. (2016). Fishers' perceptions about the EU discards policy and its economic impact on small-scale fisheries in Galicia (North West Spain). *Ecol. Econ.* 130, 130–138. doi: 10.1016/j.ecolecon.2016.05.008

Villasante, S., Rodríguez-González, D., Antelo, M., Rivero-Rodríguez, S., and Lebrancón-Nieto, J. (2013). Why are prices in wild catch and aquaculture industries so different? *Ambio* 42, 937–950. doi: 10.1007/s13280-013-0449-8

Voyer, M., Barclay, K., McIlgorm, A., and Mazur, N. (2017). Connections or conflict? a social and economic analysis of the interconnections between the professional fishing industry, recreational fishing and marine tourism in coastal communities in NSW, Australia. *Mar. Policy* 76, 114–121. doi: 10.1016/j.marpol.2016.11.029

Williams, C., Davies, W., Clark, R. E., Muench, A., and Hyder, K. (2020). The economic contribution of sea angling from charter boats: A case study from the south coast of England. *Mar. Policy* 119, 104066. doi: 10.1016/j.marpol.2020.104066

frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 24 August 2022
DOI 10.3389/fmars.2022.975089

Check for updates

OPEN ACCESS

EDITED BY
Pablo Pita,
University of Santiago de Compostela, Spain

REVIEWED BY
Sophia Kochalski,
University of Santiago de Compostela, Spain
Tommaso Russo,
University of Rome Tor Vergata, Italy

*CORRESPONDENCE
Eneko Bachiller
ebachiller@azti.es

†These authors have contributed equally to this work and share senior authorship

SPECIALTY SECTION
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

RECEIVED 21 June 2022
ACCEPTED 27 July 2022
PUBLISHED 24 August 2022

CITATION
Bachiller E, Korta M, Mateo M, Mugerza E and Zarauz L (2022) Assessing the unassessed marine recreational fishery in the Eastern Cantabrian coast. *Front. Mar. Sci.* 9:975089. doi: 10.3389/fmars.2022.975089



# Assessing the unassessed marine recreational fishery in the Eastern Cantabrian coast

Eneko Bachiller*, Maria Korta, Maria Mateo, Estanis Mugerza† and Lucia Zarauz†

AZTI, Sustainable Fisheries Management, Basque Research and Technology Alliance (BRTA), Sukarrieta, Spain

Within the first attempt to assess marine recreational fisheries (MRF) along the coastal villages of the Basque Country (Eastern Cantabrian Sea), off-site surveys were carried out from 2015 to 2019 to estimate captures of the main targeted species by shore fishing, boat fishing and spearfishing. Phone calls got better response rates (>50%) than email questionnaires (<25%). Spearfishing population was smaller (1000 licenses, <2% of total MRF effort) and younger, whereas boat fishers (5000 licenses, 9% MRF effort) were generally older and more experienced. Shore fishing was the most extended MRF activity (50000 licenses, 90% of MRF effort), showing wider age and experience ranges. Boat fishing targeting albacore in summer was the main MRF activity interacting with regional commercial small-scale fishery. Squids were also important for both shore and boat fishing, followed by seabass, the main target species for shore anglers. Despite surveys were primarily designed to gather information about these three species, they also evidenced, moreover with clear underestimation bias, frequent captures of generally unassessed species, such as sargo-bream (*Diplodus* spp.), gilthead seabream (*Sparus aurata*), common dentex (*Dentex dentex*), red mullet (*Mullus surmuletus*) or scorpionfish (*Scorpaena* spp.). Fishers with more experience, as well as spearfishers in general, captured a wider diversity of species, but individual fishers were more specialized (i.e., showing less variation between trips). Our off-site survey assessment highlights the importance of incorporating multispecies sampling schemes to develop future MRF assessment criteria, within a context of an ecosystem approach that should also consider potential interactions with commercial small-scale fishery.

KEYWORDS

MRF, off-site surveys, fisher's profile, target species, catch estimates, unreported catches, fishing interactions

# 1 Introduction

Marine recreational fisheries (MRF) are defined as "*fishing of aquatic animals (mainly fish) that do not constitute the individual´s primary resource to meet basic nutritional needs and are not generally sold or otherwise traded on export, domestic or black markets*" (FAO, 2012). This activity is one of the most frequent leisure activities in coastal zones worldwide, and it involves large number of people and consequently high levels of fishing effort (Cowx and Arlinghaus, 2008; Hyder et al., 2017b; Hyder et al., 2020; Radford et al., 2018). In the case of Europe, participation has shown to be high, with significant social and economic benefits, but also has impacts on some fish stocks (Hyder et al., 2017b; Hyder et al., 2017a). Recent research has shown that in Europe there are around 8.7 million people engaged in MRF, fishing for almost 78 million days, and spending about €5.9 billion each year (Hyder et al., 2017b). This creates a total economic impact of €10.5 billion per year and supports almost 100,000 jobs across Europe (Hyder et al., 2017b). Recreational removals (kept fish plus post release mortality) can be significant for some species representing between 2-43% of the total catch (Radford et al., 2018) and recreational fishing also has environmental impacts (Lewin et al., 2019). The importance of proper management is covered under the Common Fisheries Policy (CFP) (EU, 2013) where it states that "*recreational fisheries can have a significant impact on fish resources and Member States should, therefore, ensure that they are conducted in a manner that is compatible with the objectives of the CFP*".

However, knowledge of the MRF activity is scarce and this leads to the fact that governance of MRF is lacking, and it is not embedded in the marine management and policy process of many countries (Pita et al., 2017; Hyder et al., 2020). For EU countries, there has been a legal requirement from the European Commission to collect annual recreational catches for salmon and bluefin tuna under the Data Collection Framework (DCF) since 2001 (EU, 2001). For the Atlantic region, the list of required species increased in subsequent regulations (EU, 2008a; EU, 2010; EU, 2016; EU, 2021), including estimates of catches and releases for Atlantic cod (*Gadus morhua*), European seabass (*Dicentrarchus labrax*), European eel (*Anguilla anguilla*), Atlantic salmon (*Salmo salar*), pollack (*Pollachius pollachius*), elasmobranchs and for all highly migratory species, e.g., tuna species assessed by the International Commission for the Conservation of Atlantic Tunas (ICCAT). For the first time Member States are urged to implement multispecies sampling schemes that enable catch quantities to be estimated for certain stocks that were selected at regional level, in accordance with the relevant end user needs (EU, 2021).

A second mechanism for data collection of recreational fishery in Europe is the Control Regulation that specifies recreational fisheries are conducted in a manner compatible with the CFP and that recreational catches of stocks subject to recovery plans must be monitored on vessels registered in each country (EU, 2011). There has been limited data collected on MRF despite these requirements, mainly due to the challenges of delivering robust surveys and the varied and dispersed nature of MRF. In addition, there are relevant EU directives such as the Marine Strategy Framework Directive (MSFD) (EU, 2008b), The Maritime Spatial Planning Directive (EU, 2014; EU, 2022) where the objectives are to protect more effectively the marine environment across Europe in the case of the former, and to manage the use of the European seas and oceans coherently to ensure that human activities take place in an efficient, safe and sustainable way in the case of the latter. Therefore, despite these legal requirements, in many European countries the data collection programs on MRF are still a pending issue (Hyder et al., 2020). In Spain, Gordoa et al. (2019) and Dedeu et al. (2019) carried out recently the first assessment of marine recreational fishing at a national scale. Before that, MRF studies had been performed at a smaller scale by some Autonomous Communities (AC), which are the administrative bodies responsible for MRF management in the inshore waters (Morales-Nin et al., 2005; Lloret et al., 2008a; Lloret et al., 2008b; García-Flórez et al., 2012; Ruiz et al., 2014; Zarauz et al., 2015). These studies allowed a first characterisation of the biological and socio-economic importance of MRF in these regions. However, there is not a national data collection programme set up to answer the requirements of the new EU Multiannual Program (EUMAP) for data collection, which establishes the data requirements to be collected, the list of mandatory surveys in each sea basin and the thresholds to collect data. The data requirements for MRF are included under one of these legal acts: Commission Delegated Decision (EU) 2021/1167 of 27 April 2021, establishing the multiannual Union Program for the collection and management of biological environmental, technical, and socioeconomic data in the fisheries and aquaculture sectors. On the other hand, sampling schemes have considered selected species individually, which implicitly assumed independent distributions among species. In fact, species distributions are correlated with each other, driven by either biotic interactions or environmental variables (Zhang et al., 2020 and references therein). Therefore, in order to successfully manage these fisheries, it is essential to perform a detailed assessment of the critical gaps in the scientific knowledge (Pita et al., 2020), e.g., pointing towards multispecies sampling schemes for MRF.

The situation in the coastal region of the Basque Country (Figure 1), as in the rest of the Spanish coastal regions, is quite similar to other EU countries in relation to the knowledge of the activity of the MRF (Pita et al., 2020). The first study on the establishment of a systematic data collection system on MRF in

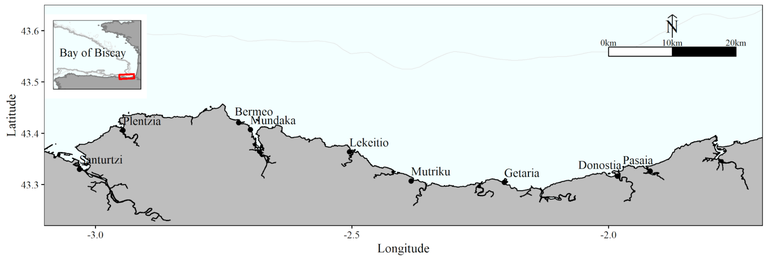



FIGURE 1
Area of study where recreational fishing activity data was collected. Red box in the upper left small map indicates the zoomed region of the Bay of Biscay presented in the main panel. The most important harbors are indicated within the map. Grey lines represent the 200m (the closest to the shore, visible in both maps), 500m and 1000m isobaths.

this region was carried out in 2012-2013 (Ruiz et al., 2014) to provide the first estimates of seabass catches in response to EUMAP requirements, using different off-site methods such as telephone and email surveys (Zarauz et al., 2015). This study allowed comparing estimates obtained through the different sampling methods as well as evaluating the suitability of the different methodologies, but also potentially related biases. The results from Zarauz et al. (2015) made it possible to establish, for the first time in the Basque Country, a routine collection system using off-site methods, which has been in place since 2015.

In this study we analyse data collected between 2015-2019 under the established routinary sampling programme. We characterize the profile of marine recreational fishers and we provide 5–year catch estimates for seabass (*D. labrax*), albacore (*Thunus alalunga*) and squids (*Loligo* spp.) for the first time. Although the surveys were initially designed to gather information about these three species, they could also be used to estimate the minimum abundance of other target species of MRF in the Basque Country, evidencing the relevance of additional species groups not reported previously for this activity, which highlights the need of multispecies sampling schemes able to capture the variability of the catch profile of MRF.

# 2 Materials and methods

## 2.1 Data collection: Off-site surveys

The study area was the Basque coastline, which extends 176 km in the Southeast corner of the Bay of Biscay (Figure 1). The management of recreational fishing depends on the Basque Government, who issues recreational fishing licenses that are mandatory for anglers and spearfishers older than 16 years and are valid to be used all over the Spanish coast. There are two types of licenses: one for surface fishing (shore and boat fishing) and one for spearfishing. The first one is renewed every 5 years, and the second one, annually. Additionally, for boat fishing, boat owners should register their boats in a specific census. For the purposes of this study, only the licenses of fishers living in the Basque Country were considered.

To collect data from different recreational fishing activities, off-site surveys were carried out from 2015 to 2019, both by email and through phone calls. In the first four years, surveys were conducted in July and January, collecting information from the corresponding previous semesters. In 2019 three surveys were conducted, one every three months, i.e., in May, September and December. A company was subcontracted to carry out the telephone surveys. The e-mail surveys were directly done using SurveyMonkey (www.surveymonkey.com). In 2017, only email surveys were performed, due to logistical problems. Sampling was stopped at the end of 2019 because of restrictions due to de personal data protection regulation (BOE, 2018), which requires the license application system to be changed to gather the explicit consent of the fishers.

Our sampling frame considered only licenses from fishers living in the Basque Country. The study population for shore and spear fishing was defined by the list of licensed anglers and spearfishers respectively, which, according to Basque regulations, is mandatory for recreational fishers older than 16 years (Eusko Jaurlaritza, 2000).The population of boat fishing was based on the list of fishers owning a license and having a vessel registered in the boat census. The contact information available in the license census was not complete. Namely, for surface licenses, an average of 35% fishers provided their telephone, and 27% their email; an average of 56% and 55% of spearfishers' phone and emails were available, respectively. The sampling frames for shore and spearfishing were constructed using the contact information available in the corresponding license census. The sampling frame for boat fishing was built with the contact information of fishers owning a license and having a vessel registered in the boat census. Therefore, only boat owners were targeted, i.e., not licensed boat fishers without their own boat.

For phone sampling, the fishers were randomly selected from each sampling frame. The target number of surveys completed was set in 400. When no phone answer was obtained in a household, at least four attempts were done at different times of the day before considering that sample as a non-response. For email surveys, all available e-mails were used to send the questionnaire. A second email was sent to the fishers that did not reply to the questionnaire at the first round. According to that, the whole *sampling frame* is defined as the available phone numbers and emails. The *gross sample* accounts for the number of fishers contacted out of the sampling frame. The *net sample* is the number of available samples after accounting for *sample loss* (e.g., invalid contact information). This way, the *response rate* was calculated as the number of fully responding questionnaires divided by the gross sample, so only fishers that received the survey request were considered.

All surveys fall in the category of recall surveys, in which interviewers are asked about an event performed in the past. To minimize the non-response during the survey, 300€ were raffled among all participants. Both email and phone surveys were based on the same questionnaires aiming to collect information about fisher's profile (i.e., age and years of experience) and fishing activities. Regarding the latter, fishers were asked about their fishing mode, fishing location, fishing effort (i.e., number of days of each reported fishing activity during the surveyed period) and catch information. Fishers were first asked to report captures (i.e., total number and, if possible, total weight) of seabass, squids and albacore. Captures of sea bass and albacore were needed to answer the requirements of the DCF (EU, 2010; EU, 2016; EU, 2021). Squids were included in the surveys because their relevance in the Basque MRF (Ruiz et al., 2014; Palas et al., 2017). Captures of other species were reported as additional information, but often qualitatively, as part of an open field regarding 'other captured species' within the questionnaires. Although both retained and released capture information was requested, the reported information of released fish was almost null and therefore only data of retained fish will be considered in this study. Boat owners were asked to report the total catch and effort performed from their vessel, which may correspond to several fishers; however, and since such information was not available, it was assumed that all the fishing activity of each vessel corresponded to its owner.

## 2.2 Data analysis

### 2.2.1 Response rates and fishers' profiles

To characterize the coverage of the Basque recreational fishing community, response rates were assessed in terms of percentages (Table S01), by survey type (i.e., email vs phone calls), year (2015-2019), period (month ranges), and fishing mode (shore fishing, boat fishing, spearfishing).

The recreational fisher's profile was assessed by age, fishing experience (in years) and fishing effort (fishing days) of those who responded to different surveys, for each fishing mode.

A t-test was applied to test for differences on response rates between survey sources (phone vs email).

### 2.2.2 Fishing effort

Fishing effort was assessed with the total fishing days declared by each fisher. To check whether estimated total fishing effort varied depending on fishing mode and years, two-way ANOVA (F test) was applied.

### 2.2.3 Catch estimates based on abundance and weight of captured species

Questionnaires collected species' catch information from fishers practicing each recreational fishing mode. Each fisher reported detailed information about captured numbers of seabass, albacore or (especially) squids; for such species, weight was also occasionally reported. For all other captured species, the total number was often unspecified, and the information was sometimes limited to singular (i.e., 1 individual) vs plural (i.e., at least 2 individuals) capture reports. To ease later interpretation of results, the following 16 species groups were defined: tunids (i.e., *Thunnus alalunga*, *Sarda sarda*, *Katsuwonus pelamis*, *Auxis* spp.), squids (*Loligo* spp.), seabass (*D. labrax*), sargo-breams *Diplodus* spp. (*D. sargus*, *D. vulgaris*, *D. puntazzo* and *D. cervinus*), *Scomber* spp. (Atlantic mackerel, *S. scombrus*, and Atlantic Chub mackerel, *S. colias*), Trachurus spp. (*T. trachurus* and *T. mediterraneus*), gilthead seabream (*Sparus aurata*), *Lithognathus mormyrus*, *Pagellus* spp. (*P. bogaraveo*, *P. erythrinus* and *P. acarne*), common dentex (*Dentex dentex*), scorpionfish *Scorpaena* spp. (*S. porcus*, *S. notata* and *S. scrofa*), *Mullus surmuletus*, *Conger conger*, other fish species (*Solea solea*, *Platichthys flesus*, *Scophthalmus* spp., *Lepidorhombus* spp., *Dicologlossa cuneata*, *Coris julis*, *Serranus cabrilla*, *Balistes capriscus*, Triglidae fam., *Labrus* spp. (*L. bergylta*, *L. mixtus*), *Trachinus draco*, *Beryx decadactylus*, *Trisopterus luscus*, *Helicolenus dactylopterus*, *Zeus faber*, *Boops boops*, *Umbrina* spp. (*U. cirrosa*, *U. canariensis*), *Argyrosomus regius*, *Oblada melanura*, *Spondyliosoma cantharus*, *Mugil* spp., *Belone belone*, *Pagrus pagrus*, *Brama brama*, *Sarpa salpa*, *Merluccius merluccius*, *Pollachius pollachius* and *Micromesistius poutassou*), swordfish, sharks and rays (*Xiphias gladius*, *Scyliorhinus canicula*, *Galeus melastomus* and *Raja* spp.), and other species (*Anguilla anguilla*, *Maja squinado* and *Palaemon* spp.).

The *total catch* of seabass, tunids and squid was estimated using the Horvitz & Thompson estimator and assuming simple random sampling (Lumley, 2011; ICES, 2012) for each fishing mode:

$$\hat{C} = \sum_{i=0}^{n} \frac{c_i}{\pi_i} = \frac{N}{n} \sum_{i=0}^{n} c_i$$

where $N$ is size of the study population, $C$ is the estimated total catch, $c_i$ is the catch reported by the surveyed fishers, and $\pi_i$ is the probability of including unit $i$ in a sample of size $n$. In the case of simple random sampling, $\pi$ equals $\frac{n}{N}$.

For other species, the *minimum catch abundance* was assessed. For weight estimates, data was considered from reports when available, and re-calculated from abundances and mean weights for surveys not providing weight information. Catch estimates were extrapolated for each fishing mode, according to the covered sampling frame and assuming simple random sampling (see details in Lumley, 2020). Given that both phone and email surveys extrapolated captures to the total fishers' numbers from census, the mean catches between the two methods were considered for further analyses.

In addition, we used two-way ANOVAs (F tests) to evaluate variables affecting the estimated total catches. Fishing mode, years, number of fishers, response rates and estimated fishing effort (total fishing days) were used as explanatory variables, whereas the estimated total catch (kg) was used as the response. Akaike's information criterion (AIC) was applied to get the most parsimonious model.

#### 2.2.4 Variation in captured species composition

First, we used multinomial logistic regression models (iterated 2500 times) with reported data (i.e., absolute catch abundances) to evaluate variables affecting the captured species composition. Year, fisher's age and fishing experience, fishing mode and fishing effort were used as explanatory variables and multivariate species compositional data (i.e., species abundance composition matrix) was used as the response. Since preliminary data exploration recommended in Zuur et al. (2010) determined a high collinearity between age and experience, we kept experience and dropped age for the multivariate analyses.

Several authors concern about the use of count data in recreational fishery reports, given that high amount of zero values are common (Taylor et al., 2011) and may ignore overdispersed data (Zuur et al., 2009; Carlos-Júnior et al., 2020; Stoklosa et al., 2022 and references therein). Accordingly, we also determined significant variables affecting the species composition, fitting a zero inflated negative binomial model (iterated 999 times) with the species occurrence as response variable, as proposed by Solow and Smith (2010); i.e., 0 representing absence of species, 1 representing singletons (true single individuals), and 2 representing *two or more* (Solow and Smith, 2010; Stoklosa et al., 2022).

The variation in captured species composition was then assessed in detail, in terms of beta-diversity, comparing the fishing modes first, and different experience ranges (defined as <5 years, 5-30 and >30 years) in a second analysis. Following the approach proposed by Baselga (2010); Baselga (2012), we used captured species' presence-absence data to compute the monotonic transformation (Chao et al., 2012) of beta-diversity – Sørensen dissimilarity index ($\beta_{SOR}$) and its partition into two additive components, accounting for pure spatial turnover and nestedness. The turnover component is species replacement, consists of the substitution of species in an individual fisher's captures by different species in captures of the other fishers, and is measured as the Simpson-based dissimilarity component ($\beta_{SIM}$). The nestedness-resultant dissimilarity component ($\beta_{NES}$) is species loss (or gain), which implies the elimination (or addition) of species in only one individual fisher, as leads to the poorest assemblage being a strict subset of the richest one Baselga (2010); Baselga (2012).

### 2.3 Software and statistical packages

We used R software v.2.4.0 (R Core Team, 2021) for all analyses and graphical representations, using especially package ggplot2 v.3.2.1 (Wickham, 2009) for figures. Catch estimates were calculated using 'svyby' and 'svytotal' functions from *survey* package v.4.0 (Lumley, 2020). We fitted multinomial regressions using 'multinom' function in *nnet* package (Venables and Ripley, 2002), and zero inflated negative binomial models using 'zeroinfl' function in package *pscl* (Zeileis et al., 2008). For the beta-diversity analysis, we used the *betapart* package v1.5.6 (Baselga and Orme, 2012) and in particular, the 'betapart.core' function to compute and plot captured species dissimilarity, turnover, and nestedness components.

## 3 Results

### 3.1 Response rates and fishers' profiles

The study population (number of fishers), sampling frame (contact information available), the gross sample (phone calls and emails sent), lost and refused calls, number of answers obtained and response rates per fishing mode and year, are presented as Supplementary Material (Supplementary Table S01).

According to the census, the number of active fishing licenses during the sampling period was around 50000, 5000 and 1000 for shore fishing, boat fishing and spearfishing, respectively (Supplementary Table S01). With both phone and email survey methods around 50% of spearfishers and <20% of shore and boat fishers were contacted.

Although the contacted numbers varied during the study period, both for email and phone calls, the aimed 400 responses were achieved in most of the sampling years and fishing modes (Figure 2). Such response numbers were higher in surveys made by phone in all modes, spearfishers showing relatively higher response numbers than shore fishers and boat fishers (Figure 2). When accounting for the email survey, the response numbers were lower in all modes, with especially few answers from boat fishers in all years (Figure 2; Supplementary Table S01).

Accordingly, the response rate was significantly higher (t-test, $p < 0.05$) for phone calls (57–68%, Table 1) than for emails (13–24%, Table 1). While the response rate of phone surveys was

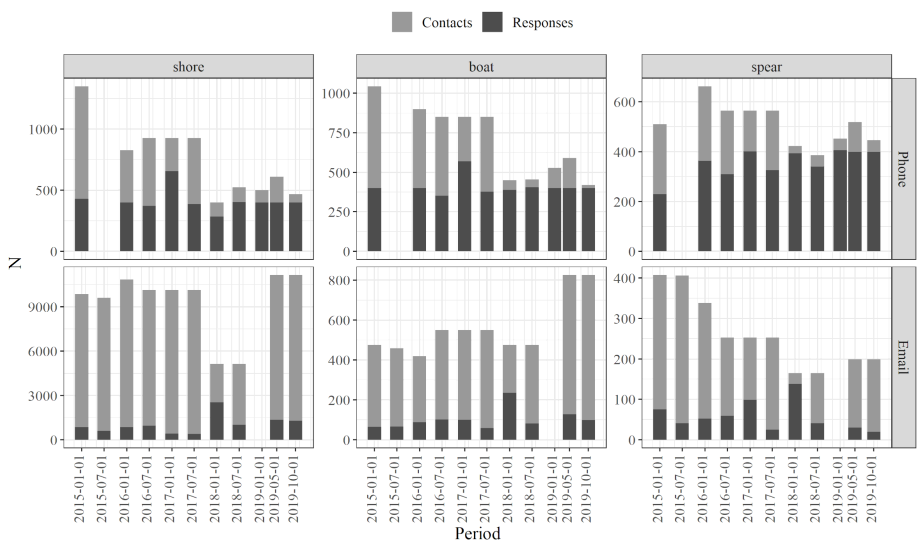



FIGURE 2
Number of contacted fishers and obtained positive responses though different months of the sampling period (2015 – 2019), separated by survey type (i.e., phone calls and emails) and fishing mode (i.e., shore fishing, boat fishing and spearfishing). Note the different scales in Y axes.

similar for the three fishing modes, in relation to the total license numbers, spearfishers showed relatively higher response rates than the boat and shore fishers (Table 1; Supplementary Table S01). The response rates obtained especially from phone surveys increased during the last two years, i.e., 2018 – 2019 (Figure 2; Supplementary Table S01).

Regarding the age of fishers based on both phone and email survey responses, most of responses were obtained from 30–50 year old fishers until 2017, and even from older fishers (40–60 years old) in the last two years (Figure 3). In any case, age-range differences were more due to fishing modes than to any inter-annual trends. Boat fishers showed an older age-range in comparison with shore fishers and spearfishers, with even clearer differences on email surveys. Spearfishers presented a slightly younger and narrower age-range, whereas higher abundances were observed in all age ranges of shore fishers, going from 1 year up to 80 (Figure 3).

In all fishing modes, fishers with experience ranging from 1 to 10 years were the most abundant, dropping as the number of years of experience increased. The main drop was for fishers with >40 years of experience in shore fishing, whereas the number of spear fishers declined when considering >10 years of experience, suggesting an overall shorter experience degree than for fishers in the other two modes. Number of boat fishers also declined as the degree of experience increased but such a decline was smoother than in other modes (Figure 4).

## 3.2 Fishing effort

Estimated total fishing effort varied significantly depending on fishing mode but not between years (two-way ANOVA; year: $F$ = 1.923, *d.f.* = 4, $p$ = 0.2; fishing mode: $F$ = 492.87, *d.f.* = 2, $p$ <0.001; year*mode interaction: $F$ = 0.62, *d.f.* = 8, $p$ = 0.57). Shore fishers exerted by far much higher fishing effort, followed by boat fishers and spearfishers (Supplementary Figure S01), the latter accounting for <2% of the total estimated recreational fishing effort.

In accordance with age distribution, fishers reporting the highest fishing effort (i.e., those who declared a higher number of fishing days per corresponding surveyed period) were the shore fishers from

TABLE 1 Means ( ± SD, Standard Deviation) of the number of fishers (i.e., licenses), conducted surveys (i.e., gross sample) by phone and email during the sampling period (2015 – 2019), and of the total response rates obtained (absolute numbers and percentages), for each fishing mode.

| | Fishing licenses | Phone | | Email | |
|---|---|---|---|---|---|
| | | Surveys | Response Rate (%) | Surveys | Response Rate (%) |
| **Shore fishing** | 49668 ± 3041 | 808 ± 352 | 57 ± 19 | 9340 ± 2409 | 13 ± 12 |
| **Boat fishing** | 5223 ± 657 | 727 ± 247 | 59 ± 22 | 561 ± 152 | 18 ± 9 |
| **Spearfishing** | 1189 ± 188 | 504 ± 76 | 68 ± 19 | 264 ± 94 | 24 ± 18 |


FIGURE 3
Age distribution of fishers that provided information on phone and email surveys from 2015 to 2019, for each of the fishing modes (shore fishing, boat fishing, spearfishing).

40 to 50 years old, boat fishers from 50 to 70 years old, and spearfishers from 30 to 40 years old (Supplementary Figure S02). Number of fishing days reported were significantly different between phone and email surveys during different years (two-way ANOVA; year: $F$ = 98.79, *d.f.* = 4, $p$ < 0.001; source: $F$ = 402.39, *d.f.* = 1, $p$ < 0.001; year*source interaction: $F$ = 245.78, *d.f.* = 1, $p$ < 0.001).

## 3.3 Catch estimates

The estimated total catch differed significantly depending on the fishing mode and on its interaction with response rates (two-way ANOVA; fishing mode: $F$ = 14.78, *d.f.* = 2, $p$ <0.001; response rate: $F$ =0.98, *d.f.* = 1, $p$ = 0.33; mode*response rate

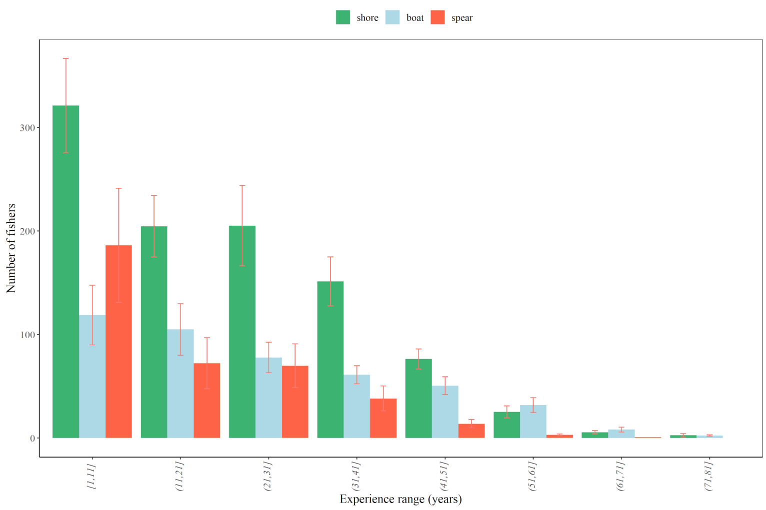



FIGURE 4
Number of fishers per range of degree of experience (in years) for each fishing mode, considering all sampling years and survey sources together (phone and email surveys, 2015-2019). Error bars denote the standard error.

interaction: $F$ =2.46, $d.f.$ = 2, $p < 0.1$), whereas 'sampling year', 'number of fishers' and 'fishing effort' were not significant explanatory variables based on the AIC. However, we decided to assess the following catch estimates analysis keeping the sampling years separately to check for suggested temporal trends.

Squids caught from shore and boats were by far the most abundant captures in numbers in almost all sampling years, whereas most of the total catch weight was due to captures of tunids from boats. In terms of total weight, tunid landings were estimated between 68 t and 358 t, depending on the year (showing the minimum and maximum landings in 2015 and 2019, respectively; Figure 5). Squid landings ranged from 89 t to 156 t, and were within similar ranges as seabass estimates, the main target species for shore fishers, ranging from 71 t to 147 t (Figure 5).

In terms of percentages by fishing modes (Figure 6), squids were around one third of captures in numbers in shore fishing and more than the half in boat fishing; together with seabass and sargo-breams (*Diplodus* spp.) in shore fishing, and with tunids in boat fishing, they comprised >75% of the total catches in numbers. In contrast, in terms of weight, seabass and seabreams were the half of the total shore fishing catches in weight, whereas tunids were by far the most important in boat fishing (>70% of the total catch), followed by squids in the two fishing modes. For spearfishing, seabass and seabreams were the most important captured species both in numbers and weight (>50%), with a wide variety of additional species (e.g., congers, scorpionfish, gilthead seabreams) completing the targeted species (Figure 6).

## 3.4 Variation in captured species composition

Species composition data (i.e., absolute reported catch values) were first analyzed using logistic multinomial regressions. AIC tests showed that in addition to the fishing mode (standardized null model, $AIC_{\mu}$ 357437), the consecutive incorporation of the variables 'sampling year' ($AIC_{\mu+year}$ 352452), 'years of experience' ($AIC_{\mu+year+experience}$ 351418) and 'fishing effort' ($AIC_{\mu+year+experience+effort}$ 343810) resulted in the last option as the most parsimonious model.

The negative binomial model (Zuur et al., 2009; Stoklosa et al., 2022) also showed that occurrence density of species varied significantly by fishing mode, fishing effort, sampling year and experience; the zero inflated negative binomial model showed that both fishing mode and sampling effort were significant variables predicting excessive non-occurrences (i.e., zero values) (Table 2).

Regarding the variations in captured species composition (beta-diversity), shore-fishing and spearfishing showed the highest and the lowest individual variations in species composition, respectively (i.e., Sørensen dissimilarity index

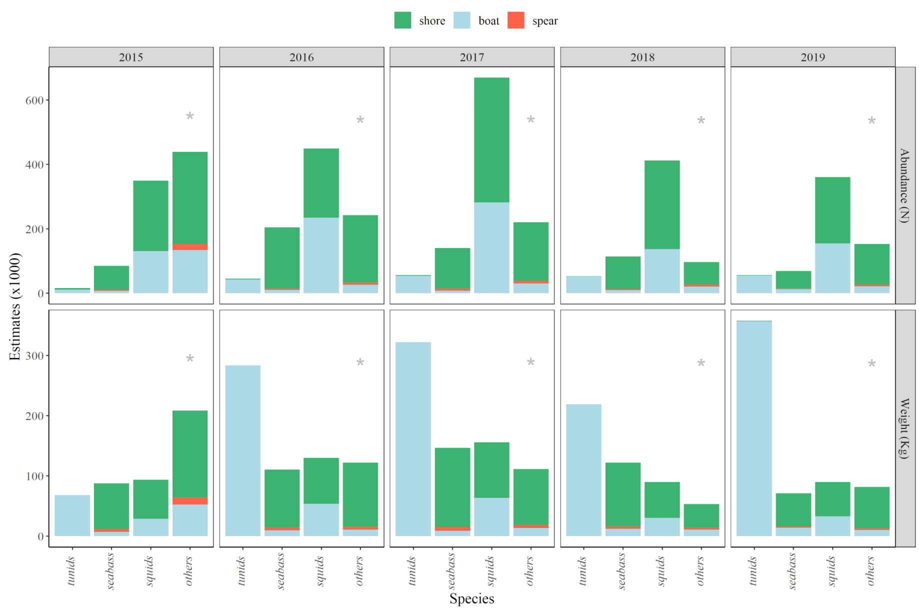



FIGURE 5
Mean values of estimated catches (i.e., between phone and email surveys, see Methods section), in terms of abundance (numbers) and weight (kg), for the main species groups caught by each fishing mode (i.e., shore fishing, boat fishing, spearfishing) during the sampling years (2015-2019). Grey "*" denotes minimum abundance, based on additional notes from fishers (see Methods section).

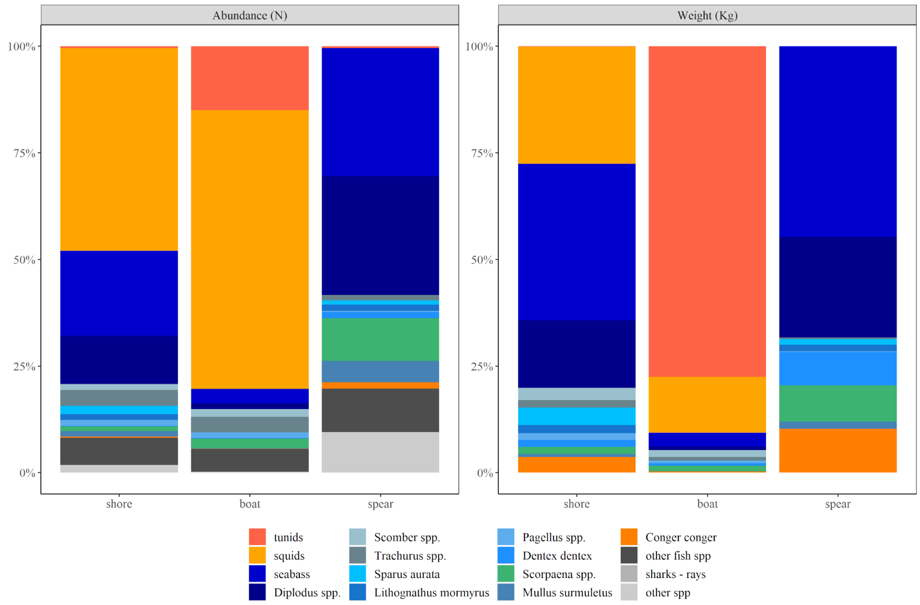



FIGURE 6
Estimated captures in percentages of abundance (number) and weight (kg), for all species groups caught with different fishing modes (i.e., shore fishing, boat fishing, spearfishing), considering all years (2015-2019) and survey methods (phone and email) together.

$\beta_{SOR}$, Figure 7A). The lower beta diversity in spearfishing was primarily explained by the turnover component, which defined spearfishing as the most different fishing mode in terms of captured species composition due to a lower species alternating in comparison with boat and shore fishing (i.e., Simpson dissimilarity $\beta_{SIM}$, Figure 7B). Shore and boat fishing modes had a similar species loss (i.e., prey richness), in contrast with higher richness variation observed in spearfishing (i.e., nestedness component $\beta_{NES}$, Figure 7C).

When comparing variations in captured species composition ($\beta_{SOR}$) caught by fishers with different experience ranges, it was mostly the same for all groups, the most experienced fishers (i.e., >30 years' experience) showing a bit lower individual variations in species composition (Supplementary Figure S03A). The captured species composition was most variable for amateur fishers (i.e., <5 years' experience), due to a higher species replacement ($\beta_{SIM}$) in comparison with fishers with longer experience (Supplementary Figure S03B). The nestedness component ($\beta_{NES}$) showed a similar species loss among different levels of experience, suggesting lower species richness in the catch of fishers with shorter experience (Supplementary Figure S03C).

# 4 Discussion

## 4.1 Survey assessment

From the total number of contacted fishers, within reasonable ranges compared with previous surveys in other areas (Herfault et al., 2013; Rocklin et al., 2014; Hyder et al.,

TABLE 2 Summary statistics of the zero inflated negative binomial model fitted to species occurrence compositional data as response variable.

| **Response variable: *Spp occurrence*** | **Count model coefficients** | | | **ZI model coefficients** | | |
|---|---|---|---|---|---|---|
| | **Estimate** | **SE** | **p** | **Estimate** | **SE** | **p** |
| (Intercept) | -0.170 | 0.03 | *** | 1.524 | 0.04 | *** |
| Mode | 0.114 | 0.01 | *** | 0.251 | 0.01 | *** |
| Year | 0.003 | 0.0006 | *** | 0.0001 | 0.0007 | ns |
| Experience | -0.013 | 0.006 | * | -0.008 | 0.007 | ns |
| Fishing effort | 0.003 | 0.0004 | *** | -0.004 | 0.0004 | *** |
| Log (theta) | 16.72 | 1.717 | *** | | | |

Estimates for count model (i.e., negative binomial with log link) and zero inflated (ZI) model (i.e., binomial with logit link) are presented. SE is the Standard Error. Significance of explanatory variables are defined as: *** $p<0.001$; * $p<0.05$; *ns*: non-significant.

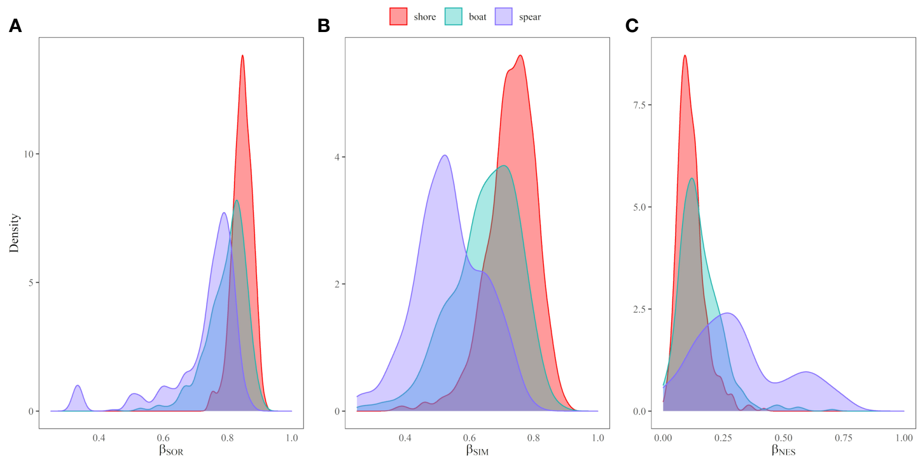



FIGURE 7
The partition of beta-diversity transformed as **(A)** Sørensen dissimilarity index ($\beta_{SOR}$), and the partition in the **(B)** turnover ($\beta_{SIM}$) and **(C)** nestedness ($\beta_{NES}$) components, for shore fishing (red), boat fishing (light green) and spear fishing (blue).

2017b), response rates obtained were higher in phone surveys, despite the emails contacting a larger sample of the fishing population. Such better responses obtained by phone could be interpreted in terms of bias risk due to non-responses, as avid fishers are more likely to answer than fishers reporting zero catches (Tarrant and Manfredo, 1993; Tarrant et al., 1993; National Research Council, 2006). In our study, non-responses in phone surveys were more due to erroneous phone numbers rather than to people refusing to answer, which were less than 10%, in accordance with first surveys in the region in the last decade (Zarauz et al., 2015). This way, and although the increase of phone survey refusals observed with time might probably be related with survey fatigue (National Research Council, 2006), the response rates increased with time in all fishing modes, due to a better depuration when preparing the phone numbers lists. In contrast, it might be easier for less avid fishers not to respond to email surveys, lead either by little interest to provide information about their own catches, moreover filling forms manually. As a conclusion, we can say that phone surveys were less likely to be influenced by non-response bias than email surveys.

Besides, only retained species were reported, and therefore information about released species was almost null, suggesting that in future questionnaires a dedicated section and/or a special sampling effort should be incorporated to characterize the catch-and-release activity.

Concerning the sampling frame, the proportion of fishers providing contact information when getting the license increased over time (Table S01, Supplementary Material), probably due to improvements in the webpage of the corresponding administration that aimed to encourage fishers to fill in such information and to quality check that provided information. Accordingly, and given that we do not expect any significant bias related with fishers who did not provide their contact information, the increase in number of contacts also represented an increase in the quality of the sampling frame, as a larger proportion of the fishing population would be covered. However, there is potential bias due to the lack of information about the fishing activity carried out by the non-licensed fraction of the population. In fact, Gordoa et al. (2019) estimated that the 5% of fishers in Spain did not have a license, and that percentage would be even higher when considering fishers younger than 16 years old, who are not required to have such licenses (Eusko Jaurlaritza, 2000).

Still, it is not clear whether the amount and quality of the provided information is more related with survey method (e.g., time spent with each survey) or avidity (and therefore interest) of fishers' community. In fact, considering fishing effort as an approximation of avidity, estimates would be affected by year or source (i.e., phone vs email). Most of the responses were obtained from 30–50 year old fishers, which is in accordance with that observed throughout different regions of Spain by Dedeu et al. (2019). However, fulfilling email surveys might have been harder for older fishing population, which might skew the use of age distribution for different fishing modes based on survey responses. In any case, differences between responses from different fishing modes might be more related with fisher's age (e.g., spearfishing population is generally younger than boat fishers' population), experience, and interest, rather than with the survey methodology (National Research Council, 2006; Rocklin et al., 2014). According to that, both survey methods seem to be useful, although questionnaires should be re-defined to get more detailed information about (1) all captured species and (2) fishing effort, which might consider some additional variables such as the number of hooks per fisher or the number of fishers per boat, ignored in actual surveys.

Regarding catch estimates, data was more detailed in directed questionnaires by phone (i.e., surveys oriented to get estimates for seabass, tunids, squids), whereas the information regarding other captured species was much more extended on email surveys. This might be because fishers spent longer time thinking and filling the forms this way and were therefore more eager to include written information rather than providing extended information by phone. However, estimates of 'other species', written in open fields as 'additional information' and often qualitatively, resulted in underestimation biases. This was assessed here considering minimum catch estimates, which, in any case, showed conservative information about captured species not previously reported for MRF in the region. Nonetheless, adding more species in questionnaires also resulted in high amounts reported zero catches, which might indicate either real zeros or absence of information (e.g., Solow and Smith, 2010; Stoklosa et al., 2022). In fact, fishing mode and effort significantly affected the zero inflation in species composition, according to our results. Such zero-inflation bias might therefore be potentially related also with the fishers' profile, considering the degree of detail of the information provided by fishers from different modes and with different degree of experience, especially for those captures defined as 'other species'.

The main sources of bias in our probabilistic approach based on random selection of licenses to survey, might be associated with (1) undercoverage of the sampling frame, (2) previously mentioned non-responses (<10% for phone surveys), (3) the potential recall bias, (4) the non-licensed fraction of fishers from which no information could be obtained. Table 3 summarizes the generalized sources of bias, their potential consequences and suggested improvements that might be considered for future surveys. In this sense, while non-responses and potential recall bias could potentially be related to the fishers' profile (e.g., avidity, age, experience, or interest when providing data), other sources would be more due to logistic and/or budget limitations. In fact, in our study only retained species were reported so that data regarding released captures was not available for further analyses. On the other hand, the different sampling effort when conducting different surveys throughout our sampling period (e.g., no phone surveys could be made in 2017; in 2019 three sampling periods were defined contrasting with two periods considered during previous years) might also have affected final estimates. Besides, the lower response rates obtained by email which, at the same time, were filled by more avid fishers, might also suggest that further research is needed to determine the uncertainty and errors derived from different surveying methodologies, especially concerning catch estimates.

## 4.2 Basque MRF characterization

### 4.2.1 Fishers' profiles and fishing effort

The age range of the population in shore fishing was the highest, ranging from the youngest to the oldest fishers, since angling is always the most accessible recreational fishing mode. This was also well reflected in terms of fishing experience, which, in accordance with Papadopoulos et al. (2022), was relatively shorter for spearfishers. Those were generally younger than boat fishers, which in contrast, were older and had a higher degree of fishing experience (Vitale et al., 2021; Papadopoulos et al., 2022). However, most of fishers showed experiences ranging from 1 to 10 years in all fishing modes, which seems reasonable considering that most of the people that gets the fishing license goes fishing sporadically of in certain seasons of the year (e.g., during summer vacations). Given that age distribution of fishers was stable for the three fishing modes through years, we might not expect any relevant behavioral change in recreational fishing population in a near future.

The avidity of fishers was well reflected in the fishing effort, which varied depending on fishing mode. In accordance with general trends shore fishers, more in numbers and with more

TABLE 3 Summary of the main sources of bias in MRF surveys, potential consequences and suggested improvements that might be considered for future research.

| Source of bias for effort and catch estimates | Description | Potential consequences | Survey method affected | Suggested survey improvements |
|---|---|---|---|---|
| Undercoverage of sampling frame | Contact details from all fishers not available or uncomplete | Uncertainty on sample representativeness | Phone & Email | Make contact information mandatory for all licensed fishers |
| Non-responses | Catch and effort from less avid fishers is lost | Overestimated effort and catch estimates | Email > phone | Communication campaign |
| Recall bias | Difficulty to remember past fishing catch data | Overestimated catch estimates | Phone > Email | Reduce recall period<br>On-site surveys<br>Apps |
| Non-licensed fraction | Information from unlicensed fishers and <16 year old fishers is unavailable | Underestimated effort and catch estimates | Phone & Email | Surveys made for the whole population.<br>On-site surveys |

variable profiles, summed much higher fishing effort than boat fishers and spearfishers (Pita et al., 2018), the latter exerting <2% of the total recreational fishing effort during the sampling period. However, and similar to that observed, for instance, in northern Europe (van der Hammen et al., 2016), most fishers were active few days a year, whereas the most avid fishers were much less in numbers.

### 4.2.2 Catch estimates and captured species composition

This is the first study providing results of a 5–year sampling program of MRF in the Basque Country, answering to the DCF requirements in terms of annual catch estimates of seabass and albacore in the region (EU, 2016). Additionally, and despite they are not included as mandatory species in catch-reporting regulations, the same time series is provided for squids, given their importance especially for fishers in charge of small recreational boats that are designed for such purpose.

However, our estimates are skewed due to different bias identified, such as non-response, recall, quality of species' information and the sampling coverage. For instance, given that reported catches were extrapolated to the whole recreational population (i.e., total number of licenses), and despite both reported (real) zeros and non-response-derived zero inflation (Carlos-Júnior et al., 2020; Stoklosa et al., 2022), it might be reasonable to think that, for instance, not all recreational vessels exert fishing effort on tunids. This way and considering that recreational tuna fishery seems to be specialized, more dedicated surveys would be required to get better estimates that might be then compared with landings from commercial small-scale fishery, which could be the fishing sector that might present relevant potential interactions with MRF (Pascual-Fernández et al., 2015). In the same way, most of squid landings are known to be under-reported by commercial fishery, which might also make it difficult to determine this kind of interaction. Therefore, catch estimates are treated for relative comparisons between fishing modes, but could not be used to compare with landings from the commercial fishery. In the same way, the bias caused by dedicated questionnaires asking about albacore, squids and seabass suggests that relative comparisons should only be applied between these species.

Focusing on the three species targeted in our surveys, in terms of total landings, tunids were the most important species in MRF, all captured from boats and therefore by more experienced (and relatively older) fishers. Except the results from year 2015, which showed very low weights, the mean catch estimates for tunids ranged from 200 to 360 t (Figure 5), which, considering that are mostly due to albacore catches, are in line with catches estimated for this species by Ruiz et al. (2014) and Dedeu et al. (2019). Squids were the most abundant in numbers for both shore and especially boat fishing, and the second most important species for MRF in terms of landed weights. Estimated catches for the period of study ranged from 89 to 160 t, which is comparable with the weight calculated by Ruiz et al. (2014) but lower than those estimated by Dedeu et al. (2019) for the same region. Sea bass catches in the period of study ranged between 71 and 147 t, in accordance with previous results obtained in the area by Ruiz et al. (2014) and Zarauz et al. (2015) but being smaller than estimates from Dedeu et al. (2019).

On the other hand, additional capture information evidenced that many other species were often targeted by recreational fishers, as shown by minimum catch estimates. Shore fishers varied targeted species between trips more than boat and spearfishers but showed less species richness in each trip. This might be related with less experienced fishers, who might spend less time fishing by trip and have less success when capturing large amounts of different species. This way, in addition to the already assessed seabass, captures of sargo-breams (*Diplodus* spp.), gilthead seabream (*Sparus aurata*), common dentex (*Dentex dentex*) might also be relevant. In fact, considering their economic importance (Lloret et al., 2018), some dedicated shore fishing activity might be expected, which could derive in potential interactions with commercial small-scale fishery, the only fishing sector that brings such species into the local market (Lloret et al., 2018). Also, Atlantic mackerel (*Scomber scombrus*) might get some interest from shore fishers, especially in spring when this species gets closer to the coast (Uriarte and Lucio, 2001) allowing relatively important captures in short time. Despite the potential competition with commercial fishery is still open to discussion (i.e., due to the relatively low total landings in comparison with commercial catches), this might attract both avid and other fishers with a wide range of experience or age, that would be interested in shore fishing only during the corresponding season. The dedicated seasonal fishing activity (e.g., for sargo-breams and mackerel) might also explain the significant relationship found between captures and presence-absence capture probability with the fishing effort (i.e., fishing days). Captures of scorpionfish (*Scorpaena* spp.) might be related with anglers that search rocky areas not so accessible to everyone, which might suggest profiles with some degree of experience.

Regarding boat fishers, the variation in species composition was close to that observed for shore fishers, probably because the most important captured species (i.e., aside from albacore, seabass, and squids) were mackerel –which might also be concentrated in certain periods in spring (González-Álvarez et al., 2016)– and scorpionfish –appreciated species captured in rocky areas.

Spearfishers, much less in numbers in comparison with other fishing modes (Sbragaglia et al., 2021), showed the highest differences, with lower species alternation between trips, but different spearfishers targeting different specific fish groups. In addition to seabass, minimum catch estimates for sargo-breams were close to the 25% of the total catch in weight, which suggests that the real catch of this species by the whole spearfishing community might be important (Pita and Freire, 2016). Other important species targeted by spearfishers would be scorpionfish and conger, not so frequent but important in terms of weight. In this sense, spearfishers might be the most selective recreational fishers (Sbragaglia et al., 2021).

### 4.3 Conclusive remarks and future steps

This study shows evidence that not only tunids, squids and seabass are important but also other assessed (e.g., mackerel caught by shore and boat fishers) or unassessed species (e.g., sargo-breams, gilthead seabreams or common dentex caught by shore fishers and spearfishers) are commonly caught and might be relevant in terms of total landings. However, an improved re-definition of the sampling frame by each fishing mode and perhaps even by each fishery –based on target species (e.g., boat fishing targeting tunids, MRF targeting mackerel in spring, etc.)–, as well as dedicated sampling to collect information about all captured species, are required to get useful estimates. Results suggest that captures of certain species might be important, but further research is needed to determine the potential consequences of such an interaction with local commercial small-scale fisheries, which also exert certain fishing effort to those unassessed but still commercially important species.

This goes in line with the recent inclusion of statistically robust multispecies sampling schemes for MRF in the DCF (EU, 2021) which had been recommended repeatedly (Hyder et al., 2017a). This modification of the DCF is relevant, as recreational fishers are not required to register their activity, and the DCF is presently the main tool to collect information for this fishery. Historically, scientific assessments of marine fish stocks in Europe have been focused on the impacts caused by commercial fisheries and these have become the main target for data collection. Consequently, the impact of MRF has been underestimated and reduced to a limited list of species (ICES, 2020). With the inclusion of multispecies sampling schemes for MRF, it will be possible to obtain data on the overall impact of this activity in marine fish stocks.

In this sense, in addition to off-site surveys, questionnaires filled on-site allow getting better estimates of fishing effort (resolution in hours), captures (including fish length distribution and qualified identification) and detailed information about the fishing location and/or conditions (weather, tides, interactions with other fishing activities, etc.). Furthermore, the use and implementation of novel technologies such as smartphones application (apps) for data collection will also improve the collection of MRF data and their knowledge (Skov et al., 2021) for retained and released species, both required to feed models to get reliable recreational fishing effort estimates. Angler apps are potentially valuable source of conventional and novel data that are both frequent and extensive, and an opportunity to engage anglers through data sharing and citizen science (Venturelli et al., 2017). However, repeated surveys might cause less interest from fishers (vs. feeling of being controlled), so especially considering future on-site surveys in small villages, a balance between off-site and onsite surveys might be achieved.

Future MRF survey designs should therefore have to deal with getting the balance right between survey cost, precision, and accuracy, to get better catch estimates of both assessed and unassessed species that might be comparable with catches from commercial small-scale fishery in potential future scenarios with increased MRF activities (Freire et al., 2020).

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

## Funding

This work was cofounded by the Department of Economic Development, Sustainability and the Environment of the Basque Government, and the European Commission Data Collection Framework.

## Acknowledgments

We thank all the people who agreed to participate in telephone and e-mail surveys for providing information about their fishing activity. We are also thankful to all interviewers from Lanalden Contact Center for carrying out the telephone surveys. Finally, thanks are due to the reviewers for their useful comments, which contributed to improve the manuscript. This is contribution no. 1104 from AZTI (Marine Research Division).

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.975089/full#supplementary-material

## References


Baselga, A. (2010). Partitioning the turnover and nestedness components of beta diversity. *Glob. Ecol. Biogeogr.* 19, 134–143. doi: 10.1111/j.1466-8238.2009.00490.x

Baselga, A. (2012). The relationship between species replacement, dissimilarity derived from nestedness, and nestedness. *Glob. Ecol. Biogeogr.* 21, 1223–1232. doi: 10.1111/j.1466-8238.2011.00756.x

Baselga, A., and Orme, C. D. L. (2012). betapart : an r package for the study of beta diversity. *Methods Ecol. Evol.* 3, 808–812. doi: 10.1111/j.2041-210X.2012.00224.x

BOE (2018). Ley orgánica 3/2018, de 5 de diciembre, de protección de datos personales y garantía de los derechos digitales. *Sección I: Disposiciones Generales* p.119788–119857.

Carlos-Júnior, L. A., Creed, J. C., Marrs, R., Lewis, R. J., Moulton, T. P., Feijó-Lima, R., et al. (2020). Generalized linear models outperform commonly used canonical analysis in estimating spatial structure of presence/absence data. *PeerJ* 8, e9777. doi: 10.7717/peerj.9777

Chao, A., Chiu, C.-H., and Hsieh, T. C. (2012). Proposing a resolution to debates on diversity partitioning. *Ecology* 93, 2037–2051. doi: 10.1890/11-1817.1

Cowx, I. G., and Arlinghaus, R. (2008). ""Recreational fisheries in the twenty-first century: Towards a code of conduct,"," in *Global challenges in recreational fisheries* (Oxford, UK: Blackwell Publishing Ltd), 338–352. doi: 10.1002/9780470697597.ch17

Dedeu, A. L., Boada, J., and Gordoa, A. (2019). The first estimates of species compositions of Spanish marine recreational fishing reveal the activity's inner and geographical variability. *Fish. Res.* 216, 65–73. doi: 10.1016/j.fishres.2019.03.025

EU (2001). Council regulation (EC) no. 1639/2001 of 25 July 2001 establishing the minimum and extended community programmes for the collection of data in the fisheries sector and laying down detailed rules for the application of council regulation (EC) no. 1543/20. *Off. J. Eur. Union. L 222* p.53–115

EU (2008a). Commission decision of 6 November 2008 adopting a multiannual community programme pursuant to council regulation (EC) no 199/2008 establishing a community framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the Common Fisheries Policy. *Off. J. Eur. Union* L 60 5.3.2008, p. 1–12

EU (2008b). Directive 2008/56/EC of the European parliament and of the council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine strategy framework directive). *Off. J. Eur. Union.* L 164 p.19–40

EU (2010). Commission decision of 18 December 2009 adopting a multiannual community programme for the collection, management and use of data in the fisheries sector for the period 2011–2013. *Off. J. Eur. Union.* L 41, p.8–71

EU (2011). Commission implementing regulation (EU) no 404/2011 of 8 April 2011 laying down detailed rules for the implementation of council regulation (EC) no 1224/2009 establishing a community control system for ensuring compliance with the rules of the common fish. *Off. J. Eur. Union.* L 112, p.1–153.

EU (2013). Regulation (EU) no 1380/2013 of the European parliament and of the council, on the common fisheries policy, amending council regulations (EC) no 1954/2003 and (EC) no 1224/2009 and repealing council regulations (EC) no 2371/2002 and (EC) no 639/2004 and Council Decision 2004/585/EC. *Off. J. Eur. Union..* L 354, p.22–61

EU (2014). Directive 2014/89/EU of the European parliament and of the council of 23 July 2014 establishing a framework for maritime spatial planning. *Off. J. Eur. Union,* L 257, p.135–145.

EU (2016). *Commission implementing decision (EU) 2016/1251 of 12. July 2016 adopting a multiannual union programme for the collection, management and use of data in the fisheries and aquaculture sectors for the period 2017-2019 (European Union). Off. J. Eur. Union* L 207, p.113–177.

EU (2021). Commission delegated decision (EU) 2021/1167 of 27 April 2021 establishing the multiannual union programme for the collection and management of biological, environmental, technical and socioeconomic data in the fisheries and aquaculture sectors from 2022 (European Union). *Off. J. Eur. Union,* L 253, p.51–90.

FAO (2022). *Rreport from the commission to the European parliament and the council outlining the progress made in implementing directive 2014/89/EU establishing a framework for maritime spatial planning* (Brussels:Aquatic Science and Fisheries Abstracts (ASFA)), 19pp.

Eusko Jaurlaritza (2000). *198/2000 DEKRETUA, urriaren 3koa, itsasoko kirol arrantzaren arautegia onartzeko dena* (Basque Country: Eusko Jaurlaritza (EJ-GV).

FAO (2012). "*Recreational fisheries,*" in *FAO technical guidelines for responsible fisheries. no. 13* (Rome: Food and Agriculture Organization of the United Nations (FAO)).

Freire, K. M. F., Belhabib, D., Espedido, J. C., Hood, L., Kleisner, K. M., Lam, V. W. L., et al. (2020). Estimating global catches of marine recreational fisheries. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00012

García-Flórez, L., Alcázar-Álvarez, J. L., Fernández-Rueda, M. P., Mortera-Piorno, H., and Apilánez-Piniella, I. (2012). Caracterización de la pesca marítima de recreo en el principado de asturias. gobierno del principado de asturias. Chapter 1. Asturias, Spain: Report from Centro de Experimentación Pesquera, 71pp

González-Álvarez, J., García-de-la-Fuente, L., García-Flórez, L., Fernández-Rueda, M., del, P., and Luis Alcázar-Álvarez, J. (2016). Identification and characterization of métiers in multi-species artisanal fisheries. a case study in Northwest Spain. *Nat. Resour.* 07, 295–314. doi: 10.4236/nr.2016.76026

Gordoa, A., Dedeu, A. L., and Boada, J. (2019). Recreational fishing in Spain: First national estimates of fisher population size, fishing activity and fisher social profile. *Fish. Res.* 211, 1–12. doi: 10.1016/j.fishres.2018.10.026

Herfault, J., Levrel, H., Thebaud, O., and Veron, G. (2013). The nationwide assessment of marine recreational fishing: A French example. *Ocean. Coast. Manage.* 78, 121–131. doi: 10.1016/j.ocecoaman.2013.02.026

Hyder, K., Maravelias, C. D., Kraan, M., Radford, Z., and Prellezo, R. (2020). Marine recreational fisheries — current state and future opportunities. *ICES. J. Mar. Sci.* 77, 2171–2180. doi: 10.1093/icesjms/fsaa147

Hyder, K., Radford, Z., Prellezo, R., Weltersbach, M. S., Lewin, W.-C., Zarauz, L., et al. (2017a). Research for PECH committee - marine recreational and semi-subsistence fishing - its value and its impact on fish stocks. *Eur. Parliam. Policy Departm. Struct. Cohes. Polic. Brussels.* 140pp. doi: 10.2861/277908

Hyder, K., Weltersbach, M. S., Armstrong, M., Ferter, K., Townhill, B., Ahvonen, A., et al. (2017b). Recreational sea fishing in Europe in a global context-participation rates, fishing effort, expenditure, and implications for monitoring and assessment. *Fish. Fish.* 19, 225–243. doi: 10.1111/faf.12251

ICES (2012). *Report of the second workshop on practical implementation of statistical sound catch sampling programmes, 6 - 9 November* (Copenhagen, Denmark:ACOM 52), 72pp

ICES (2020). *Working Group on Recreational Fisheries Surveys (WGRFS; outputs from 2019 meeting). ICES Scientific Reports* vol. 2 ICES :Copenhagen, Denmark, 86pp

Lewin, W.-C., Weltersbach, M. S., Ferter, K., Hyder, K., Mugerza, E., Prellezo, R., et al. (2019). Potential environmental impacts of recreational fishing on marine fish stocks and ecosystems. *Rev. Fish. Sci. Aquac.* 27, 287–330. doi: 10.1080/23308249.2019.1586829

Lloret, J., Cowx, I. G., Cabral, H., Castro, M., Font, T., Gonçalves, J. M. S., et al. (2018). Small-scale coastal fisheries in European seas are not what they were: Ecological, social and economic changes. *Mar. Policy* 98, 176–186. doi: 10.1016/j.marpol.2016.11.007

Lloret, J., Zaragoza, N., Caballero, D., Font, T., Casadevall, M., and Riera, V. (2008a). Spearfishing pressure on fish communities in rocky coastal habitats in a Mediterranean marine protected area. *Fish. Res.* 94, 84–91. doi: 10.1016/j.fishres.2008.07.002

Lloret, J., Zaragoza, N., Caballero, D. , and Riera, V. (2008b). Biological and socioeconomic implications of recreational boat fishing for the management of fishery resources in the marine reserve of cap de creus (NW Mediterranean). *Fish. Res.* 91, 252–259. doi: 10.1016/j.fishres.2007.12.002

Lumley, T. (2011). *Complex surveys: A guide to analysis using r 16th Edition* (Harvard, Boston, USA:Wiley), 296pp.

Lumley, T. (2020). *Survey: analysis of complex survey samples.*

Morales-Nin, B., Moranta, J., García, C., Tugores, M. P., Grau, A. M., Riera, F., et al. (2005). The recreational fishery off Majorca island (western mediterranean): some implications for coastal resource management. *ICES. J. Mar. Sci.* 62, 727–739. doi: 10.1016/j.icesjms.2005.01.022

National Research Council (2006). *Review of recreational fisheries survey methods* (Washington, D.C: National Academies Press). doi: 10.17226/11616

Palas, S., Villasante, S., and Pita, P. (2017). Combining fishers' knowledge and cost-effective monitoring tools in the management of marine recreational fisheries: A case study of the squid and cuttlefish fishery of the ría of vigo (NW Spain). *Fish. Manage. Ecol.* 24, 469–477. doi: 10.1111/fme.12255

Papadopoulos, A., Touloumis, K., Tziolas, E., Boulamatsis, D., and Koutrakis, E. (2022). Evaluation of marine recreational fisheries and their relation to sustainability of fisheries resources in Greece. *Sustainability* 14, 3824. doi: 10.3390/su14073824

Pascual-Fernández, J. J., Chinea-Mederos, I., and de la Cruz-Modino, R. (2015). *"Marine protected areas, small-scale commercial versus recreational fishers: Governability challenges in the canary islands, spain,"*. 397–412. doi: 10.1007/978-3-319-17034-3_21

Pita, P., Alós, J., Antelo, M., Artetxe, I., Biton-Porsmoguer, S., Carreño, A., et al. (2020). Assessing knowledge gaps and management needs to cope with barriers for environmental, economic, and social sustainability of marine recreational fisheries: The case of Spain. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00023

Pita, P., Artetxe, I., Diogo, H., Gomes, P., Gordoa, A., Hyder, K., et al. (2017). Research and management priorities for Atlantic marine recreational fisheries in southern Europe. *Mar. Policy* 86, 1–8. doi: 10.1016/j.marpol.2017.08.030

Pita, P., and Freire, J. (2016). Assessing the impact of spear fishing by using competitions records and underwater visual censuses. *Sci. Mar.* 80, 27–38. doi: 10.3989/scimar.04352.15A

Pita, P., Hyder, K., Gomes, P., Pita, C., Rangel, M., Veiga, P., et al. (2018). Economic, social and ecological attributes of marine recreational fisheries in Galicia, Spain. *Fish. Res.* 208, 58–69. doi: 10.1016/j.fishres.2018.07.014

Radford, Z., Hyder, K., Zarauz, L., Mugerza, E., Ferter, K., Prellezo, R., et al. (2018). The impact of marine recreational fishing on key fish stocks in European waters. *PloS One* 13, e0201666. doi: 10.1371/journal.pone.0201666

R Core Team (2021) *R: A language and environment for statistical computing.* Available at: http://www.mendeley.com/research/r-language-environment-statistical-computing-96/%5Cnpapers2://publication/uuid/A1207DAB-22D3-4A04-82FB-D4DD5AD57C28.

Rocklin, D., Levrel, H., Drogou, M., Herfaut, J., and Veron, G. (2014). Combining telephone surveys and fishing catches self-report: The French Sea bass recreational fishery assessment. *PloS One* 9, e87271. doi: 10.1371/journal.pone.0087271

Ruiz, J., Zarauz, L., Urtizberea, A., Andonegi, E., Mugerza, E., and Artetxe, I. (2014). *Establecimiento de un sistema de recogida sistemática de datos sobre pesca recreativa.*

Sbragaglia, V., Arlinghaus, R., Blumstein, D., Coll, M., Dedeu, A., Diogo, H., et al. (2021). Spearing into the future: a global review of marine recreational spearfishing. *EcoEvoRxiv. Prepr.*, 44pp doi: 10.32942/osf.io/f5whn

Skov, C., Hyder, K., Gundelund, C., Ahvonen, A., Baudrier, J., Borch, T., et al. (2021). Expert opinion on using angler smartphone apps to inform marine fisheries management: status, prospects, and needs. *ICES. J. Mar. Sci.* 78, 967–978. doi: 10.1093/icesjms/fsaa243

Solow, A. R., and Smith, W. K. (2010). On predicting abundance from occupancy. *Am. Nat.* 176, 96–98. doi: 10.1086/653077

Stoklosa, J., Blakey, R. V., and Hui, F. K. C. (2022). An overview of modern applications of negative binomial modelling in ecology and biodiversity. *Diversity* 14, 320. doi: 10.3390/d14050320

Tarrant, M. A., and Manfredo, M. (1993). Digit preference, recall bias, and nonresponse bias in self reports of angling participation. *Leis. Sci.* 15, 231–238. doi: 10.1080/01490409309513202

Tarrant, M. A., Manfredo, M., Bayley, P. B., and Hess, R. (1993). Effects of recall bias and nonresponse bias on self-report estimates of angling participation. *North Am. J. Fish. Manage.* 13, 217–222. doi: 10.1577/1548-8675(1993)013<0217:EORBAN>2.3.CO;2

Taylor, S. M., Webley, J. A. C., and Mayer, D. G. (2011). Improving the precision of recreational fishing harvest estimates using two-part conditional general linear models. *Fish. Res.* 110, 408–414. doi: 10.1016/j.fishres.2011.05.001

Uriarte, A., and Lucio, P. (2001). Migration of adult mackerel along the Atlantic European shelf edge from a tagging experiment in the south of the bay of Biscay in 1994. *Fish. Res.* 50, 129–139. doi: 10.1016/S0165-7836(00)00246-0

van der Hammen, T., de Graaf, M., and Lyle, J. M. (2016). Estimating catches of marine and freshwater recreational fisheries in the Netherlands using an online panel survey. *ICES. J. Mar. Sci. J. Du. Cons.* 73, 441–450. doi: 10.1093/icesjms/fsv190

Venables, W. N., and Ripley, B. D. (2002). *Modern applied statistics with s. fourth edi* (New York: Springer, New York). Available at: http://scholar.google.com/scholar?q=related:29252RNVomwJ:scholar.google.com/&hl=en&num=100&as_sdt=0,5%5Cnpapers2://publication/uuid/E2522B53-755A-48D4-925F-A02094784F2C.

Venturelli, P. A., Hyder, K., and Skov, C. (2017). Angler apps as a source of recreational fisheries data: opportunities, challenges and proposed standards. *Fish. Fish.* 18, 578–595. doi: 10.1111/faf.12189

Vitale, G., Dedeu, A. L., Pujol, M., and Sbragaglia, V. (2021). Characterizing the profile of recreational fishers who share their catches on social media. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.768047

Wickham, H. (2009). *ggplot2: elegant graphics for data analysis* (New York, USA.:Springer), 213pp. Available at: http://books.google.com/books?id=rhRqtQAACAAJ&dq=intitle:ggplot2+inauthor:wickham&ie=ISO-8859-1&source=gbs_gdata.

Zarauz, L., Ruiz, J., Urtizberea, A., Andonegi, E., Mugerza, E., and Artetxe, I. (2015). Comparing different survey methods to estimate European sea bass recreational catches in the Basque country. *ICES. J. Mar. Sci.* 72, 1181–1191. doi: 10.1093/icesjms/fsv054

Zeileis, A., Kleiber, C., and Jackman, S. (2008). Regression models for count data in r. *J. Stat. Software* 27 (8), 1–25. doi: 10.18637/jss.v027.i08

Zhang, C., Xu, B., Xue, Y., and Ren, Y. (2020). Evaluating multispecies survey designs using a joint species distribution model. *Aquac. Fish.* 5, 156–162. doi: 10.1016/j.aaf.2019.11.002

Zuur, A. F., Ieno, E. N., and Elphick, C. S. (2010). A protocol for data exploration to avoid common statistical problems. *Methods Ecol. Evol.* 1, 3–14. doi: 10.1111/j.2041-210X.2009.00001.x

Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A., and Smith, G. M. (2009). *Mixed effects models and extensions in ecology with r* (New York: Springer-Verlag).

frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 20 September 2022
DOI 10.3389/fmars.2022.973251



# Assessing the importance of kelp forests for small-scale fisheries under a global change scenario

Cristina Piñeiro-Corbeira[1]*, Sara Barrientos[1], Rodolfo Barreiro[1] and Raquel de la Cruz-Modino[2]*

[1]BioCost Research Group, Facultad de Ciencias and Centro de Investigaciones Científicas Avanzadas (CICA), Universidad de A Coruña, A Coruña, Spain, [2]Instituto de Investigación Social y Turismo, University of La Laguna, Tenerife, Spain

OPEN ACCESS

EDITED BY
Pablo Pita,
University of Santiago de Compostela, Spain

REVIEWED BY
Diana Fernández Márquez,
Regional Government of Galicia, Spain
Luis Malpica-Cruz,
Universidad Autónoma de Baja California, Mexico

*CORRESPONDENCE
Cristina Piñeiro-Corbeira
c.pcorbeira@udc.es
Raquel de la Cruz-Modino
rmodino@ull.edu.es

SPECIALTY SECTION
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

RECEIVED 19 June 2022
ACCEPTED 29 August 2022
PUBLISHED 20 September 2022

CITATION
Piñeiro-Corbeira C, Barrientos S, Barreiro R and de la Cruz-Modino R (2022) Assessing the importance of kelp forests for small-scale fisheries under a global change scenario. *Front. Mar. Sci.* 9:973251. doi: 10.3389/fmars.2022.973251



Kelp forests are critical habitats for temperate coasts that are experiencing dramatic declines worldwide in recent decades. Yet, even though they often support wildlife populations of high socioeconomic value, the consequences of kelp forest decline for small-scale fisheries (SSFs) have received surprisingly little attention. Here, we take the first step to fill this gap through the local ecological knowledge (LEK) of SSF fishers whose fisheries are associated with this habitat in NW Spain. LEK was used to 1) estimate kelp forest loss, 2) identify the main fisheries associated with kelp forests, 3) gain insight into the changes these fisheries may have undergone in recent times, 4) evaluate the economic importance of kelp in the study area, and 5) describe the commercial chain of exploited kelps and relevant fisheries related to them. Fisher's knowledge of kelp forests was documented through interviews with the help of a semi-structured questionnaire with open–closed questions about the small-scale fishery and its target species. Additionally, participants were asked to map the current and former (20 years ago) distribution of kelp forests in their fishing area. Results show that a range of fish, crustaceans, mollusks, echinoderms, and even the kelp itself are fished/harvested in the study area, suggesting the socioeconomic value of those species. The most intensively targeted species usually belong to fisheries with high commercial value, and first-sale data indicate that they are worth some 10 million euros to the local economy. On the other hand, compared to two decades ago, fishers reported a substantial contraction in the area occupied by kelp forests and decreases in the fisheries typically associated with this habitat. Landing data partly support this perception of a decline in catches. Altogether, this information will be useful to foster kelp forest conservation and to evaluate their socioecological and economic implications for SSFs.

KEYWORDS
**management, fisheries, ecological knowledge, kelp forest, small-scale fisheries**

## Introduction

Kelp forests are highly productive habitats that dominate temperate rocky reefs in most marine environments worldwide, providing multiple ecological, economic, and cultural ecosystem services (Steneck and Johnson, 2014; Vergés and Campbell, 2020). Among other functions, kelps enhance local biodiversity by being foundation species that create biogenic habitats and facilitate complex biological interactions (Dayton, 1985; Steneck and Johnson, 2014, Krumhansl et al., 2016). Their role as habitat providers include many commercial species with high economic value (Blamey and Bolton, 2018; Vergés and Campbell, 2020). In particular, abalones and lobsters are typically regarded as the most important commercial fisheries linked to kelp forests, generating millions every year worldwide (Smale et al., 2013, Bennett et al., 2016, Carr and Reed, 2016; Blamey and Bolton, 2018). The best estimates of the value of the ecosystem services (e.g., fisheries) provided by kelp forests are from South Africa and Australia. In South Africa (Blamey and Bolton, 2018) and the Australian Great Southern Reef (Bennett et al., 2016), it has been estimated that kelp forests generate a revenue of 434 million/year US$ (427 million/year €) and 1,066.4 million/year AU$ (726 million/year €), respectively, of commercial/recreational fisheries. In Europe, only a few investigations have explored in depth the commercial fisheries linked to kelp forests in the NE Atlantic. Those studies have estimated, for example, a revenue of ~£30 million per year (35 million/year €) to the UK economy alone for the lobster fishery (*Homarus gammarus*) (Smale et al., 2013 and references within). Despite the importance of kelp forests for the fishing sector (Bertocci et al., 2015), there are still gaps in the knowledge of commercial fisheries that depend on these habitats in many areas.

Kelp species themselves are a valuable economic resource in many areas (Bajjouk et al., 2015, Blamey and Bolton, 2018, González-Roca et al., 2021). In Europe, the use of kelps dates back to the Neolithic period (Mesnildrey et al., 2012). Currently, kelp harvesting is a traditional activity in many Atlantic European small-scale communities, such as Northwest Brittany (Alban et al., 2004) or Norway (Frangoudes, 2011), and it has had different social purposes including human consumption, animal feed, medicines, fertilizers, and even as building materials (Frangoudes and Garineaud, 2015, Delaney et al., 2016). In this regard, many of the ecosystem services that kelp forests provide for human well-being are also threatened by their losses (Hynes et al., 2021).

In NW Spain, kelp forests host a diversity of faunal groups with commercial value in the region, such as fishes (e.g., *Labrus bergylta*, *Dicentrarchus labrax*, and *Pollachius pollachius*), crustaceans (e.g., *Maja brachydactyla*), mollusks (e.g., *Octopus vulgaris*), and echinoderms (*Paracentrotus lividus*) (Pita et al., 2018, Pita and Freire, 2019, Fernández et al., 2020). Many of these species move millions of euros (€) annually (Pita et al., 2016, Piñeiro-Corbeira et al., 2022) in the region. Fishing in this region is mainly characterized as small-scale fisheries (SSFs), where the fishing activity plays a vital role in providing employment and sustainable livelihoods for people and maintaining cultural heritage (Pascual-Fernández et al., 2020a). Here, SSF fishing activities are conducted nearshore, many of them on rocky reefs dominated by kelp forests (Guyader et al., 2013, Piñeiro-Corbeira et al., 2022). In fact, Galicia concentrates 57.37% of the Spanish small-scale fleet, being one of the regions with the highest socioeconomic dependence on fishing in the European Union (EU) (Villasante et al., 2015). Fishing landings are sold fresh in the fish markets of each zone at daily auctions (Surís-Regueiro and Santiago, 2014). Many of the fish auctions are managed by *cofradías* (fisher organizations) (Bavinck et al., 2015, Pascual-Fernández et al., 2020b). After that, marine products are distributed, thanks to large fish processors, local fish merchants, and retail traders, until they reach the local marketplace and supermarkets and restaurateurs. Seaweeds themselves also have a relevant economic value, being the kelp-harvesting sector that has grown in recent decades (Piñeiro-Corbeira et al., 2022). In fact, in Galicia, four species are harvested, processed, and distributed by national and international retailers.

As in other regions, kelp forests are also declining in Galicia (Barrientos et al., 2022a, Barrientos et al., 2022b), and it has been especially dramatic in the only marine and terrestrial National Park on the Atlantic Spanish coast. To fill this gap in southern Europe, in this study, we have incorporated the SSF knowledge to assess, on the one hand, the loss of kelp forests and its implications using their historical perspective and their local ecological knowledge (LEK) (Neis et al., 1999). Specifically, we carried out this study in collaboration with the small-scale fishers in the study areas of Ría de Vigo and the Islas Atlanticas National Park (IANP). On the other hand, the study was performed to define which are the most important fisheries associated with kelp forests and finally to gain insight into the changes that these fisheries have suffered due to the loss of kelp forests. This collaborative research through participatory mapping (Aswani and Lauer, 2006) and interviews allowed us to advance on research under a data-poor scenario and then assess local stakeholders' perceptions about it (Trimble and Berkes, 2013).

## Materials and methods

The study was carried out in NW Spain along the Galician Ría de Vigo fishing zone and its area of influence, which includes the Cíes Archipelago belonging to the IANP (Figure 1). In this fishing area, 16 *cofradías* concentrate approximately 573 small-scale fishing boats, but not all of them fish on kelp areas. For this reason, we focused our study on three of them: Cofradía de Vigo, Cofradía de Cangas, and Cofradía de Baiona, with 227 small-scale fishing boats.

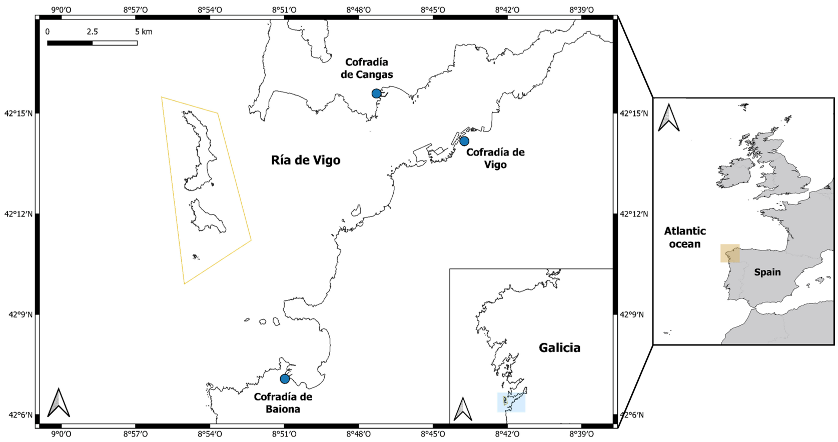



FIGURE 1
Map showing the study area (colored boxes) and the location of the three *cofradías* involved in the study. Polygon is the National Park boundary.

Collaborative research activities were carried out by combining individual small-scale fishers' face-to-face semi-structured interviews (Bernard, 2017) and informal conversations with key stakeholders (e.g., secretaries of *cofradías*, scuba divers, scientists) (n = 20). A questionnaire was used for gathering information from local fishers (Berkström et al., 2019) with open-ended questions. Interviews were conducted between 2020 and 2021 in the three *cofradías* selected, with a questionnaire of 38 questions including binomial (YES/NO), open-ended, and 1 to 5 liker-scale answers. Data collection and storage procedures were followed to ensure proper information, confidentiality, anonymity, and consent. The collected data will remain confidential, will be used only for research purposes, and will not be made available to third parties. The acquisition and processing of personal data were done in conformity with the European legislation (Directive 95/46/EC). Questions covered three main topics: 1) characterization of the main fisheries, including those in kelp forests and kelp harvesting, and 2) main fisheries and 3) harvesting activities in the IANP and Ría de Vigo. In all cases, fishers' perceptions of changes in the described activities and in the marine environment were included.

In addition, different participatory maps (n = 50) (Aswani and Lauer, 2006) were produced with the collaboration of the fishers who were interviewed. Information provided by fishers about the historical reconstruction of kelp forests was compared with data from underwater visual census in the area made by other studies carried out in parallel by the research team of this study (Piñeiro-Corbeira et al., 2021, Barrientos, et al., 2022a, Barrientos et al., 2022b). The *cofradías* had a critical facilitating role in identifying the most experienced fishers who usually work in kelp forest areas. Consequently, four fishing productive units that harvest seaweeds (*Laminaria ochroleuca* and *Laminaria hyperborea*) in Ría de Vigo were extensively interviewed. A small-scale fishing productive unit integrates a group of people involved in the economic activity of fishing (e.g., catching, processing, and distribution) and who may assume different roles (Pascual Fernández, 1991). They can have more than one boat and, considering their members, accumulate knowledge, expertise, and skills over generations, which allows them to position themselves in the marine environment activities (De la Cruz-Modino et al., 2022, Piñeiro-Corbeira et al., 2022). Additionally, 16 small-scale fishers who harvest target species associated with kelp forests in Ría de Vigo and the IANP were likewise interviewed. All were asked to mark on a map their fishing areas, kelp forest locations, and places where kelp has disappeared. A nautical chart (1:42,000) of the study area was provided to each participant together with fine-tipped colored pens to mark the areas where kelp is still present, areas where it has disappeared, and fishing areas for their most valuable fisheries associated with these habitats. Information provided during the questionnaire-led interviews and the kelp forest and fishing areas drawn in maps were digitized and georeferenced into a Geographic Information System (GIS) using a polygon shapefile using QGIS 3.24.3-Tisler. Digitized maps were combined into a single map to visualize similarities and differences in the information provided by the interviewees.

Landings data (weight and economic value in €) from 2001 and 2021 for species associated with kelp forests were obtained from the regional government called *Xunta de Galicia* (https://www.pescadegalicia.gal/). This information derives from sales notes issued by fish auctions or authorized centers for the first sale of fresh fish products. Landings trends between 2001 and 2021 were analyzed using a simple regression procedure with the help of the statistical package Statgraphics Centurion XVI (StatPoint Technologies, Inc.). Data from *Xunta de Galicia* were also employed to identify the seaweed harvesting landings by *cofradía* and their value. Thanks to the support of the biologists of the *cofradías*, we identified the most experienced fishers related to kelps. On the other hand, thanks to the support of the *cofradías* and some regional fishing responsible, we could reconstruct the distribution chain of the different marine resources that can be exploited in the kelp forests, including the kelp itself. We reconstructed these patterns for several species through a graphical component in this paper.

## Results

Given that this project was carried out during the coronavirus disease 2019 (COVID-19) pandemic and that some fishers temporarily ceased activity, we estimate that there were 200 fishers actively working during this period in the study area. Some of them fish by combining different productive units (De la Cruz-Modino et al., 2022, Piñeiro-Corbeira et al., 2022) and different fisheries along the year. Based on the interviews and questionnaires implemented to the three *cofradías* that contributed to this project, we estimate that at least 150 fishers may focus their extractive activity mainly on kelp forest habitats, and all of them work in the IANP regularly.

### Historical reconstruction of kelp forests

According to the fishers who were interviewed, kelp forests occur along the entire rocky coast of Ría de Vigo and nearby areas. However, they have perceived a decline in their occurrence (Figure 2). Most of them agree that this loss started about 15 years ago and increased more recently. According to their perceptions, most of the kelp forest loss occurred outside Ría, where only isolated patches of kelp forest habitat remain in some areas (Figure 2). On the other hand, kelp forests persist along most of the rocky coastline inside Ría, although, also in this area, some fishers identified sites where kelp forest areas have shrunk. Overall, according to information obtained from fishers, in recent years, kelp forests would have lost 1,913.59 ha and would still be present on 2,708.905 ha. This represents a loss of 41.4% of the kelp forests estimated to have existed at least 15 years ago. These results coincide with the observations of key informants (e.g., researchers, National Park managers) who observed the loss of kelp forests in the IANP and the presence of healthy forests inside Ría.

### Fisheries associated with kelp forests

Fishers in Ría de Vigo dedicate their fishing effort to more than one species. According to information obtained by the interviews, 32 species are fished in kelp forest areas (Supplementary Material Table S1) contributing to the local economy, with 17 million € in 2021, at the first sale point. Most fishers focus on between four and six species throughout the year, although three of the interviewed catch between eight and 14 species (Supplementary Material Figure S1). In most cases, these species were caught in areas currently or formerly occupied by kelp forests. The main groups captured in kelp forest sites were fishes, mollusks, and crustaceans, followed by echinoderms, seaweeds, and cnidarians (Supplementary Material Figure S2).

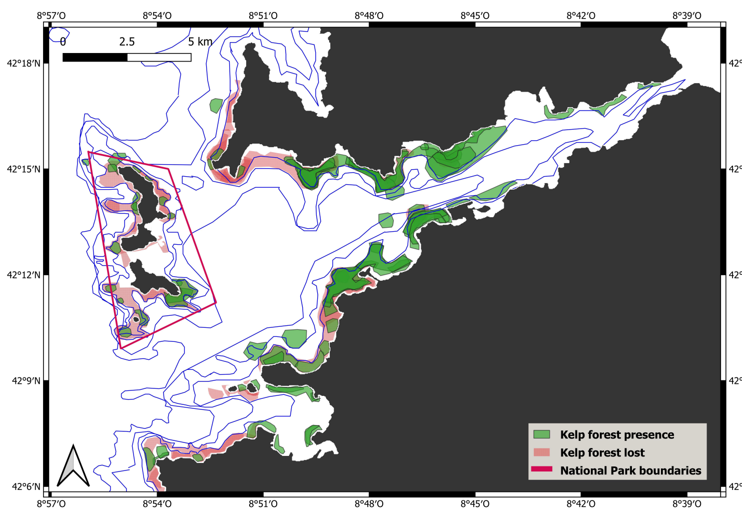



FIGURE 2
Kelp forest distribution in the study area inferred from local ecological knowledge. The map integrates the information provided by local small-scale fishers on the current (kelp forest present) and historical (kelp forest lost) occurrence of kelp forest areas in Ría de Vigo.

*Necora puber*, *M. brachydactyla*, and *O. vulgaris* were the main fisheries, considering their commercial value, followed by the fishes *D. labrax* and *L. bergylta* and the sea urchin *P. lividus* (Figure 3).

Our results indicate that kelp forest areas are under high fishing pressure throughout the year. All of the small-scale fishers who were interviewed carry out their activity in Ría de Vigo and the IANP, although the particular places where they do most of their fishing depend on which *cofradía* they belong to (Supplementary Material Figure S3). Most fishers always fish in the same areas, regardless of the target species, and only change the fishing gear they use at any given time. They employ a range of nets (purse seines, gillnets, and trammel nets) and pots and hook-and-line gear (longlines, drifting longlines). Nets are mainly used for some fishes (e.g., *Mullus surmuletus*, *Diplodus sargus*, *L. bergylta*) and spider crab *M. brachydactyla*, while hook-and-line gear is used for fishes such as *D. labrax* and *P. pollachius*. On the other hand, pots are used to fish all crustaceans (e.g., *N. puber*, *H. gammarus*, *Palaemon serratus*), some fishes (*Trisopterus luscus*, *Conger conger*), and some mollusks (*O. vulgaris*, *Sepia officinalis*). Seaweeds, the sea urchin *P. lividus*, and the mollusk *Haliotis tuberculata* are fished by hookah diving.

Although all species are eventually caught everywhere along the rocky coastline in the study area, our results show that invertebrates (Figure 3) are fished over larger areas than fish (Figure 4). *N. puber* is the species that is captured at most sites, followed by *M. brachydactyla* and *O. vulgaris*. This information is consistent with landings data, where these species were among those landed in largest quantities between 2001 and 2021 (Figure 5). In fact, together with *P. serratus*,

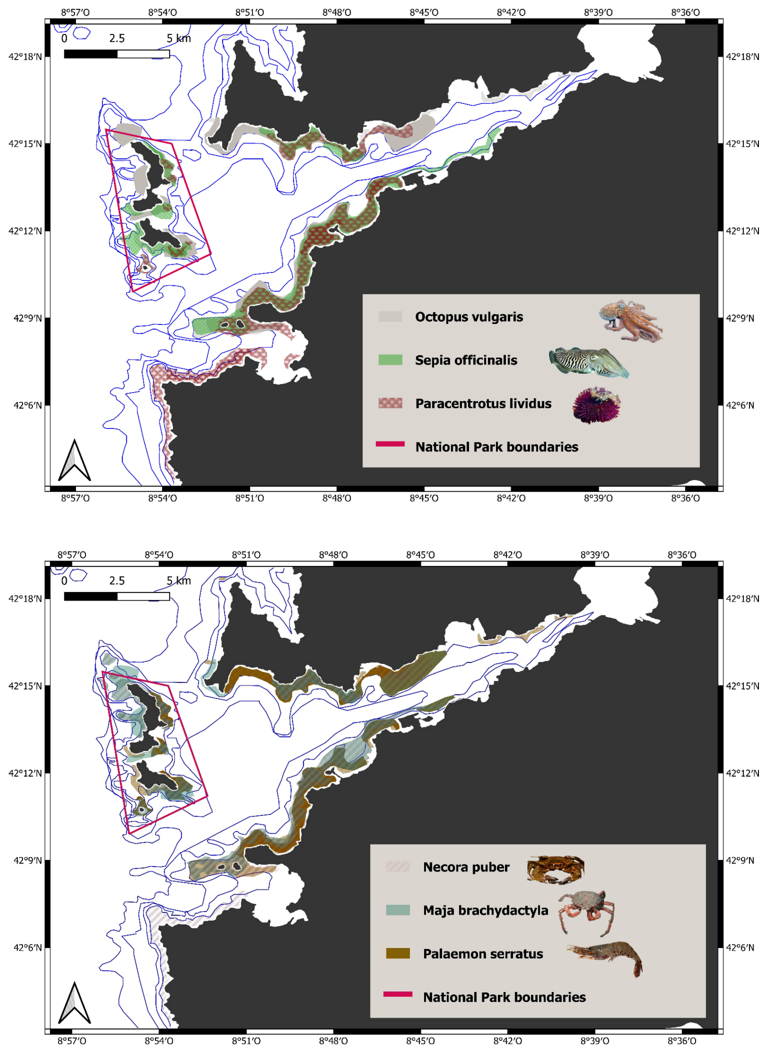



FIGURE 3
Fishing areas of invertebrate commercial species with higher economic value in Ría de Vigo inferred from fishers who were interviewed.

*S.officinalis*, and *P. lividus*, these species are among the highest priced in the region, contributing to the local economy an average of ~5.5 million €/year (first sale estimate, value-added is not included) (Figure 5). Of the fish that inhabit kelp forest areas, the interviewed fishers caught some of the most economically valuable fish according to 2001–2021 landings data (*D. labrax*, *D. sargus*, *C. conger*, and *Pagellus bogaraveo*). *D. labrax* and *D. sargus* are the species caught in most sites in Ría, especially within the National Park, followed by *C. conger*. *P. bogaraveo*, on the other hand, is fished in small well-defined areas. All of them together contributed an average of ~3 million €/year to the local economy (first sale estimate, value-added is not included) (Figure 5).

## Fishers' perceptions about kelp forest loss and its impact on small-scale fisheries

Most fishers noticed changes in their fishing areas at rocky reefs dominated by kelp forests ($n$ = 14). In most cases, they highlighted a decrease in fishing catches in the areas where kelps were no longer present. Some said that since there was no kelp forest, fish breed less or even move to deeper areas where kelp is still found. Three of the interviewees said that they did not know the reasons why there is less fishing in areas where kelps disappeared and that these changes vary from one year to another. Some believe that overfishing could also be another reason for the decline in fisheries. One of the interviewees stated that he had had to change the way he fished because of these changes. Most of the interviewees agreed that these fishing changes have been taking place for the last 10 years. Overall, landings data partly support these perceptions, as two of the main fisheries showed a clear decline over the last 10 years: octopus (slope = -0.030 ± 0.017 kg/year; $P$-value = 0.0921) and the conger eel (slope = -0.066 ± 0.012 kg/year; $P$-value = 0.0000). On the other hand, landings for spider crab (slope = 0.081 ± 0.016 kg/year; $P$-value = 0.0001) and velvet swimming crab *N. puber* (slope = 2.067 ± 0.658 kg/year; $P$-value = 0.0054) showed an increase in recent years (Supplementary Material Figure S4). Other fisheries showed no obvious trend over time, with small fluctuations among years.

Seaweed harvesters ($n$ = 4) also admitted to having noticed changes in their seaweed harvesting areas. In their case, they have had to devote their fishing effort to other kelps and even to other seaweeds. Two harvesters said that they have been noticing these changes for more than 10 years. Contrary to this, two of them believe that the changes have a seasonal component and vary greatly from year to year. In any case, all kelp harvesters affirm that the increase in herbivory pressure by an herbivorous fish (*Sarpa salpa*) was the reason for the loss of kelp forest areas. Many of the interviewed highlighted that this fish increased its abundance in recent years. In fact, fishers reported that they capture *S. salpa* in the waters of the IANP frequently, precisely where the greatest losses of kelp forest area have been reported (Supplementary Material Figure S5). Data landings support this fishers' perception (slope = 0.192 ± 0.058 kg/year; $P$-value = 0.0037) (Supplementary Material Figure S4).

## Kelp harvesting and associated species commercialization

Our results showed that different kelp species are harvested by *cofradías* with different intensities and manufactured by different

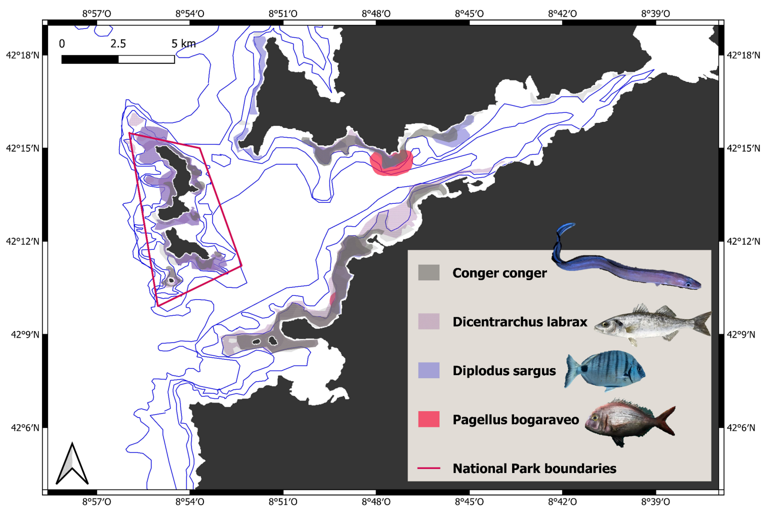



FIGURE 4
Fishing areas of finfish commercial species with higher economic value in Ría de Vigo inferred from fishers who were interviewed.

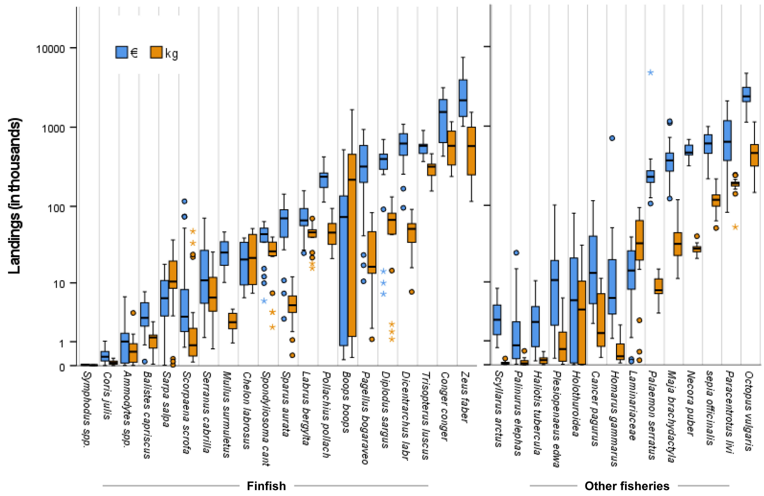



FIGURE 5
Landings data (2001–2021) in euros and kilograms for fisheries typically linked to kelp forest areas in NW Spain. From bottom to top, boxplots show minimum, first quartile, median, third quartile, and maximum. Outside (>1.5 times the interquartile range above or below the box) and far outside (>3 times the interquartile range) values are displayed as dots and asterisks, respectively.

companies. These species are the invasive wakame—named locally as *golfo* (*Undaria pinnatifida*)—and the kelps *L. ochroleuca* and *L. hyperborea* (named locally as *argazo*). *Saccorhiza polyschides* (named locally as *argazo bravo*), which is similar in appearance to the Laminariales, is also harvested in the study area. In addition to kelp harvesting, seaweed harvesters mentioned that there are other species of seaweed that they harvest, such as the red algae *Palmaria palmata*, which grows associated with kelp forest, and also green algae such as *Codium* spp.

According to the auction sales data provided by the *Xunta de Galicia*, there were six *cofradías* (Table S2 Supplementary Material) with authorization for seaweed harvesting in the study area during 2020 and 2021. The *Cofradía de Cangas* is the one that recorded the highest sales of seaweed compared to the other *cofradías*, and it has two seaweed harvesters working actively in the area. Kelps species were the most harvested species during 2021—after the 2020 COVID restrictions—and provided higher revenues. For example, in 2021, 99,935 kg of *U. pinnatifida* were harvested with a revenue of 89,131.50 € at the first sale. Despite those differences in the total amount harvested each year, generally, kelps are semi-processed and commercialized fresh, dehydrated, and preserved. This represents an average of 22 jobs related to this process. Kelp products are distributed nationally and internationally to more than 1,000 retailers.

Among the species associated with kelps, octopus and spider crab should be highlighted due to their popularity and the various ways in which they reach the final customer. Crabs, mollusks, and fishes (e.g., spider crab, octopus, European seabass, or ballan wrasse) are very popular in local gastronomy, and they are consumed both at home and at restaurants. Figure 6 shows the different marketing channels for these species, reflecting the diversity that they can reach the final consumer, who can be both local and visitors. The heterogeneity of the marketing agents involved is also a sign of the important socioeconomic network around the fisheries developed by these three *cofradías* in kelp areas.

## Discussion

Global change is causing shifts in marine ecosystems that have consequences for human well-being by disrupting the ecosystem services they provide (Singh et al., 2020). Changes in marine ecosystems are affecting different fisheries along regions with varying intensities and characteristics (Barange et al., 2014). The effects of these changes may affect the accessibility to fish resources, projected to decrease under climatic change, especially for artisanal SSFs (Barange et al., 2018). This decrease may be driven by the direct effects of climatic change, considered the major challenge for global fisheries (Lam et al., 2016), but also by local impacts such as habitat loss (Barange et al., 2018). In fact, in the last decade, the small-scale fleet has declined by 20% in the EU (Lloret et al., 2018) and is expected to continue decreasing according to future projections of fishery catches, which showed a substantial decrease in this region in contrast to colder regions (Barange et al., 2014; Barange et al., 2018). There are still knowledge gaps and insufficient information on changes in marine ecosystems

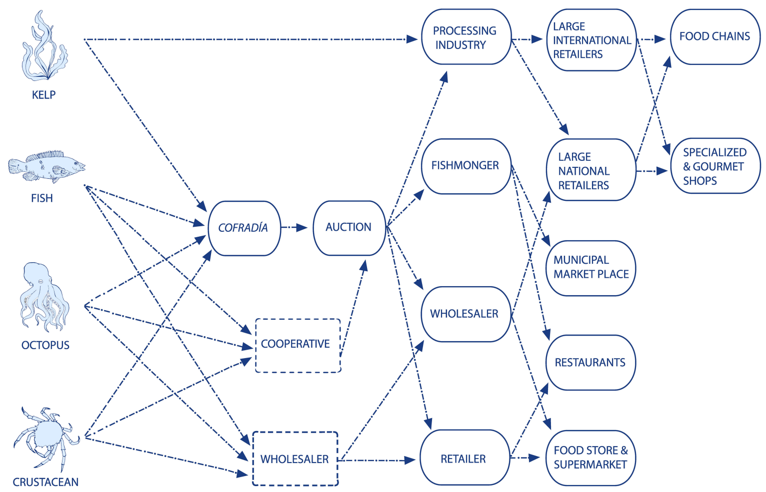



FIGURE 6
Distribution of kelp harvested and marine resources associated along the commercial chain in the study area.

and on the impact that these changes may have on the ecosystem services they provide. In these cases, obtaining LEK through collaborative work with fishers or other stakeholders can be very useful to advance research, including global change or natural hazard scenarios where scientific data are still scarce (Pita et al., 2020, De la Cruz-Modino, et al., 2022). The information obtained from stakeholders can be very useful when designing future scientific work to advance knowledge. In our study, direct work with fishers and key informants who work in the kelp forests of Ría de Vigo has served to reveal the magnitude of the loss of these key habitats. This loss was confirmed by monitoring studies in the same region (Barrientos, et al., 2022a; Barrientos et al., 2022b), showing the extent of these changes as they directly affect a part of the society that lives from the resources obtained from these habitats.

Kelp forests are one of the main ecosystem engineers on temperate rocky coasts around the world. Despite their importance as biodiversity-enhancing facilitators, including many economically important organisms, the relationship between SSFs and the occurrence of kelp forests has received little attention (Bertocci et al., 2015). Our results show that at least three fisheries linked to kelps are very important in economic terms. The 32 species caught in areas with kelp forests in Ría de Vigo were sold for 17 million € in 2021 at the first sale point. Unlike in other regions of the world where abalone and lobsters are the most valuable commercial species linked to kelp forests (Bennett et al., 2016; Carr and Reed, 2016; Blamey and Bolton, 2018), the main fisheries in Galicia are octopus (*O. vulgaris*), John Dory (*Zeus faber*), Conger eel (*C. conger*), and sea urchins (*P. lividus*). These species, together with the velvet swimming crabs (*N. puber*), the common cuttlefish (*S. officinalis*), the shrimp *P. serratus*, the spider crab (*M. brachydactyla*), the European sea bass (*D. labrax*), the white seabream *D. sargus*, the blackspot seabream (*P. bogaraveo*), and the pouting (*T. luscus*), each contributes more than 200,000 €/year to the local economy. In South Africa, a current value of 434 million/year US$ of kelp forest is estimated, of which fishing activities both recreational and commercial represent 28% and 15%, respectively (Blamey and Bolton, 2018). There are 39 species with economic value associated with kelp forests (including the kelps *Ecklonia maxima* and *Laminaria pallida*); the West Coast rock lobster (*Jasus lalandii*), abalone (*Haliotis midae*), and kelps being the most important industries (Blamey et al., 2014, Blamey and Bolton, 2018). Kelp forests from the Australian Great Southern Reef have also been estimated to provide high economic attributes that include a revenue of 512.6 million AU$/year of commercial fisheries (both rock lobster and abalone) and 553.8 million AU$/year of recreational fisheries (Bennett et al., 2016). California kelp forests also support important commercial fisheries, including kelp harvesting, several abalone species (genus *Haliotus*), spiny lobster (*Panulirus interruptus*), and about 15 rockfish species (Carr and Reed, 2016). Commercial fisheries linked to kelp forests in the NE Atlantic are also economically important, such as the lobster fishery (*H. gammarus*), which brings in about ~£30 million per year to the UK economy alone (Smale et al., 2013). In addition, fisheries like the velvet swimming crabs (*N. puber*), the spider crab (*M. brachydactyla*), the European sea bass (*D. labrax*), or the Conger eels (*C. conger*) together with the kelp harvesting are also important commercial fisheries of the European coastline (Smale et al., 2013). It is important to note that this study has only calculated the economic value of these species for catches in Ría de Vigo, which could explain why the economic value of species associated with kelp forests is much higher in other regions of the world.

Kelp forests have been undergoing changes in their distribution and abundance for several years due to global change (Wernberg et al., 2019, Wernberg et al., 2020). The reasons for this regression vary from one region to another, so local knowledge seems necessary to develop management tools fitted to each particular case (Krumhansl et al., 2016). In our study area, although fishers have perceived a decline in kelp forests in recent decades, the extent of this decline remains largely undetermined in part because of the challenge of conducting subtidal surveys over large areas. In this context, using the ecological knowledge of fishers seems a good working approach (Neis et al., 1999; Pita et al., 2020). In this regard, the information provided by fishers reveals that, in recent years, large portions of kelp forest area have been lost in Ría de Vigo, especially at the entrance of the ria where the IANP is located, while kelp forests are still common further inside the ria. This perception is consistent with seasonal monitoring studies of the ria where the collapse of kelp forests within the IANP and the persistence of healthy forests further inland were extensively described (Barrientos et al., 2022a; Barrientos et al., 2022b). Sea urchins are widely regarded as the major consumers of kelp in temperate latitudes, and their ability to overgraze kelp forest stands down to a canopy-free state has been frequently observed elsewhere (Christie et al., 2019). In this regard, fishers' reports indicate that sea urchins in Ría de Vigo are mostly harvested in areas currently or formerly covered by kelp forest stands (Figure 3). However, the seasonal dynamics of kelp forest collapse, the very low local abundances of sea urchins in the surveyed sites, and a detailed analysis of bite marks in more than 1,000 kelp individuals provide little support to the hypothesis that sea urchins may explain the demise of kelp forests at the entrance of Ría de Vigo. Instead, intensive seasonal overgrazing by *S. salpa*, the only herbivorous fish in the region, seems a more likely driver for the contraction of kelp forest areas, being the first time that a fish is shown to cause kelp forest collapse on a reef scale in the temperate Atlantic ( Barrientos et al., 2022b). Furthermore, the information obtained from fishers in this study provides further support for this conclusion. Thus, while *S. salpa* catches are restricted to the entrance of the ria and largely overlap with the zones where kelp forests collapsed in recent years, sea urchin harvesting occurs over a wider range and includes zones further inland of the ria where kelp forests are still in good condition (Supplementary Material Figure S5).

Despite the loss of kelp forests, kelp harvesting is one of the commercial fisheries in this region involving SSFs and companies, although small-scale fishers combine kelp harvesting and other wild fisheries. The amount of kelp harvested is comparable in weight (kg) to the catches of other species with economic value such as the white seabream and the blackspot seabream. However, the economic value of the resource is far below its catch volume (<1 €/kg). Taking into account that the commercialization chain of kelps and other seaweeds, in general, is much shorter than other resources and their high market value when they reach the consumer (e.g., medicines, cosmetics, food), their first sale price should be higher. In this regard, the increase of seaweed producers and traders in the last years may be affecting the first sale price. In this regard, kelps, like other natural resources, require careful management to be sustainable and efficiently harvested, and all actors involved in their exploitation should make the effort to manage the resource and the ecosystem richness associated with it in sustainable ways (Frangoudes and Garineaud, 2015; Delaney et al., 2016; Chuenpagdee and Jentoft, 2018). Our observations suggest that the management of kelp and other seaweed harvesting should be reviewed in Galicia, since, in terms of ecological value and the ecosystem services they provide to humans, they should have a comparatively higher economic value. As well as its market value, considering the growth of the harvesting activities and stakeholders involved in seaweed commercialization

In this context, the support provided by the regional government seems relevant to maintaining the activity, as traditionally, the *Xunta de Galicia* has supported the fishing and aquaculture sectors in general in Galicia, which contribute to the entire regional economy, thanks to the job creation and its effect in other productive sectors (Garza-Gil et al., 2017). In the case of kelps, also their contribution to maintaining local food resources, present in the local gastronomy and restoration, is relevant. NW Spain gastronomy is known for its variety of fish and seafood (Carral et al., 2020), and many of those are caught in the kelp forests, such as the octopus, spider crab, or velvet swimming crab, as this study shows.

Fishers' perceptions and landings data also pointed out relevant fishing changes. According to fishers, in some cases, these changes resulted in less fishing or changes in fishing areas due to the movement of the species to other zones where kelp forests persist. The fishery that had shown a significant decline in landings was the octopus, one of the most important fisheries in this region (Pita et al., 2016). Interestingly, the decrease of octopus coincides with the increase of the spider crab and velvet swimming crab, which could be related to the food chain (Smith, 2003). Although the loss of kelps and the decline in fishing seem to coincide in time, this correlation is not enough to confirm that these changes are due to the loss of kelp forests. Therefore, studies aimed to address these issues are needed to determine whether the loss of kelp could be behind the decline of some commercial species (Araujo et al., 2013).

Many commercial species are still caught in areas where kelp forests were lost, although in lesser abundance. This could be attributed to the presence of other habitat-forming species that could be playing the role of the *Laminaria* spp. in this region (Piñeiro-Corbeira et al., 2022), such as the seasonal species *S.*

*polyschides* and/or *Cystoseira* sensu lato. According to recent studies, these species have increased their frequency of occurrence in this region in parallel to the loss of *Laminaria* spp. in the last decade (Piñeiro-Corbeira et al., 2016; Barrientos et al., 2020). In this regard, these observations invite us to consider the possibility that some commercial species may not be highly dependent on kelp forest-forming species *per se* but on habitat-forming macroalgae in general. In our study, we have considered kelp forest-forming species to be those in the order Laminariales. However, other studies use the term "kelp" more broadly, including as "kelps" other habitat-forming species such as large brown algae of the order Fucales (e.g., *Cystoseira* sensu lato) and Tilopteridales (e.g., *S. polyschides*), since they provide similar functions (Fraser, 2012; Bolton, 2016; Wernberg et al., 2019).

## Conclusions

Despite the importance of kelp forests for coastal ecosystems and the communities that live from their resources, only a few studies have been carried out on the ecology of kelp forests in NW Spain as well as on their social, economic, and cultural importance (Barrientos et al., 2022a; Barrientos et al., 2022b; Piñeiro-Corbeira, et al., 2022). However, information on SSFs and their catches is not easily available (Pita et al., 2019), which makes collaborative activities essential for fisheries research and management. There are some criticisms about introducing local or traditional fishers' knowledge into regular/traditional scientific knowledge and fisheries research (Davis and Wagner, 2003) attending to different methodological and empirical questions. However, under data-poor scenarios or in data-limited locations (Roux et al., 2019), some collaborative activities, as we carried out, can be useful in building knowledge. Simple cost-effective methods can provide important baseline information on several aspects of small-scale fishing activities (Pita et al., 2019) and the status of different habitats, expanding our understanding of the environment (Berkström et al., 2019). Our study highlights the importance of these habitats for the SSFs in the area. In this regard, it would be interesting to know the level of dependence of commercial species on kelp forests as a first step to understanding how their loss will affect the SSFs. This could be a starting point for the design of management tools for the conservation of these ecosystems and their associated fisheries.

## Data availability statement

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

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## Author contributions

CP-C: conceptualization, methodology, field sampling, formal analysis, visualization, project administration, and writing-original draft preparation. SB: field sampling, formal analysis, assistance in manuscript writing. RB: funding acquisition, project administration, formal analysis, assistance in manuscript writing, and supervision. RC-M: funding acquisition, conceptualization, methodology, formal analysis, visualization, assistance in manuscript writing, and supervision. All authors revised and approved the manuscript.

## Funding

This research was funded by the "Fundación Biodiversidad y el Ministerio de Transición Ecológica y el Reto Demográfico." BioCost Research Group acknowledges funding from Xunta de Galicia (grants ED431D 2017/2020 and ED431B 2018/49 of "Axudas para a consolidación e estructuración de unidades de investigación competitivas do SUG" program). CP-C received financial support from Xunta de Galicia "Axudas de apoio á etapa de formación posdoutoral "(grant ED481B-2021/095)". SB received financial support from the Xunta de Galicia and the European Union (European Social Found – ESF) (grant ED481A2018/101). This publication has been funded by the University of la Laguna though the Vicerrectorado de Investigación, Transferencia y Campus Santa Cruz y Sur.

## Acknowledgments

The authors would like to thank the fishers who participated in this work. Special thanks are due to Berta Barreiro, Txetxu Santiago and Jorge Alfaya for their help in organizing the meetings with the fishers. We also thanks to Iñaki Ferreiro, Manuel García, Jose Luis Gonález, and Jose Nogueira for their help with the historical reconstruction.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.973251/full#supplementary-material

## References


Alban, F., Le Floc'h, P., and Boncoeur, J. (2004). The impact of economic and regulatory factors on the relative profitability of fishing boats: A case study of the seaweed harvesting fleet of Northwest Brittany (France). *Aquat. Living Resour.* 17 (2), 185–193. doi: 10.1051/alr:2004013

Araujo, R. M., Bartsch, I., Bekkby, T., Erzini, K., and Sousa-Pinto, I. (2013). What is the impact of kelp forest density and/or area on fisheries? *Environ. Evid.* 2 (1), 15. doi: 10.1186/2047-2382-2-15

Aswani, S., and Lauer, M. (2006). Incorporating fishermen's local knowledge and behavior into geographical information systems (GIS) for designing marine protected areas in Oceania. *Hum. Organ.* 65 (1), 81–102. doi: 10.17730/humo.65.1.4y2q0vhe4l30n0uj

Bajjouk, T., Rochette, S., Laurans, M., Ehrhold, A., Hamdi, A., and Le Niliot, P. (2015). Multi-approach mapping to help spatial planning and management of the kelp species *L. digitata* and *L. hyperborea*: Case study of the molène archipelago, Brittany. *J. Sea Res.* 100 (Supplement C), 2–21. doi: 10.1186/2047-2382-2-15

Barange, M., Bahri, T., Beveridge, M. C. M., Cochrane, K. L., Funge-Smith, S., and Poulain, F. (2018). Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options. *FAO Fish. Aquac. Tech. Pap.* 627, 628.

Barange, M., Merino, G., Blanchard, J. L., Scholtens, J., Harle, J., Allison, E. H., et al. (2014). Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nat. Climate Change* 4, 211. doi: 10.1038/nclimate2119

Barrientos, S., Barreiro, R., Cremades, J., and Pineiro-Corbeira, C. (2020). Setting the basis for a long-term monitoring network of intertidal seaweed assemblages in northwest Spain. *Mar. Environ. Res.* 160, 105039. doi: 10.1016/j.marenvres.2020.105039

Barrientos, S., Barreiro, R. , and Piñeiro-Corbeira, C. (2022a). Paradoxical failure of *Laminaria ochroleuca* (Laminariales, phaeophyceae) to consolidate a kelp forest inside a marine national park. *Eur. J. Phycol.* doi: 10.1080/09670262.2022.2065365

Barrientos, S., Piñeiro-Corbeira, C., and Barreiro, R. (2022b). Temperate kelp forest collapse by fish herbivory: a detailed demographic study. *Front. Mar. Sci.* 9, 817021. doi: 10.3389/fmars.2022.817021

Bavinck, M., Jentoft, S., Pascual-Fernández, J. J., and Marciniak, B. (2015). Interactive coastal governance: The role of pre-modern fisher organizations in improving governability. *Ocean Coast. Manage.* 117, 52–60. doi: 10.1016/j.ocecoaman.2015.05.012

Bennett, S., Wernberg, T., Connell, S. D., Hobday, A. J., Johnson, C. R., and Poloczanska, E. S. (2016). The 'Great southern reef': social, ecological and economic value of australia's neglected kelp forests. *Mar. Freshw. Res.* 67 (1), 47–56. doi: 10.1071/MF15232

Berkström, C., Papadopoulos, M., Jiddawi, N. S., and Nordlund, L. M. (2019). Fishers' local ecological knowledge (LEK) on connectivity and seascape management. *Front. Mar. Sci.* 6 (130). doi: 10.3389/fmars.2019.00130

Bernard, H. R. (2017). *Research methods in anthropology: Qualitative and quantitative approaches* (Maryland: Rowman & Littlefield).

Bertocci, I., Araújo, R., Oliveira, P., Sousa-Pinto, I., and Österblom, H. (2015). REVIEW: Potential effects of kelp species on local fisheries. *J. Appl. Ecol.* 52 (5), 1216–1226. doi: 10.1111/1365-2664.12483

Blamey, L. K., and Bolton, J. J. (2018). The economic value of south African kelp forests and temperate reefs: Past, present and future. *J. Mar. Syst.* 188, 172–181. doi: 10.1016/j.jmarsys.2017.06.003

Blamey, L. K., Shannon, L. J., Bolton, J. J., Crawford, R. J. M., Dufois, F., Evers-King, H., et al. (2014). Ecosystem change in the southern benguela and the underlying processes. *J. Mar. Syst.* 144, 9–29. doi: 10.1016/j.jmarsys.2014.11.006

Bolton, J. J. (2016). What is aquatic botany? and why algae are plants: The importance of non-taxonomic terms for groups of organisms. *Aquat. Bot.* 132, 1–4. doi: 10.1016/j.aquabot.2016.02.006

Carral, E. V., del Río, M., and López, Z (2020). Gastronomy and tourism: Socioeconomic and territorial implications in Santiago de compostela-galiza (NW Spain). *Int. J. Environ. Res. Public Health* 17 (17), 6173. doi: 10.3390/ijerph17176173

Carr, M. H., and Reed, D. C (2016). "SEVENTEEN. shallow rocky reefs and kelp forests," in *Ecosystems of California*. Eds. M. Harold and Z. Erika (Berkeley: University of California Press), 311–336.

Christie, H., Gundersen, H., Rinde, E., Filbee-Dexter, K., Norderhaug, K. M., Pedersen, T., et al. (2019). Can multitrophic interactions and ocean warming influence large-scale kelp recovery? *Ecol. Evol.* 9 (5), 2847–2862. doi: 10.1002/ece3.4963

Chuenpagdee, R., and Jentoft, S. (2018). Transforming the governance of small-scale fisheries. *Maritime Stud.* 17 (1), 101–115. doi: 10.1007/s40152-018-0087-7

Davis, A., and Wagner, J. R. (2003). Who knows? on the importance of identifying "Experts" when researching local ecological knowledge. *Hum. Ecol.* 31 (3), 463–489. doi: 10.1023/A:1025075923297

Dayton, P. K. (1985). Ecology of kelp communities. *Annu. Rev. Ecol. Syst.* 16, 215–245. doi: 10.1146/annurev.es.16.110185.001243

De la Cruz-Modino, R., Piñeiro-Corbeira, C., Gutiérrez-Barroso, J., González-Cruz, C., Barreiro, R., Batista-Medina, J. A., et al. (2022). Small but strong: Socioeconomic and ecological resilience of a small European fishing community affected by a submarine volcanic eruption. *Ocean Coast. Manage.* 223, 106124. doi: 10.1016/j.ocecoaman.2022.106124

Delaney, A., Frangoudes, K., and Ii, S. A. (2016). "Chapter 2 - society and seaweed: Understanding the past and present," in *Seaweed in health and disease prevention*. Eds. J. Fleurence and I. Levine (San Diego: Academic Press), 7–40.

Fernández, E., Barañano, C., Alejo, I., Barreiro, R., Bellas, J., Besada, V., et al. (2020). "Islas cíes," in *Un ecosistema en la frontera*(Vigo, Concello de Vigo).

Frangoudes, K. (2011). Seaweeds fisheries management in France, Japan, Chile and Norway. *Cahiers de Biologie Marine, Station Biologique* 52 (4), 517–525

Frangoudes, K., and Garineaud, C. (2015). "Governability of kelp forest small-scale harvesting in iroise Sea, France," in *Interactive governance for small-scale fisheries: Global reflections*. Eds. S. Jentoft and R. Chuenpagdee (Cham:Cham, Springer International Publishing), 101–115. doi: 10.1007/978-3-319-17034-3_6

Fraser, C. I. (2012). Is bull-kelp kelp? the role of common names in science. *New Z. J. Mar. Freshw. Res.* 46 (2), 279–284. doi: 10.1080/00288330.2011.621130

Garza-Gil, M. D., Surís-Regueiro, J. C., and Varela-Lafuente, M. M. (2017). Using input–output methods to assess the effects of fishing and aquaculture on a regional economy: The case of Galicia, Spain. *Mar. Policy* 85, 48–53. doi: 10.1016/j.marpol.2017.08.003

González-Roca, F., Gelcich, S., Pérez-Ruzafa, Á., Vega, J. M. A., and Vásquez, J. A. (2021). Exploring the role of access regimes over an economically important intertidal kelp species. *Ocean Coast. Manage.* 212, 105811. doi: 10.1016/j.ocecoaman.2021.105811

Guyader, O., Berthou, P., Koutsikopoulos, C., Alban, F., Demanèche, S., Gaspar, M. B., et al. (2013). Small scale fisheries in Europe: A comparative analysis based on a selection of case studies. *Fish. Res.* 140, 1–13. doi: 10.1016/j.fishres.2012.11.008

Hynes, S., Chen, W., Vondolia, K., Armstrong, C., and O'Connor, E. (2021). Valuing the ecosystem service benefits from kelp forest restoration: A choice experiment from Norway. *Ecol. Econ.* 179, 106833. doi: 10.1016/j.ecolecon.2020.106833

Krumhansl, K. A., Okamoto, D. K., Rassweiler, A., Novak, M., Bolton, J. J., Cavanaugh, K. C., et al. (2016). Global patterns of kelp forest change over the past half-century. *Proc. Natl. Acad. Sci. U.S.A.* 113 (48), 13785–13790. doi: 10.1073/pnas.1606102113

Lam, V. W. Y., Cheung, W. W. L., Reygondeau, G., and Sumaila, U. R. (2016). Projected change in global fisheries revenues under climate change. *Sci. Rep.* 6, 32607. doi: 10.1038/srep32607

Lloret, J., Cowx, I. G., Cabral, H., Castro, M., Font, T., Gonçalves, J. M. S., et al. (2018). Small-scale coastal fisheries in European seas are not what they were: Ecological, social and economic changes. *Mar. Policy* 98, 176–186. doi: 10.1016/j.marpol.2016.11.007

Mesnildrey, L., Jacob, C., Frangoudes, K., Reunavot, M., and Lesueur, M. (2012). Seaweed industry in france. report interreg program NETALGAE. Les publications du Pôle halieutique AGROCAMPUS OUEST n°9, 34 p.

Neis, B., Schneider, D. C., Felt, L., Haedrich, R. L., Fischer, J., and Hutchings, J. A. (1999). Fisheries assessment: what can be learned from interviewing resource users? *Can. J. Fish. Aquat. Sci.* 56 (10), 1949–1963. doi: 10.1139/f99-115

Pascual Fernández, J. (1991). *Entre el mar y la tierra: Los pescadores artesanales canarios* (Santa Cruz de Tenerife: Ministerio de Cultura-Interinsular Canaria).

Pascual-Fernández, J. J., Florido-del-Corral, D., de la Cruz-Modino, R., and Villasante, S. (2020b). "Small-scale fisheries in Spain: Diversity and challenges," in *Small-scale fisheries in Europe: Status, resilience and governance*. Eds. J. J. Pascual-Fernández, C. Pita and M. Bavinck (Cham: Springer International Publishing). pp. 253–282.

Pascual-Fernández, J. J., Pita, C., and Bavinck, M. (2020a). *Small-scale fisheries in Europe: Status, resilience and governance* (Cham Switzerland: MARE Publication Series 23, Springer Nature Switzerland AG), pp. 610.

Piñeiro-Corbeira, C., Barreiro, R., and Cremades, J. (2016). Decadal changes in the distribution of common intertidal seaweeds in Galicia (NW Iberia). *Mar. Environ. Res.* 113, 106–115. doi: 10.1016/j.marenvres.2015.11.012

Piñeiro-Corbeira, C., Barrientos, S., Barreiro, R., Aswani, S., Pascual-Fernández, J. J., de la Cruz-Modino, R., et al. (2022). *Can local knowledge of small-scale fishers be used to monitor and assess changes in marine ecosystems in a European context? human-nature interactions: Exploring nature's values across landscapes*. Eds. I. Misiune and D. I Depellegrin (Cham, Switzerland: Springer International Publishing), 299–314.

Piñeiro-Corbeira, C., Iglesias, L., Nogueira, R., Campos, S., Jiménez, A., Regueira, M., et al. (2021). Structure and trophic niches in mobile epifauna assemblages associated with seaweeds and habitats of syngnathid fishes in cíes archipelago (Atlantic islands marine national park, north West Iberia). *Front. Mar. Sci.* 8 (1582). doi: 10.3389/fmars.2021.773367

Pita, P., Antelo, M., Hyder, K., Vingada, J., and Villasante, S (2020). The use of recreational fishers' ecological knowledge to assess the conservation status of marine ecosystems. *Front. Mar. Sci.* 7 (242). doi: 10.3389/fmars.2020.00242

Pita, P., Fernández-Márquez, D., and Freire, J (2018). Spatiotemporal variation in the structure of reef fish and macroalgal assemblages in a north-east Atlantic kelp forest ecosystem: implications for the management of temperate rocky reefs. *Mar. Freshw. Res.* 69 (4), 525–541. doi: 10.1071/MF17193

Pita, P., Fernández-Vidal, D., García-Galdo, J., and Muíño, R. (2016). The use of the traditional ecological knowledge of fishermen, cost-effective tools and participatory models in artisanal fisheries: Towards the co-management of common octopus in Galicia (NW Spain). *Fish. Res.* 178, 4–12. doi: 10.1016/j.fishres.2015.07.021

Pita, P., and Freire, J. (2019). Trophic ecology of an Atlantic kelp forest fish assemblage (NW Spain) targeted by recreational fishers and implications for coastal management. *J. Mar. Biol. Assoc. United Kingdom* 99 (1), 19–29. doi: 10.1017/S0025315417001862

Pita, C., Villasante, S., and Pascual-Fernández, J. J. (2019). Managing small-scale fisheries under data poor scenarios: lessons from around the world. *Mar. Policy* 101, 154–157. doi: 10.1016/j.marpol.2019.02.008

Roux, M.-J., Tallman, R. F., and Martin, Z. A. (2019). Small-scale fisheries in canada's Arctic: Combining science and fishers knowledge towards sustainable management. *Mar. Policy* 101, 177–186. doi: 10.1016/j.marpol.2018.01.016

Singh, G. G., Eddy, I. M. S., Halpern, B. S., Neslo, R., Satterfield, T., and Chan, K. M. A (2020). Mapping cumulative impacts to coastal ecosystem services in British Columbia. *PloS One* 15 (5), e0220092. doi: 10.1371/journal.pone.0220092

Smale, D. A., Burrows, M. T., Moore, P., O'Connor, N., and . Hawkins, S. J (2013). Threats and knowledge gaps for ecosystem services provided by kelp forests: A northeast Atlantic perspective. *Ecol. Evol.* 3, 4016–4038. doi: 10.1002/ece3.774

Smith, C. D. (2003). Diet of octopus vulgaris in false bay, south Africa. *Mar. Biol.* 143 (6), 1127–1133. doi: 10.1007/s00227-003-1144-2

Steneck, R. S., and Johnson, C. (2014). "Kelp forests: Dynamic patterns, processes, and feedbacks," in *Marine community ecology and conservation*. Eds. M. D. Bertness, J. F. Bruno, B. R. Silliman and J. J. Stachowicz (Sunderland: MA, Sinauer), 315–336.

Surís-Regueiro, J. C., and Santiago, J. L. (2014). Characterization of fisheries dependence in Galicia (Spain). *Mar. Policy* 47, 99–109. doi: 10.1016/j.marpol.2014.02.006

Trimble, M., and Berkes, F. (2013). Participatory research towards co-management: Lessons from artisanal fisheries in coastal Uruguay. *J. Environ. Manage.* 128, 768–778. doi: 10.1016/j.jenvman.2013.06.032

Vergés, A., and Campbell, A. H. (2020). Kelp forests. *Curr. Biol.* 30 (16), R919–R920. doi: 10.1016/j.cub.2020.06.053

Villasante, S., Pazos Guimeráns, C., Rodrigues, J., Antelo, M., Rivero-Rodríguez, S., Da Rocha, J. M., et al. (2015). *Small-scale fisheries and the zero discard target*. doi: 10.2861/305277

Wernberg, T., Couraudon-Réale, M., Tuya, F., and Thomsen, M. (2020). Disturbance intensity, disturbance extent and ocean climate modulate kelp forest understory communities. *Mar. Ecol. Prog. Ser.* 651, 57–69. doi: 10.3354/meps13443

Wernberg, T., Krumhansl, K., Filbee-Dexter, K., and Pedersen, M. F. (2019). "Status and trends for the world's kelp forests," in *World seas: an environmental evaluation (Second edition)*. Ed. C. Sheppard (Cambridge:Academic Press), 57–78. doi: 10.1016/B978-0-12-805052-1.00003-6

frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 29 September 2022
DOI 10.3389/fmars.2022.971262

Check for updates

OPEN ACCESS

EDITED BY
Pablo Pita,
University of Santiago de Compostela, Spain

REVIEWED BY
Martín Laporta,
Dirección Nacional de Recursos Acuáticos, Rocha, Uruguay
Raquel De La Cruz Modino,
University of La Laguna, Spain

*CORRESPONDENCE
Kayla M. Hamelin
kayla.hamelin@dal.ca

SPECIALTY SECTION
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

RECEIVED 16 June 2022
ACCEPTED 17 August 2022
PUBLISHED 29 September 2022

CITATION
Hamelin KM, MacNeil MA, Curran K and Bailey M (2022) "The people's fish": Sociocultural dimensions of recreational fishing for Atlantic mackerel in Nova Scotia. *Front. Mar. Sci.* 9:971262. doi: 10.3389/fmars.2022.971262



# "The people's fish": Sociocultural dimensions of recreational fishing for Atlantic mackerel in Nova Scotia

Kayla M. Hamelin[1,2]*, M. Aaron MacNeil[1], Kaitlyn Curran[2] and Megan Bailey[2]

[1]Ocean Frontier Institute, Department of Biology, Dalhousie University, Halifax, NS, Canada,
[2]Marine Affairs Program, Dalhousie University, Halifax, NS, Canada

Atlantic mackerel or Amalamaq (*Scomber scombrus*) has been subject to diverse fishing pressures in Atlantic Canada for commercial, bait, recreational, and Indigenous food-social-ceremonial (FSC) fisheries, resulting in its substantial social and cultural significance in the region. Recent stock declines have led to closures of the commercial and bait mackerel fisheries, while recreational and FSC harvesters retain respectively the ability or right to fish. Here we assess the human dimensions of the recreational mackerel fishery through administration of a voluntary questionnaire shared at wharfs and through online/social media channels. A total of 285 responses were received, with results providing a rich picture of this poorly-engaged stakeholder community. The operational dimensions of this fishery and benefits derived from recreational fishing are explored. While recommendations for conservation and management measures were not solicited explicitly, many respondents shared comments and suggestions regarding management of the stock. Engaging more actively with recreational mackerel anglers may allow for enhanced assessments of the fishery and foster local stewardship toward more effective fisheries management.

KEYWORDS

**sustainability, human dimensions, recreational fishing, angling, fisheries management, social-ecological systems, ecosystem services**

## Introduction

The overarching goal of fisheries management is often stated simply as 'sustainability'. For some time, it has been acknowledged that fisheries represent complex social-ecological systems (Charles, 1994; Charles, 1995; McLeod and Leslie, 2009; Link et al., 2011; Fogarty, 2014; Long et al., 2015), and thus sustainability can be understood to involve multiple dimensions including ecological, economic, social (including cultural), and institutional (or governance) pillars (DeYoung et al., 1999;

Stephenson et al., 2017; Foley et al., 2020). Indeed, these multiple components are often included in frameworks in support of ecosystem-based management (EBM), an approach many jurisdictions are in the process of formally adopting (Marasco et al., 2007; DeYoung et al., 2008; Garcia et al., 2014; Long et al., 2015; DePiper et al., 2017). However, many fisheries assessments, including those in Canada, still focus largely on the biological or ecological and, to a lesser extent, economic components of the coastal and marine systems within which fisheries operate (Charles, 1994; Charles, 1995; Ommer et al., 2012; Urquhart et al., 2013; Stephenson et al., 2019; Paul and Stephenson, 2020).

Reliance solely on population or bioeconomic assessments may result in fisheries management decisions that ignore important cultural and social objectives (Fowler et al., 2022). For example, core social objectives identified by the collaborative, multi-stakeholder Canadian Fisheries Research Network (Stephenson et al., 2019) included sustainable communities, health and well-being, and ethical fisheries. Socio-cultural benefits from fisheries may also be defined using an ecosystem services framework, with 'cultural services' comprising culture and amenity, recreation, aesthetics, and education and research (UNEP, 2006; McLeod and Leslie, 2009). So-called 'human dimensions' research is the key to capturing these aspects of fisheries, allowing for an understanding of human cognitions, behaviours, and relationships related to fishing and fisheries governance, and consequently the mapping of links and feedbacks between both the human and natural components of the system (DeYoung et al., 2008; Hunt et al., 2013).

Although human dimensions research has been taking place since the 1960s, and is on the rise in contemporary fisheries research (DeYoung et al., 2008; Bennett, 2019), recreational fisheries are generally understudied compared to commercial sector fisheries (Brownscombe et al., 2019; Cooke et al., 2019; Holder et al., 2020). The Food and Agriculture Organization defines recreational fishers as those that do not rely on fishing to supply a necessary part of their diet or income (FAO, 2012), and thus they fish for other benefits (e.g., cultural ecosystem services). There are several parallels between marine recreational fisheries and small-scale fisheries in the sense that they are often poorly defined, diverse in scope, and often not well represented in research and assessment procedures (Pita et al., 2020a; Pascual-Fernandez et al., 2020). In any case, without assessment of the full breadth of human-fish interactions within these socio-ecological systems, it is unlikely we will be able to achieve the goal of both sustainable ecological and human communities.

The Atlantic mackerel or Amalamaq (*Scomber scombrus*) fishery in Atlantic Canada operates in a complex socioeconomic seascape, encompassing the ancestral and unceded territory of the Mi'kmaq, Wolastoqey, Peskotomuhkati, and Beothuk who fished mackerel for millenia (Denny et al., 2020). Atlantic mackerel is a once-common forage fish that provides a critical intermediate link in the North Atlantic food web between small fish and invertebrates at lower trophic levels and top predators at higher trophic levels, including larger fish, birds, marine mammals, and humans (DFO, 2007; Van Beveren et al., 2017a). While Atlantic mackerel are found throughout the North Atlantic, the Northern contingent of the western Atlantic population is found largely within Canadian waters (Gíslason et al., 2020; Moura et al., 2020; Van Beveren et al., 2020). Unfortunately, after significant population declines in recent years attributed to overexploitation, and possible ecosystem changes or climate change impacts, the Canadian Department of Fisheries and Oceans (DFO) has assessed mackerel in the 'critical' zone under the Sustainable Fisheries Framework, meaning that the stock is below the defined Limit Reference Point and requires conservation action to rebuild the population (DFO, 2021).

However, Canadian mackerel stock recovery has been complicated by the fact that there are a variety of fisheries that target this stock with differing objectives (Figure 1) (DFO, 2007; Van Beveren et al., 2017a). The species continues to hold significance to Indigenous groups such as the Mi'kmaq (Denny et al., 2020), who retain Aboriginal rights and title to fishery resources (Wiber and Milley, 2007). Furthermore, there has been a commercial fishery harvesting mackerel for sale and export, supporting livelihoods across the region. There has also been a commercial bait fishery which harvests mackerel for use as bait in other commercial fisheries, including the multi-billion-dollar lobster or Jakej (*Homarus americanus*) industry (Fisheries and Oceans Canada, 2022), and as bait for bluefin tuna sport fishing. Finally, there is a long history of a culturally significant recreational fishery throughout the region (Brushett et al., 2019), with mackerel representing the second most frequently caught recreational species in the provinces of Nova Scotia and Prince Edward Island (DFO, 2015). Most recreational anglers fish for mackerel in coastal waters using a standard rod-and-reel fishing pole, typically with multiple hooks per line.

To address the precarious state of Atlantic mackerel, a combination of conservation measures has been put in place in recent years, most significantly the closure of the commercial and bait fisheries in spring 2022 (Government of Canada, 2022). Currently, FSC fisheries are allowed to continue uninterrupted, while recreational fishing is permitted with ongoing restrictions on the season, gear, minimum size, and number of fish able to be retained by recreational fishers (https://www.dfo-mpo.gc.ca/fisheries-peches/decisions/fm-2021-gp/atl-31-eng.html). There is neither a licensing requirement nor formal data collection (e.g., creel survey) for recreational mackerel fishing in the region, and thus it is challenging to know how many anglers are fishing and how many fish they catch. Data collection in recreational fisheries is notoriously challenging (Griffiths et al., 2017; Hyder et al., 2020) and, for many recreational fisheries in North America, recreational fishing is viewed as a public good

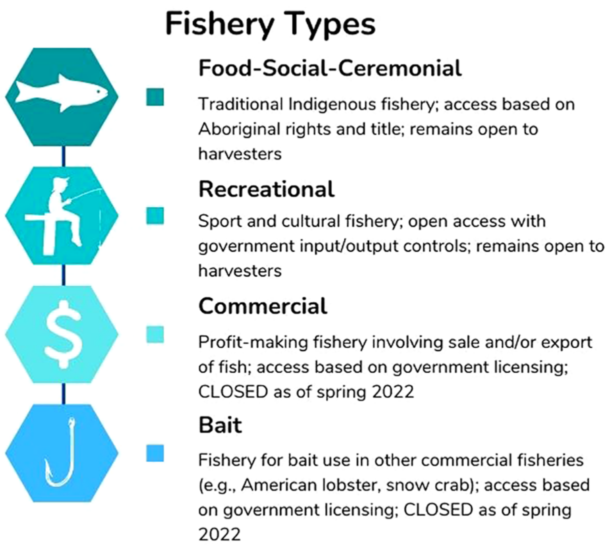



FIGURE 1
Summary of fishery types targeting Atlantic mackerel or Amalamaq (*Scomber scombrus*) in Atlantic Canada.

(i.e. open access) with less influence from managers on where and how often anglers fish (Cox et al., 2002; Daedlow et al., 2011; Hunt et al., 2021). Nevertheless, the recreational fishery now likely represents both the largest group of stakeholders interacting with Atlantic mackerel and the most valuable source of fishery-dependent data.

Human dimensions research on the recreational component of the mackerel fishery in eastern Canada has been much-needed, given that within fisheries management, recreational anglers are less frequently consulted than commercial fishers – likely due to difficulty in accessing individuals not represented by stakeholder associations, rather than a lack of willingness to participate (Hyder et al., 2020). Furthermore, while the number of recreational mackerel anglers in the region is presently unknown given the lack of licensing and data collection in the fishery, this community of under-engaged stakeholders might in fact be the most numerous, given the ubiquity of the activity in the region (Brushett et al., 2019), and the fact that globally, recreational anglers are considered significantly more numerous than commercial harvesters (Arlinghaus et al., 2019). Furthermore, there have been substantial economic, social, and cultural benefits from recreational fishing documented around the world (Cisneros-Montemayor and Sumaila, 2010; McManus et al., 2011; Arlinghaus et al., 2015; Griffiths et al., 2017; Arlinghaus et al., 2019; Hyder et al., 2020; Pita et al., 2020b), and it remains unclear which of these might be most relevant to mackerel anglers in our region.

The present study – conducted one year before the current commercial closure - focused on exploring the sociocultural and operational aspects of the recreational mackerel fishery. Using a questionnaire, we asked 1) who fishes for Atlantic mackerel for recreational purposes, 2) how they fish (i.e., an assessment of common practices and behaviours), and crucially, 3) why they fish for Atlantic mackerel, in order to determine sociocultural benefits (e.g., cultural ecosystem services) and who in the fishing community is likely to benefit in different ways. Just as a commercial industry might be jeopardized, these recreational benefits equally stand to be lost if the Canadian mackerel stock continues to decline, although it can be difficult to assign value to recreational fishing when considering management options because of a lack of methods to integrate cultural value into the current assessment process. Furthermore, while the focus of recent media attention in eastern Canada has, understandably, been on what is lost when a commercial fishery is closed (e.g., FFAW, 2022), here we investigated the benefits that are retained when traditional and recreational fisheries maintain access to their target species.

# Methods

## Data collection

The study population comprised adults (18+) of all backgrounds who 1) self-identified as recreational mackerel anglers and who 2) fish in Nova Scotia, Canada (Figure 2). Nova Scotia, a province known by the slogan “Canada’s Ocean Playground” (Develop Nova Scotia, 2021), hosts a large number of recreational anglers, and has coastal access points in both rural areas and Halifax Regional Municipality (HRM;

 10.3389/fmars.2022.971262

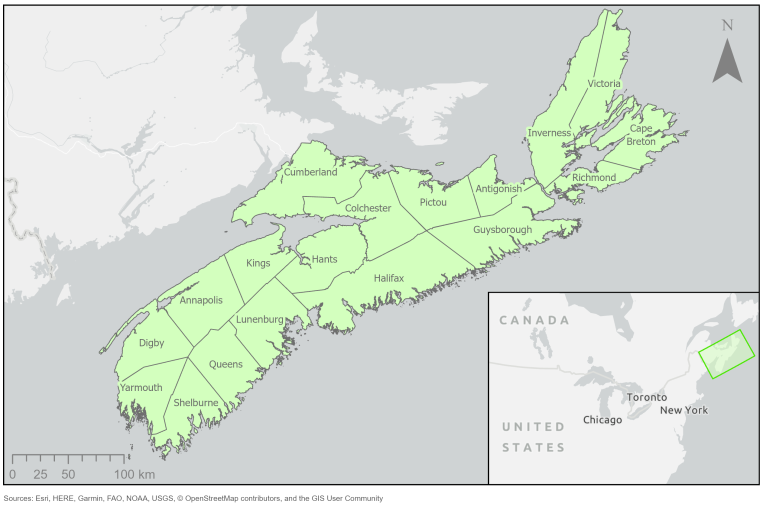



FIGURE 2
Map of Nova Scotia, the province in eastern Canada (located within the traditional and unceded territory of the Mi'kmaq and Wolastoqey) which compromised the geographic scope of recruitment for a research study on recreational mackerel fishing in the region. Solid lines delineate county borders within the province (Nova Scotia Geographic Data Directory, https://nsgi.novascotia.ca/gdd/).

K'jipuktuk), the capital of the province and the largest urban area in Atlantic Canada. The province has a population of approximately 923 598[1], of which approximately 83% are 18 or older[2], with a median age of 45.6 years[3]. The population of the capital of HRM represents approximately 48% of the provincial population[4]. The total number of recreational mackerel anglers within the province is unknown. A DFO report from 2015 estimates that there are 49 714 recreational anglers across all target species (freshwater and marine) in the province (DFO, 2015). However, these data are at least 7 years out-of-date, and the survey yielding the 2015 report was distributed primarily to anglers in licensing databases, which might not cover groups who target mackerel.

A voluntary questionnaire of 39 questions (Appendix A) was administered online using password-protected Opinio software, which provided an anonymous web link to open the survey. A 'cookies' feature was used to ensure only one submission was received per participant. Ethical approval was obtained from the Dalhousie University Research Ethics Board (2021-5622) and the survey included an introduction page outlining the objectives, risks, and benefits of the research and requesting the consent of participants before proceeding to the questionnaire. Our research questionnaire was offered in English, as this is the primary language understood by all members of the research team, and is the most commonly spoken language in the study region. While there was no compensation offered for participation, the chance to win 1 of 5 $100 Mastercard gift cards *via* random draw was offered as an incentive. Contact information for prize winners and for respondents interested in receiving a copy of research results was disaggregated from survey data to maintain anonymity.

Participants were recruited by distributing information cards with a survey link during dockside visits to known recreational fishing locations in HRM and opportunistically at fishing sites elsewhere in the province. Additional information cards were distributed to libraries, community centres, and outdoor sports shops throughout HRM. Although the survey was conducted in English, to convey project objectives and recruit individuals from diverse populations, some of the project summary information on the recruitment card was translated into French, Arabic, Mandarin Chinese, Spanish, Korean, and Hindi, representing additional significant language groups in Nova Scotia[5]. While we attempted to work with colleagues and collaborators to translate materials into Mi'kmaq, we were

1 https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/hlt-fst/pd-pl/Comprehensive.cfm

2 https://novascotia.ca/finance/stats.div/papers/demograf/demo4.htm

3 https://novascotia.ca/finance/statistics/news.asp?id=17752#:~:text=Nationally%2C%20median%20age%20increased%20from,over%20the%20last%20five%20years.

4 https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/hlt-fst/pd-pl/Comprehensive.cfm

5 https://www12.statcan.gc.ca/census-recensement/2011/dp-pd/vc-rv/index.cfm?Lang=ENG&VIEW=D&GEOCODE=12&TOPIC_ID=4

unable to do so for this study. While this was unfortunate, given our project goals around equity and inclusion, we acknowledge that most Indigenous individuals in Nova Scotia speak English (Nova Scotia, 2021), and thus it is unlikely this represented a language barrier.

The survey was shared online through social media accounts associated with this research project (@gofishns on Facebook and Instagram) to increase geographic reach around the province. In addition, the link was posted on relevant local fishing social media groups (e.g., 'Mackerel and Squid Fishing Nova Scotia' on Facebook), and sent to relevant organizations for distribution (e.g., Fishermen and Scientists Research Society, Nova Scotia Federation of Hunters and Anglers) to invite anglers from elsewhere in Nova Scotia to respond. The survey was also distributed *via* university channels, including the email list servs for the Dalhousie Department of Biology and the Marine Affairs Program, and was featured on the 'Today at Dal' news page.

Although these opt-in recruitment methods meant participants were largely self-selecting, the combination of recruitment *via* social media and recruitment in-person allowed for both access to a broad range of participants around the province, in addition to more personalized invitations to those who might be less familiar with social technologies. Survey invitations and information cards encouraged participants to request a paper copy of the survey if preferred, but no such requests were made and all submissions were received through the online Opinio platform.

Survey responses were collected between Monday June 14 and Friday October 8, 2021, which approximately corresponds to the primary recreational mackerel fishing season in Nova Scotia, based on previous survey work (Brushett et al., 2019). The questionnaire (see Appendix 1) was divided into two sections: 1) Fishing Activity and 2) Demographics. Within the Fishing Activity section, a combination of multiple-choice (MC) and open-ended (OE) questions were used to identify: experience with fishing (MC), target species of interest (MC/OE), locations of fishing activity (MC), additional types of mackerel fishing conducted (MC), years of experience (MC), fishing season (MC), frequency of fishing activity (MC), observed changes to size or abundance of fish (MC), observed changes to fishing regulations (MC), sharing of fishing data (MC), reasons for fishing (OE), consumption of mackerel (MC), importance of mackerel as food (MC), value of mackerel in diet (MC), financial valuation of mackerel as a food source (OE), importance of fishing activity (MC), social context of fishing (MC), personal effects if fishing were no longer possible (OE), and additional comments or concerns (OE).

Within the Demographics section, multiple-choice questions were be used to identify the region in which the participant resides, identity as an immigrant or refugee, ethnic identity, level of English proficiency, languages other than English used, gender identity, LGBTQIA2S+ identity, age, disability status, education level, income, and employment status and sector. In co-authoring this paper, our diverse positionalities reflect non-Indigenous, Canadian-born men and women, who are academic researchers and a health care professional, living with and without disability. At the end of each section (i.e., after 'Fishing Activity' mid-way through; after 'Demographics' at the end of the survey), there were opportunities for respondents to share any additional thoughts or ideas not captured by the structured questions. Providing open-ended questions was important to ensure respondents had opportunities for self-expression and to facilitate the solicitation of concerns or perspectives from the community unanticipated by the research team.

## Analysis

A mixed-methods approach was used to analyze questionnaire responses. For demographic data, summary statistics (frequency counts and proportions [%]) were generated using Opinio software. It should be noted that sample size varied among questions because responses were not mandatory, and respondents varied in the number of questions answered. Furthermore, some multiple-choice questions allowed the respondents to 'check all that apply', and thus in those cases the counts reported always represent the number of selections, not the number of respondents. These data were compared with similar data from Statistics Canada (https://www.statcan.gc.ca/en/start) or Nova Scotia Economics and Statistics (https://novascotia.ca/finance/statistics/) to characterize the angler community of respondents relative to the general population of the province.

For open-ended questions (e.g., reasons for fishing), an inductive qualitative thematic coding method was used. First, responses were read to identify keywords, which became a list of potential codes. Similar potential codes were then grouped into themes. Responses were read a second time and tagged with these themes to determine their prevalence. A response may have been associated with multiple themes if warranted. Coding was performed by the first author.

To quantify relationships between the reasons for fishing identified and various other demographic or behavioural characteristics, we developed a suite of Bayesian statistical models in PyMC (v4; www.pymc.io). Multiple reasons for fishing were often identified within a given response, leading to multinomial responses. As our objective was to summarize responses among groups, rather than pursue predictive modelling or causal inference, models were built for each covariate, using a Dirichlet multinomial data likelihood. Selected key covariates included 1) when a participant learned to fish (young/adult), 2) where a participant learned to fish (in Nova Scotia/elsewhere), 3) newcomer status (immigrant or refugee/born in Canada), 4) target species (target mackerel/other or no preference for target), 5) disability (disability identified/no disability identified), 6) fishing platform (wharf/beach or shoreline/boat), and 8) social context (alone/friends/family/kids). Models were evaluated for convergence using traceplots and R-hat statistics (McElreath, 2020), and full model code and outputs are available online (https://gist.github.com/mamacneil/69680dd42be3c4174ae6f9759d7b6919).

# Results

## Demographics of survey respondents

There were 285 total responses received, with 215 (75.4%) fully completed surveys. About half of respondents (n=115, 51.6%) live in HRM, which is similar to, but may slightly overrepresent, the proportion of Nova Scotians who reside in HRM (48%)[6]. The next most numerous counties included nearby Lunenburg County on the south shore of Nova Scotia (n=22, 9.9%) and Cape Breton Regional Municipality (n=15, 6.7%), the largest community on Cape Breton Island, although rural Queens, Shelburne, Yarmouth, Annapolis, Kings, Hants, Colchester, Cumberland, Pictou, Antigonish, Guysborough, Richmond, Inverness, and Victoria counties were all represented (Figure 2). These results are largely consistent with the counties in which anglers said they fished, suggesting that while there is some intra-provincial travel to fishing spots (notably anglers from HRM leaving the urban setting to fish in more rural counties), most people tend to fish relatively close to where they live. A relatively large number of respondents (n=25, 11.4%) identified as newcomers to Canada (i.e., immigrants or refugees; nearly double the 6.1% of the provincial population comprising immigrants[7]). Furthermore, 14 respondents (5.9%) identified as Indigenous (on par with 5.7% of the provincial population that identifies as Indigenous[8]), suggesting that some people with Indigenous rights to fish (i.e., *via* FSC fishing) self-identify as recreational anglers. While the vast majority (n=186, 83.8%) of respondents were native English speakers, there were numerous French-speaking anglers (n=27), perhaps representing the province's long-standing Acadian population, in addition to smaller groups of speakers representing dozens of other languages.

With respect to gender identity, those who responded suggest that the fishing community is a largely male-dominated group, with 182 (82%) identifying as male. Additionally, 48 (24%) identified as having a disability, which was a slightly lower proportion than the provincial prevalence of 30%[9]. Physical (i.e., mobility, flexibility, pain) challenges were the most common disabilities identified by respondents. Only 3 of these individuals were off work due to their disability, while the others were either working or retired. Education levels were largely consistent with the general population of Nova Scotia[10], with 44 (19.7%) respondents identifying a high school diploma as the highest level achieved (versus 25.3% of the provincial population, the largest education category) and 44 (19.3%) respondents identifying a community college diploma (21.8% of the general population). Completion of an apprenticeship was slightly more prevalent among respondents (n=33, 14.8%) than the general population (9.9%), whereas the prevalence of having attained a university Bachelor's degree (n=36, 16.1%) was slightly below provincial metrics (20.8%), despite the fact that local university publication channels were one of the various methods used to promote the survey. The most common annual household income within the group was the $25 000-50 000 (CAD) band (n=49, 22.2%), which was below the median household income in NS (median income in 2020: $66 300, excluding zeros, for "economic families and persons not in economic families, per Statistics Canada[11]). The majority of respondents (n=121, 54.5%) were employed full-time, with a substantial secondary group of retired individuals (n=44, 19.8%). There were 18 respondents (8.2%) who identified as working (or having worked) in the commercial fishery sector.

## Benefits from fishing

In asking why respondents fish recreationally for Atlantic mackerel, eight key themes emerged (ordered from highest to lowest probability of an angler choosing the reason): 1) food, 2) sport, 3) bait, 4) social connection, 5) time outdoors, 6) accessibility, 7) relaxation/mental health, and 8) tradition (Table 1). We found that fishing for food, sport, and bait were the most likely reasons to fish for mackerel (Table 1). Most respondents cited the taste and nutritional value (e.g., omega-3 fatty acids) of the fish as key reasons they eat mackerel as food. Our respondents also explained that this fishing activity may contribute to their own food security (e.g., "Mackerel is a vital resource for our family, we try to stock up some to help get us

6 https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/hlt-fst/pd-pl/Comprehensive.cfm

7 https://www12.statcan.gc.ca/census-recensement/2016/as-sa/fogs-spg/Facts-pr-eng.cfm?LANG=Eng&GK=PR&GC=12&TOPIC=7

8 https://www12.statcan.gc.ca/census-recensement/2016/as-sa/fogs-spg/Facts-PR-Eng.cfm?TOPIC=9&LANG=Eng&GK=PR&GC=12

9 https://novascotia.ca/accessibility/prevalence/

10 https://novascotia.ca/finance/statistics/news.asp?id=13362#:~:text=sex%20cohorts%20and-,HIGHEST%20LEVEL%20OF%20EDUCATION,Scotians%20reported%20a%20college%20diploma.

11 https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1110019101&pickMembers%5B0%5D=1.5&cubeTimeFrame.startYear=2016&cubeTimeFrame.endYear=2020&referencePeriods=20160101%2C20200101

TABLE 1 Prevalence of motivations for anglers fish for Atlantic mackerel or Amalamaq (*Scomber scombrus*) in Nova Scotia/Mi'kma'ki for recreational purposes.

| | Mean | SD | HPD 3% | HPD 97% |
|---|---|---|---|---|
| **Food** | 0.443 | 0.024 | 0.399 | 0.490 |
| **Sport** | 0.216 | 0.021 | 0.178 | 0.257 |
| **Bait** | 0.173 | 0.019 | 0.138 | 0.209 |
| **Social** | 0.065 | 0.013 | 0.041 | 0.089 |
| **Outdoors** | 0.036 | 0.009 | 0.020 | 0.055 |
| **Accessibility** | 0.033 | 0.009 | 0.018 | 0.051 |
| **Relaxation** | 0.023 | 0.008 | 0.010 | 0.038 |
| **Tradition** | 0.010 | 0.005 | 0.002 | 0.020 |

Values are posterior means and standard deviations (SD), with lower (HPD 3%) and upper (HPD %97) 94% uncertainty intervals, given by the highest posterior density (HPD) from an intercept-only Bayesian model.

through the winter"), provide food for pets (e.g., domestic cats), or be shared with friends, family, and especially elders in their community who enjoy eating mackerel. However, most identified that there was limited impact on their grocery budget or that the expenditures on gas and equipment negated any financial benefit of the value of the food. Individuals who fished for sport found the activity "fun", "challenging", "engaging", or found the 'thrill of the chase' satisfying (e.g., "I love the feeling of catching 3-4 on the line it's a great fight…"). Among anglers who aim to acquire bait to use in other fishing activities, most cited recreational striped bass (*Morone saxatilis*) fishing as the use of the bait, although others mentioned targeting sharks, groundfish (e.g., Atlantic cod), and one respondent even used it in bear hunting, with the bear meat harvested serving as subsistence food for them.

Social connection was the next most likely reason for fishing, with respondents citing the great camaraderie that takes place while mackerel fishing, "bonding with friends and family", and the opportunity to meet people from different backgrounds, ages, and cultures. The motivation to get outdoors was another key benefit, i.e., "the enjoyment of being in nature" or "something to do while enjoying the sea". Accessibility of the fish and fishing activity was another reason respondents choose mackerel fishing, citing that they "are relatively easy to catch compared to other fish", require little gear, and are "youth friendly" (i.e., appropriate for teaching children to fish). Relaxation or mental health was identified as an additional reason for fishing (e.g., "It is a wonderful peaceful way of relaxing, love the solitude with nature."). Tradition was a theme that emerged from comments identifying mackerel fishing as a regular seasonal activity they anticipate, an activity they learned from their family growing up (e.g., "…it is an outdoor activity that I have enjoyed since I was a child. I was raised in a fishing family."), or as an activity to pass on to youth in their community. Crucially, most respondents identified multiple reasons for, and benefits derived from, recreational mackerel fishing.

## Covariates of fishing benefits

Modeling reasons for fishing as a function of when a respondent learned to fish revealed that those who grew up fishing from a young age were much more likely to fish for food (2.8x, Bayesian highest posterior density [HPD] odds ratio) or bait (2.2x) than an angler who learned to fish as an adult (Figure 3). On the other hand, anglers who learned to fish as adults were more motivated by relaxation (2.8x), tradition (1.7x), and accessibility (3.5x). Anglers who learned to fish in Nova Scotia were more likely to fish for food and bait than those who learned to fish elsewhere. In contrast, folks who learned to fish elsewhere were much more likely to be motivated by tradition (2.1x) and accessibility of the fishery (3.1x). Modelling results suggest newcomers (i.e., immigrants or refugees) to Canada were more likely to fish mackerel for accessibility (2.2x), sport (1.9x), and food (1.5x) than Canadian-born anglers. In contrast, Canadian-born anglers were more likely to fish for social connection, relaxation, or bait.

Model results suggest that anglers targeting mackerel specifically were more likely to fish for sport (1.6x), food (1.4x), and social (1.3x) reasons than those with less target specificity. Those with less preference for catching mackerel specifically were more likely to be motivated by tradition (2.6x), accessibility (1.9x) or bait (1.6x). In addition to Atlantic mackerel, anglers most frequently caught pollock (n=99 responses), striped bass (n=69 responses), cod (n=57 responses), squid (n=55 responses), and flounder (n=44 responses; Table 2). It should be noted that it appears some of these species are caught incidentally or concurrently while Atlantic mackerel fishing (e.g., pollock, squid), while others are likely caught during separate recreational fishing trips (e.g., striped bass; suggested by the differences in species distribution and gear types required), but it was not always possible to conclusively distinguish between the two scenarios.

Anglers who identified as having a disability were much more likely to fish for food (2.1x) than others, whereas, perhaps

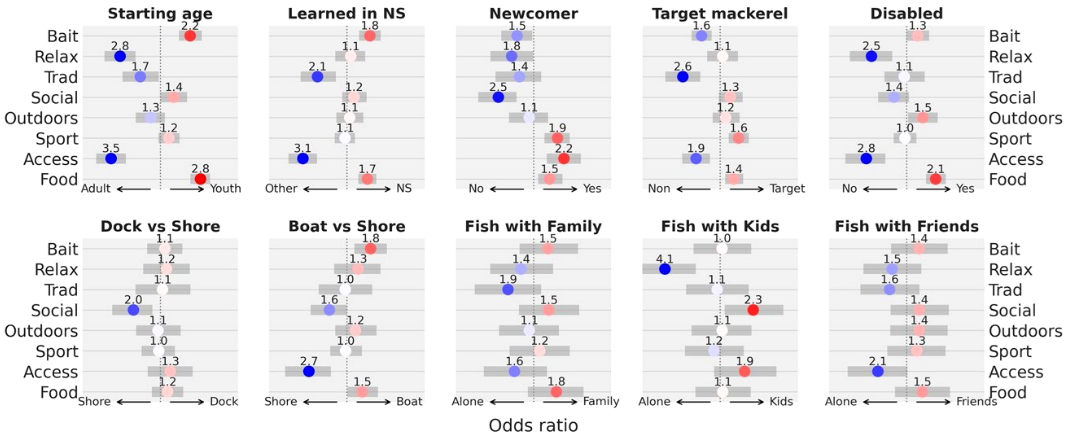



FIGURE 3
Odds ratio plots for reasons anglers fish for Atlantic mackerel or Amalamaq (*Scomber scombrus*) in Nova Scotia/Mi'kma'ki for recreational purposes as a function of selected key covariates. Points are highest posterior density (HPD) odds ratios for conditions listed at the bottom of each panel, with grey bars representing 50% HPD intervals. Grey bars not spanning unity (vertical 1:1) are considered to have clear evidence of differences between groups. Colours shaded for magnitude of the odds ratio for conditions on the left (blue) and right (red).

surprisingly, those who did not identify as having a disability cited relaxation (2.5x) and fishery accessibility (2.8x) more often. Considering fishing platforms, those fishing from a wharf/dock and beach/shore had relatively high interest in fishery accessibility compared to those fishing from a boat. Anglers fishing from a beach/shore were more likely to cite social connection as a reason for fishing (e.g., 2x more than wharf/dock). Modelling reasons for fishing as a function of social context suggests that those fishing alone are more motivated by tradition and accessibility than those fishing with friends or family. Anglers fishing with children are much more likely to be interested in the value of social connection (2.3x) and accessibility of the fishery (1.9x), but they are much less likely to fish for relaxation.

There was no evidence of a relationship between reasons for fishing and avidity (frequency of fishing trips). Anglers of various income levels fished for similar reasons, with increased income associated with a slightly higher likelihood to be motivated by food and slightly smaller likelihood for fishing as a tradition. While men and women both fished for similar reasons, model results suggest that women were much less likely to fish for mackerel to use as bait than their male counterparts.

**TABLE 2** Additional species of fishes caught by recreational Atlantic mackerel fishers in Nova Scotia/Mi'kma'ki.

| Common name | Species name | Number of mentions |
|---|---|---|
| Pollock | *Pollachius virens* | 99 |
| Striped bass | *Morone saxatilis* | 69 |
| Cod | *Gadus morhua* | 57 |
| Squid (Shortfin) | *Illex illecebrosus* | 55 |
| Flounder (Various, e.g., Yellowtail, Winter) | *Various (e.g., Pseudopleuronectes americanus, Limanda ferruginea* | 44 |
| Cunner/Perch | *Tautogolabrus adspersus* | 41 |
| Sculpin | *Myoxocephalus* spp. | 40 |
| Herring | *Clupea harengus* | 24 |
| Trout (Various, e.g., Speckled/brook, brown, lake, rainbow) | *e.g., Salvelinus fontinalis, Salmo trutta, Salvelinus namaycush, Oncorhynchus mykiss* | 13 |
| Haddock | *Melanogrammus aeglefinus* | 13 |
| Eel | *Anguilla rostrata* | 10 |
| Smelt | *Osmerus mordax* | 9 |
| Other | Various | 140 |

## Management and conservation

About half of respondents identified that they catch fewer Atlantic mackerel now than in the past (n=122, 48.8%) and most reported that they are smaller than they used to be (n=148, 59%). Notes shared by survey respondents suggest that this might vary among sites (not specified), at different times of the year, and that there were sometimes trade-offs between number and size (i.e., they might see more fish, but fewer of legal size to retain). It is likely that individuals who selected "Not sure" for these questions did not have a long enough time series to compare, as the majority in this category had been fishing <1 year or 1-3 years. Virtually all respondents have observed fishing regulations for Atlantic mackerel getting stricter over time.

While the purpose of the questionnaire was not to identify support for or alternatives to current management practices, many opinions on conservation and management were shared in the open-ended comments, suggesting an interest in engaging with management procedures (Figure 4). The group was split in supporting current regulations (n=22 comments), opposing current regulations (n=21 comments), and advocating for changes to regulations (n=20 comments). A total of 35 comments across these categories highlighted concerns over the impact of commercial fisheries or explicitly blamed the commercial fishery for declines in the mackerel stock. Assessing relative impacts of these fisheries is beyond the scope of the present research.

Those in favour of the regulations expressed desire for a sustainable fishery, sometimes citing concerns about other depleted fish populations in Atlantic Canada, including herring and various groundfish, such as Atlantic cod. They believe stricter rules in response to fewer and smaller fish made sense, acknowledging that all anglers "have a role to play" in ensuring future stock health. Many cited concerns about the large amount of catch (sometimes caught for the commercial bait fishery under the guise of recreational fishing, particularly before there was a bag limit instated), illegal retention of undersized fish, and unethical handling/discard methods that they had observed from other recreational anglers. One respondent drew a comparison with hunting and described surprise at the lack of education, enforcement, and licencing in recreational fishing compared to the rigorous protocols in place to ensure sustainable harvest of land animals in the region. Another individual mentioned interest in a saltwater licence that would apply to recreational species including mackerel. However, importantly, it was made clear that in any case, these regulations must be developed and implemented in cooperation with the fishing community and informed by the local knowledge of anglers to ensure that they are based upon credible, legitimate, and salient information. As one respondent put it, "We're out here fishing and understand the species and therefore it would be beneficial to listen to us."

On the other hand, respondents who opposed current regulations largely felt that the restrictions were disproportionate to the small perceived impact that recreational anglers have on the resource, particularly in comparison to the more intensive commercial fishery. A sentiment shared by numerous respondents was that "recreational fishers are being penalized for

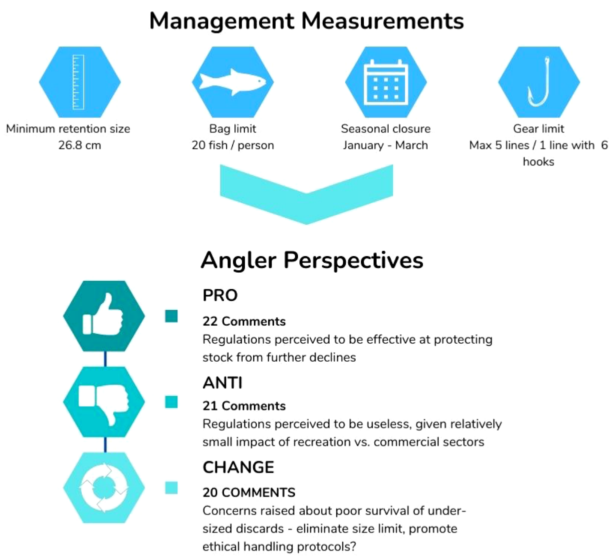



FIGURE 4
Summary of current restrictions and angler perspectives on current management measures (2021-2022) for recreational Atlantic mackerel or Amalamaq (*Scomber scombrus*) fishing in Nova Scotia/Mi'kma'ki.

commercial overfishing". The impact of purse seiners was specifically cited as an example of a commercial fishery capable of making detrimental impacts on the stock. There were concerns that management efforts might jeopardize important food-gathering activities of locals. Some expressed dismay that a fish so well-suited to human consumption (e.g., because of taste/nutrition) was commonly used as a bait fish. In any case, most anglers felt that it is important that this fishery resource remains a public good ("the people's fish"), rather than a species only accessible for commercial purposes

Advocates for regulation changes unanimously highlighted concern over post-release survival of undersized discarded fish, given that "current regulations mean that often undersized fish are thrown back even after they are seriously injured by the hooks". It is believed by many respondents that mackerel has a high vulnerability to handling stress relative to other species. Given that there is a minimum size limit, a 20-fish/person bag limit, and overall fewer big fish to be caught, the result may be forced high-grading and a much higher rate of mortality of mackerel than the bag limit would suggest. Some anglers propose doing away with the size limit and allowing the first 20 fish caught (of any size) to be retained to reduce waste. Alternatively, gear modification (e.g., hook type) and ethical handling practices were suggested to improve survival of discards.

Additional insights from open-ended comments included concerns about climate change (e.g., impacts on timing to migration), access to preferred fishing spots (e.g., overcrowding at popular wharfs, addition of 'no fishing' signs in certain locales, accessibility for anglers with disabilities), food safety (e.g., possible signs of contamination in fish from heavily industrialized Halifax Harbour), and continuity of Indigenous traditions (i.e., connection between declines in wildlife populations and loss of Mi'kmaq culture). With respect to Indigenous traditions, one participant elaborated that they are one of the few left in their reservation community who still practices traditional Mi'kmaw culture, including mackerel fishing. They cite environmental challenges such as global warming and social challenges such as prevalence of social media as key barriers to the continuity of traditional Mi'kmaw ways of life.

Other participants felt that mackerel fishing is an activity that binds Nova Scotians together, with one participant describing it as a shared cultural activity uniting and benefiting African Nova Scotians, Mi'kmaq, Acadians, and newcomers to the province. Another respondent even suggested it could be an untapped opportunity for ecotourism. In particular, fishing was highlighted as a means of engaging youth in ocean stewardship (e.g., through activities such as the Little Fishers Club, Bedford, NS; https://www.facebook.com/groups/382070278528023). Additionally, a number of anglers expressed interest in future research on another local, understudied recreational species, often targeted by mackerel anglers: shortfin squid (*Illex illecebrosus*).

# Discussion

## Benefits from fishing

If fisheries are valuable for benefits beyond economic gain, it is important to engage with the full range of rightsholders and stakeholders utilising the resource to understand who they are, and how and why they fish, in order to make management decisions in consideration of continued access to the full range of benefits derived from fishing. Here we identified numerous important motivations for, and benefits derived from, recreational mackerel fishing in Nova Scotia, including the recreation value and aesthetic aspects of getting outside in nature (i.e., cultural ecosystem services) highlighted from other studies (UNEP, 2006; Hunt et al., 2013), in addition to the provisioning of nutritious, culturally appropriate food. These benefits contribute to numerous social objectives for fisheries, such as those outlined by the Canadian Fisheries Research Network (Stephenson et al., 2019), namely the objectives of health and well-being (e.g., *via* the physical and mental health benefits of relaxation, time outdoors, and nutritious food) and sustainable communities (e.g., *via* local, accessible food, social connection, and tradition).

Fishing for mackerel for consumption was the most-cited reason to fish in our study. Thus, Atlantic mackerel represents a relatively rare example of a fish stock harvested in eastern Canada and largely consumed locally (as opposed to exported to high-value markets; Fisheries and Oceans Canada, 2022) and prepared at home (as opposed to consumed in a restaurant). An analogous fishery in the region could be the recreational fishery (sometimes known locally as the "food fishery") for Atlantic cod, most notably within the neighbouring waters of the province of Newfoundland and Labrador, another stock (famously) under commercial moratorium. While Arlinghaus and Cooke (2008) discuss recreational fisheries as "non-commercial fishing activities that are not the individual's primary resource to meet nutritional needs", this definition may underplay the various ways food plays a role in coastal communities. For example, while mackerel might not be necessary for food security in the region [defined as "physical and economic access to sufficient safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO, 2003)], it might play a significant role in food sovereignty, a concept which encapsulates "the right of local peoples to control their own food systems, including markets, ecological resources, food cultures, and production modes" (Wittman, 2011). There might be alternative protein sources available for many, but Atlantic mackerel fishing is a form of small-scale fishery that provides culturally appropriate and nutritious seafood for a wide range of communities across the region, with a relatively high degree of accessibility, insofar as limited equipment or expertise is required to catch mackerel during high-density 'runs' in the summer and autumn months.

However, the desire to harvest food synergizes with other social and cultural motivations and benefits. The activity of fishing for mackerel also contributes significantly to cultural heritage in the region, for Indigenous communities who have harvested mackerel in the region for millennia (Denny et al., 2020), for those in non-Indigenous communities in Nova Scotia with centuries of experience mackerel fishing (Fisheries and Oceans Canada, 1982), and for newcomers arriving in Nova Scotia from around the country and around the world, bringing their traditions of catching and consuming fish with them, as evidenced by this study. Recreational mackerel fishing is an intergenerational activity, in terms of sharing food with community elders, bonding with family members, and teaching children about the marine environment and food harvest.

## Access to fishing

Our findings highlight that accessibility is also a significant motivation to take part in this fishery for those who learned to fish as adults (and perhaps have less fishing skills and experience), newcomers to Canada (who may have less knowledge about local species, fishing locations, and practices), and those fishing with children (who seek a 'starter' fish to teach children angling techniques). Individuals fishing with children appear to be focused on the youth experience, prioritizing the social connection, as opposed to their own relaxation. Anglers with disabilities were less likely to say they fished mackerel because it was easily accessible, perhaps because they face additional barriers, or perhaps because this group already consists of experienced anglers who need not seek out an 'easy catch'. Our findings suggest that public availability of dock and wharf infrastructure, as well as appropriate stretches of shoreline (ideally with a deeper 'drop-off'), are associated with fishery accessibility. Beach and shoreline locations appear particularly important for social connection, perhaps because there is more space to congregate and they offer alternative activities for other friends and family members.

While the diversity of the angler community creates rich opportunities for multicultural and intergenerational relationship-building at the wharf and on the water, this means that there are also several complex priorities to balance in managing fishery access moving forward. This includes access for rural coastal communities, access for urban anglers in the face of coastal gentrification and industrial development[12], and access for newcomers to Canada. Recreational fishing effort in and near urban centres (such as HRM) is particularly understudied (McPhee, 2017; Kadfak and Oskarsson, 2020; Griffin et al., 2021). However, social processes such as demographic change and urbanization, including those occurring recently in the rapidly growing HRM[13], are known to affect recreational fishing participation (Bissell et al., 1998), so it is essential to consider these mechanisms in visioning a future for this fishery.

Interestingly, we found that those with less preference for mackerel as a target species were more interested in tradition, accessibility, and bait than those with target specificity. This highlights that for many, the activity of fishing itself is as important as what is caught. Awareness of these non-catch benefits of recreational fishing is important, particularly for a stock in decline. When satisfaction with fishing experience is decoupled from catch, high levels of effort may be maintained despite declines in fish abundance (Hyder et al., 2020; Kleivan et al., 2020; Nieman and Solomon, 2021). On the other hand, anglers can continue to enjoy some of the benefits of fishing as a sport even if retention of fish is limited.

## Management and conservation implications

The value of recreational angler experiential knowledge, such as the information documented here, is greater than ever before as of the upcoming 2022 fishing season in light of the recent commercial fishery closure. Many of the respondents to our survey noticed declines in fish abundance and size over time, and thus this community might represent a pool of potential local resource stewards who could help enact win-win solutions for people and the environment (Granek et al., 2008), perhaps analogous to partnerships between Ducks Unlimited and hunters (Reid et al., 2002). As demonstrated here, anglers find management measures more acceptable when they reflect their knowledge base and address the most urgent perceived threats to the fishery (Granek et al., 2008; Zukowski et al., 2011; Hyder et al., 2020). Granek et al. (2008) identified enforcement, advocacy, conservation, and research as key venues through which recreational anglers could directly engage with management.

Indeed, in this study, some important insights were captured incidentally with implications for fisheries management efforts. First, it appears that recent increases in recreational restrictions on Atlantic mackerel have largely been imposed to reduce large-scale fishing (e.g., for commercial bait) under the guise of 'recreational' fishing (Van Beveren et al., 2017a). Respondents' perceptions that recreational catch may be less of a management concern than harvest for commercial reasons seem correct, although accurate measures of catch from recreational

12 https://www150.statcan.gc.ca/n1/daily-quotidien/220209/g-b001-eng.htm

13 https://www150.statcan.gc.ca/n1/daily-quotidien/220209/g-b001-eng.htm?utm_source=citynews%20halifax&utm_campaign=citynews%20halifax%3A%20outbound&utm_medium=referral

mackerel fishing remain unknown (Brushett et al., 2019; Van Beveren et al., 2017b). This was reflected in the 2022 government decision to close commercial and bait fisheries, while maintaining FSC and recreational access (Government of Canada, 2022). Furthermore, current restrictions on the fishing season implemented during the winter months do not appear to limit true recreational fishing activity in practice, given that recreational fishing largely takes place in summer and autumn. While a saltwater licence, brought up by one respondent, has been discussed as an option within the DFO advisory process in the past, it has yet to be implemented, perhaps due to lack of support from stakeholders or lack of prioritization by internal decision-makers. Given the numerous comments contributed here opposing increasing restrictions, it is unclear whether recreational mackerel anglers would be supportive of licensing. Additional comments about the influence of climate change on mackerel abundance or distribution are also important, as these issues are of interest to fisheries scientists and fisheries managers as well (Overholtz et al., 2011; Bruge et al., 2016; McManus et al., 2018; Mbaye et al., 2020). In fact, there are numerous calls to action (Boyce et al., 2021) and work is underway (Pepin et al., 2022) to better integrate climate and other oceanographic considerations into fisheries assessments in Canada.

Many community concerns shared in open-ended comments centred on post-release mortality of undersized fish. While it may be controversial to advocate for the removal of a minimum size limit for a fish stock in decline, given long-standing inclusion of size limits for conservation purposes in a wide range of fisheries, this regulation ignores the particular sensitivity of mackerel to handling stress observed by many of the respondents (see also Tenningen et al., 2021). Instead, relying primarily on the bag limit to restrict catch might actually lead to reduced mackerel mortality in the recreational fishery. Although in freshwater fisheries, long dominated by recreational users, catching fish of a certain size is optimized as opposed to maximizing yield (Ihde et al., 2011), it is well known that there are a variety of species, particularly in the marine environment, for which catch-and-release measures are ineffective for a variety of reasons [e.g., Atlantic cod (Ferter et al., 2015) or rockfish (Granek et al., 2008) barometric effects, admittedly less of a concern for a fish like mackerel which lacks a swim bladder]. Alternatively, or additionally, community-led education efforts around gear recommendations and ethical guidelines for handling fish could minimize handling stress and improve survival of undersized discarded fish. It is essential that restrictions are effective and appreciated by the community, given that effective data collection and management rely on an engaged fishing community that understands and wants to support management (Cooke et al., 2019; Hyder et al., 2020).

A key challenge for rebuilding the Atlantic mackerel stock is the use of mackerel for bait in large commercial fisheries. It appears that bait usage in recreational fishing also has a (likely much smaller) impact on the mackerel stock as well. A shift from conventional use of bait fish to the development of alternative bait products has been proposed as a conservation solution in the commercial sector (Hewitt, 2018; Patanasatienkul et al., 2020; Zhou, 2021). Recreational anglers may also benefit from alternative bait options in the pursuit of species such as striped bass, which could shift recreational fishing pressure on mackerel to prioritize access for those fishing for food/nutritional or cultural purposes. Given that we found evidence of more interest in bait among individuals with less target species specificity, it appears that mackerel bycatch or species able to be caught concurrently with mackerel might be acceptable bait equivalents for recreational anglers. It is essential that, in any case, recreational fishers are engaged directly to help inform or test the efficacy and acceptability of bait alternatives.

## Methodological reflections

It is important to acknowledge that due to the opt-in nature of the questionnaire used in this study, "historical legacies and contemporary realities" introduce bias with respect to who would choose to respond, which would in turn influence results documented here (Biggs et al., 2021). For example, given that language barriers were sometimes encountered during community outreach, and given the relatively high proportion of immigrants and refugees identified in the survey, it is likely that respondents from this group represent a subset of a larger, more diverse community of newcomer anglers. While multilingual outreach materials were developed, it was not possible to administer and analyze the questionnaire itself in multiple languages, and additional sociocultural factors may have influenced willingness to share personal information. Also, while FSC fishing was not the focus of this study, our work demonstrates that at least some FSC mackerel fishers harvest alongside other anglers. A recent study of the Mi'kmaw mackerel fishery has been explored through a Mi'kmaw Ecological Knowledge workshop conducted by Unama'ki Institute of Natural Resources (Denny et al., 2020), and is worthy of separate consideration by management officials in light of differential rights to fishery access held by Indigenous groups in the region.

Furthermore, there is a history of mistrust among fish harvesters, scientists, and fisheries managers in eastern Canada which can be traced back decades to the Atlantic cod stock collapse and moratorium in the 1990s (Hutchings et al., 1997; Neis et al., 1999; Murray et al., 2006; Haggan et al., 2007; Murray et al., 2008; Hutchings, 2022). Willingness for some anglers to participate in fisheries research may have been impacted by personal experience with, or media exposure to, these issues. In addition, there was likely a bias toward engagement with urban anglers given that the research team was based in HRM and was able to conduct more regular dockside visits in the (sub)urban area. Having the questionnaire available online increased reach province-wide, but potential respondents without reliable internet access, or those who have less comfort or interest in use of technology, may have been underrepresented because of our reliance on a virtual survey platform. Despite these limitations, there is qualitative evidence of information saturation in most response categories, and thus the insights presented here are still of great value. Although cultural traditions might be similar in other parts of eastern Canada where Atlantic mackerel is caught for recreational purposes, it is unclear the extent to which it is appropriate to extrapolate our findings to other provinces beyond Nova Scotia.

## Conclusion

For Atlantic mackerel in Canadian waters, there remain important knowledge gaps in understanding of biological processes, relatively short and few survey inputs, and under-reporting of catch from both domestic and bordering international fisheries (e.g., overlap with the Southern contingent of Atlantic mackerel in neighbouring American waters) (Van Beveren et al., 2017b). These must be addressed if successful rebuilding of the stock for ecosystem health, continued FSC/recreational access, and a reopening of commercial/bait access, is to be realized. At the same time, it is important that in developing conservation strategies, particularly in light of scientific uncertainty, these efforts do not unintentionally cause social harms which might undermine local stewardship capacity and support for stock recovery (Bennett et al., 2021). For example, here we document a range of benefits relating to both food provisioning and cultural ecosystem services currently enjoyed by the large community of recreational mackerel anglers in Nova Scotia, which might be threatened threatened either by continued decline of the stock, or regulations which may limit access to the fish.

In order to make management decisions informed by this complexity, more holistic fisheries assessments are necessary, which will likely require greater input from a larger and more diverse group of rightsholders and stakeholders (e.g., for recreational fishing: Cooke and Cowx, 2006; Granek et al., 2008; Mapstone et al., 2008). For example, here we demonstrate that recreational mackerel anglers from a variety of rural, suburban, and urban communities must be engaged, and that resources to facilitate the inclusion of both Indigenous fishers and newcomer anglers must be available. By speaking directly to members of the fishing community, as we have done in our study, fisheries scientists and managers can avoid traps such as reinventing the wheel when knowledge is already held by the fishing community; making incorrect assumptions about human behaviour; dismissing human components of the system as too complex; or distilling human influence to an inappropriately simplistic assessment of 'impact' (Hunt et al., 2013). Assessing the wide range of different ways people rely on and interact with fish is an essential first step toward healthier human-nature relationships, thriving ocean ecosystems, and sustainable and equitable provisioning of benefits for fish harvesters of all stripes.

## Data availability statement

The datasets presented in this article are not readily available because Ethics approval was subject to the dataset being kept confidential and saved securely by the research team. However, all results and Python code used for analysis are publicly available, as noted in the manuscript (https://gist.github.com/mamacneil/69680dd42be3c4174ae6f9759d7b6919). Requests to access the datasets should be directed to kayla.hamelin@Dal.ca.

## Ethics statement

The studies involving human participants were reviewed and approved by Dalhousie University Research Ethics Board (2021-5622). The patients/participants provided their written informed consent to participate in this study.

## Author contributions

KH led the conceptualization, methodology, investigation, formal analysis, writing (original draft), visualization, and project administration. MM was involved in methodology, formal analysis, writing (review and editing), visualization, and funding acquisition. KC contributed to conceptualization, investigation, and writing (review and editing). MB was involved in conceptualization, methodology, writing (review and editing), supervision, and funding acquisition. All authors contributed to the article and approved the submitted version.

## Funding

This work was supported by an NSERC Alexander Graham Bell Canada Graduate Scholarship and a Killam Doctoral Scholarship awarded to KH. Additional funding support came from a Canada First Research Excellence Fund Award from the Ocean Frontier Institute. MB also acknowledges support from the Nippon Foundation Ocean Nexus Centre. CGSD3 - 547199 - 2020 for KMH NSERC award.

## Acknowledgments

We thank first and foremost the generosity of the hundreds of recreational mackerel anglers of Nova Scotia who took the time to respond to the research questionnaire. KH would like to gratefully acknowledge the time, energy, and expertise shared with her by these anglers, and many others encountered during the dozens of wharf visits conducted in summers 2020 and 2021 as part of this project. Sincere thanks also to the late Dr. Jeffrey A. Hutchings, doctoral co-advisor to KH, who was involved in early project planning and provided support during field work. We are grateful to Spencer Hamelin, Leighton Young (Yan Shu Fang), Valeria Mantilla Morales, Lee Sun, Jasspreet Sahib, Faten Bahjat Yusef Zanaa, and Jocelyn and Tony Amyoony for their assistance with translation in developing multilingual information cards. Thanks also to Dr. Elisabeth van Beveren (DFO Quebec), Dr. Andrew Smith (DFO Quebec), Katie Schleit (Oceans North), Shannon Arnold (Ecology Action Centre), and Sebastiàn Pardo (Ecology Action Centre) for helpful discussions about mackerel management during project development. We thank two anonymous reviewers for their helpful comments in improving the original manuscript.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.


## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.971262/full#supplementary-material

## References


Arlinghaus, R., Abbott, J. K., Fenichel, E. P., Carpenter, S. R., Hunt, L. M., Alós, J., et al. (2019). Governing the recreational dimension of global fisheries. *Proc. Natl. Acad. Sci. U. S. A.* 116, 5209–5213. doi: 10.1073/pnas.1902796116

Arlinghaus, R., and Cooke, S. J. (2008). Recreational fisheries: Socioeconomic importance, conservation issues and management challenges. *Recreat. Hunting Conserv. Rural Livelihoods Sci. Pract.*, 39–58. doi: 10.1002/9781444303179.ch3

Arlinghaus, R., Tillner, R., and Bork, M. (2015). Explaining participation rates in recreational fishing across industrialised countries. *Fish. Manage. Ecol.* 22, 45–55. doi: 10.1111/fme.12075

Bennett, N. J. (2019). Marine social science for the peopled seas. *Coast. Manage.* 47, 244–252. doi: 10.1080/08920753.2019.1564958

Bennett, N. J., Katz, L., Yadao-Evans, W., Ahmadia, G. N., Atkinson, S., Ban, N. C., et al. (2021). Advancing social equity in and through marine conservation. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.711538

Biggs, R., De Vos, A., Preiser, R., Clements, H., Maciejewski, K., and Schlüter, M. (2021). The routledge handbook of research methods for social-ecological systems. 112. doi: 10.4324/9781003021339

Bissell, S. J., Duda, M. D., and Young, K. C. (1998). Recent studies on hunting and fishing participation in the united states. *Hum. Dimens. Wildl.* 3, 75–80. doi: 10.1080/10871209809359118

Boyce, D. G., Fuller, S., Karbowski, C., Schleit, K., and Worm, B. (2021). Leading or lagging: How well are climate change considerations being incorporated into canadian fisheries management? *Can. J. Fish. Aquat. Sci.* 78, 1120–1129. doi: 10.1139/cjfas-2020-0394

Brownscombe, J. W., Hyder, K., Potts, W., Wilson, K. L., Pope, K. L., Danylchuk, A. J., et al. (2019). The future of recreational fisheries: Advances in science, monitoring, management, and practice. *Fish. Res.* 211, 247–255. doi: 10.1016/j.fishres.2018.10.019

Bruge, A., Alvarez, P., Fontán, A., Cotano, U., and Chust, G. (2016). Thermal niche tracking and future distribution of Atlantic mackerel spawning in response to ocean warming. *Front. Mar. Sci.* 3. doi: 10.3389/fmars.2016.00086

Brushett, R., Carmichael, E., Arnold, S., and Shin, Y. (2019) *What's happening at the wharf? ecology action centre*. Available at: https://ecologyaction.ca/sites/default/files/images-documents/Mackerel_Report_Final.pdf.

Charles, A. T. (1994). Towards sustainability: the fishery experience. *Ecol. Econ.* 11, 201–211. doi: 10.1016/0921-8009(94)90201-1

Charles, A. T. (1995). Fishery science: The study of fishery systems. *Aquat. Living Resour.* 8, 233–239. doi: 10.1051/alr:1995023

Cisneros-Montemayor, A. M., and Sumaila, U. R. (2010). A global estimate of benefits from ecosystem-based marine recreation: Potential impacts and implications for management. *J. Bioeconomics* 12, 245–268. doi: 10.1007/s10818-010-9092-7

Cooke, S. J., and Cowx, I. G. (2006). Contrasting recreational and commercial fishing: Searching for common issues to promote unified conservation of fisheries resources and aquatic environments. *Biol. Conserv.* 128, 93–108. doi: 10.1016/j.biocon.2005.09.019

Cooke, S. J., Twardek, W. M., Reid, A. J., Lennox, R. J., Danylchuk, S. C., Brownscombe, J. W., et al. (2019). Searching for responsible and sustainable recreational fisheries in the anthropocene. *J. Fish Biol.* 94, 845–856. doi: 10.1111/jfb.13935

Cox, S. P., Doug Beard, T., and Walters, C. (2002). Harvest control in open-access sport fisheries: Hot rod or asleep at the reel? *Bull. Mar. Sci.* 70, 749–761. Available at: https://www.ingentaconnect.com/content/umrsmas/bullmar/2002/00000070/00000002/art00024#.

Daedlow, K., Beckmann, V., and Arlinghaus, R. (2011). Assessing an adaptive cycle in a social system under external pressure to change: The importance of intergroup relations in recreational fisheries governance. *Ecol. Soc* 16 (2), 3. Available at: http://www.ecologyandsociety.org/vol16/iss2/art3/.

Denny, S., Denny, A., Paul, T., Sylliboy, J., Doucette, C., et al. (2020) *Amalamaq*. Available at: https://www.uinr.ca/wp-content/uploads/2020/11/Mackerel-MEK.pdf.

DePiper, G. S., Gaichas, S. K., Lucey, S. M., Da Silva, P. P., Anderson, M. R., Breeze, H., et al. (2017). Operationalizing integrated ecosystem assessments within a multidisciplinary team: Lessons learned from a worked example. *ICES J. Mar. Sci.* 74, 2076–2086. doi: 10.1093/icesjms/fsx038

Develop Nova Scotia (2021). Available at: https://developns.ca/wp-content/uploads/2021/03/DEVNS-Marina-Book-20-Spreads_FINAL.pdf.

DeYoung,, Peterman, R. M., Dobell, A. R., Pinkerton, E., Breton, Y, Charles, A. T., et al. (1999). "Canadian Marine fisheries in a changing and uncertain world," in *Canadian Special pub. Fish. and Aquat. Sci*, vol. 129. , 199.

DeYoung,, Charles, A., and Hjort, A. (2008). "Human dimensions of the ecosystem approach to fisheries: an overview of context, cocnepts, tools, and methods," in *FAO fisheries technical paper*, vol. 489. , 152.

DFO (2007). *Integrated fisheries management plan Atlantic mackerel effective*. URL: https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/348914.pdf.

DFO (2015). *Survey of recreational fishing in Canada*. URL: https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/40753220.pdf.

DFO (2021). Assessment of the northern contingent of Atlantic mackerel (Scomber scombrus) in 2020. *Can. Sci. Advis. Secr. Sci. Advis. Rep*. 2021/029.

FAO (2003). *Trade reforms and food security: Conceptualising the linkages*. Rome: Commodity policy and projections service, commodities and trade division. URL: https://www.fao.org/3/y4671e/y4671e.pdf.

FAO (2012). *Recreational fisheries* (Rome: FAO Guidelines for Responsible Fisheries).

Ferter, K., Weltersbach, M.S., Humborstad, O-B, Fjelldal, P-G, Sambraus, F., Strehlow, H.V., et al. (2015) Dive to survive: effects of capture depth on barotrauma and post-release survival of Atlantic cod (Gadus morhua) in recreational fisheries. *ICES journal of marine science*. 72 (8), 2467–81

FFAW (2022). *Media release: DFO Minister shuts mackerel fishery, refuses to conduct adequate science*. URL: https://ffaw.ca/the-latest/news/media-release-dfo-minister-shuts-mackerel-fishery-refuses-conduct-adequate-science/.

Fisheries and Oceans Canada (1982). *Underwater world: Atlantic mackerel*. URL: https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/40627524.pdf.

Fisheries and Oceans Canada (2022) *Canada's fish and seafood trade in 2020: Overview*. Available at: https://waves-vagues.dfo-mpo.gc.ca/Library/41037005.pdf.

Fogarty, M. J. (2014). The art of ecosystem-based fishery management. *Can. J. Fish. Aquat. Sci.* 71, 479–490. doi: 10.1139/cjfas-2013-0203

Foley, P., Pinkerton, E., Wiber, M. G., and Stephenson, R. L. (2020). Full-spectrum sustainability: an alternative to fisheries management. *Ecol. Soc* 25, 1. doi: 10.5751/ES-11509-250201

Fowler, A. M., Ochwada-Doyle, F. A., Dowling, N. A., Folpp, H., Hughes, J. M., Lowry, M. B., et al. (2022). Integrating recreational fishing into harvest strategies: linking data with objectives. *ICES J. Mar. Sci*. 79 (2), 285–307. doi: 10.1093/icesjms/fsab270

Garcia, S. M., Rice, J., and Charles, A. (2014). *Governance of marine fisheries and biodiversity conservation: interaction and co-evolution* (Wiley-Blackwell, Oxford). 552 pp.

Gíslason, D., Helyar, S. J., Óskarsson, G. J., Ólafsdóttir, G., Slotte, A., Jansen, T., et al. (2020). The genetic composition of feeding aggregations of the Atlantic mackerel (Scomber scombrus) in the central north Atlantic: A microsatellite loci approach. *ICES J. Mar. Sci.* 77, 604–612. doi: 10.1093/icesjms/fsaa003

Government of Canada (2022). *Rebuilding key forage fish stocks for healthier East coast fisheries*. 1–5. URL: https://www.canada.ca/en/fisheries-oceans/news/2022/03/rebuilding-key-forage-fish-stocks-for-healthier-east-coast-fisheries.html.

Granek, E. F., Madin, E. M. P., Brown, M. A., Figueira, W., Cameron, D. S., Hogan, Z., et al. (2008). Engaging recreational fishers in management and conservation: Global case studies. *Conserv. Biol.* 22, 1125–1134. doi: 10.1111/j.1523-1739.2008.00977.x

Griffin, K. J., Hedge, L. H., Warton, D. I., Astles, K. L., and Johnston, E. L. (2021). Modeling recreational fishing intensity in a complex urbanised estuary. *J. Environ. Manage.* 279, 111529. doi: 10.1016/j.jenvman.2020.111529

Griffiths, S. P., Bryant, J., Raymond, H. F., and Newcombe, P. A. (2017). Quantifying subjective human dimensions of recreational fishing: does good health come to those who bait? *Fish Fish.* 18, 171–184. doi: 10.1111/faf.12149

Haggan, N., Neis, B., and Baird, I. G. (2017). *Putting Fishers' Knowledge to Work Conference Proceedings August 27-30, 2001 Fisheries Centre Research Reports* 11, 35–40. doi: 10.14288/1.0074793

Hewitt, M. A. (2018). Evaluating alternative bait options for the prince Edward island lobster fishery in lobster fishing area (LFA) 25, Atlantic Canada Charlottetown, PE: University of Prince Edward Island. Retrieved from https://islandscholar.ca/islandora/object/ir:22406/datastream/PDF/download/citation.pdf.

Holder, P. E., Jeanson, A. L., Lennox, R. J., Brownscombe, J. W., Arlinghaus, R., Danylchuk, A. J., et al. (2020). Preparing for a changing future in recreational fisheries: 100 research questions for global consideration emerging from a horizon scan. *Rev. Fish Biol. Fish.* 30, 137–151. doi: 10.1007/s11160-020-09595-y

Hunt, L. M., Arlinghaus, R., Scott, D., and Kyle, G. (2020). *Diversity of anglers: Drivers and implications for fisheries management*, Vol. 28.

Hunt, L. M., Sutton, S. G., and Arlinghaus, R. (2013). Illustrating the critical role of human dimensions research for understanding and managing recreational fisheries within a social-ecological system framework. *Fish. Manage. Ecol.* 20, 111–124. doi: 10.1111/j.1365-2400.2012.00870.x

Hutchings, J. A. (2022). Tensions in the communication of science advice on fish and fisheries: northern cod, species at risk, sustainable seafood. *ICES J. Mar. Sci*. 1–11. doi: 10.1093/icesjms/fsab271

Hutchings, J. A., Haedrich, R. L., and Walters, C. (1997). Reply: Scientific inquiry and fish stock assessment in the Canadian department of fisheries and OceansandReply: The interplay of policy, politics, and science. *Can. J. Fish. Aquat. Sci.* 54, 1430–1431. doi: 10.1139/f97-246

Hyder, K., Maravelias, C. D., Kraan, M., Radford, Z., and Prellezo, R. (2020). Marine recreational fisheries-current state and future opportunities. *ICES J. Mar. Sci.* 77, 2171–2180. doi: 10.1093/ICESJMS/FSAA147

Ihde, T. F., Wilberg, M. J., Loewensteiner, D. A., Secor, D. H., and Miller, T. J. (2011). The increasing importance of marine recreational fishing in the US: Challenges for management. *Fish. Res.* 108, 268–276. doi: 10.1016/j.fishres.2010.12.016

Kadfak, A., and Oskarsson, P. (2020). An (Urban) political ecology approach to small-scale fisheries in the global south. *Geoforum* 108, 237–245. doi: 10.1016/j.geoforum.2019.11.008

Kleivan, A., Moland, E., and Sumaila, U. R. (2020). No fear of bankruptcy: the innate self-subsidizing forces in recreational fishing A. R. Kleiven, E. Moland and U. R. Sumaila *ICES Journal of Marine Science* 77 (6), 2304–2307.

Link, J. S., Bundy, A., Shackell, N., Overholtz, W. J., Manderson, J., Duplisea, D., et al. (2011). Northwest Atlantic Ecosystem-based management for fisheries. *Ecosyst. Manage. Mar. Fish. Evol. Perspect.* 12 (2), 32–112. doi: 10.1017/CBO9780511973956.005

Long, R. D., Charles, A., and Stephenson, R. L. (2015). Key principles of marine ecosystem-based management. *Mar. Policy* 57, 53–60. doi: 10.1016/j.marpol.2015.01.013

Mapstone, B. D., Little, L. R., Punt, A. E., Davies, C. R., Smith, A. D. M., Pantus, F., et al. (2008). Management strategy evaluation for line fishing in the great barrier reef: Balancing conservation and multi-sector fishery objectives. *Fish. Res.* 94, 315–329. doi: 10.1016/j.fishres.2008.07.013

Marasco, R. J., Goodman, D., Grimes, C. B., Lawson, P. W., Punt, A. E., and Quinn, T. J. (2007). Ecosystem-based fisheries management: Some practical suggestions. *Can. J. Fish. Aquat. Sci.* 64, 928–939. doi: 10.1139/F07-062

Mbaye, B., Doniol-Valcroze, T., Brosset, P., Castonguay, M., Van Beveren, E., Smith, A., et al. (2020). Modelling Atlantic mackerel spawning habitat suitability and its future distribution in the north-west Atlantic. *Fish. Oceanogr.* 29, 84–99. doi: 10.1111/fog.12456

McElreath, R. (2020). Statistical rethinking: A Bayesian course with examples in R and Stan. *Chapman and Hall/CRC.* 470.

McLeod, K. L., and Leslie, H. M. (2009). "Why ecosystem-based management," in *Ecosystem-based management for the oceans* (Washington, DC: Island Press), 3–12.

McManus, M. C., Hare, J. A., Richardson, D. E., and Collie, J. S. (2018). Tracking shifts in Atlantic mackerel (Scomber scombrus) larval habitat suitability on the northeast U.S. continental shelf. *Fish. Oceanogr.* 27, 49–62. doi: 10.1111/fog.12233

McManus, A., Storey, J., and White, J. (2011). Identifying the health and well-being benefits of recreational fishing identifying the health and well-being benefits of recreational fishing (FRDC project number: 2011/217). *Curtin University of Technology, Centre of Excellence for Science, Seafood & Health (CoESSH).*

McPhee, D. P. (2017). Urban recreational fisheries in the australian coastal zone: The sustainability challenge. *Sustain.* 9, 1–12. doi: 10.3390/su9030422

Moura, A., Muniz, A. A., Mullis, E., Wilson, J. M., Vieira, R. P., Almeida, A. A., et al. (2020). Population structure and dynamics of the Atlantic mackerel (Scomber scombrus) in the north Atlantic inferred from otolith chemical and shape signatures. *Fish. Res.* 230, 105621. doi: 10.1016/j.fishres.2020.105621

Murray, G., Neis, B., and Johnsen, J. P. (2006). Lessons learned from reconstructing interactions between local ecological knowledge, fisheries science, and fisheries management in the commercial fisheries of Newfoundland and Labrador, Canada. *Hum. Ecol.* 34, 549–571. doi: 10.1007/s10745-006-9010-8

Murray, G., Neis, B., Palmer, C. T., and Schneider, D. C. (2008). Mapping cod: Fisheries science, fish harvesters' ecological knowledge and cod migrations in the northern gulf of st. Lawrence. *Hum. Ecol.* 36, 581–598. doi: 10.1007/s10745-008-9178-1

Neis, B., Schneider, D. C., Felt, L., Haedrich, R. L., Fischer, J., and Hutchings, J. A. (1999). Fisheries assessment: What can be learned from interviewing resource users? *Can. J. Fish. Aquat. Sci.* 56, 1949–1963. doi: 10.1139/f99-115

Nieman, C. L., and Solomon, C. T. (2021). Slow social change: Implications for open access recreational fisheries. *Fish Fish.* 23 (1), 1–7. doi: 10.1111/faf.12608

Nova Scotia (2021) *Mi'kmaq language instruction attracting non-native students*. Available at: https://novascotia.ca/news/release/?id=20070717001 (Accessed July 18, 2022).

Ommer, R. E., Ian Perry, R., Murray, G., and Neis, B. (2012). Social-ecological dynamism, knowledge, and sustainable coastal marine fisheries. *Curr. Opin. Environ. Sustain.* 4, 316–322. doi: 10.1016/j.cosust.2012.05.010

Overholtz, W. J., Hare, J. A., and Keith, C. M. (2011). Impacts of interannual environmental forcing and climate change on the distribution of atlantic mackerel on the u. s. northeast continental shelf. *Mar. Coast. Fish.* 3, 219–232. doi: 10.1080/19425120.2011.578485

Pascual-Fernández, J. J., Pita, C., and Bavinck, M. (2020). *Small-Scale Fisheries in Europe: Status, Resilience and Governance*. MARE Publication Series 23, (Cham Switzerland: Springer Nature Switzerland AG). 610 pp.

Patanasatienkul, T., Delphino, M. K. V. C., and Thakur, K. K. (2020). Comparing the effectiveness of traditional and alternative baits in prince Edward island, Canada lobster fishery. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.589549

Paul, S. D., and Stephenson, R. L. (2020). The integration of full-spectrum ecosystem-based management in Canadian fisheries management plans. *Can. Tech. Rep. Fish. Aquat. Sci.* 3350: v + 16 p. URL: https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/40857384.pdf.

Pepin, P., King, J., Holt, C., Gurney-Smith, H., Shackell, N., Hedges, K., et al. (2022). Incorporating climate, oceanographic and ecological change considerations into population assessments: A review of fisheries and oceans canada's science advisory pr. *Fish and Fisheries*. 1–15

Pita, P., Alós, J., Antelo, M., Artetxe, I., Biton-Porsmoguer, S., Carreño, A., et al. (2020a). Assessing knowledge gaps and management needs to cope with barriers for environmental, economic, and social sustainability of marine recreational fisheries: The case of Spain. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00023

Pita, P., Antelo, M., Hyder, K., and Vingada, J. (2020b). The use of recreational fishers‘ ecological knowledge to assess the conservation status of marine ecosystems. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00242

Reid, A., Tori, G. M., Mcleod, S., Mcknight, K., Moorman, T., and Reid, F. A. (2002). Wetland conservation and ducks Unlimited : Real world approaches to multispecies management. G. M. Tori, S. McLeod, K. McKnight, T. Moorman and F. A. Reid *Waterbirds: The International Journal of Waterbird Biology* Vol. 25, Special Publication 2: Managing Wetlands for Waterbirds: Integrated Approaches pp. 115–121 (7 pages)

Stephenson, R. L., Benson, A. J., Brooks, K., Charles, A., Degnbol, P., Dichmont, C. M., et al. (2017). Practical steps toward integrating economic, social and institutional elements in fisheries policy and management. *ICES J. Mar. Sci.* 74, 1981–1989. doi: 10.1093/icesjms/fsx057

Stephenson, R. L., Wiber, M., Paul, S., Angel, E., Benson, A., Charles, A., et al. (2019). Integrating diverse objectives for sustainable fisheries in Canada. *Can. J. Fish. Aquat. Sci.* 76, 480–496. doi: 10.1139/cjfas-2017-0345

Tenningen, M., Zimmermann, F., and Enberg, K. (2021). Pre-catch and discard mortality in northeast Atlantic herring and mackerel fisheries: Consequences for stock estimates and advice. *ICES J. Mar. Sci.* 78, 2603–2614. doi: 10.1093/icesjms/fsab135

UNEP (2006). Marine and coastal ecosystems and human wellbeing: A synthesis report based on the findings of the Millennium Ecosystem Assessment. *UNEP*. 76. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/9461/-Marine%20and%20Coastal%20Ecosystems%20and%20Human%20Well-Being_%20A%20synthesis%20report%20based%20on%20the%20findings%20of%20the%20Millennium%20Ecosystems%20Assessment-2006652.pdf?sequence=3&%3BisAllowed=.

Urquhart, J., Acott, T., and Zhao, M. (2013). Introduction: Social and cultural impacts of marine fisheries. *Mar. Policy* 37, 1–2. doi: 10.1016/j.marpol.2012.04.007

Van Beveren, E., Castonguay, M., Doniol-valcroze, T., and Duplisea, D. (2017a). Results of an informal survey of Canadian Atlantic mackerel commercial, recreational and bait fishers. *Can. Sci. Advis. Sec. Res.* 2017/029. v + 26 p.

Van Beveren, E., Duplisea, D., Castonguay, M., Doniol-Valcroze, T., Plourde, S., and Cadigan, N. (2017b). How catch underreporting can bias stock assessment of and advice for northwest Atlantic mackerel and a possible resolution using censored catch. *Fish. Res.* 194, 146–154. doi: 10.1016/j.fishres.2017.05.015

Van Beveren, E., Duplisea, D. E., Marentette, J. R., Smith, A., and Castonguay, M. (2020). An example of how catch uncertainty hinders effective stock management and rebuilding. *Fish. Res.* 224, 105473. doi: 10.1016/j.fishres.2019.105473

Wiber, M., and Milley, C. (2007). After marshall: Implementation of aboriginal fishing rights in atlantic Canada. *J. Leg. Plur. Unoff. Law* 39, 163–186. doi: 10.1080/07329113.2007.10756611

Wittman, H. (2011). Food soveriegnty: a new rights framework for food and nature? *Environ. Society.* 2 (1), 19.

Zhou, M. (2021). Alternative baits to improe the sustainability of the snow crab (Chionoecetes opilio) and American lobster (Homarus americanus) fishery. Available at: https://dalspace.library.dal.ca/bitstream/handle/10222/80740/MengdiZhou2021.pdf?sequence=3&isAllowed=y.

Zukowski, S., Curtis, A., and Watts, R. J. (2011). Using fisher local ecological knowledge to improve management: The Murray crayfish in Australia. *Fish. Res.* 110, 120–127. doi: 10.1016/j.fishres.2011.03.020

frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 01 December 2022
DOI 10.3389/fmars.2022.1049893



OPEN ACCESS

EDITED BY
Sebastian Villasante,
University of Santiago de Compostela,
Spain

REVIEWED BY
Kui Zhang,
South China Sea Fisheries Research
Institute, (CAFS), China
Chongliang Zhang,
Ocean University of China, China

*CORRESPONDENCE
Xiujuan Shan
shanxj@ysfri.ac.cn

SPECIALTY SECTION
This article was submitted to
Marine Fisheries, Aquaculture and
Living Resources,
a section of the journal
Frontiers in Marine Science

RECEIVED 21 September 2022
ACCEPTED 17 November 2022
PUBLISHED 01 December 2022

CITATION
Ding Q, Shan X, Jin X and Gorfine H
(2022) Achieving greater equity in
allocation of catch shares: A case
study in China.
*Front. Mar. Sci.* 9:1049893.
doi: 10.3389/fmars.2022.1049893



# Achieving greater equity in allocation of catch shares: A case study in China

Qi Ding[1,2,3], Xiujuan Shan[1,2,3*], Xianshi Jin[1,2,3] and Harry Gorfine[4]

[1]Key Laboratory of Sustainable Development of Marine Fisheries, Ministry of Agriculture and Rural Affairs; Shandong Provincial Key Laboratory of Fishery Resources and Ecological Environment, Yellow Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, Qingdao, China, [2]Function Laboratory for Marine Fisheries Science and Food Production Processes, Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao, China, [3]National Observation and Research Station for Fishery Resources in Changdao, Shandong, Yantai, China, [4]School of Biosciences, The University of Melbourne, Parkville, VIC, Australia

The allocation of catch shares among fishing entities is a key element of a total allowable catch control system. Current allocation schemes fall short in their ability in terms of ensuring fairness and feasibility and there is much scope for improvement. In this study, a new allocation method based on applying a relative deprivation coefficient is introduced into the allocation of catch shares, and demonstrated in a case study involving the 11 coastal provinces in China. Advantages of this process of quota allocation in comparison with well-established allocation methods were investigated. Compared with the conventional single-criterion approach and simple multi-criteria-based allocation with equal weights, the new allocation scheme integrating the new weighting method with multi-criteria allocation showed superior performance in rendering the outcomes in catch shares allocation fairer and more reasonable, with a Gini coefficient below 0.2. Quota proportions for the 11 coastal provinces under the newly developed allocation scheme were between maximum and minimum ratios of those under schemes using a single-criterion, which shows strong utility in reducing the rigidity of a single-criterion allocation approach and improving the acceptability of the allocation results. This study offers a viable yet fairer alternative for facilitating sustainable fisheries *via* quota management and provides a reference for fisheries policy makers in equitably allocating catch shares.

KEYWORDS

**total allowable catch system, multi-criteria allocation, relative deprivation coefficient, Gini coefficient, quota management**

## 1 Introduction

Food security, social well-being and economic prosperity of coastal communities can be highly dependent on sustainable marine fisheries (McClanahan et al., 2015; Asche et al., 2018; FAO, 2022). Output controls such as Total Allowable Catch (TAC) provide a direct method for curbing fishing mortality to maintain biomass at levels where population recruitment is not impaired (Liu et al., 2016). TACs can take the form of tradeable shares of a variable quota owned by individuals and corporations. However, a problem common to all catch shares programs is how to determine the initial allocation of quota among fishing entities.

Reliance on a legacy of historical catch records is the most frequently used means for initial quota allocation when transitioning to a catch shares system. Lynham (2014) reports that among fisheries in the global database 91% employed this method to proportionately allocate a TAC, with sole reliance on historical records in 54% of the world's main catch share fisheries. However, issuing shares based on a legacy of prior involvement is by no means the only option. Bailey et al. (2013) point out the lack of success in delivering sustainable outcomes with this allocation method because participants who stand to benefit financially are inclined to force delays on implementation until production and catching capacity have risen to ecologically harmful levels.

Establishing a fair and reasonable initial allocation scheme for catch shares is an important precept for ensuring TAC systems are effective (Plummer et al., 2012; Severance, 2014; Bellanger et al., 2016). Applying multiple criteria is likely advantageous compared with using a single criterion when allocating catch shares because it is often more readily accepted by participants and simplifies decisions through its integration of diverse information. A more agile system of weighted metrics reviewed annually avoids the rigidity of predetermined allocation outcomes, which can deliver greater benefits compared with a system reliant on personal catch histories (Seto et al., 2021).

Currently, many Regional Fisheries Management Organizations (RFMOs) have outlined the principles of equity, citizenship, and legitimacy to guide allocation. Specifically, equity relates to access to employment and social welfare, citizenship enshrines the rights of those contributing cooperatively to resource management, and legitimacy recognizes those with a long-standing involvement in the fishery. However, different criteria may incur various allocation outcomes, and different fishing entities prefer to choose and adopt criteria that are most beneficial for them as individuals, often resulting in the various fishing entities being unable to reach consensus on a proposed multi-criteria allocation scheme (Seto et al., 2021). In practice, there has been an absence of these principles from the process for allocating access to fish resources. Clearly, a suitable process for promoting sustainability through the issuance of catch shares, has yet to become established more generally for fisheries. Constructing an improved multi-criteria allocation method to increase its feasibility is necessarily required for effective catch shares programs. However, catch shares allocation schemes have not yet been thoroughly investigated in this regard.

China having the greatest number of fishers and fishing vessels worldwide lands the largest fish catch of any nation (China Daily, 2017; Huang and He, 2019; Zhang et al., 2020). Persistently high fishing pressure has resulted in abrupt declines in stock abundance in China's major fishing grounds. This has disrupted ecological relationships as fishing has progressively targeted species of lower trophic status as higher order species have depleted (Cao et al., 2017; Szuwalski et al., 2017; Su et al., 2020). Marine fisheries management in China has in recent years sought to strengthen its strict input control with the addition of output control (Su et al., 2021; Zhang et al., 2022). To build an output control system, an initial allocation of catch shares among fishing entities is fundamental. This has challenged policy-makers deliberating over the best way to allocate catch quotas among China's coastal fishing provinces to achieve the total allowable catch target.

This study explores options for the allocation of catch shares in China. Instead of conventional allocation approaches such as using catch histories as a basis for allocation, this study builds improved allocation methods to increase both fishing entities' acceptance and equity. Furthermore, to demonstrate the advantages of the new allocation method, a comparative analysis of the allocation schemes proposed in the study is conducted. It is anticipated that the scheme developed in this study will better facilitate sustainable fishing and provide a reference for effective and equitable allocation of catch shares.

## 2 Materials and methods

A comparative analysis of different allocation schemes was undertaken with data acquired from the China Fishery Statistical Yearbook 2018–2022 (Fisheries Bureau of the Ministry of Agriculture and Rural Affairs, 2018; Fisheries Bureau of the Ministry of Agriculture and Rural Affairs, 2019; Fisheries Bureau of the Ministry of Agriculture and Rural Affairs, 2020; Fisheries Bureau of the Ministry of Agriculture and Rural Affairs, 2021; Fisheries Bureau of the Ministry of Agriculture and Rural Affairs, 2022). Results were generated from applications of three single-criterion allocation approaches and an alternative multi-criteria allocation method in this study, using an identical dataset.

## 2.1 The allocation of catch shares using the single-criterion approach

Based on existing studies, three criteria including legitimacy, equity, and citizenship are adopted in this study for catch shares allocation. The specific indicators for each of the three criteria are as follows:

### 2.1.1 An allocation scheme based on legitimacy

The legitimacy principle is built upon the cumulative historical domestic catch from 2017 to 2021 according to the latest available data. The details are as follows:

$$Q_i^1 = \frac{\sum_{t=2017}^{2021} C_{it}}{\sum_{i=1}^{11}\sum_{t=2017}^{2021} C_{it}}$$

where $Q_i^1$ ($i$=1, 2, 3, …, 11) is the quota proportion obtained by province $i$ with the legacy approach; $C_{it}$ is the domestic marine catches of province $i$ in year $t$.

### 2.1.2 An allocation scheme based on equity

The equity principle is expressed by the accumulated number of professional marine fishers from 2017 to 2021. The quota proportion ($Q_i^2$) for province $i$ can be obtained by:

$$Q_i^2 = \frac{\sum_{t=2017}^{2021} F_{it}}{\sum_{i=1}^{11}\sum_{t=2017}^{2021} F_{it}}$$

where $F_{it}$ is the number of professional marine fishers of province $i$ in year $t$.

### 2.1.3 An allocation scheme based on citizenship

Fisheries resources in many countries such as China are under severe pressure. Reducing fishing capacity to appropriate levels is crucial in achieving sustainable fisheries goal (Yu and Yu, 2008; Zhao and Jia, 2020). This study develops an allocation method that integrates the conventional legacy approach based on individual catch histories with an efficiency index to create incentives to reduce fishing pressure, and uses it as a proxy for citizenship principle for quota allocation. To be specific,

$$Q_i^3 = \frac{\sum_{t=2017}^{2021} (C_{it} * CPUE_{it})}{\sum_{i=1}^{11}\sum_{t=2017}^{2021} (C_{it} * CPUE_{it})}$$

where $Q_i^3$ is the quota proportion for $i$ province. $CPUE_{it}$ is the catch per unit of effort (t/kW) of province $i$ in year $t$.

## 2.2 A composite indictor construction method

A common problem in the multi-criteria-based allocations is how to determine the weight of each index. In this study, a new weighting method utilizing a relative deprivation coefficient is introduced into the allocation of catch shares, reflecting the requirements of perceived fairness among the fishing entities. The main difference between this new allocation method and the existing methods is that existing single or multi-criteria approaches can only support one allocation scheme prone to rigidity. In contrast, under the newly developed allocation scheme, each of the fishing entities can adopt a different weighting scheme according to their preferences about the criteria, which is actually a "one fishing entity, one allocation scheme", which satisfies the requirement for perception of fairness among all fishing entities. Figure 1 provides a flowchart of the allocation procedure used.

### 2.2.1 Measuring perceived fairness of the allocation based on coefficient of relative deprivation

According to the concept of relative deprivation defined by Runciman (1966) and the computational formula for a relative deprivation coefficient proposed by Yitzhaki (1979); assuming group $X$=($x_1$, $x_2$, …, $x_j$), $j$ is the number of samples (here $j$ equals to 11), $x_i$ and $x_s$ are the individual $i$ and $s$ in group $X$. In terms of individual $i$, feelings of relative deprivation would arise when $x_i$<$x_s$. To be specific,

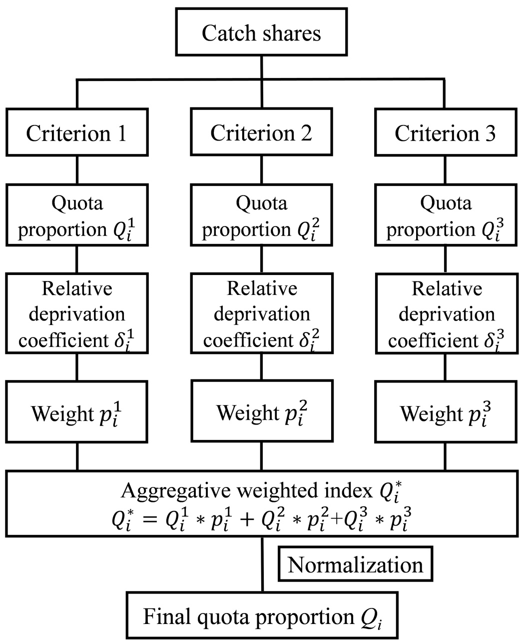



FIGURE 1
Flowchart of the allocation procedure under the multi-criteria comprehensive weighted scheme based on a relative deprivation coefficient.

$$d_{is} = \begin{cases} x_s - x_i & ,if \quad x_i < x_s \\ 0 & ,if \quad x_i \geq x_s \end{cases}$$

The relative deprivation coefficient $\delta$ of $x_i$ relative to group $X$ is calculated by the following equation:

$$d(x, x_i) = \sum_{s=1}^{j} d_{is} / (j * x_i)$$

### 2.2.2 Determining the weights based on coefficient of relative deprivation

Based on the calculation of a relative deprivation coefficient, the sense of deprivation of fishing entity $i$ under a certain criterion is high when the value of the relative deprivation coefficient is large. Therefore, to improve the perception of fairness, a smaller weight should be assigned to this criterion (Wu et al., 2021). In contrast, a larger weight would be given in instances which have a small value of the relative deprivation coefficient. In terms of the multi-criteria allocation scheme based on perceptual fairness, the weights should be inversely associated with the relative deprivation coefficient (Wu et al., 2021). Therefore, the weight function is constructed as follows: (i) $p_i^k$ is the weight of criterion $k$ for $i$ province, and $\sum_{k=1}^{3} p_i^k = 1$; (ii) $\delta_i^k$ is the relative deprivation coefficient of criterion $k$ for $i$ province, and the mapping relation of weights function $p_i^k = f(\delta_i^k)$ should satisfy the following equations including $dp/d\delta<0$ and $p_i^k \subset [0, 1]$. In this study, we calculated the weights using the probability functions. To be specific,

$$p = f(\delta) = \frac{1}{1 + e^{\delta}}$$

$$p_i^k = \frac{f(\delta_i^k)}{\sum_{k=1}^{3} f(\delta_i^k)}$$

And then quota proportion $Q_i^*$ for province $i$ can be obtained by:

$$Q_i^* = \sum_{k=1}^{3} Q_i^k p_i^k$$

Lastly normalize $Q_i^*$ to get the final quota proportion $Q_i$:

$$Q_i = \frac{Q_i^*}{\sum_{i=1}^{11} Q_i^*}$$

## 2.3 Gini coefficient in catch shares allocation system

As a powerful tool to examine the equality of income distribution in an economic system, the Gini coefficient method has been widely used to quantify the inequality in the allocation of environmental resources (Yuan et al., 2017; Ma et al., 2020; He and Zhang, 2021). The Gini coefficient ranges from 0 to 1. A small Gini coefficient means a higher level of equality, and 0.4 has been regarded as the warning line of impending inequity risk. To apply the Gini coefficient to the allocation of catch shares, we replaced human population and income with the number of professional marine fishers in 2021 and allocated catch shares respectively and calculate the corresponding Gini coefficient. According to Kong et al. (2019), the calculation process of the Gini coefficient is simplified as follows:

$$G = \frac{S_A}{S_A + S_B} = \frac{S_A}{0.5} = 2S_A = 1 - 2S_B$$

$$S_B = \sum_{i=1}^{11} \frac{(X_i - X_{i-1})(Y_i + Y_{i-1})}{2}$$

Where $S_A$ represents the area between the Lorenz curve and the straight "absolute equality line", $S_B$ is the area under the Lorenz curve, $S_A$+$S_B$=0.5, $X_i$ represents the cumulative share of fishers up to province $i$, $X_0 = 0$; $Y_i$ refers to the cumulative proportion of catch quotas up to province $i$, $Y_0 = 0$; and $G$ is the Gini coefficient for the equality evaluation of allocation results, which can be calculated by:

$$G = 1 - \sum_{i=1}^{11} (X_i - X_{i-1})(Y_i + Y_{i-1})$$

# 3 Results

## 3.1 Allocation results using the single-criterion approach

As is shown in Figure 2, the three single-criterion allocations gave rise to diverse results. When a legitimacy criterion was applied, the top three provinces were Zhejiang (27.35%), Shandong (16.77%), and Fujian (16.05%), followed by Guangdong, Hainan, Guangxi, Liaoning, and Jiangsu with catch shares proportions of 12.20%, 10.49%, 5.31%, 4.95%, and 4.51%, respectively. Catch shares proportions were lowest in Hebei, Tianjin and Shanghai, with respective values of 1.98%, 0.27%, and 0.12%.

When an equity criterion was applied, Guangdong, Fujian, Liaoning, Jiangsu, Hebei, and Shanghai had much higher catch shares proportions compared with those obtained from application of the other two single-criterion allocations, with catch shares proportions of 20.84%, 18.29%, 11.08%, 4.95%, 2.73% and 0.33%, respectively. In contrast, when a citizenship criterion was applied, Shandong had much higher catch shares

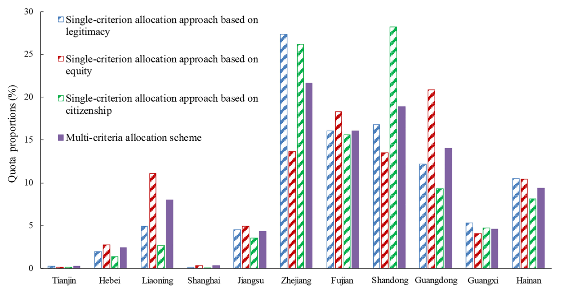



FIGURE 2
Allocation results under the different schemes.

proportions amongst the three single-criterion approaches, with a catch shares proportion of 28.20%.

## 3.2 Weights of criteria determined by relative deprivation coefficient

This study obtained the weights of selected criteria in the multi-criteria allocation scheme based on the relative deprivation coefficient. The weights of criteria for each province were determined by their different preference for the three selected criteria, which can effectively avoid the drawbacks of a one-size-fits-all approach. Specifically, in terms of Tianjin, applying the criterion of legitimacy was the most advantageous, having the lowest value of relative deprivation coefficient amongst the three criteria. In contrast, the values of relative deprivation coefficient for the three criteria including legitimacy, equity, and citizenship in Hebei were 3.76, 2.50, and 5.61, with corresponding weights of 0.22, 0.74, and 0.04, respectively. However, adopting the criterion of citizenship was the most advantageous to Shandong, and the relative deprivation coefficient was equal to zero. The distribution of weights across criteria reflected the preferences of fishing provinces, which increased both the acceptability and the practical value of the allocation scheme. The relative deprivation coefficients and weights of the three criteria for the 11 fishing provinces are shown in Table 1.

## 3.3 Allocation results using the multi-criteria approach

Based on the weights of the three criteria listed in Table 1, this study obtained catch shares proportions for the 11 coastal provinces derived using the multi-index based method (Figure 2). The ranking from high to low was Zhejiang, Shandong, Fujian, Guangdong, Hainan, Liaoning, Guangxi, Jiangsu, Hebei, Shanghai, and Tianjin provinces, with corresponding ratios of 21.67%, 18.90%, 16.07%, 14.01%, 9.40%, 8.03%, 4.60%, 4.31%, 2.42%, 0.32% and 0.26%, respectively. Quota proportions for the 11 coastal provinces under the multi-criteria approach lay between the maximum and minimum ratios of those under the schemes using a single-criterion, effectively reducing the rigidity of the single-criterion allocation approach (resulting in very low or very high values of catch shares proportions).

## 3.4 A comparative analysis of the equality of allocation results

The equality of allocation results generated by different allocation schemes were measured by the Gini coefficient method. Figure 3 presents the Lorenz curves of the catch shares allocation results derived from the three single criterion allocation schemes and one multi-criteria approach.

TABLE 1 Relative deprivation coefficients of the three criteria and corresponding weights under the multi-criteria allocation scheme.

| Provinces | Relative deprivation coefficient | | | Weight | | |
|---|---|---|---|---|---|---|
| | Legitimacy | Equity | Citizenship | Legitimacy | Equity | Citizenship |
| Tianjin | 33.06 | 73.48 | 56.40 | 1 | 0 | 0 |
| Hebei | 3.76 | 2.50 | 5.61 | 0.22 | 0.74 | 0.04 |
| Liaoning | 1.07 | 0.18 | 2.60 | 0.33 | 0.58 | 0.09 |
| Shanghai | 73.27 | 26.23 | 167.36 | 0 | 1 | 0 |
| Jiangsu | 1.24 | 1.07 | 1.82 | 0.36 | 0.41 | 0.22 |
| Zhejiang | 0 | 0.08 | 0.01 | 0.34 | 0.32 | 0.34 |
| Fujian | 0.07 | 0.01 | 0.13 | 0.33 | 0.34 | 0.32 |
| Shandong | 0.06 | 0.08 | 0 | 0.33 | 0.33 | 0.34 |
| Guangdong | 0.18 | 0 | 0.41 | 0.34 | 0.37 | 0.29 |
| Guangxi | 0.96 | 1.42 | 1.24 | 0.40 | 0.28 | 0.32 |
| Hainan | 0.26 | 0.22 | 0.52 | 0.35 | 0.36 | 0.30 |

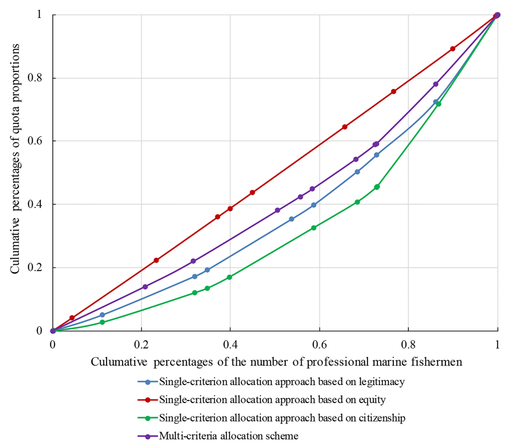



FIGURE 3
The Lorenz curves of allocation results derived from the schemes using single-criterion and multi-criteria allocation approaches.

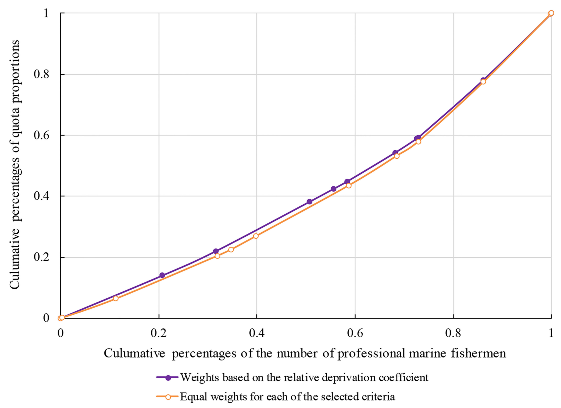



FIGURE 4
The Lorenz curves of allocation results under the multi-criteria-based allocations.

Unsurprisingly, the Gini coefficients of the allocation results derived from the scheme that solely considered the equity criterion had the smallest Gini coefficient among the four schemes, with the curve above those generated by the other three schemes. It's worth noting that the Gini coefficient is below 0.2 under the multi-criteria approach, indicating a high equality distribution interval. In contrast, the Gini coefficients for the schemes that exclusively considered either legitimacy or citizenship were 0.25 and 0.35, respectively.

To illustrate the advantages of the newly developed weighting method in improving the equality of allocation results in the multi-criteria-based allocations, we compared two scenarios under the multi-criteria allocation schemes, as follows: (1) determination of the weight of each index based on the relative deprivation coefficient; and (2) equal weights for each of the selected principles. The scenario analysis resulted in small changes to the Gini coefficients as shown in Figure 4. The Gini coefficient of the scheme based on the relative deprivation coefficient was smaller than that based on the equal weights method.

## 4 Discussion

Among the many challenges which confront governing the exploitation of a common pool resource, the allocation of access entitlements is fundamental (Ostrom, 1990; Ostrom, 2003). To date, most catch share programs appear to have relied heavily on the principle of historical catch in determining allocations, but also recognize, in different ways, that this single criterion is not the most effective and equitable strategy (Cox, 2009; Bailey et al., 2013). This study initially conducted a comparative analysis of different allocation approaches of catch shares, our analysis suggested that quota proportions for the 11 coastal provinces vary widely under the three single-criterion approaches, which may face challenges in their practical feasibility. When the single criterion approach which analyzed legitimacy, equity, and citizenship criteria separately was applied, provinces that obtained the largest quota proportions among the 11 coastal provinces were Zhejiang, Guangdong, and Shandong, respectively. Different provinces have diametrically opposed preferences depending on the allocation criterion in each instance. In contrast, the newly developed allocation scheme shows strong utility in addressing the problems of rigidity which have existed in single-criterion approaches, thus facilitating a substantial improvement the practicality of ensuring fairness in sustainable resource allocation.

Allocation models with multiple weighted criteria would facilitate the quantitative incorporation of multiple principles that have historically been under-represented and may offer alternative allocation possibilities that could improve the management of fish resources (Bailey et al., 2013). Weight determination is one of the most significant steps in a multi-criteria allocation scheme. Compared with the conventional multi-criteria allocation scheme based on an equal weights method, the improved catch shares allocation scheme incorporated not only a multi-criteria system but also requirements for perceptual fairness among the fishing entities participating in the allocation scheme, thereby increasing the equity and feasibility of multi-criteria-based allocations. Our analysis suggests that the new allocation scheme will ensure a more equitable distribution of catch shares among China's coastal fishing provinces, with the Gini coefficient below 0.2.

Overfishing has been a problem facing China since the early 1990s (Zheng et al., 2021) and overcapacity is one of the leading causes of this problem (Han, 2018; Liu, 2019). To achieve sustainable development of the marine fishing industry in China, excess fishing capacity must be addressed through a timely reduction in the number of fishing vessels operating in marine waters (Wang, 2019; Zheng et al., 2021). Domestic fishery management in China is stepping into a new era of output control (Su et al., 2021). Establishing a fair and reasonable allocation scheme for catch shares is an important requisite for China's implementation of an output control system. However, current allocation schemes based on catch histories have not provided the right incentive structure to eliminate overcapacity, leaving much scope for improvement. In this study, an improved catch shares allocation scheme has been developed which places consideration on creating incentives to eliminate overcapacity. Provinces with higher CPUE, such as Shandong Province which has the highest among the 11 coastal provinces, would have higher quota proportions.

The newly developed allocation scheme satisfies simultaneously both individual perceptions of fairness and overall equity, thereby contributing to consensus on catch shares allocation among fishing entities. Instead of setting the weights to zero or one under single-criterion approaches, each province determines the values of the weights for different criteria between zero and one according to its preference under the newly developed allocation scheme, thereby increasing both fairness and feasibility of the allocations. In addition, the proposed method in quota allocation has great advantages in terms of future compatibility. Although only three indicators are incorporated into the multi-criteria allocation scheme in this study, more indicators could be added upon the specific needs. This concept paves the way for further research in formulating fairer and more reasonable allocation schemes for catch shares.

Based upon the main findings of this study, the following policy implications are proposed. First, when policy makers in China allocate catch shares among different provinces, they should not only consider historical catch as a legacy criterion, as this explicitly ignores motivators of fisher behavior and fails to elucidate tradeoffs among policy decisions. Allocating catch shares should be a consistent practice which is applied flexibly but equitably with changing circumstances. Although by integrating multiple indicators from different perspectives the multi-criteria decision analysis model can make the outcomes more reasonable, it may become highly contentious during the implementation process on account of the different preferences among the fishing provinces for the allocation criteria. Hence, the proposed allocation scheme integrating the new weighting method with multi-criteria allocation not only renders the outcomes fairer and more reasonable in catch shares allocation but also increases the likelihood of acceptability.

Second, this study focused on the allocation method of catch shares, however, setting scientifically based catch limits is also an indispensable part of TAC systems (Emery et al., 2014). Annual maximum allowable catch in China is approximately 8–9 million tonnes (China National Radio, 2016). However, domestic marine catches in China reached 9.3 million tonnes in 1994, and the actual exploitation of fishing resources has long exceeded the maximum allowable catch (Fisheries Bureau of the Ministry of Agriculture and Rural Affairs, 1995). Further reduction of fishing capacity is needed considering that problems of overcapacity and depleted fisheries stocks continue to pose a serious threat to marine ecosystems in China. Occupational transfer of marine fishers to other industries is a vital measure that can contribute substantially to fishing effort reduction (China Fisheries News, 2017; Zhao and Jia, 2020), thus serious attempts should be made to implement effective transfer programs across the 11 coastal provinces. In particular, policy options including providing greater financial investment in boosting onshore employment opportunities for former fishers augmented by enhancing training programs should be considered. Meanwhile, the government could increase policy support and financial input for the development of marine ranching and recreational angling, which have been playing vital roles in helping to protect fisheries ecosystems, conserve fish stocks and create alternative employment opportunities as local fish farmers throughout China (Yu and Zhang, 2020; Qin et al., 2021; Qiu et al., 2021).

Third, China should strengthen its procedures for the allocation of the total catch and enhance its fisheries monitoring. Unified approaches to policy management and implementation at and below provincial scales, using a suite of control indicators should be instituted from the top to the bottom of the governance hierarchy in an integrated way. The Chinese government needs to reform its fisheries statistical system and develop a strong set of robust monitoring programs that take advantage of emerging technology. Fisheries monitoring is a crucial instrument in fisheries management that records and reports fishery-dependent data to inform decision-makers (Zhu et al., 2021) and China will need this if its approach towards catch share allocation is to lead to long-term ecologically sustainable development outcomes.

## 5 Conclusions

Developing a reasonable allocation scheme for catch shares amongst fishing entities is an essential part of a volume control policy. This study constructs a multi-criteria comprehensive weighted scheme based on a relative deprivation coefficient, and further compares the allocation outcomes from this new scheme with those obtained using single-criterion approaches to show the advantage and feasibility of the proposed method in quota allocation. The allocation of catch shares among the 11 coastal provinces in China is illustrated as a case study. The results reveal that quota proportions for the 11 coastal provinces vary widely under the three single-criterion approaches, which may impede their implementation in practice. However, the newly developed allocation scheme shows strong utility in increasing the fairness and feasibility of the allocations. Quota proportions for the 11 coastal provinces under the newly developed allocation scheme were between the maximum and minimum ratios of those under the schemes using a single criterion. This study will help to enrich catch shares allocation methods and provides a new fair and reasonable method for policy makers to assign catch shares.

## Data availability statement

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

## Author contributions

QD, conceptualization, methodology, and writing. XS, investigation and validation. XJ, visualization and reviewing. HG, reviewing and editing. All authors contributed to manuscript revision, read, and approved the submitted version.

## Funding

This work was supported by the National Natural Science Foundation of China (Grant No. 42176151), the Special Funds for Taishan Scholars Project of Shandong Province and the Innovation Team of Fishery Resources and Ecology in the Yellow Sea and Bohai Sea (2020TD01).

## Acknowledgments

We thank two reviewers for constructive comments that improved this manuscript.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## References

Asche, F., Garlock, T. M., Anderson, J. L., Bush, S. R., Smith, M. D., Anderson, C. M., et al. (2018). Three pillars of sustainability in fisheries. *Proc. Natl. Acad. Sci. U. S. A.* 115 (44), 11221–11225. doi: 10.1073/pnas.1807677115

Bailey, M., Ishimura, G., Paisley, R., and Sumaila, U. R. (2013). Moving beyond catch in allocation approaches for internationally shared fish stocks. *Mar. Pol.* 40, 124–136. doi: 10.1016/j.marpol.2012.12.014

Bellanger, M., Macher, C., and Guyader, O. (2016). A new approach to determine the distributional effects of quota management in fisheries. *Fish Res.* 181, 116–126. doi: 10.1016/j.fishres.2016.04.002

Cao, L., Chen, Y., Dong, S., Hanson, A., Huang, B., Leadbitter, D., et al. (2017). Opportunity for marine fisheries reform in China. *Proc. Natl. Acad. Sci. U. S. A.* 114 (3), 435–442. doi: 10.1073/pnas.1616583114

China Daily (2017) *Fishing ban imposed earlier this year*. Available at: http://www.chinadaily.com.cn/a/201705/02/WS59bb9417a310d4d9ab7eabd2.html. (Accessed 1st September 2021).

China Fisheries News (2017). Implementing the system for managing total marine fisheries esources, protecting aquatic biological resources–the interpretation of notice on further strengthening the management of domestic fishing vessels and implementing the system for managing total marine fisheries resources by kangzhen yu, minister of the ministry of agriculture and rural affairs. China fisheries. *China fisheries* 2, 31–33.

China National Radio (2016) *Three fatal problems of fishery development at present in China, said han changfu, vice minister of the ministry of agriculture and rural affairs.* Available at: http://country.cnr.cn/gundong/20160816/t20160816_523000411.shtml. (Accessed 9th October 2021).

Cox, A. (2009). "Quota allocation in international fisheries," in *Technical report. OECD food, agriculture and fisheries working papers, no. 22* (France: OECD Publishing).

Emery, T. J., Hartmann, K., Green, B. S., Gardner, C., and Tisdell, J. (2014). Does 'race to fish'behaviour emerge in an individual transferable quota fishery when the total allowable catch becomes non-binding. *Fish. Fish.* 15 (1), 151–169. doi: 10.1111/faf.12015

FAO (2022). *The state of world fisheries and aquaculture* (Rome: Food and Agriculture Organization of the United Nations press).

Fisheries Bureau of the Ministry of Agriculture and Rural Affairs (1995). *China Fisheries statistical yearbook 1995* (Beijing, China: Agricultural Press).

Fisheries Bureau of the Ministry of Agriculture and Rural Affairs (2018). *China Fisheries statistical yearbook 2018* (Beijing, China: Agricultural Press).

Fisheries Bureau of the Ministry of Agriculture and Rural Affairs (2019). *China Fisheries statistical yearbook 2019* (Beijing, China: Agricultural Press).

Fisheries Bureau of the Ministry of Agriculture and Rural Affairs (2020). *China Fisheries statistical yearbook 2020* (Beijing, China: Agricultural Press).

Fisheries Bureau of the Ministry of Agriculture and Rural Affairs (2021). *China Fisheries statistical yearbook 2021* (Beijing, China: Agricultural Press).

Fisheries Bureau of the Ministry of Agriculture and Rural Affairs (2022). *China Fisheries statistical yearbook 2022* (Beijing, China: Agricultural Press).

Han, Y. (2018). Marine fishery resources management and policy adjustment in China since 1949. *Chin. Rural Economy.* 9, 14–28.

He, W., and Zhang, B. (2021). A comparative analysis of Chinese provincial carbon dioxide emissions allowances allocation schemes in 2030: An egalitarian perspective. *Sci. Total Environ.* 765, 142705. doi: 10.1016/j.scitotenv.2020.142705

Huang, S., and He, Y. (2019). Management of china's capture fisheries: Review and prospect. *Aquac. Fish.* 4 (5), 173–182. doi: 10.1016/j.aaf.2019.05.004

Kong, Y., Zhao, T., Yuan, R., and Chen, C. (2019). Allocation of carbon emission quotas in Chinese provinces based on equality and efficiency principles. *J. Clean Prod.* 211, 222–232. doi: 10.1016/j.jclepro.2018.11.178

Liu, Z. (2019). Research on the status, causes and governance of marine fishing ground desertification. *Issues Agric. Economy.* 6, 105–116.

Liu, O. R., Thomas, L. R., Clemence, M., Fujita, R., Kritzer, J. P., McDonald, G., et al. (2016). An evaluation of harvest control methods for fishery management. *Rev. Fish. Sci. Aquac.* 24 (3), 244–263. doi: 10.1080/23308249.2016.1161002

Lynham, J. (2014). How have catch shares been allocated. *Mar. Pol.* 44, 42–48. doi: 10.1016/j.marpol.2013.08.007

Ma, G., Li, X., and Zheng, J. (2020). Efficiency and equity in regional coal de-capacity allocation in China: a multiple objective programming model based on gini coefficient and data envelopment analysis. *Resour. Policy* 66, 101621. doi: 10.1016/j.resourpol.2020.101621

McClanahan, T., Allison, E. H., and Cinner, J. E. (2015). Managing fisheries for human and food security. *Fish. Fish.* 16 (1), 78–103. doi: 10.1111/faf.12045

Ostrom, E. (1990). *Governing the commons* (Cambribge: Cambridge University Press).

Ostrom, E. (2003). How types of goods and property rights jointly affect collective action. *J. Theor. Polit.* 15 (3), 239–270. doi: 10.1177/0951692803015003002

Plummer, M. L., Morrison, W., and Steiner, E. (2012). *Allocation of fishery harvests under the Magnuson–stevens fishery conservation and management act: Principles and practice* (National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center. Seattle, WA: US Department of Commerce), 1–84.

Qin, M., Wang, X., Du, Y., and Wan, X. (2021). Influencing factors of spatial variation of national marine ranching in China. *Ocean Coast. Manage.* 199, 105407. doi: 10.1016/j.ocecoaman.2020.105407

Qiu, Y., Wang, E., Bu, Y., and Yu, Y. (2021). Valuing recreational fishery attributes, opportunities and associated activities in China from the tourists' satisfaction perspectives. *Mar. Pol.* 131, 104616. doi: 10.1016/j.marpol.2021.104616

Runciman, W. G. (1966). *Relative deprivation and social justice: A study of attitudes to social inequality in twentieth-century England* (Berkeley and Los Angeles: University of California Press).

Seto, K., Galland, G. R., McDonald, A., Abolhassani, A., Azmi, K., Sinan, H., et al. (2021). Resource allocation in transboundary tuna fisheries: A global analysis. *Ambio* 50 (1), 242–259. doi: 10.1007/s13280-020-01371-3

Severance, C. (2014). Sharing the catch or catching the shares: Catch shares for the western pacific region. *Mar. Pol.* 44, 3–8. doi: 10.1016/j.marpol.2013.08.002

Su, S., Tang, Y., Chang, B., Zhu, W., and Chen, Y. (2020). Evolution of marine fisheries management in China from 1949 to 2019: How did China get here and where does China go next? *Fish. Fish.* 21 (2), 435–452. doi: 10.1111/faf.12439

Su, M., Wang, L., Xiang, J., and Ma, Y. (2021). Adjustment trend of china's marine fishery policy since 2011. *Mar. Pol.* 124, 104322. doi: 10.1016/j.marpol.2020.104322

Szuwalski, C. S., Burgess, M. G., Costello, C., and Gaines, S. D. (2017). High fishery catches through trophic cascades in China. *Proc. Natl. Acad. Sci. U. S. A.* 114 (4), 717–721. doi: 10.1073/pnas.1612722114

Wang, J. (2019). Research on the supply side structure reform of marine capture fisheries from the perspective of policy and institutional supply. *Issues Agric. Economy.* 11, 25–31.

Wu, L., Wang, Q., and Tian, Q. (2021). Research on global carbon emission rights allocation and emission reduction sharing–based on the perspective of environmental constraints and perceived fairness. *Chin. J. Environ. Manage.* 13 (04), 100–110.

Yitzhaki, S. (1979). Relative deprivation and the gini coefficient. *Q. J. Econ.* 93, 321–324. doi: 10.2307/1883197

Yuan, Q., McIntyre, N., Wu, Y., Liu, Y., and Liu, Y. (2017). Towards greater socio-economic equality in allocation of wastewater discharge permits in China based on the weighted gini coefficient. *Resour. Conserv. Recycl.* 127, 196–205. doi: 10.1016/j.resconrec.2017.08.023

Yu, H., and Yu, Y. (2008). Fishing capacity management in China: Theoretic and practical perspectives. *Mar. Pol.* 32 (3), 351–359. doi: 10.1016/j.marpol.2007.07.004

Yu, J., and Zhang, L. (2020). Evolution of marine ranching policies in China: Review, performance and prospects. *Sci. Total Environ.* 737, 139782. doi: 10.1016/j.scitotenv.2020.139782

Zhang, K., Geng, P., Li, J., Xu, Y., Kalhoro, M. A., Sun, M., et al. (2022). Influences of fisheries management measures on biological characteristics of threadfin bream (Nemipterus virgatus) in the beibu gulf, south China Sea. *Acta Oceanol. Sin.* 41 (3), 24–33. doi: 10.1007/s13131-021-1925-9

Zhang, W., Liu, M., Sadovy de Mitcheson, Y., Cao, L., Leadbitter, D., Newton, R., et al. (2020). Fishing for feed in China: Facts, impacts and implications. *Fish. Fish.* 21 (1), 47–62. doi: 10.1111/faf.12414

Zhao, X., and Jia, P. (2020). Towards sustainable small-scale fisheries in China: A case study of hainan. *Mar. Pol.* 121, 103935. doi: 10.1016/j.marpol.2020.103935

Zheng, S., Wang, S., Xu, W., and Liu, Q. (2021). Research on the job transfer pathway of Chinese marine fishermen and its driving factors. *Mar. Pol.* 129, 104572. doi: 10.1016/j.marpol.2021.104572

Zhu, W., Lu, Z., Dai, Q., Lu, K., Li, Z., Zhou, Y., et al. (2021). Transition to timely and accurate reporting: An evaluation of monitoring programs for china's first total allowable catch (TAC) pilot fishery. *Mar. Pol.* 129, 104503. doi: 10.1016/j.marpol.2021.104503

10.3389/fmars.2022.1049893

# Appendix A

TABLE A.1 The cumulative value of selected indictors for 11 fishing provinces in China during 2017–2021.

| Provinces | Domestic marine catches $C_{it}$ (tons) | Number of professional marine fishers $F_{it}$ | Index that is calculated by multiplying the domestic marine catches by the catch per unit effort ($C_{it}$*$CPUE_{it}$) |
|---|---|---|---|
| Tianjin | 135145 | 5636 | 86379 |
| Hebei | 999844 | 126012 | 769370 |
| Liaoning | 2502689 | 511651 | 1465365 |
| Shanghai | 61884 | 15449 | 29417 |
| Jiangsu | 2281607 | 228547 | 1926932 |
| Zhejiang | 13828070 | 628864 | 14256951 |
| Fujian | 8116112 | 844550 | 8507994 |
| Shandong | 8476230 | 625029 | 15361644 |
| Guangdong | 6167616 | 962266 | 5087997 |
| Guangxi | 2684116 | 189095 | 2560353 |
| Hainan | 5305740 | 480579 | 4426723 |

TYPE Review
PUBLISHED 24 March 2023
DOI 10.3389/fmars.2023.1151810



OPEN ACCESS

EDITED BY
Pablo Pita,
University of Santiago de Compostela,
Spain

REVIEWED BY
Moslem Sharifinia,
Iranian Fisheries Science Research Institute,
Iran
Xiujuan Shan,
Yellow Sea Fisheries Research Institute
(CAFS), China

*CORRESPONDENCE
Rómulo E. Loayza-Aguilar
rloayza@uns.edu.pe

SPECIALTY SECTION
This article was submitted to
Marine Fisheries, Aquaculture and Living
Resources,
a section of the journal
Frontiers in Marine Science

RECEIVED 26 January 2023
ACCEPTED 13 March 2023
PUBLISHED 24 March 2023

CITATION
Loayza-Aguilar RE, Huamancondor-Paz YP,
Saldaña-Rojas GB and Olivos-Ramirez GE
(2023) Integrated Multi-Trophic
Aquaculture (IMTA): Strategic model
for sustainable mariculture in
Samanco Bay, Peru.
*Front. Mar. Sci.* 10:1151810.
doi: 10.3389/fmars.2023.1151810



# Integrated Multi-Trophic Aquaculture (IMTA): Strategic model for sustainable mariculture in Samanco Bay, Peru

Rómulo E. Loayza-Aguilar*, Yolanda P. Huamancondor-Paz, Guillermo B. Saldaña-Rojas and Gustavo E. Olivos-Ramirez

Escuela de Biología en Acuicultura, Universidad Nacional del Santa, Av. Universitaria S/N, Nuevo Chimbote, Peru

The development of industrial mariculture in Peruvian coasts will continue to grow according to global trends; however, it is characterized by being mostly monospecific, resulting in ecosystemic impacts due to organic matter, which deteriorate the benthic system and encourage eutrophication, negatively affecting biodiversity and fishery resources, which in a long term could turn the activity into an unsustainable practice. Therefore, it is imperative to adopt new production models, focused on the sustainability principle, such as Integrated Multi-Trophic Aquaculture (IMTA), that allow for greater efficiency, competitiveness, and profitability, while guaranteeing environmental balance. In this context, the present study has addressed the problem of *Argopecten purpuratus* cultivation in Samanco Bay, in which, based on a diagnosis of the bay's conditions, details of the cultivation, and a thorough analysis of the IMTA concept, a strategic model for mariculture is proposed in order to be adopted by private companies, after a validation process. These concepts can be transferred for their adaptation to other scenarios. Furthermore, it is expected that the academic sector, private companies, and the competent authority will be able to intervene synergistically in this process.

KEYWORDS

**integrated multi-trophic aquaculture, mariculture, Samanco bay, organic matter, extractive aquaculture, macroalgae**

## 1 Introduction

Aquaculture is an activity that has provided food for humanity since the ancient ages (Beveridge and Little, 2002). Its origins date back to 3500 B.C. from ancient China (Vela and Ojeda, 2007). However, as a productive-economic activity, it has experienced great growth in recent years, becoming one of the most important economic activities in the world (Asche et al., 2022). Moreover, a major contribution of aquatic resources from aquaculture is expected in the future (Fiorella et al., 2021) since capture fishing has stabilized at levels that are practically impossible to overcome (Gephart et al., 2023). In addition to this, the growing demand for fish (FAO, 2022a), together with global population growth, which is about to reach the milestone of 10 billion people (FAO, 2020), requires that aquaculture activities be developed efficiently and sustainably in order to achieve global food security.

Globally, aquaculture reached a record of 122.6 million tons in 2020, which represents a value of USD 28.5 billion, and is estimated to grow by 13% in 2030 (FAO, 2022b). In 2022, aquaculture provided 50% of the total fish for direct human consumption in the world, being the Asia-Pacific region the major producer (Bartley, 2022). Regarding the diversity of cultivated species, macroalgae currently represent the largest production (51.3%), followed by mollusks (27.4%), crustaceans (9.1%), and other aquatic animals (0.6%) (Chopin and Tacon, 2021). It is important to highlight that modern aquaculture has developed to an advanced technological level that can be extended to all types of ecosystems (Goswami et al., 2023). But it must be recognized that most of the worldwide aquaculture operations are highly dependent on the environment and ecosystem performances (Pailan and Biswas, 2022). Despite this, traditional aquaculture, which is mainly developed in the form of monocultures Park et al. (2018), is disturbing these environments to such a degree that in many regions the activity has been affected to nearly disappear (Han, 2002; Thomsen et al., 2020). Therefore, the current global trend is developing strategies aimed at reducing the impacts of aquaculture to conserve natural capital, thus making it an environmentally friendly, efficient, profitable, and socially beneficial activity (Buschmann et al., 2001).

In Peru, aquaculture is sustained on monoculture: *Argopecten purpuratus* (36.4%), *Oncorhynchus mykiss* (34.2%), and *Litopenaeus vannamei* (24.2%) (PRODUCE, 2022). Here, the culture of the mollusk *A. purpuratus* notoriously outstands in the bays of Sechura and Samanco, which in 2018, with a production of 89,872 t, ranked 1 in Latin America and 4 in the world (Kluger et al., 2018). During the 20 century, aquaculture development has been characterized by intensive monospecific cultivation, based on species of high commercial value and high economic benefit. However, this aquaculture approach generates an important ecological footprint due to the organic waste produced in the cultivation and processing stages, threatening the integrity of ecosystems and the future viability of the sector (González Henríquez et al., 2015). As a result, aquaculture is often associated with pollution (Vela and Ojeda, 2007).

For producers, it is necessary to find measures that are compatible with profitability, as well as sustainability. In addition, it is imperative to migrate from traditional monoculture practices to integrated and sustainable models (Chopin, 2013), in order to ensure the continuity of the aquaculture activity. Under this need, the ecosystem approach to aquaculture (EAA) concept has emerged, which is considered as a strategy aimed at integrating the activity into a broader ecosystem that articulates sustainable development, equity, and resilience of interconnected socio-ecological systems (Brugère et al., 2019). In this sense, associating two or more species from different trophic levels is the most optimal way to reduce the environmental impacts of aquaculture. This aquaculture approach has the advantage of not generating competition among the organisms in captivity, and additionally, improving the flow of matter and energy in the culture. Therefore, the worldwide trend is to implement integrated multi-trophic aquaculture (IMTA) (Chopin et al., 2001; Buschmann et al., 2013).

The IMTA represents the integration of four types of aquaculture: a) feed (fish), b) organic extractive (filter-feeding and suspension-feeding invertebrates), c) inorganic extractive (macroalgae), and d) deposit extractive (suspension-feeding and sediment-feeding invertebrates) (Chopin et al., 2001; Chopin, 2010; Chopin et al., 2010). Nevertheless, to integrate them it is necessary to establish the proportion between the species, according to their specific roles and the abiotic conditions of the ecosystem. This approach is addressed to maximize the benefits of different trophic levels, diversifying the activity, ensuring environmental sustainability and economic viability, while also improving the aquaculture image across society (Salinas-Morrondo, 2012).

The application of IMTA has been successful in several regions. In China, IMTA has been developed in coastal inlets integrating the culture of *Chlamys farreri*, *Crassostrea gigas* and *Laminaria japonica*, allowing them to estimate the exploitation load capacity of *C. farreri* and *C. gigas* in bays and the harvest potential, demonstrating that it is possible to control phytoplankton abundance by managing the density of extractive species (Buschmann et al., 2008b). In Dalian (China), the potential of the marine sponge *Hymeniacidon perleve* has been investigated, revealing a removal capacity between 44-61% of total organic carbon (TOC) in IMTA in co-culture with the marine fish *Fugu rubripes*, and also determining an increase in sponge biomass of 22.8% (Fu et al., 2007). Moreover, in Canada, it has been integrated macroalgae Laminariales and mussel *Mytilus edulis* into the culture of Atlantic salmon in cages, observing that the algae and mussels grow 50% faster than in control sites, proving that the food and nutrient residues generated in the cages have economic potential (Chopin and Robinson, 2004). In that sense, macroalgae can remove dissolved N between 35-100% (Thomas, 2010).

Under the scope of improving aquaculture in accordance with world trends, it is necessary to introduce the IMTA concept in order to be applied in the *A. purpuratus* cultures developed in Peru. Therefore, the purpose of this work is to present the problems of marine aquaculture in Peru and to develop the concepts and advantages of the IMTA model. This model is vital for the continuity *A. purpuratus* culture in Samanco Bay, in addition to providing other economic advantages for the aquaculture producers. The model presented here is also suitable for application to other types of aquaculture cultures in other regions of the world.

## 2 Aquaculture problems in PERU

### 2.1 Context of the *A. purpuratus* culture in Peru

The culture of this filter-feeding species is successful due to the high phytoplankton productivity of the Peruvian coast (Guillén and Rondán, 1968). Cultivation is performed in bays such as Sechura, Nonura, Lobos de Tierra (Piura region), Samanco, Guaynuma, Los Chimus, Salinas, Tortugas, Casma (Ancash region), Independencia, and Paracas (Ica region). In total, the culture of *A. purpuratus* is developed in around 15,999.67 ha, corresponding to 374 rights in modalities of Micro and Small Enterprise Aquaculture (AMYPE, <150 t, 82%), Medium and Large Enterprise Aquaculture (AMYGE, >150 t, 18%) and Aquaculture of Limited Resources (AREL, <3.5 t, <1%) (PRODUCE, 2021). The main form of culture is performed in suspended lines with longline systems, but corrals under the seabed are also used by small-scale producers.

Suspended cultivation is practiced in long-line systems of 100 m, located at a depth of 6 m. Here, lanterns of 2 m in height and 0.5 m in diameter are suspended in the long line systems every 1 m. As a general rule, 3 lines are installed in 1 ha, which remains immovable. The growth process lasts between 12-14 months, and the final phase is carried out at a density of 250 organisms per lantern, employing approximately 49.2 million organisms in 1000 ha approximately. In the final stage of culture, *A. purpuratus* is harvested at 106.5 ± 23.6 g each.

The evolution of the *A. purpuratus* culture shows two stages (Figure 1): a slow growth between 1996-2009, and a fast growth from 2010 onwards. The latest is explained mainly by the formalization of a large number of fishermen's associations that were previously considered informal and were not recorded in the statistics at that time. Notably, the 2010-2018 period is characterized by great instability due to massive mortalities of cultured organisms in Sechura Bay, associated with oxygen deficiency due to harmful algal blooms (HAB) (Gonzales and Yepez, 2007; IMARPE, 2019), the occurrence of El Nino event, such as the one in 2017 (Salazar Camacho, 2023), and deficiencies in the supply of seed from the natural environment.

Despite this, the activity generated more than 10,162 new jobs in 2019 (PRODUCE, 2020), and incomes of USD 420.7 million in 2021, from exportation (PRODUCE, 2022), contributing foreign exchange to the country. Although the economic advantages of this activity are significant, it has also caused serious problems derived from organic contamination, with repercussions on water quality, eutrophication, and impacts on benthic biodiversity. Thus, this activity is clearly not aligned with the principles of sustainability and, if not accounted for, could restrict the continuity of the activity in the medium to long term. In addition, it will have repercussions on other economic value chains, small producers, and the recreational landscape of the bays.

## 2.2 Environmental impacts of *A. purpuratus* culture in Samanco Bay

The production process generates impacts due to: a) ammonia excretion products from cultured organisms and biofouling, b) biodeposition (feces and pseudofeces) by *A. purpuratus* and biofouling, and c) disposal of biofouling *in situ*, due to bad practices, not yet quantified (Loayza Aguilar, 2018). Further contamination is contributed by the disposal of lines, buoys, lanterns, and perl net (broken or unusable), not yet quantified as well.

Biofouling represents the main source of contamination during cultivation. This is composed of algae and invertebrates that develop attached to the culture structures (lanterns, lines, buoys, floating structures). It has been estimated that in the final phase of culture, a lantern can produce between 68.04 to 131.87 kg of biofouling (Loayza and Tresierra, 2014; Loayza Aguilar, 2018). The filter-feeding species *Semimytilus algosus* and *Ciona intestinalis* have been identified as the main biofouling components, which account for 58.6 to 73.0 and 22.3 to 50.0% of the biofouling per lantern, respectively (Loayza Aguilar, 2018). Likewise, Uribe et al. (2008) and Uribe and Blanco (2001), reported that in Tongoy Bay (Chile), a lantern can produce between 100 to 120 kg of biofouling every 3 months. These data show the magnitude of impacts by *A. purpuratus* cultivation.

Besides, feces and pseudofeces are produced by *A. purpuratus* in conjunction with the biofouling organisms represent an important source of pollution. These pollutants release $NH_4$, $NO_3$, and $PO_4$, which are initially deposited in the water column and then distributed throughout the environment by the effect of marine currents (Buschmann et al., 2001), promoting primary productivity. The release of feces and pseudofeces also promotes the biodeposition of organic matter (OM) in the water column, decreasing transparency. In addition, these particulate residues precipitate to the seabed where they accumulate and modify the granulometric composition of the substrate. This has proven to be the main source of sludge

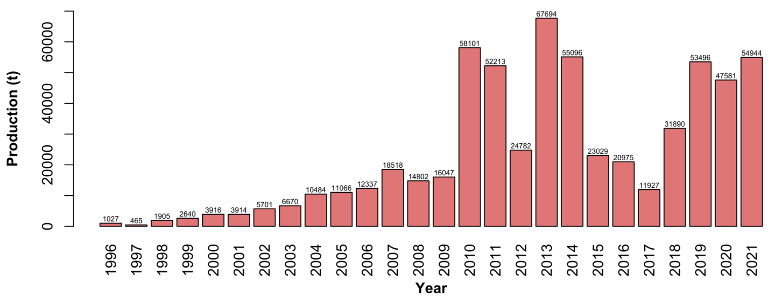



FIGURE 1
Production of *A. purpuratus* from aquaculture in Peru, during the period 1996 to 2021 (Cavero and Rodríguez, 2008; PRODUCE, 2015; PRODUCE, 2020; PRODUCE, 2021; PRODUCE, 2022). The production of *A. purpuratus* had an important growth since 2010, however, due to extraordinary events, such as the El Nino phenomenon, ˜ in 2012 and during the period 2015-17, the production declined significantly. The production remains sustained in the last years despite environmental concerns.

generation at the bottom of the bays. As a consequence, a decrease in dissolved oxygen in the marine environment has been observed, with the release of toxic substances such as $H_2S$ and $NO_2$. Naturally, biodiversity and natural banks of interest to small-scale fishing are significantly affected. On the subject, there are no data on the rates of biodeposition and excretion of $NH_4$ from *A. purpuratus* and biofouling, or about the production of $NO_3$ and $PO_4$ by bacterial action, which we could have a deeper understanding of their impacts.

Regarding the impact of biodeposition, assuming the biodeposition rate recorded in Tongoy Bay (Chile) of 3.9 times the weight of the organisms (Uribe and Blanco, 2001), we can estimate that Samanco Bay would be producing 5,239.8 t in feces and pseudofeces every 12-14 months. This unavoidable quantity, directly related to production volumes, is of great concern, considering that dissipation in the bay is slow according to the currents. Biofouling biodepositions (due to detachment) should be added to this, although due to lack of information, it is not possible to provide accurate estimations.

Among other impacts, we have the disturbance of the benthic ecosystem. Herein, a key aspect to consider is the calcareous valves that are deposited on the seabed, which quantities have not yet been quantified. However, it is known that 67% of the biomass of *A. purpuratus* is composed by valves (Loayza Aguilar, 2018). The valves cause capping of the substrate, trapping of OM, and increase bacterial activity on the seabed. This event drives an exacerbated production of $H_2S$ and $NO_2$, limiting oxygen exchange at the water-sediment interface (anoxic conditions). Studies have been conducted to reduce biofouling production bacteria (Colunche Díaz et al., 2016) and doubling lantern exchange (Loayza Aguilar, 2018), but remain as proposals.

The organic matter released also encourages the eutrophication of the bay. Excessive phytoplankton biomass reduces water transparency and it sediments to the bottom when is not consumed, increasing OM and therefore a microbial activity that demands oxygen in specific areas referred to as "dead zones". This obviously alters the diversity in the water column and on the seafloor (Buschmann et al., 2008b; Buschmann et al., 2009; Chopin et al., 2012), causing mortality of benthic-demersal and pelagic resources as reported in Sechura Bay in 2019 (IMARPE, 2019). In addition, nutrients promote excess biomass of macroscopic algae, with increased OM decomposition and repercussions on fisheries, and loss of the landscape value of the coasts (Camargo and Alonso, 2007; Buschmann et al., 2008b) This is related to the exuberant production of macroalgae in the bay, such as *Caulerpa filiformis* and *Ulva* spp. which, by accumulating on the beaches, affect the habitat and the intertidal and subtidal benthic community, affecting fishery resources such as *Donax marincovichi*, *Emerita analoga*, and others of ecological importance, such as *Excirolana braziliensis* and *Lepidopa chilensis*, which are food for seabirds.

## 2.3 Water and sediment quality in Samanco bay

Due to the importance of the aquaculture activity, studies on water and sediment quality are conducted periodically in Samanco Bay. The following tables present the 13-year historical evolution of the conditions concerning water quality and sediment (Tables 1, 2), and those of the *A. purpuratus* culture concession area (Table 3), compared to the Environmental Quality Standards (EQS) for Water (MINAM, 2017), and the standards of the Canadian Environmental Quality Guidelines (Guidelines CEQ, 1999).

Oxygen in the water column tends to increase, exceeding EQS category 2C1 values (Table 1), which can be attributed to a process of eutrophication, linked to an accumulation of nutrients (N and P) due to bacterial mineralization of biodepositions and biofouling in the concession area. Two aspects characterize eutrophication: a) dissolved P is present in excess and dissolved N ($NH_4$, $NO_2$, and $NO_3$) near or below detection levels (Ryther and Dunstan, 1971), and b) levels above 440 µg NT l (0.44 mg l) and 30 µg PT l (0.03 mg l), can generate eutrophication in coastal areas (Swedish, 2000). As shown in Table 1, P is 2.68 to 6.15 times higher than EQS, and is no longer a limiting factor for phytoplankton productivity, hence any excess of N will stimulate eutrophication.

A study evaluated the behavior of oxygen for the period 2013-18, in one of the companies dedicated to the production of *A. purpuratus* in Samanco Bay, encountering 2.8 ± 0.96 mg $l^{-1}$ at the bottom (16 m) (Ramos Alfaro and Villegas Ruiz, 2019). This coincides with the data for the periods 2005-10 and 2014-15 (Table 1). As these values are below the EQS category 4E3, benthic community organisms, including those of artisanal fishing, would be affected, with social and economic repercussions for the fishing community. In the cultivation area, OM (Table 3) was between 1.48 and 2.71 times higher than in the rest of the bay (Table 2), confirmed by IMARPE (IMARPE, 2009b) and OEFA (OEFA, 2013), that found values of 7.18% in 2000, 28.17% in 2008, and 20.8% in 2012, with respect to the baseline of 2.14%. In addition, for the period 2013-18, it has been reported that sediment from the cultivation area of one of the companies dedicated to the production of *A. purpuratus* was characterized by fine-black sludge with a sulfurous odor, and in 75% of the biannual samplings, no live organisms were recorded, but empty shells of *S. algosus* and *A. purpuratus* were found (Ramos Alfaro and Villegas Ruiz, 2019). These characteristics are related to the concentration of 279 mg $kg^{-1}$ of $H_2S$ found in 2013 by OEFA (2013), a value 266 times higher than that reported in the baseline (1.05 mg $kg^{-1}$). These findings demonstrate the impact that the culture exerts, altering not only the chemical and granulometric composition of the sediment but also benthic biodiversity and abundance, including some fishery interest, as *A. purpuratus* cultures, as well as socio-economic repercussions, in addition to the economic profitability of the company (Figure 2).

The accumulation of biodepositions, biofouling, and phytoplankton biomass on the bottom of Samanco Bay would be increased by the resistance of the anchoring system of the cultivation lines (700 kg weight and 1 m height), from operational and abandoned concessions to the velocity of the bottom currents, retaining OM and calcareous valvae. On the other hand, cultivation operations are carried out in approximately 65% of each concession, which implies the use of roughly 196,800 lanterns, which generate a field of resistance to the current velocity, and therefore an increase in the sedimentation velocity of the seston generated by the cultivation, contributing to the accumulation of OM on the seabed.

TABLE 1 Physico-chemical parameters of water in Samanco Bay during the period 2005-10, 2014-15, and November 2018.

| Parameter | Surface | Middle | Bottom | Quality standard |
|---|---|---|---|---|
| Dissolved oxygen (mg $l^{-1}$) | | | | |
| 2005-10* | 7.66 ± 1.23 | No data | 2.85 ± 1.22 | EQS categories 2 |
| 2014-15** | 8.40 ± 0.75 | 4.77 ± 0.47 | 4.19 ± 0.81 | and 4 (≥ 4 mg $l^{-1}$) |
| November 2018*** | 8.52 | 8.31 | 5.60 | |
| Nitrates (mg $l^{-1}$) | | | | |
| 2005-10* | 0.343 ± 0.283 | No data | No Data | EQS categories 2 |
| 2014-15** | <EQS | <EQS | <EQS | (16 mg $l^{-1}$) and 4 |
| November 2018*** | 0.130 | 0.085 | 0.240 | (200 mg $l^{-1}$) |
| Phosphates (mg $l^{-1}$) | | | | |
| 2005-10* | 0.288 ± 0.203 | No data | 0.381 ± 0.192 | EQS categories 2 |
| 2014-15** | 0.056 ± 0.001 | 0.099 ± 0.002 | 0.086 ± 0.004 | and 4 (0.062 mg $l^{-1}$) |
| November 2018*** | 0.135 | 0.130 | 0.166 | |
| SST (mg $l^{-1}$) | | | | |
| 2005-10* | 31.37 ± 7.83 | No data | 30.30 ± 8.87 | EQS categories 2 |
| 2014-15** | 20.55 ± 2.32 | 19.02 ± 0.52 | 19.81 ± 4.72 | (80 mg $l^{-1}$) and |
| November 2018*** | 12.55 | No data | 12.95 | 4 (≤ 30 mg $l^{-1}$) |

Data source: *García et al. (2013), **García et al. (2015), ***García Nolazco et al. (2019). Environmental Quality Standards (EQS) for Water (MINAM, 2017).

There are few studies on the impacts of biodeposition from shellfish culture. In Canada, Richard et al. (2007), observed the accumulation of feces and pseudofeces in the M. edulis and Placopecten magellanicus culture area were twice as high as in the control area, and the abundance of benthic macrofauna was 6 times lower than in the control area. Heavy metals such as Cd, Pb, Cr, As, and Hg in marine sediments are of concern because they bioaccumulate and biomagnify, with high toxicity (Sadiq, 2021), and affect communities (Kennish, 2002), biogeochemical cycles (Sadiq, 2021), and humans who use them in their consumption. In hydrodynamically stable environments, such as Samanco Bay, heavy metals have a strong affinity for finer sediments (Calderón and Valdés, 2012), such as clay, humic acid, OM, Fe, Mn, and $CaCO_3$ oxides, capable of forming complexes with metal ions and being adsorbed (Kennish, 2002; Sadiq, 2021). Deep-sea currents, waves, storms, and activities such as dredging, shipping, and commercial fishing can resuspend heavy metals (Kennish, 2002), and re-enter in food chains.

In Samanco Bay, the sources of heavy metals (Table 2) may be lixiviated from the bedrock area and contributions from the Nepeña River, which irrigates 9,000 ha of agricultural land (ANA, 2009), and its flows discharge in the southeastern part very close to the mouth of the bay (García Nolazco et al., 2019). This river has a small discharge, however, during El Nino events, it has a great influence and may be transporting As, Se, Ba, Cd, Cr, Pb, Hg, and Ag, pollutants that may come from agricultural and livestock farming activities (Metcalf and Eddy, 1995), especially Cd that is an ingredient of phosphate fertilizers (Arnous and Hassan, 2015). The values of Cr, Cu, and Pb in sediments in the bay (Table 2) and within the marine cultivation area are below the Interim Sediment Quality Guideline (ISQG) and Probable Effect Level (PEL); however, As, Cd and Hg are at risk levels, since in the sediment outside the marine concessions they represent, respectively, 9.55, 3.33 and 1.31 times the ISQG, and within the concessions 3.2, 8.27 and 2.62 times, respectively, the ISQG. It is advisable to study the dynamics of these metals in sediments, water, and the bioaccumulation and biomagnification in the biota of Samanco Bay, and in the organisms in culture.

Due to its biological, bathymetric, and marine dynamic qualities, Samanco Bay is suitable for greater development of mariculture. The diagnosis made in previous paragraphs reveals that it urgently requires a new approach. It should focus on two fundamental aspects: a) within the scope of the General Aquaculture Law which invokes two principles: (a1) sustainability, e.g. profitable and competitive aquaculture, but in harmony with the conservation of resources and the ecosystem, which guarantees the satisfaction of the necessities of future generations, and (a2) the ecosystem approach, which considers the environmental, social and institutional dimensions, which encourages equity in the distribution of benefits, respect for the integrity and functionality of ecosystems; and, (b) adopt technologies to satisfy these principles, through the IMTA concept.

# 3 Integrated multi-trophic aquaculture (IMTA)

## 3.1 Foundations of the IMTA model

Integrated multi-trophic aquaculture (IMTA) involves the culture of two or more aquatic species from different trophic levels to improve efficiency, reduce waste and provide ecosystem

TABLE 2 Organic and inorganic water pollution in Samanco Bay during the period 2005-10, 2014-15, and November 2018.

| Parameter | Surface | Middle | Bottom | Quality standard |
|---|---|---|---|---|
| Organic matter (%) | | | | |
| 2005-10* | 2.26 | 4.49 | 3.77 ± 0.57 | |
| 2014-15** | 4.15 | 9.82 | 6.89 ± 2.24 | No standard |
| November 2018*** | No data | No data | 4.83 | |
| Heavy metals | | | | |
| Arsenic (mg $kg^{-1}$) | | | | |
| 2005-10* | 10.95 | 155.73 | 69.13 ± 69.36 | ISQG (7.24 mg $kg^{-1}$), PEL (41.6 mg $kg^{-1}$) |
| Mercury (mg $kg^{-1}$) | | | | |
| 2005-10* | 0.12 | 0.32 | 0.17 ± 0.08 | ISQG (0.13 mg $kg^{-1}$), PEL (0.70 mg $kg^{-1}$) |
| Cadmium (mg $kg^{-1}$) | | | | |
| 2005-10* | 0.23 | 2.54 | 1.19 ± 0.74 | ISQG (0.7 mg $kg^{-1}$), PEL (4.2 mg $kg^{-1}$) |
| 2014-15** | 0.68 | 5.04 | 2.33 ± 1.46 | ISQG (0.7 mg $kg^{-1}$), PEL (4.2 mg $kg^{-1}$) |
| Chromium (mg $kg^{-1}$) | | | | |
| 2014-15** | 19.13 | 29.76 | 23.44 ± 4.15 | ISQG (52.3 mg $kg^{-1}$), PEL (160 mg $kg^{-1}$) |
| Cooper (mg $kg^{-1}$) | | | | |
| 2005-10* | 29.43 | 37.65 | 35.06 ± 2.93 | ISQG (18.7 mg $kg^{-1}$), PEL (108 mg $kg^{-1}$) |
| 2014-15** | 0.68 | 5.04 | 2.21 ± 1.61 | ISQG (18.7 mg $kg^{-1}$), PEL (108 mg $kg^{-1}$) |
| Lead (mg $kg^{-1}$) | | | | |
| 2005-10* | 1.11 | 3.25 | 2.16 ± 0.97 | ISQG (30.2 mg $kg^{-1}$), PEL (112 mg $kg^{-1}$) |
| 2014-15** | 3.69 | 13.39 | 8.78 ± 3.19 | ISQG (30.2 mg $kg^{-1}$), PEL (112 mg $kg^{-1}$) |

Data source: *García et al. (2013), **García et al. (2015), ***García Nolazco et al. (2019). ISQG (Interim Sediment Quality Guideline): concentration below which there is no adverse biological effect, and PEL (Probable Effect Level): concentration above which adverse biological effects are frequently encountered Guidelines CEQ (1999).

services, such as bioremediation FAO (2022). IMTA is the practice of combining, in appropriate proportions, the culture of fed aquaculture species (e.g. fish and shrimp) with organic extractive aquaculture species (e.g. shellfish and detritivores) and inorganic extractive aquaculture species (e.g. seaweed) (Sasikumar and Viji, 2015). The IMTA's goal is to create balanced systems for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction), and social acceptability (best management practices). Currently, IMTA is an appropriate method for developing economically viable and socially beneficial coastal aquaculture Hossain et al. (2022).

A fundamental aspect of developing the IMTA model is species selection. Careful consideration must be given to the suitability of species in a particular habitat/farming unit, and they must be economically viable as aquaculture products Sukhdhane et al. (2018). To this end, the following aspects are recommended for the selection of species in the IMTA model: a) the selected species must have complementary roles with the other species in the system, b) they must be species adaptable to the cultivation technologies and environmental conditions of the site, c) they must possess the capacity to provide efficient biomitigation, and d) market demand and an attractive price (Sasikumar and Viji, 2015).

## 3.2 Perception

Mariculture in the 20 century did not acknowledge that when the development of any economic activity exceeds natural limits, it implies the deterioration of ecosystems, which can be irreversible and hinder the permanence of the activity that originates them (Martínez and Roca, 2015). For instance, in the Bay of Fundy (Canada), the production of 35,000 t of salmon had an exogenous input of 1,225 t of N and 245 t of P, a load that is retained, since the residence time of the water within the bay is about 76 days (Chopin et al., 2007). At fish cage culture locations, N can be 1.8-2.3 times more compared to a control site (Wen et al., 2007), accumulate sediment within 100 m and elevate N and P by 8-25 times up to 1,000 m from the cages (Tolga et al., 2017), promoting eutrophication and affecting the resilient capacity of the ecosystem.

In view of the situation described above, a new approach is required, which contemplates the ecosystemic balance, using species of multiple trophic levels. The approach of culturing organisms as primary producers, filter feeders, detritivores, and carnivores in a defined area, allows the recycling of the waste produced, minimizing environmental deterioration, under a circular economy approach (Buschmann et al., 2013; González Henríquez et al., 2015; Correia et al., 2020). This brings us to the

TABLE 3 Water and sediment quality values in Samanco Bay during the period 2005-10, 2014-15, and November 2018.

| Parameter | Surface | Middle | Bottom | Quality standard |
|---|---|---|---|---|
| Water | | | | |
| Dissolved oxygen (mg $l^{-1}$) | | | | |
| Surface | 8.13 | 11.46 | 9.35 | 3*EQS categories 2 and 4 (≥ 4 mg $l^{-1}$) |
| Middle | 1.77 | 9.10 | 5.76 | |
| Bottom | 3.46 | 7.66 | 3.46 | |
| SST (mg $l^{-1}$) | | | | |
| Surface | 3.60 | 49.60 | 19.27 | EQS categories 2 (80 mg $l^{-1}$) |
| Middle | 2.40 | 24.40 | 15.01 | and 4 (≤ 30 mg $l^{-1}$) |
| Bottom | 4.00 | 47.20 | 16.80 | |
| Sediment | | | | |
| **Organic matter (%)** | 3.45 | 19.20 | 10.20 | |
| Heavy metals (mg $l^{-1}$) | | | | |
| Arsenic (mg $kg^{-1}$) | 0 | 48.3 | 23.16 | ISQG (7.24 mg $kg^{-1}$), PEL (41.6 mg $kg^{-1}$) |
| Mercury (mg $kg^{-1}$) | 0 | 1.36 | 0.34 | ISQG (0.13 mg $kg^{-1}$), PEL (0.70 mg $kg^{-1}$) |
| Cadmium (mg $kg^{-1}$) | 0 | 15.20 | 5.79 | ISQG (0.7 mg $kg^{-1}$), PEL (4.2 mg $kg^{-1}$) |
| Chromium (mg $kg^{-1}$) | 10.46 | 61.70 | 32.42 | ISQG (52.3 mg $kg^{-1}$), PEL (160 mg $kg^{-1}$) |

Data source: *García et al. (2013), **García et al. (2015), ***García Nolazco et al. (2019). ISQG (Interim Sediment Quality Guideline): concentration below which there is no adverse biological effect, and PEL (Probable Effect Level): concentration above which adverse biological effects are frequently encountered Guidelines CEQ (1999).

point of addressing the IMTA concept, which guarantees the viability of aquaculture in the long term, generating social acceptability.

## 3.3 IMTA model proposal for Samanco Bay

The proposed IMTA model (Figure 3) is a design for environmental sustainability, and implies using cultures in proximity, with commercially valuable species of different trophic levels and with complementary ecosystemic functions, which synergistically act in the recycling and biomitigation processes (Chopin et al., 2010; Chopin et al., 2012; González Henríquez et al., 2015). In this sense, the system would be integrated by: a) extractive aquaculture of organic suspension, which represents the production of *A. purpuratus*, b) extractive aquaculture of inorganic suspension, based on macroalgae, and c) extractive aquaculture of deposit, using holothurians (Figure 4). In this model, the OM (feces, pseudofeces, biofouling organisms) are disposed into the water by the main culture, and the nutrients released, such as N and P, are no longer contaminants as they are biotransformed into valuable resources by the other organisms.

As a result of the implementation of the IMTA model, we would have: biodiversity preserved, aquaculture diversified and

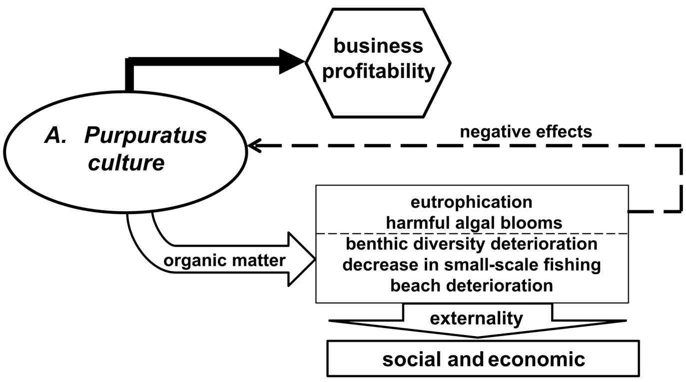



FIGURE 2
Traditional marine culture model in Samanco Bay.

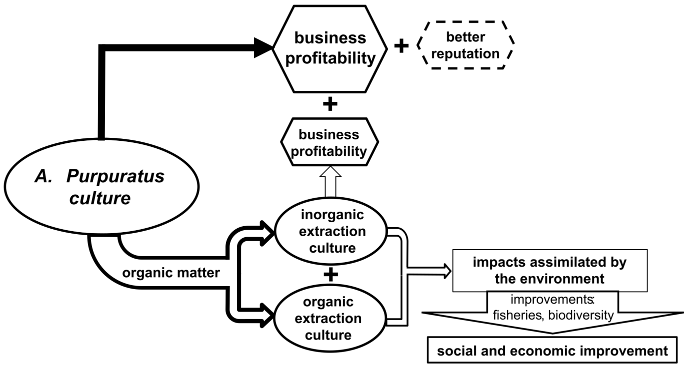



FIGURE 3
Proposed IMTA marine culture model for Samanco Bay.

profitability improved, as the proposed biotransformer species have current or potential economic value (Table 4). As an additional advantage, the main culture will be more efficient by reducing the impacts of eutrophication and HAB, and therefore more profitable. These advantages are transferred to the ecosystem, since, as less OM reaches the bottom and the accumulated is used by the organisms in the benthic system; therefore, the artisanal fishing activity and the balneability of the summer beaches would be recovered. This translates into social benefits for the activity, thus improving its image in society. This principle, which is practiced on a commercial scale mainly in China, improves the sustainability of the aquaculture systems, clearly reducing environmental risks and increasing profits (Han et al., 2016).

It is worth mentioning that, in the IMTA context, marine macroalgae are an indispensable and mandatory component to solve nutrient accumulation, since they constitute the primary organisms that require solar energy and sequester C, N, and P from the environment (Neori et al., 2004). In this sense, its great bioremediation capacity is highlighted. (Buschmann et al., 2013). The best criterion for choosing algal species for integration into the IMTA is to combine commercial value with high growth rates and N concentration in their tissues (Neori et al., 2004).

On the other hand, holothurians or sea cucumbers as deep-sea extractive organisms, act as nutrient recyclers and bioturbation agents, allowing bottom oxygenation and preventing OM stratification. Hence, their participation is indispensable for the management of marine ecosystems (Han et al., 2016; Tolga et al., 2017), and enhances the detrimental effects of coastal mariculture (Purcell et al., 2012).

An aspect of relevance in terms of economic value is related to the internalization of nutrient removal costs. This is aimed at encouraging the development of technologies to reduce environmental threats (Buschmann et al., 1996; Neori et al., 2007; Buschmann et al., 2008a; Buschmann et al., 2013), and political strategies, such as the idea of developing N bonds, as is currently practiced in the municipality of Lysekil (Sweden), which pays USD 10 kg of N extracted by *M. edulis*. Furthermore, the creation of incentives for cultivation under the IMTA model can be a policy that promotes the recovery of disturbed environments (Buschmann et al., 2008a) especially in Samanco Bay.

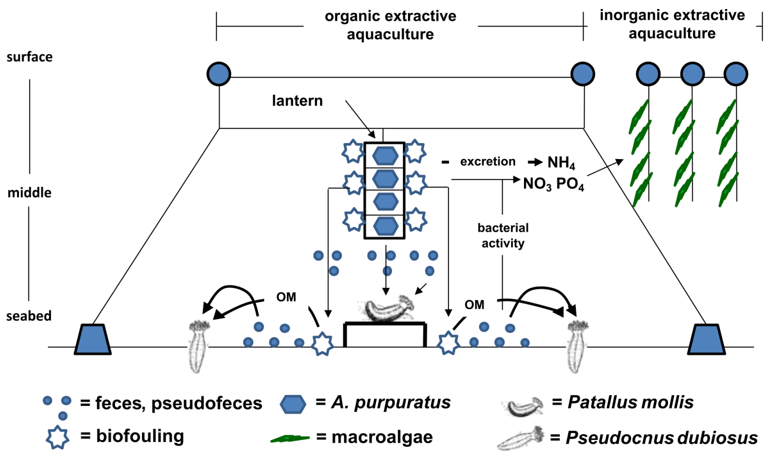



FIGURE 4
Diagram of the IMTA model proposed for experimental assays in Samanco Bay.

TABLE 4 Components of the IMTA and local candidate species for cultivation in Samanco Bay.

| Aquaculture type | Commercial expectations |
|---|---|
| Organic extractive in suspension | |
| Bivalve molluscs | |
| *A. purpuratus* | Known and secure foreign market |
| Inorganic extractive in suspension | |
| Macroalgae | |
| *Chondracanthus chamissoi* | Human consumption (IMARPE, 2009a; Saavedra et al., 2019; Avila-Peltroche and Padilla-Vallejos, 2020) and carrageenan (Buschmann et al., 2001; Avila et al., 2011) |
| *Porphyra columbina* | Human consumption (Romo et al., 2005; Avila-Peltroche and Padilla-Vallejos, 2020) |
| *Gracilariopsis lemaneiformiss* | Agarophyte (Ramírez and Tapia, 1991; Pang et al., 2010) |
| *Ulva lactuca* | Potential feed input for *Lipenaeus vannamei*, terrestrial animals (Villalobos, 2012), *Macrobrachium rosenbergii* (Felix and Brindo, 2014), human food ("anori" in Japan) (Bolton et al., 2009), aquaculture feed, IMTA pilot systems (Bolton et al., 2009), biomass energy, bioactive principles (Coste et al., 2015), potential food for cultivation of herbivorous aquatic species |
| Organic extractive deposit | |
| Holothurids | |
| *Patallus mollis* | Human consumption (Uribe et al., 2013) |
| *Pseudocnus dubiosus* | Potencial alimento para aves, sustancias anticancerígenas (Ruzafa and Diego, 1985) |

## 3.4 Conclusion

The industrial cultivation of *A. purpuratus*, in Samanco Bay, has generated jobs and related activities that stimulate the local economy and contribute to foreign exchange in Peru. However, it is being developed under a classic model (monospecific cultivation), prioritizing economic profits with almost no environmental responsibility. We anticipate that if this situation persists, it could exacerbate the impacts on the ecosystem, but at the same time generate inadequate physical and chemical conditions for the sustainability of the activity itself.

The proposed IMTA model has great potential to be an economically much more profitable activity, but in a balanced ecosystem, for which it is necessary to adopt this new production model with an ecological engineering approach. The integration of species from different trophic levels is the key concept for their adaptation. This model will allow them to diversify their production, improve their economic and social profitability, and guarantee their sustainability.

Finally, we consider that the adaptation of the proposed model will not be an effortless task. The main challenges will be the technological adaptation in addition to government policies that encourage the transition to an IMTA model. It will also be necessary to study the physical and chemical characteristics of the water mass, oceanographic dynamics, physical and chemical description of the bottom, and a better understanding of the socioeconomic conditions for businesses. It is therefore imperative to involve academia, the competent authority, and the business community.

## Author contributions

RL-A conceived the idea, conducted the research, obtained the grant, wrote the original draft, edited, revised, and supervised the work. YH-P investigated, wrote, reviewed, edited, and administrated the project. GS-R investigated, wrote, edited, reviewed, and supervised the work. GO-R reviewed, wrote, edited, and produced the images. All authors contributed to the article and approved the submitted version.

## Funding

This work was funded by the PNIPA-CU-SFOCA-PP-000045 Subproject "Capacity building for the management of multi-trophic crops in Samanco Bay (Ancash, Peru)", Contract N° 021-2018-PNIPA-SUBPROYECTOS.

## Acknowledgments

We would like to express our gratitude to the Vicerrectorado de Investigación at Universidad Nacional del Santa (VRIN-UNS), who supported us in the publication process.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



## References


ANA (Autoridad Nacional del Agua) (2009). *Evaluación de los recursos hídricos en las cuencas de los ríos santa, lacramarca y nepeña: Estudio hidrológico de la cuenca del río nepeña (informe final).*

Arnous, M. O., and Hassan, M. A. (2015). Heavy metals risk assessment in water and bottom sediments of the eastern part of lake manzala, egypt, based on remote sensing and GIS. *Arab J Geosci* 8, 7899–7918. doi: 10.1007/s12517-014-1763-6

Asche, F., Eggert, H., Oglend, A., Roheim, C. A., and Smith, M. D. (2022). Aquaculture: Externalities and policy options. *Rev. Environ. Economics Policy* 16, 282–305. doi: 10.1086/721055

Avila, M., Piel, M. I., Caceres, J. H., and Alveal, K. (2011). *Cultivation of the red alga chondracanthus chamissoi: sexual reproduction and seedling production in culture under controlled conditions* Vol. 23 (Springer), 529–536.

Avila-Peltroche, J., and Padilla-Vallejos, J. (2020). The seaweed resources of peru. *Botanixa Marin* 63, 381–394. doi: 10.1515/bot-2020-0026

Bartley, D. M. (2022). *World aquaculture 2020 - a brief overview* (FAO Fisheries and Aquaculture Circular No. 1233). doi: 10.4060/cb7669en

Beveridge, M. C., and Little, D. C. (2002). "The history of aquaculture in traditional societies," in *Ecological aquaculture. the evolution of the blue revolution* 1, 1–29. doi: 10.1002/9780470995051.ch1

Bolton, J. J., Robertson-Andersson, D. V., Shuuluka, D., and Kandjengo, L. (2009). Growing ulva (chlorophyta) in integrated systems as a commercial crop for abalone feed in south africa: a SWOT analysis. *J Appl Phycol*, 21, 575–583. doi: 10.1007/s10811-008-9385-6

Brugère, C., Aguilar-Manjarrez, J., Beveridge, M. C. M., and Soto, D. (2019). The ecosystem approach to aquaculture 10 years on - a critical review and consideration of its future role in blue growth. *Reviews in Aquaculture*11. 493–514. doi: 10.1111/raq.12242

Buschmann, A. H., Cabello, F., Young, K., Carvajal, J., Varela, D. A., and HenrÃquez, L. (2009). Salmon aquaculture and coastal ecosystem health in chile: analysis of regulations, environmental impacts and bioremediation systems. *Ocean & Coastal Management* 52 (5), 243–249. doi: 10.1016/j.ocecoaman.2009.03.002

Buschmann, A. H., Correa, J. A., Westermeier, R., Hernández-González, M., and Norambuena, R. (2001). Red algal farming in chile: a review. *Aquaculture* 194 (3-4) , 203–220. doi: 10.1016/S0044-8486(00)00518-4

Buschmann, A. H., Gonzalez, M. H., and Varela, D. (2008b). Seaweed future cultivation in chile: perspectives and challenges. International Journal of Environment and Pollution 33 (4), 432-456. doi: 10.1504/IJEP.2008.020571

Buschmann, A., Hernández-González, M., Aranda, C., Chopin, T., Neori, A., Halling, C., et al. (2008a). "Mariculture waste management," in *Encyclopedia of ecology* (Elsevier) *Ecological Engineering*, 5, 2211–2217. doi: 10.1016/B978-008045405-4.00045-8

Buschmann, A. H., López, D. A., and Medina, A. (1996). A review of the environmental effects and alternative production strategies of marine aquaculture in chile. *Aquacultural Eng.* 15, 397–421. doi: 10.1016/S0144-8609(96)01006-0

Buschmann, A. H., Stead, R. A., Hernández-González, M., Pereda, S. V., Paredes, J. E., and Maldonado, M. A. (2013). Un anÃ¡lisis crÃtico sobre el uso de macroalgas como base para una acuicultura sustentable. *Rev. chil. hist. nat.* 86 (3), 251–264. doi: 10.4067/S0716-078X2013000300003

Calderón, C., and Valdés, J. (2012). *Contenido de metales en sedimentos y organismos bentónicos de la bahÃa san jorge, antofagasta, chile. Rev. biol. mar. oceanogr*, 47 (1), 121–133. doi: 10.4067/S0718-19572012000100011

Camargo, J. A., and Alonso, A. (2007). *Contaminación por nitrógeno inorgánico en los ecosistemas acuáticos: problemas medioambientales, criterios de calidad del agua, e implicaciones del cambio climático.*16 (2), 8-110.

Cerrato, P. C., and Rodríguez, P. P. (2008). *Producción sostenida de moluscos bivalvos en el perú: Acuicultura y repoblamiento*, en. A. Lovatelli, A. Farías and e. I. Uriarte (eds). Estado actual del cultivo y manejo de moluscos bivalvos y su proyección futura: factores que afectan su sustentabilidad en América Latina. Taller Técnico Regional de la FAO. 20-24 de agosto de 2007, Puerto M ontt, Chile. FAO Actas de Pesca y Acuicultura. FAO 12,209-218.

OECD, Chopin, T. (2010). *Integrated multi-trophic aquaculture*. Advancing the aquaculture agenda: Workshop proceedings (Paris: OECD Publishing), doi: 10.1787/9789264088726-15-en

Chopin, T. (2013). "Aquaculture, integrated multi-trophic (IMTA)," in *Sustainable food production*. Eds. P. Christou, R. Savin, B. A. Costa-Pierce, I. Misztal and C. B. A. Whitelaw (Springer New York), 184–205. doi: 10.1007/978-1-4614-5797-8\s\do5(1)73

Chopin, T., Buschmann, A. H., Halling, C., Troell, M., Kautsky, N., Neori, A., et al. (2001). Integrating seaweeds into marine aquaculture systems: a key toward sustainability. *Journal of Phycology* 37, 975–986. doi: 10.1046/j.1529-8817.2001.01137.x

Chopin, T., Cooper, J. A., Reid, G., Cross, S., and Moore, C. (2012). Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. *Reviews in Aquaculture* 4, 209–220. doi: 10.1111/j.1753-5131.2012.01074.x

Chopin, T., and Robinson, S. M. (2004). *Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practices: introduction to the workshop and positioning of the issues. Bull. Aquacul. Assoc. Canada* 104–3.

Chopin, T., and Tacon, A. G. (2021). Importance of seaweeds and extractive species in global aquaculture production. *Rev. Fisheries Sci. Aquaculture* 29, 139–148. doi: 10.1080/23308249.2020.1810626

Chopin, T., Troell, M., Reid, G. K., Knowler, D., Robinson, S., Neori, A., et al. (2010). *Integrated multi-trophic aquaculture. part i. responsible practice provides diversified products, biomitigation.*

Chopin, T., Yarish, C., and Sharp, G. (2007). "Beyond the monospecific approach to animal aquacultureâ€"the light of integrated multi-trophic aquaculture. *Methods and Technologies in Fish Biology and Fisheries*, vol 6. Springer, Dordrecht, 447–458. doi: 10.1007/978-1-4020-6148-6_25

Colunche Díaz, J. L., Gonzales Veintimilla, F., Quiñones Paredes, P., and Terán Iparraguirre, R. (2016). Efecto del antifouling en la abundancia de ciona intestinalis y en el crecimiento de argopecten purpuratus. *Arnaldoa* 23, 631–648. doi: 10.22497/arnaldoa.232.23214

Correia, M., Azevedo, I. C., Peres, H., Magalhaes, R., Oliva-Teles, A., Almeida, C. M. R., et al. (2020). Integrated multi-trophic aquaculture: a laboratory and hands-on experimental activity to promote environmental sustainability awareness and value of aquaculture products . *Front. Mar. Sci.*, 7, 156. doi: 10.3389/fmars.2020.00156

Coste, O., Malta, E.-j., López, J. C., and Fernández-Díaz, C. (2015). Production of sulfated oligosaccharides from the seaweed ulva sp. using a new ulvan-degrading enzymatic bacterial crude extract. *Algal Research*, 10, 224–231.

FAO (2020). "El Estado mundial de la pesca y la acuicultura 2020," in *La sostenibilidad en acción*.

FAO (2022a). *El Estado mundial de la pesca y la acuicultura 2022* (FAO). doi: 10.4060/cc0461es

FAO (2022b). *Integrated multitrophic aquaculture: lessons from china*, Roma. doi: 10.4060/ca9229es

Felix, N., and Brindo, R. A. (2014). *Evaluation of raw and fermented seaweed, ulva lactuca as feed ingredient in giant freshwater prawn macrobrachium rosenbergii .Int J Fish Aquat Stud* 1 (3), 199–204.

Fiorella, K. J., Okronipa, H., Baker, K., and Heilpern, S. (2021). Contemporary aquaculture: implications for human nutrition. *Curr. Opin. Biotechnol.* 70, 83–90. doi: 10.1016/j.copbio.2020.11.014

Fu, W., Wu, Y., Sun, L., and Zhang, W. (2007). Efficient bioremediation of total organic carbon (toc) in integrated aquaculture system by marine sponge hymeniacidon perleve. *Biotechnol. Bioengineering* 97, 1387–1397. doi: 10.1002/bit.21352

García, F., Amaya Rojas, C. M., Gonzales Rossel, J. A., Monzón Anticona, J. A., Aldave Agüero, S. S., Ventura Miranda, F. A., et al. (2015). *Informe de evaluación ambiental de la bahía de samanco, ejecutado durante los años 2014 y 2015.*

García, V., Huerto Rengifo, M., Cervantes Renjifo, C., León, J., and Córdova, N. (2013). CaracterizaciÃ³n ambiental y potencial pesquero 2004-2011: Bahía de samanco, chimbote, perú. *Inf Inst Mar Perú*, (Callao), 40 (1-2), 8–30.

García Nolazco, V., de la Matta, P., and Orozco, M. R. (2019). Calidad del ambiente marino y costero en la regiÃ³n Ã ncash 2018. *Bol Inst Mar Perú* (Instituto del Mar del Perú), 34 (2), 406-431.

Gephart, J., Gephart, J. A., Bejarano, R. A., Gorospe, K., Godwin, A., Golden, C. D., et al. (2023). *Globalization of wild capture and farmed aquatic foods* (Authorea Preprints).

Gonzales, E., and Yepez, V. (2007). *Estudio de línea base del ámbito marino de la bahía de sechura 14-28 enero 2007* (Callao: Instituto del Mar del Peru).

González Henríquez, M. N., Rey-Méndez, M., Pérez, Y., Bilbao, A., Pavón, N., Louzara, G., et al. (2015). *Cultivos multitróficos: complementos a la explotación de otras especies de fuerte presencia en el mercado* (Universidad catÃ³lica de Oriente (UCO).

Goswami, M., Trudeau, V. L., and Lakra, W. S. (2023). "Chapter 1 - biotechnology in modern aquaculture: Innovations, advancements, and challenges," in *Frontiers in aquaculture biotechnology*. Eds. W. S. Lakra, M. Goswami and V. L. Trudeau (Academic Press), 1–13. doi: 10.1016/B978-0-323-91240-2.00003-8

Guidelines CEQ (1999). *Canadian Environmental quality guidelines 1999.*

Guillén, O., and Rondán, R. I. D. (1968). Producción primaria de las aguas costeras del perú en el año 1964. *Bol. Inst. Mar Perú*, 1 (7), 349–376.

Han, M. (2002). "Chapter twelve human influences on muddy coasts," in *Muddy coasts of the world*. Eds. T. Healy, Y. Wang and J.-A. Healy (Elsevier) 4, 293–317. doi: 10.1016/S1568-2692(02)80086-9

Han, Q., Keesing, J. K., and Liu, D. (2016). A review of sea cucumber aquaculture, ranching, and stock enhancement in china. *Rev. Fisheries Sci. Aquaculture* 24, 326–341. doi: 10.1080/23308249.2016.1193472

Hossain, A., Senff, P., and Glaser, M. (2022). Lessons for coastal applications of imta as a way towards sustainable development: A review. *Appl. Sci.* 12, 11920. doi: 10.3390/app122311920

IMARPE (2009a). *Catálogo de macroalgas marinas de la región la libertad.*

IMARPE (2009b). *Informe final de la línea base en el ambito marino de la bahía de samanco 13 - 24 diciembre 2008.*

IMARPE (2019). *IMARPE registra mortandad de concha de abanico argopecten purpuratus y varazón de peces en bahía de sechura.*

Kennish, M. J. (2002). Environmental threats and environmental future of estuaries. *Environmental Conservation* (Cambridge University Press) 29 (1), 78–107.

Kluger, L. C., Taylor, M. H., Wolff, M., Stotz, W., and Mendo, J. (2018). From an open-access fishery to a regulated aquaculture business: the case of the most important latin american bay scallop (argopecten purpuratus). *Rev. Aquaculture* 11, 187–203. doi: 10.1111/raq.12234

Loayza, R. E., and Tresierra, Ã. (2014). Variación del "biofouling" en linternas de cultivo de "concha de abanico" argopecten purpuratus en bahía samanco, ancash, perú. *Revista Ciencia y Tecnología* 2, 19.

Loayza Aguilar, R. E. (2018). *Duplicación del recambio de linternas y su efecto biológico y economico en la etapa final del cultivo suspendido de argopecten purpuratus, en la bahia de samanco (ancash, perú)*, Universidad Nacional del Santa.

Martínez, J., and Roca, J. (2015). Economía ecológica y política ambiental. *Nueva antropología* 21 (68), 131–138.

Metcalf and Eddy (1995). *Ingeniería de aguas residuales: Tratamiento, vertido y reutilización*. Madrid (Spain), McGraw-Hil 3ª ed.

MINAM (2017). *EstÃ¡ndares de calidad ambiental (ECA) para agua.*

Neori, A., Chopin, T., Troell, M., Buschmann, A. H., Kraemer, G. P., Halling, C., et al. (2004). Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture*, 231 (1-4), 361–391.

Neori, A., Troell, M., Chopin, T., Yarish, C., Critchley, A., and Buschmann, A. H. (2007). "The need for a balanced ecosystem approach to blue revolution aquaculture," in *Environment: science and policy for sustainable development*, vol. 49. , 36–43. doi: 10.1016/j.aquaculture.2003.11.015

OEFA (2013). *Reporte público del informe n°00120-2013-OEFA/DS-PES. supervisión ambiental especial en concesión acuícola en la bahia de samanco. reporte público del informe del organismo de evaluación y fiscalización ambiental (RPI-OEFA)*, Lima, Perú.

Pailan, G. H., and Biswas, G. (2022). *Dealing the hardship in aquaculture nutrition in a changing climatic condition* (Singapore: Springer Nature Singapore), 311–322. doi: 10.1007/978-981-19-5500-6\s\do5(2)0

Pang, Q., Sui, Z., Kang, K. H., Kong, F., and Zhang, X. (2010). Application of SSR and AFLP to the analysis of genetic diversity in gracilariopsis lemaneiformis (rhodophyta). *J. Appl. Phycol.* 22, 607–612. doi: 10.1007/s10811-009-9500-3

Park, M., Shin, S. K., Do, Y. H., Yarish, C., and Kim, J. K. (2018). Application of open water integrated multi-trophic aquaculture to intensive monoculture: A review of the current status and challenges in korea. *Aquaculture* 497, 174–183. doi: 10.1016/j.aquaculture.2018.07.051

PRODUCE (2015). *Anuario estadÃstico pesquero y acuÃcola 2015.* Available at: https://sinia.minam.gob.pe/documentos/anuario-estadistico-pesquero-acuicola-2015

PRODUCE (2020). *Anuario estadÃstico pesquero y acuÃcola 2019.* Available at: https://ogeiee.produce.gob.pe/index.php/en/shortcode/oee-documentos-publicaciones/publicaciones-anuales/item/949-anuario-estadistico-pesquero-y-acuicola-2019

PRODUCE (2021). *Anuario estadÃstico pesquero y acuÃcola 2020.* Available at: https://ogeiee.produce.gob.pe/index.php/en/shortcode/oee-documentos-publicaciones/publicaciones-anuales/item/1001-anuario-estadisticoo-pesquero-y-acuicola-2020

PRODUCE (2022). *Anuario estadÃstico pesquero y acuÃcola 2021.* Available at: https://ogeiee.produce.gob.pe/index.php/en/shortcode/oee-documentos-publicaciones/publicaciones-anuales/item/1080-anuario-estadistico-pesquero-y-acuicola-2021

Purcell, S. W., Samyn, Y., and Conand, C. (2012). *Commercially important sea cucumbers of the world* (FAO) Species Catalogue for Fishery Purposes No. 6.

Ramírez, M. E., and Tapia, L. (1991). Gracilariopsis lemaneiformis (bory) dawson, acleto et foldvik en el norte de chile (rhodophyta, gracilariaceae). *Revista Chilena de Historia Natural* 64, 323–330.

Ramos Alfaro, K. J., and Villegas Ruiz, R. I. (2019). *Evaluación de monitoreos ambientales de una concesión de cultivo suspendido de argopecten purpuratus en la bahía de samanco (Áncash, perú), periodo 2013–2018, y su relación con el marco legal* (Universidad Nacional del Santa).

Richard, M., Archambault, P., Thouzeau, G., McKindsey, C. W., and Desrosiers, G. (2007). Influence of suspended scallop cages and mussel lines on pelagic and benthic biogeochemical fluxes in havre-aux-maisons lagoon, Îles-de-la-madeleine (quebec, canada). *Can. J. Fisheries Aquat. Sci.* 64, 1491–1505. doi: 10.1139/f07-116

Romo, H., Ávila, M., Candia, M., Núñez, M., Oyarzo, C., Galleguillos, F., et al. (2005). *Manual de técnicas de cultivo de luche (porphyra sp.)*. Proyecto Fondef D01I.1148.

Ruzafa, A. P., and Diego, C. M. (1985). Técnicas de recolección y estudio en la clase holothuroidea. 1. generalidades, sistemática, ecología, biología y comportamiento. *Anales de biología* 3, 13–36.

Ryther, J. H., and Dunstan, W. M. (1971). Nitrogen, phosphorus, and eutrophication in the coastal marine environment. *Science*, 171 (3975), 1008–1013. doi: 10.1126/science.171.3975.1008

Saavedra, S., Henríquez, L., Leal, P., Galleguillos, F., Cook, S., and Cárcamo, F. (2019). "Cultivo de macroalgas: Diversificación de la acuicultura de pequeña escala en chile," in *Convenio de desempeño, subsecretaría de economia y empresas de menor tamaño* (Instituto de Fomento Pesquero).

Sadiq, M. (2021). *Toxic metal chemistry in marine environments* (*1st* ed.). (CRC Press). doi: 10.1201/9781003210214

Salazar Camacho, A. I. (2023). Evaluación del riesgo por inundaciones en las viviendas del asentamiento humano tacala, distrito de castilla, provincia de piura-piura. *Bach*. Universidad Privada Antenor Orrego.

Salinas-Morrondo, J. M. (2012). *Acuicultura multitrÃ³fica integrada. una alternativa sostenible y de futuro para los cultivos marinos en galicia* (Xunta de Galicia, Conselleria do Medio Rural e do Mar).

Sasikumar, G., and Viji, C. (2015). Integrated multi-trophic aquaculture systems (imta). *Winter School on Technological Advances in Mariculture for Production Enhancement and Sustainability*

Sukhdhane, K., Kripa, V., Divu, D., Vase, V., Mojjada, S., et al. (2018). Integrated multi-trophic aquaculture systems: a solution for sustainability. *Aquaculture Asia Magazine* 22, 26–29.

Swedish, E. (2000). "Environmental quality criteria: coasts and seas," in *Swedish Environmental protection agency report*, vol. 5052. , 138.

Thomas, S. A. (2010). "Integrated multi-trophic aquaculture: A workshop," in *White paper summarizing a workshop held at peninsula college*(Port Angeles, Washington, USA: Peninsula College Port Angeles, Washington).

Thomsen, E., Herbeck, L. S., and Jennerjahn, T. C. (2020). The end of resilience: Surpassed nitrogen thresholds in coastal waters led to severe seagrass loss after decades of exposure to aquaculture effluents. *Mar. Environ. Res.* 160, 104986. doi: 10.1016/j.marenvres.2020.104986

Tolga, M. T., Emiroglu, D., Gunay, D., and Ozgul, A. (2017). *Sea Cucumber (holothuria tubulosa gmelin 1790) culture under marine fish net cages for potential use in integrated multi-trophic aquaculture (IMTA)* (India: NISCAIR-CSIR).

Uribe, E., and Blanco, J. (2001). *Capacidad de los sistemas acuáticos para el sostenimiento del cultivo de pectÃnidos: el caso de argopecten purpuratus en la bahÃa de tongoy, chile* . Los Moluscos Pectínidos de Iberoamérica: Ciencia y Acuicultura A. N. Maeda-Martínez (ed.) 2001, Cap. 12: 000-00.

Uribe, E., Moraga, J., Zúñga, S., Rosales, S., Álvarez, G., Ávalos, P., et al. (2008). *Establecimiento de un protocolo de seguimiento ambiental para la determinación de la capacidad de carga para el cultivo del ostión del norte. informe final.* INFORME FINAL PROYECTO FIP N° 2006-37

Uribe, R., RodrÃguez, J. R., Enzian, P. C., and Paz, P. B. (2013). *Invertebrados marinos bentÃ³nicos del litoral de la regiÃ³n Ã ncash, perÃ°*, Vol. 28. 136–293.

Vela, S., and Ojeda, J. (2007). *Acuicultura: La revolucion azul. publicaciones CientÃficas y TecnolÃ³gicas del observatorio EspaÃ ± ol de acuicultura.*

Villalobos, J. (2012). *Utilización de las macroalgas ulva lactuca y gracilaria parvispora en la formulación de dietas balanceadas para el camarón blanco litopenaeus vannamei* Interdisciplinary Research Center for Integral Regional Development Sinaloa Unit (CIIDIR Unidad Sinaloa).

Wen, Y., Wei, X., Shu, T., Zhou, J., Yu, G., Li, F., et al. (2007). *Forms and balance of nitrogen and phosphorus in cage culture waters in guangdong province, china. China. Geogr. Sci.* 17, 370–375. doi: 10.1007/s11769-007-0370-9

frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 20 June 2023
DOI 10.3389/fmars.2023.1150213

Check for updates

OPEN ACCESS

EDITED BY
Sebastian Villasante,
University of Santiago de Compostela,
Spain

REVIEWED BY
Dimitrios K. Moutopoulos,
University of Patras, Greece
Fikret Öndes,
Izmir Kâtip Çelebi University, Türkiye
Raquel De La Cruz Modino,
University of La Laguna, Spain

*CORRESPONDENCE
Mohammad Mojibul Hoque Mozumder
mohammad.mozumder@helsinki.fi

RECEIVED 23 January 2023
ACCEPTED 22 May 2023
PUBLISHED 20 June 2023

CITATION
Mozumder MMH, Uddin MM, Schneider P, Deb D, Hasan M, Saif SB and Nur A-AU (2023) Governance of illegal, unreported, and unregulated (IUU) fishing in Bangladesh: status, challenges, and potentials.
*Front. Mar. Sci.* 10:1150213.
doi: 10.3389/fmars.2023.1150213



# Governance of illegal, unreported, and unregulated (IUU) fishing in Bangladesh: status, challenges, and potentials

Mohammad Mojibul Hoque Mozumder[1*], Mohammad Muslem Uddin[2], Petra Schneider[3], Dibash Deb[2], Mehedi Hasan[2], Safwa Bente Saif[2] and As-Ad Ujjaman Nur[4]

[1]Fisheries and Environmental Management Group, Helsinki Institute of Sustainability Science (HELSUS), Faculty of Biological and Environmental Sciences, University of Helsinki, Helsinki, Finland, [2]Department of Oceanography, Faculty of Marine Sciences and Fisheries, University of Chittagong, Chattogram, Bangladesh, [3]Department for Water, Environment, Civil Engineering and Safety, University of Applied Sciences Magdeburg-Stendal, Magdeburg, Germany, [4]Department of Fisheries and Marine Science, Noakhali Science and Technology University, Noakhali, Bangladesh

Illegal, unreported, and unregulated (IUU) fishing can result in loss of revenue, environmental damage, and economic loss for coastal communities, as well as a reduction in fish stocks. This study aims to generate comprehensive knowledge of the historical patterns and current status of IUU fishing in the coastal and marine waters of Bangladesh (BD). Secondary, qualitative, and quantitative data were gathered using SWOT as the conceptual framework. Cluster analysis was performed using NVivo for quantitative and qualitative data analysis. This study found that, because of the lack of appropriate and robust governmental laws, regulations, and manpower, IUU fishing in BD has led to the extinction of important fish species, biodiversity loss, and increased poverty among fishers. Potential solutions include raising the standard of living for underprivileged fishermen, improving the management and oversight of artisanal and industrial fishing, motivating and training stakeholders, and coordinating across all stakeholder levels. This study serves as a crucial guideline for sustainably managing fisheries and developing legislation, rules, and regulations to prevent IUU fishing in BD.

KEYWORDS

**IUU fishing, economic loss, management, monitoring, SWOT, NVivo, coastal and marine waters, Bangladesh**

## Introduction

Humans depend extensively on fish as a significant source of animal protein in their daily lives, even though future global food security is a major issue. The demand for fish protein is still increasing owing to the massive expansion of the global population; however, many of the world's fish populations are already degraded and unable to provide maximum sustainable production (FAO, 2007; Agnew et al., 2009). In contrast to the rate of population growth, the consumption of fish as a food source has increased worldwide in the last six decades. The average annual increase in total fish consumption from 1961 to 2017 was 3.1%, exceeding the annual growth rate of the population, which was approximately 1.6% (FAO, 2020). According to estimates, 179 million tons of fish were produced globally in 2018, of which 156 million tons were used for human consumption (approximately 20.5 kg per person annually). In 2017, globally, fish accounted for 20% of the average per capita intake of animal proteins consumed by more than 3.3 billion people, reaching 50% or more in nations like Bangladesh (BD), Cambodia, the Gambia, Ghana, Indonesia, Sierra Leone, Sri Lanka, and several small island developing States (FAO, 2020). However, it is a matter of great concern that global fishery sectors are facing a potential threat due to such surging demand and continued illegal, unreported, and unregulated (IUU) fishing during the last few decades.

Fishing activities that contravene or disregard national, regional, or international fisheries' legal frameworks are referred to as IUU fishing. This can also refer to a lack of regulation or control in fisheries (DoF, 2019). According to the US National Intelligence Council (NIC, 2016: p5), illegal fishing refers to "*fishing activities by vessels from one country in the jurisdiction of another country without permission or other activities of fishing vessels that contravene fisheries laws*." Unreported fishing refers to "*activities that are unreported or deliberately misreported to proper authorities*." In addition, unregulated fishing refers to "*fishing activities in areas with no practical conservation or management measures, such as outside any country's Exclusive Economic Zone (EEZ) and not under the jurisdiction of Regional Fisheries Management Organizations (RFMOs)*".

Many studies have highlighted IUU fishing as a significant threat to global fishing (Le Gallic and Cox, 2006; Agnew et al., 2009; Polacheck, 2012; Helyar et al., 2014; Liddick, 2014; Petrossian et al., 2015; Leroy et al., 2016; Miller et al., 2016; Petrossian, 2018; Soyer et al., 2018; Sumaila, 2019; Fujii et al., 2021; Kadfak and Linke, 2021). It has become one of the most prominent issues worldwide because it threatens legitimate fishing livelihoods and operations, jeopardizes food and financial prosperity, aids international crime, skews markets, encourages human trafficking, and prevents efforts to implement sustainable fishery management practices (NIC, 2016). It also hampers marine biodiversity, natural fish stocks, and sustainable fishery management (Donlan et al., 2020). It is difficult to quantify the actual extent of IUU fishing. However, according to the most recent estimates, between 11 and 26 million tons of fish are harvested annually illegally and unreported worldwide, with a market worth \$10–\$23 billion (Widjaja et al., 2020). Moreover, owing to the increasing number of fleets, fish stocks are facing a record level of overfishing (Watson et al., 2013). Nevertheless, these fleets are up to 2–3 times larger than those generally needed to harvest fish, which the ocean can supply substantially (Joseph et al., 2010). Most importantly, modern fish detection systems and fishing equipment have made fishing boats more efficient, allowing them to accelerate the overexploitation of global fishery resources (Knauss, 2005).

Concerns have been raised in the international community since the 1950s. Any action that jeopardizes efforts to manage and rebuild fish stocks, such as IUU fishing, is no longer regarded as politically or economically acceptable from this perspective (Le Gallic and Cox, 2006). The Convention on the Conservation of Antarctic Marine Living Resources first formally used this term in a report published in 1997, highlighting the rising risk of fish overexploitation in the Southern Ocean. Since then, efforts to combat IUU fishing have gained international momentum (NIC, 2016). Many RFMOs, such as the North East Atlantic Fisheries Commission, Northwest Atlantic Fisheries Organization, South East Atlantic Fisheries Organization, South Indian Ocean Fisheries Agreement, South Pacific Regional Fisheries Management Organization, and General Fisheries Commission for the Mediterranean have been established over time by various groups to manage fishery resources (NIC, 2016) collectively. Nevertheless, at the global level, the first major international initiative to deter and eliminate IUU fishing, the Food and Agriculture Organization of the United Nations (FAO), developed the first International Plan of Action (IPOA) in 2001 to prevent and counter IUU fishing (FAO, 2001; Le Gallic and Cox, 2006). Moreover, the IPOA-IUU has supported many countries worldwide in adopting this plan at the national level, known as the National Plan of Action to Prevent, Deter, and Eliminate IUU Fishing, or, in short, the NPOA-IUU (Widjaja et al., 2020). Similarly, many regions have developed a Regional Plan of Action (RPOA), such as the RPOA-IUU of South Asia, under the IPOA-IUU, to control and properly manage fish stock (Fujii et al., 2021).

Concerns regarding IUU fishing are not new to the waters of the Indian Ocean, especially in the Bay of Bengal (BoB). Similar to many other developing countries in Southeast Asia, BD has been experiencing this issue to a greater extent for years. Despite having a large number of marine fish species (511, including shrimp) and a maritime zone in the BoB covering an area of approximately 118,813 square kilometers, including the 200 nautical miles-long EEZ and 354 nautical miles of the continental shelf, BD's marine fisheries account for a small portion of the country's overall catch (Shamsuzzaman and Islam, 2018). The fishery industry provides 2.06% of the total export revenue, 3.69% of the GDP, approximately 23% of the overall agricultural production, and 60% of the nation's total consumption of animal protein (Islam et al., 2017). Nevertheless, this sector is crucial because it supports the livelihoods of millions of people and ensures national nutrition and food security. However, the fishing sectors in BD experience many challenges because the stocks of several fish species, including shrimp, are decreasing. Consequently, the catch per unit effort is declining in coastal fisheries due to inadequate fish protection regulations, lack of knowledge, indiscriminate killing of juveniles, pollution, disease issues, and other factors (Kuperan and Jahan, 2010; Murshed-e-Jahan et al., 2014; Islam et al., 2017; Shamsuzzaman and Islam, 2018). A government-commissioned report revealed that the most important and valuable species, such as tiger prawns and Indian salmon, are nearly extinct because hundreds of vessels are overfishing at an unsustainable rate in the waters of BD (Azad and Pamment, 2020).

BD is ranked 85th among 152 countries worldwide based on the IUU fishing index (2021), which ranks nations based on their vulnerability, prevalence, and response to IUU fishing (Macfadyen and Hosch, 2022). The fishery sector of BD is adversely impacted by IUU fishing, which threatens the socioeconomic well-being of fishers. Foreign fishing vessels engaged in illegal fishing in BD waters endanger the nation's security and engage in unhealthy competition with local fishermen. Likewise, illegal fishing by locals exacerbates social tensions between licensed and unlicensed fishermen, and between artisanal fishers and commercial fishing vessels encroaching on their territories (DoF, 2019).

BD has already developed several laws and regulations for fishery resource management (Supplementary File-Section 1), such as the Marine Fisheries Ordinance 1983, Marine Fisheries Rules 1983, and Protection and Conservation of Fish Rules 1985, but the application of these laws and regulations frequently results in disputes and stakeholder disobedience (Islam et al., 2017). Very recently (November 2019), BD ratified the 2009 FAO Port State Measures Agreement, and the Department of Fisheries (DOF) developed NPOA under the IPOA-IUU to control and manage IUU fishing to ensure the development of the Blue Economy, which is a crucial step towards the Sustainable Development Goal (SDG) 14: Life Below Water (DoF, 2019).

BD has diverse fisheries and fishing gear used in its waters (Table 1). The fisheries industry is essential to BD's economy and provides livelihoods for millions of people. However, some of these fisheries have been associated with overfishing, habitat destruction, and bycatch issues, including IUU fishing (Ghose, 2014; Shamsuzzaman and Islam, 2018).

The main objective of this study is to assess the status of IUU fishing in the BoB, focusing on BD's waters, and to generate a comprehensive report on the historical patterns and current status of IUU fishing in the coastal and marine waters of BD. This study also attempted to develop a comprehensive methodology to assess and quantify IUU fishing. Finally, this study provides a detailed proposal with specific guidelines to improve the current management practices, legislation, and compliance issues in response to IUU fishing, which will aid in combating IUU fishing and promoting sustainable fishery governance. Previously, many regional-level works by numerous researchers around the globe have focused on IUU fishing. Unfortunately, no noticeable scientific literature is available on BD, except for some newspaper articles. To the best of our knowledge, this is the first study of this kind.

# Conceptual framework

## SWOT analysis

In the study context, the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis can be formulated to explore a change strategy by systematically identifying various factors. This analysis is based on logic that maximizes strengths and opportunities and minimizes weaknesses and threats (Rangkuti, 2015). The SWOT matrix illustrates how a company's external opportunities and threats can be matched with its internal weaknesses and strengths to produce four possible alternative strategies (Chaliluddin et al., 2021). This analysis method is used to evaluate the 'strengths, weaknesses, opportunities, and threats' involved in an organization, plan, project, person, or business activity (Gürel, 2017). SWOTs are frequently laid out in a 2-by-2 table or matrix (Figure 1), with internal performance enhancers labeled as strengths and internal performance inhibitors labelled as weaknesses. Likewise, external enhancing factors are categorized as opportunities, whereas external inhibiting factors are threats. Although each category may be broken out independently for practical purposes, this representation of SWOT considerations emphasizes a holistic view of the four categories. This is partly true because, at least in a traditional SWOT analysis, making comparisons between categories is not an express intent (Doug, 2009).

It is considered a crucial tool for structuring and outlining decision-making strategies. Such privileged and classified information is crucial for integrated and sustainable coastal management practices (Viegas et al., 2014). Rangsipaht and Thaipakdee (2012) used a SWOT analysis to identify co-management plans that improve the livelihoods of small-scale fishermen. This was accomplished using focus group discussions (FGD, as tools to assist participants in capturing the vital elements of co-management and obtaining a comprehensive understanding of communities during the analysis. Furthermore, using strategic SWOT analysis, Viegas et al. (2014) assessed the contribution of artisanal fishermen in small-scale fishing communities to the integration of sustainable coastal management. They believe that the fisheries administration can successfully employ strategic and prospective SWOT analyses in coastal management plans. To complete the matrix, data must be collected from a trustworthy source, along with a sampling plan that includes all actors in the territory. In addition, the fishery development strategies of the Biak Number for Regency were investigated by Wijayanto in Indonesia in 2016. A SWOT analysis was used to assess the strengths, weaknesses, opportunities, and threats of developing a fisheries development strategy for the Biak Number Regency (Wijayanto, 2016). In addition, a case study of the fishing communities of Cote d'Ivoire's Aby Lagoon demonstrates the relationship between

TABLE 1 Different fisheries, water bodies, and fishing gear used in Bangladesh.

| Types of Fisheries | Water bodies | Gear types |
|---|---|---|
| Marine fisheries | Bay of Bengal | Trawling, purse seining, gill netting, long-lining, and trolling |
| Inland capture fisheries | Rivers, canals, beels (floodplain depressions), haors (large seasonal wetlands), and other water bodies | Gill nets, cast nets, seine nets, traps, and hook and line. |
| Aquaculture/Shrimp farming | Freshwater/Marine water | Pond culture, cage culture, and pen culture |
| Small-scale fisheries | Coastal water/Marine water/Freshwater (Inland water) | Hand lines, traps, and cast nets |

| | | |
|---|---|---|
| Internal | **Strengths**<br>a<br>b<br>c | **Weaknesses**<br>a<br>b<br>c |
| External | **Opportunities**<br>a<br>b<br>c | **Threats**<br>a<br>b<br>c |
| | **Enhancer** | **Inhibitor** |

FIGURE 1
Conventional SWOT Table (Doug, 2009).

fisheries co-management and poverty reduction within the framework of a sustainable lifestyle approach. In the context of the sustainable livelihoods approach, which is emerging as a potentially helpful way of looking at policies and institutions to address poverty, the study used a combination of relatively standard and frequently overlapping participatory tools and techniques in addition to SWOT analysis (Njifonjou et al., 2006).

Moreover, in an article from BD, the authors used SWOT analysis to manage the fisheries of the Naaf River along the Teknaf coast, highlighting ongoing issues and related measures through the sustainable management of small-scale fishermen (Chowdhury et al., 2022). They identified several significant issues within the fishing community, including a high reliance on fishery resources, annual catch declines, catch price fluctuations, bycatch discards, and a lack of processing and preservation facilities, credit facilities, and training assistance, which led to a disorganized fishing community with low economic returns. Sunny et al. (2020) examined the sustainability of fishing communities in the Sylhet that are vulnerable to climate change. This study determined the demographics, mode of subsistence, challenges associated with fishing, coping mechanisms, and strengths, weaknesses, and opportunities of fishing communities using SWOT analysis. Consequently, several authors have used and implemented SWOT analyses in various studies, particularly in SSF research. While SWOT analysis can be a useful tool for strategic planning and decision-making, it also has drawbacks, including a lack of objectivity, limited scope, lack of prioritization, and lack of action orientation. Overall, while SWOT analysis can be a valuable tool, it should be used with other methods and approaches to ensure a comprehensive and balanced analysis (Pant, 2019; Lohrke et al., 2022).

## Materials and methods

This study aimed to generate comprehensive knowledge of the historical patterns and current status of IUU fishing in the coastal and marine waters of BD. We conducted in-depth individual interviews in three coastal districts (Figure 2) of BD (Chittagong, Cox's Bazar, and Khulna) with relevant stakeholders(n-93), such as commercial fishers including small-scale and industrial fishers, academics, government and non-government officials (Ministry of Fisheries and Environment), police, journalists, coastguard officials, and BD Navy (BN) officials (Table 2). Individual interviews provided an understanding of details regarding each interviewee's perspectives on their lives, experiences, and situations, expressed in their own words (Lambert & Loiselle, 2008). Hence, we collected a significant part of the empirical data from in-depth interviews, each of which lasted approximately one hour on average. Primary data were collected using a pre-tested questionnaire consisting of direct and open-ended questions. The questionnaire was structured to capture the different dimensions of IUU fishing in BD coastal and marine waters. It mainly focused on factors that drive IUU fishing, information on relevant legislation and governance, IUU fishing influencing factors, monitoring, control, and surveillance (MCS) protocols and capacity, risk identification, quantification of IUU fishing by gear and fleets, and guidelines to reduce IUU fishing. The present status includes causes and methods in BD, disadvantages caused by IUU fishing in BD, the need for control, and existing laws and regulations to prevent it. For this purpose, open-ended questions were asked, such as how IUU fishing is taking place in BD, what is the present status of IUU fishing in BD, why it is essential to control IUU fishing in BD, what are the disadvantages of IUU fishing in BD, and what are the existing laws, rules, and regulations to prevent IUU fishing (See the Supplementary File-Section 2)?

NVivo version 12 was used for the quantitative processing and qualitative analysis of the data. It is one of the most advanced and effective tools for qualitative and mixed-method data analysis (Edhlund and McDougall, 2019). To determine the structure of the underlying concepts, it supports the analysis of qualitative content found in interviews, academic articles, texts, audio, videos, emails, images, spreadsheets, and online surveys. To explore the connections among various projects and create new models for future work, sentiments, themes, and attributes can be sorted using NVivo. The results can then be visualized (Amrutha and Geetha, 2020).

Cluster analysis was performed using the NVivo software (Figure 3). It was performed to confirm manually coded phrases. Cluster analysis results are generally presented through a dendrogram, which reveals the similarities and dissimilarities between the objects classified (Hair et al., 2010). Cluster analysis

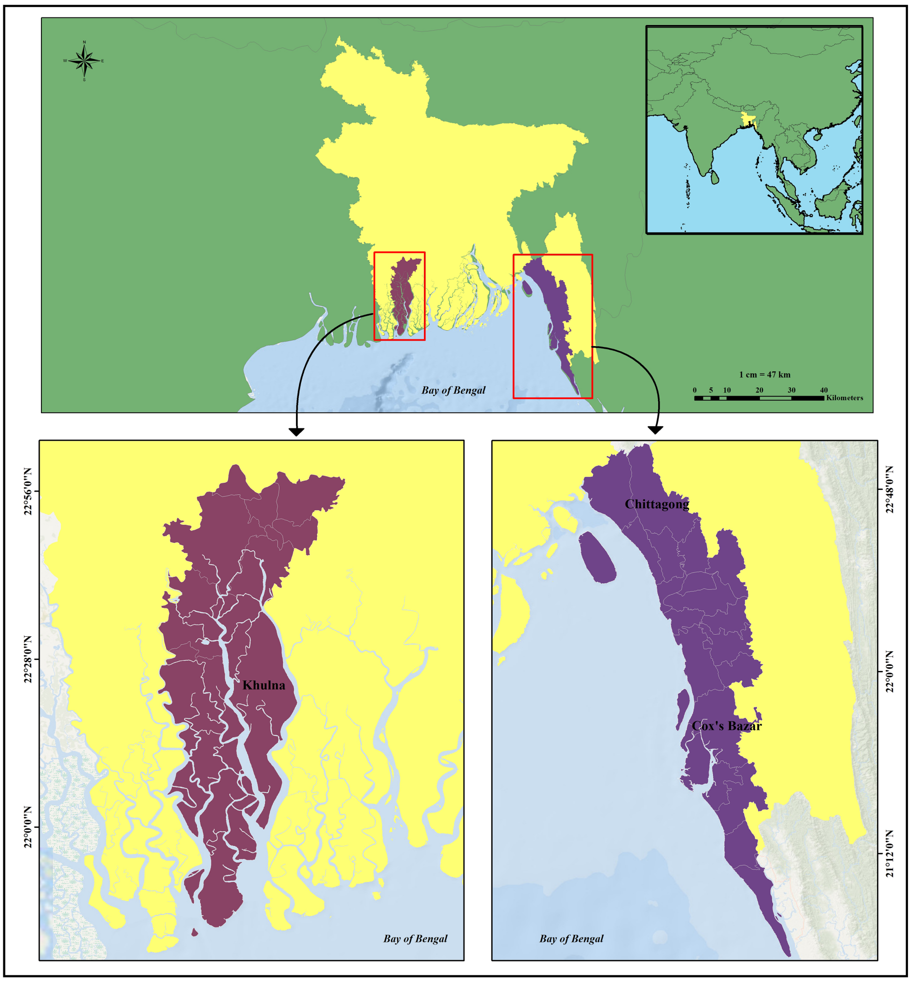



FIGURE 2
Study area map.

is an exploratory technique for visualizing patterns in a project by grouping sources or nodes that share similar words and attribute values or are coded similarly by nodes. The sources or nodes in the cluster analysis diagram that appear close together are more similar than those that appear far apart. Cluster analysis using a word tree was generated in NVivo 12 to exhibit the pattern of similarities within codes and subcodes. Based on the similarity of the words under the classification of various codes of parent themes, the respondents' reviews were analyzed cluster-wise and were closer. The machine algorithm uses simultaneous axial codes according to their group of contexts.

TABLE 2 Sample distributions of in-depth interviews.

| Stakeholder groups | Number of respondents |
|---|---|
| Commercial fishers | 45 |
| Academicians | 6 |
| Government & non-government officials | 15 |
| Coastguard officials | 6 |
| Navy officials | 6 |
| Police | 6 |
| Journalists | 3 |
| Focus group discussion (FGD) | 6 |

## Steps for cluster analysis generation

First, semi-structured questionnaires with open-ended questions were used to conduct interviews. The responses were then transcribed and translated. Data analysis was initiated by coding using NVivo. Finding relevant text units (commonly referred to as "segments") and assigning these units descriptive labels, or "codes," is the process of creating codes in NVivo 12 from qualitative data or respondents' descriptive comments. A few steps were followed to create the codes. Parent codes were generated in the "Coding" tab by right-clicking on an existing code and selecting "New Parent Code," and child codes were created by right-clicking on the parent code and selecting "New Child Code." A descriptive name was assigned to child codes that reflected a subcategory or

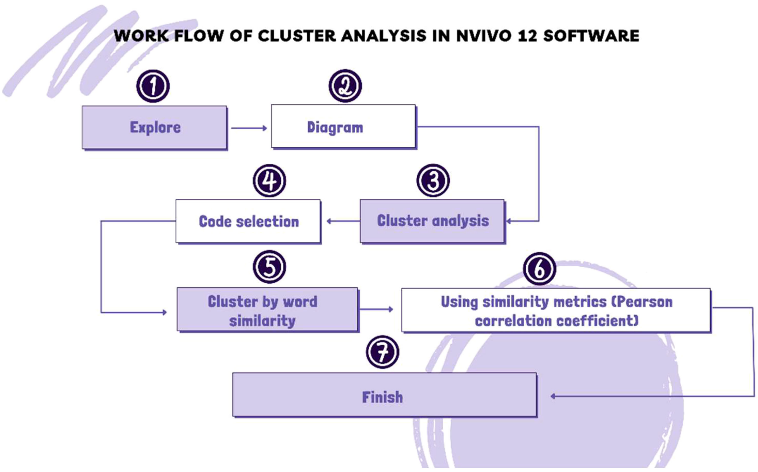



FIGURE 3
Workflow of cluster analysis in NVivo 12 software.

aspect of the overarching theme or concept represented by the parent code. The text segments were coded by dragging the selected text into an appropriate child code. The coding process was repeated for all relevant text segments and the coded data were evaluated and interpreted. The next step after coding was to perform a cluster analysis.

In NVivo 12, the procedure for conducting cluster analysis includes selecting the relevant codes for analysis, constructing a similarity matrix, selecting a clustering method, performing the analysis, evaluating and analyzing the results, improving the analysis as required, and saving and exporting the results. In the first step, cluster analysis was performed by clicking on the Explore tab in the diagram group to create the cluster analysis diagram. Subsequently, a cluster analysis wizard was created. Next, codes were selected to create a cluster analysis. In Step two, select was clicked to choose all codes. The author ensured that only child codes were selected for this analysis, because the parent codes were aggregated from the child codes. Subsequently, Next was clicked, and then OK. Next, word similarity was selected for the option *Clustered by*, and for *Using similarity matrix*, the Pearson correlation coefficient option was selected. The finish option was then clicked. Finally, a horizontal dendrogram showing similarities among the codes was obtained.

First, interview transcripts were processed using the NVivo software suite (version 12). The findings were cross-validated using cluster analysis, which provided an in-depth understanding. The general method for conducting a cluster analysis (Figure 3) that has been performed in NVivo 12 software is as follows:

## Explore

Qualitative data in NVivo were explored, and relevant words or phrases for cluster analysis were selected. This stage involved examining the data in NVivo and choosing pertinent words or phrases for the cluster analysis. The tasks in this step involve determining the data pertinent to the research question and ensuring that they are suitable for analysis.

## Diagram

A diagram is constructed to visualize the relationships between words or phrases in the data. In addition to helping discover patterns and trends, the diagram provides a visual depiction of the links between words or phrases.

## Cluster analysis

The cluster analysis method was selected, and hierarchical clustering was conducted. Based on the research question and the data being examined, the best method was selected.

## Code selection

The authors specified the codes to be included in the cluster analysis. The words or phrases in the data that are examined for patterns and relationships are represented by codes.

## Clustered by word similarity

A similarity matrix was used to conduct cluster analysis based on word similarity. Based on the relationships between words or phrases in the data, a similarity matrix was used to determine their similarity. Clusters are formed from the words or phrases that exhibit the greatest similarity.

## Using similarity matrix

Pearson's correlation coefficient was employed to organize similar words or phrases into clusters. A similarity matrix is utilized at this stage to organize the related words or phrases into clusters. The most comparable words or phrases were grouped together to allow for a more in-depth examination of the relationships between them.

### Finish

Cluster analysis results were analyzed and interpreted to make relevant judgments regarding the data. The findings were analyzed to detect patterns, correlations, and trends in the data and to provide insights into the study topic.

## Results

### Present status of IUU fishing in Bangladesh

Recently, several causes of IUU fishing have been identified in BD. A scientist from the BD Marine Fisheries Academy in Chattogram offered his perceptions of the causes of IUU fishing and how it is occurring in BD. He focused on the *illegal and unregulated* issues of IUU fishing in the following words.

"The main reason behind IUU fishing is that it does not follow the proper government rules and regulations of native fishermen. Owing to the tendency to earn more profits and catch more fish within less time, fishermen often use prohibited fishing nets or industrial fishing trawlers in shallow waters (less than 40 meters deep). However, there are many fish here because of the high quality of water. For this reason, fishermen from many neighboring countries, such as India, Myanmar, Sri Lanka, and Thailand, come here to fish illegally because they are more equipped with fishing instruments and trawlers. Many medicinal fish species are not typically consumed. Therefore, the fishermen do not catch the fish. However, fishermen from neighboring countries also catch those species and take them away, especially in the banned seasons."

Foreign fishing vessels or illegal incursions are most common in national waters from neighboring states, as stated by the Fishers Chief of the Marine Fisheries Academy when she was asked how IUU fishing is being conducted in our country.

During the FGD, some fishers (Md. Faruq, Md. Alauddin, and Md. Jasim, aged 55, 48, and 36 years, respectively, from the fishery ghat, Chattogram region) also argued about the illegal intrusion of foreign fishers. They said that "Fishing is off during the ban season. Even then, many fishers caught fish illegally. Indian fishermen have taken advantage of this opportunity. Although we could not catch fish, many Indian fishermen entered our waters at that time (mainly during the Hilsa ban period) to catch fish. Their boats are larger than ours; they have more powerful engines and modern technologies are installed in their vessels. Additionally, fishermen from Thailand often visit St. Martin Island to catch fish. However, their number is less than that of Indian fishermen."

From the perspective of the temporal evaluation of IUU fishing in BD, especially during different ban periods, the following conclusions can be drawn:

Several ban periods have been implemented in BD at different times of the year. The hilsa fishing ban was implemented for 92 days, from March 1 to May 31, whereas the juvenile hilsa (jatka) fishing ban was implemented for 61 days, from November 1 to December 31. The prawn fishing ban was implemented for 92 days, from June 1 to August 31. Additionally, the crab-fishing ban was implemented for 61 days, from July 1 to August 31. Additionally, there is a 65-day ban on fishing in the BoB implemented by the government of BD to protect the breeding and spawning seasons of marine resources. The exact dates of this ban may vary from year to year; however, it usually starts on May 20 to July 23. All fishing vessels in the BoB were prohibited from operating during this period. Violators are subject to fines and other penalties, including the seizure of fishing vessels and equipment. During these closure seasons, fishermen from neighboring states come with their boats and fish illegally (Figure 4).

Additionally, IUU fishing is generally carried out more often by local and external fishermen at night than during the day because there is a limitation in monitoring the activities of the navy and coast guard. Fishermen exploit this opportunity and fish illegally, sometimes to depths of 40 meters or less.

The lack of designated landing centers, reluctance to submit accurate catch information or provide misreporting, and a lack of rules requiring them to provide accurate catch information to the authorities are the causes of the *unreported issue*. An official from the Marine Fisheries Department (MFD) in Chattogram indicated some critical points in his speech regarding the unreported issue of IUU fishing, "The number of fish caught by Artisanal fishermen or local fishermen in BD is almost always unknown. No reports are available from them. Currently, the total number of engine-driven boats is 34000, with only 7000 are licensed. The rest of the fishing trawlers are not licensed, so no information comes from them."

According to the Survey Office of Chattogram and Cox's Bazar, "information on only 11 fish landing centers is available. The remaining 200 fish landing centers have no information on catch volume or data available on fish landing centers."

Lack of necessary sophisticated instruments is another reason why IUU fishing is happening by mechanized boat fishers as stated by Coast Guard East Zone Staff Officer (Operations), Chattogram, "Most of the time, the engine-driven wooden boats are fishing at 8–20 meters water depth region. They have no idea how deep the water is because they lack an echo sounder. Therefore, they cannot calculate their actual fishing depth and thus passively attend to IUU fishing." He also mentioned the lack of workforce and sophisticated modern equipment of the Navy and the Coast Guard for monitoring all industrial trawlers at a time in the sea. He argued this issue in his speech: "industrial fishing trawlers catch fish below 40 meters of water depth whenever they get a chance. Mostly at night, they have been seen fishing at 12 to 20 meters water depth regions. However, owing to our ineffective monitoring system, it was not possible to monitor everything simultaneously. Industrial merchant fishing vessels have echo sounders to monitor depth, but they illegally fish in shallow water by violating laws behind our eyes."

The permit required by the MFD for fishing in the sea for a specified period by industrial trawlers is known as the Sailing Permission (SP). The District Fisheries Officer (DFO), Chattogram expressed his experience on SP as follows

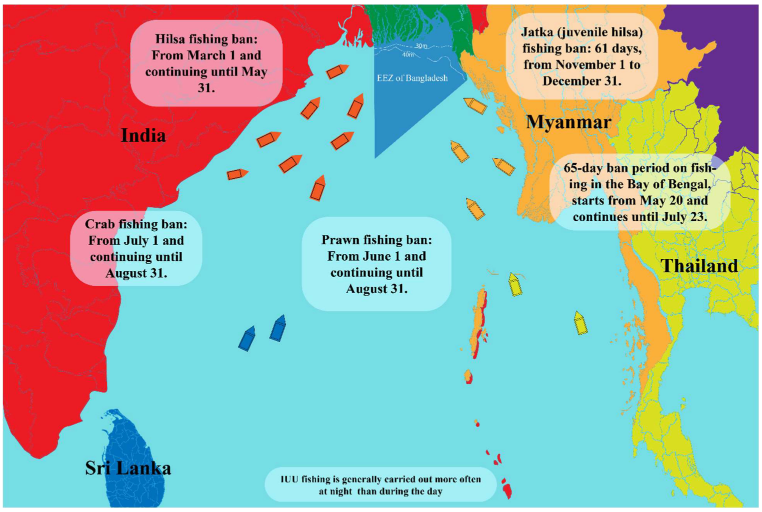



FIGURE 4
Temporal evaluation of IUU fishing in Bangladesh, especially in the different ban periods.

"Mechanized industrial fishing trawlers have SP with them. They submit a catch report, however, engine-driven small wooden boats, especially those under 15 tons, are not yet under the registration process, so they do not obtain SP because they do not need it. Furthermore, in doing so, they do not need to submit any reports about their fishing; consequently, the country's huge amount of extracted fishery resources remain unknown." As proper and accurate reports of a vast amount of fishing and catches remain unknown, IUU fishing and its marine resources are a major issue in BD.

One fisherman, Jasim, who uses a mechanized wooden boat and has been fishing in the BoB region for approximately 25 years, stated the following about SP and industrial trawlers, "We usually go fishing with 18–19 people in a trawler. We must obtain a license for the boat, but we do not have to obtain any SP for fishing. After fishing, we land the fish in a convenient place, because there is no specific fish landing station. Approximately 20 tons of fish are caught per trip. The DOF does not conduct any surveys. So, we do not have to give any reports of caught fish."

A government official from the DOF proposed a crucial aspect of IUU fishing in the deep sea. She stated,' "The country does not yet have the proper capability to monitor IUU fishing and collect all fish catch reports. Therefore, the illegal use of small mesh nets is currently the most serious issue. In addition, fishermen transfer their extra caught fish and illegal nets with the help of other boats or small boats in the deep sea to submit the correct fishing report. Consequently, the total catch data of the fisheries sector are not accurately available."

The Pearson correlation coefficient was used as a similarity matrix in the cluster analysis to quantify the similarity between distinct causes. The causes were classified into clusters based on word similarity. This technique aids in the identification of common patterns and relationships among causes, as well as the classification of causes into related groups based on their linguistic qualities. Cluster analysis allowed us to see and grasp the complicated linkages between the causes, and make intelligent decisions based on the findings.

The dendrogram (Figure 5) in this case shows that "Fishing in shallow depth" and "Using prohibited and illegal nets" are grouped together, indicating that they have similarities and are closely related. Similarly, "Foreign Fishers" and "High Water Quality and More Fish attract more fishers" are grouped together on the same branch, indicating that they also have similarities and are closely related. High water quality attracts foreign fishers. Various colors in the dendrogram were used to distinguish different branches and demonstrate the links between the elements. The more similar the components are, the closer they are to each other. The greater the distance between the elements, the less comparable they are.

## Disadvantages of IUU fishing in BD

The country is experiencing IUU Fishing, which has a wide range of disadvantages. For example, one of the officials from the BN

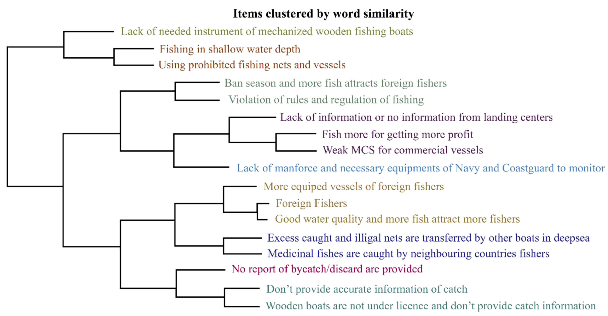



FIGURE 5
Cluster analysis of causes using Pearson correlation coefficient (similarity matric) and clustered by word similarity.

mentioned in his speech that "Due to the lack of proper fisheries statistics, it is difficult to gain proper knowledge of fish stock, which ultimately hampers the sustainable development plans of the government. Moreover, our country is experiencing economic losses."

Decreasing trends, extinction of important fish species, biodiversity loss issues, and increasing poverty due to IUU fishing have been highlighted by several scientists and professionals working in the fisheries sector in the Chattogram and Cox's Bazar region of BD. Their opinions are as follows:

"In BD, fishermen use illegal nets to catch fish before they are fully grown. Consequently, the number of fish species decreases daily, and some valuable fish species have almost become extinct. For example, lakkha, pomfret, and shrimp (Tiger Shrimp) are declining. Consequently, the government loses daily revenue."

"Due to disobeying the mesh size law of the fishing nets, bycatch fish are carried out in addition to the targeted species, threatening biodiversity."

"The loss of valuable wild brood stocks and over-exploitation of fishery resources causes degradation of the marine ecosystem. It also poses security threats to the country, as foreign intrusions generally occur. Finally, IUU fishing is a major threat to sustainable fishing, hampering fishermen's economic and social livelihoods. Consequently, poverty is exacerbated."

The analysis grouped similar causes based on context and word similarities. In this case, the causes "Hamper sustainable fishing and exacerbates poverty," "Food insecurity," and "Affect the livelihood and its change" were found to have similarities and were grouped into one cluster. The causes "Biodiversity loss" and "Degradation of marine ecosystem" were found to have dissimilarities with the previous cluster but still had context similarities and were grouped into another cluster (Figure 6).

Sustainable fishery development is hampered by IUU fishing, which destroys marine biodiversity. Additionally, the government is deprived of significant revenue. Several stakeholders have suggested the need for control measures to prevent IUU fishing. One of the officials from BD Fisheries Development Corporation, Chattogram, stated, "At present, it is vital to stop IUU fishing in BD to protect the ocean's biodiversity and maintain its sustainability. It is also necessary to obtain accurate catch reports from fishers, and then it will be possible to determine how much fishing will be sustainable in an area, or how many fish will be able to return to their previous state from a decreasing trend."

The Additional Director (AD) of the MFD expressed his perception of the need for control: "If IUU fishing continues like this, first of all, you cannot get an idea about fish population and stock. Consequently, it is impossible to determine the correct sustainable yield. Consequently, marine fishery management activities will not progress. Fish stock sustainability will be completely destroyed."

## Essential to control IUU fishing in BD and some early examples

Recently, the government took the initiative to combat IUU fishing and introduced the Marine Fisheries Act of 2020. Several scientists, academics, policymakers, and government officials are currently developing this technology. The present act came up several times in different in-depth interviews. Some of these are as follows:

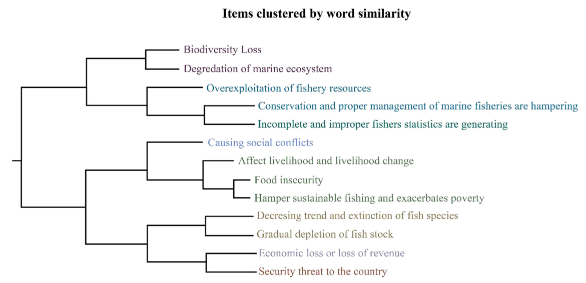



FIGURE 6
Cluster analysis of disadvantages using Pearson correlation coefficient (similarity matric) and word similarity.

"In the National Plan of Action (2020), some laws regarding IUU fishing have been passed. However, these laws have not been formulated yet. The BD Marine Fisheries Act (2020) includes several sections on IUU fishing. Currently, the Marine Fisheries Policy and Marine Fisheries Rules are drafted by the DOF (Ministry of Fisheries and Livestock) of BD."

"BD has already introduced laws to prevent IUU fishing. In particular, the Marine Fisheries Act-2020 has already been passed under the Marine Fisheries Survey Management Unit (MFSMU) and Fish Inspection Quality Control (FIQC), and currently, to combat IUU fishing rules are proposed. Currently, patrolling activities are being carried out by the DOF to prevent the illegal use of nets and comply with the Fisheries Protection Act. In addition, the ban period was 65 days during the breeding season of the hilsa. In addition, trawlers weighing more than 15 tons have been registered, and trawlers weighing less than 15 tons will be registered if the rules of the Marine Fisheries Act of 2020 are implemented."

One academician from Chattogram has specified IUU issues that were not clear in previous acts, and she stated, "Protection and Conservation of Fish Act, 1950 as well as the Marine Fisheries Ordinance of 1983 addressed the necessity of conservation of inland and marine fish. However, both laws lack comprehensive mechanisms to prevent and deter unauthorized fishing. These laws did not contain any provisions defining or recognizing IUU fishing activity as an offense."

## Challenges and potentials of IUU fishing in BD

### Challenges of IUU fishing in BD

By depleting fish stock, destroying marine habitats, and contributing to pollution through discarded fishing gear, IUU fishing has affected marine fishery resources in BD. Moreover, illegal fishers, such as artisanal fishermen, defraud local communities by catching fish. Consequently, they face food insecurity owing to their lack of income and sustenance.

Therefore, there is an urgent need to stop IUU fishing. However, there are some significant challenges to IUU fishing in BD, as revealed by different interviews with government officials and academicians.

The fisheries management officer of MFD in Chattogram expressed the significant challenges of IUU fishing: "Bringing all coastal fishing trawlers under license and registration is one of the challenges. Additionally, the lack of check-posts in the coastal belt complicates monitoring. In addition, workforce and vessel crises and a lack of Guarding Facilities are major challenges. One challenge is modernizing the monitoring system, such as by implementing a Vessel Monitoring System (VMS) for proper monitoring. According to the Marine Fisheries Act 2020, a law has been enacted to register all fishing trawlers based on a 15-ton weight. However, the biggest drawback was that the survey was not conducted properly because of IUU fishing. Another major challenge is a lack of patrol vessels for monitoring fishing trawlers."

One government official indicated some crucial challenges in his speech, "The major problem is the lack of alternative income-generating options. Therefore, many small-scale fishers are forced to fish illegally. In industrial fisheries, this is mainly caused by the greediness of businessmen/mahajans. In the absence of strict monitoring, industrial trawlers violate the rules and fish illegally."

In her talk, DFO Chattogram brought up the same issues: "Currently, a survey is being conducted under MFSMU. All fishing trawlers weighing > 15 tons are being surveyed. If these survey activities are unsuccessful, it would be nearly impossible to prevent IUU Fishing. Fishery Ghat and South Kattali Ghat are now considered fish-landing centers for artisanal fishers. Nevertheless, fishermen sometimes anchor fishing trawlers in different places, which does not provide accurate information on the total catch. In addition, many fishing boats sell fish while at sea. As a result, if the fish landing center is not specified, it will be difficult to prevent the unreported aspect of IUU fishing."

One of the top-ranked coast guards raised another issue regarding a more critical problem for combating IUU fishing: "In the coastal areas of BD, most people involved in fishing rent engine-driven trawlers from proprietors/vendors/Mahajan. Vendors collect money from fishermen and provide them with fishing nets and boats. The Coast Guard arrests fishers for illegal activities (e.g., IUU fishing). However, they release fishermen most of the time, because they are not directly involved in these activities and are forced to do so by vendors/Mahajan. So, the Coastguard cannot stop IUU fishing."

Navy officers and several government officials mentioned the following challenges for IUU fishing: the tendency to enter illegal fishing boats and their poaching in their EEZ, shortage of manpower and logistics of the DoF, lack of routine catch monitoring and database systems in the DoF, and lack of monitoring systems and VMS. A Captain in BN in Chattogram during his in-depth interview mentioned, "Due to inadequate human resources and advanced technology, the Navy and Coast Guard experience many difficulties during surveillance. The coastal guard can only maintain surveillance up to a contiguous zone. Owing to their technical limitations, they cannot conduct surveillance in the total EEZ. Moreover, they have no air support, which is one of the main obstacles to their operation. The radar used in coastal guard ships has a minimal range, generally 15–20 miles, which is unable to detect smaller ships."

The dendrogram shows interconnected codes grouped together and exhibits a pattern of similarities within the codes and subcodes. According to the dendrogram, the items "Change of approved gears and equipment of fishing vessels" and "Weak and weak logical support of fisheries department" are grouped together on the same branch. Thus, these items are believed to be similar and closely related. The items "Incomplete licensing of motorized wooden boats" and "Unauthorized construction of commercial vessels," on the other hand, are clustered further apart. This means that these items are less similar and less closely related to the items in the aforementioned cluster (Figure 7).

## Monitoring, control, and surveillance to prevent IUU fishing in Bangladesh

The MCS activities were conducted through the MFD, Marine Fisheries Surveillance, related coastal districts, and Upazila fisheries officers to prevent IUU finning by mechanized fishing boats engaged in fishing in marine and coastal areas. If IUU fishing is committed by a fishing vessel during the operation of the MCS program, penal action is taken according to the Marine Fisheries Ordinance, 1983. Fisheries management expert and AD of MFD talked about MCS of Industrial fishing trawlers, "Each trawler carries a one-year fishing license for fishing, and each time they have to take SP to fish in the sea. After submitting the fishing report, SP must be renewed. Preserving system-implemented vessels (steel bodies) were given SP for 30 days and non-preserving vessels for 13–14 days. ID cards must be kept with skippers and crew. Each trawler was carefully monitored and inspected before and after fishing. Occasionally, inspectors monitor the offloading of fish from the trawlers. If fishing nets are imported, approval must be obtained from the Department of Marine Fisheries. A catch certificate is required for exporting fish to foreign fishing vessels and trawlers. Every time fish are caught from the sea, a report has to be submitted by the fishers."

*He also talked about MCS for Artisanal/Mechanized fishing trawlers:*

"Each trawler needs a license to fish. Artisanal trawlers do not need to sail to obtain permission to fish. If the rules of the Marine

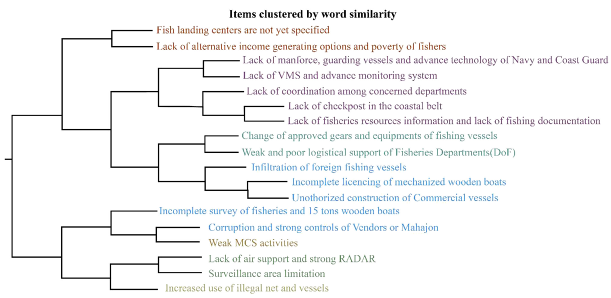



FIGURE 7
Cluster analysis of challenges using Pearson correlation coefficient (similarity matric) and clustered by word similarity.

Fisheries Act of 2020 are passed in future, they will be added with SP. However, they must obtain a fishing permit if the rules of the Marine Fisheries Act, 2020, are passed. Only one surveillance check-post at Patenga in Chittagong provides fishing information on engine-driven local trawlers. If this number does not increase, it will not be possible to obtain accurate information about local fishing trawlers. There has been a shortage of logistics support and manpower during the Corona period. For this reason, no data or reports of fish landing centers were available for the last year."

The 52-year-old industrial ship skipper of Ayub Monowara made the following comments about the existing MCS: "The MFD basically gives SP for one month. With this permission, industrial fishing trawlers can go fishing in the deep sea. If they get enough fish, they return it 15 days earlier. They must submit a report on fishing every time; otherwise, they will not obtain SP. The SP was renewed after each report was submitted."

To stop IUU fishing, it is necessary to stop fishing for certain species during their egg-laying or breeding seasons. Ban periods should be introduced, and the workforce should be increased to enforce it properly and for proper guarding activities. Therefore, appropriate monitoring systems must be implemented. All fishing trawlers were brought in with SP. Adequate numbers of check-posts should be established along the coast. Therefore, the number of patrolling vessels must increase. All of these can be considered potential solutions. An academician identified some essential points that could potentially prevent IUU fishing. She said, "The number of patrolling vessels and the workforce needs to be increased. Therefore, it is necessary to introduce Vessel Traffic Management Systems (VTMS). To protect critical species, it is essential to declare certain locations as fish sanctuaries. The spawning times/seasons of certain fish species should be identified, and a ban period should be implemented for each species. Finally, a sustainable fishing yield must be determined."

One government official used a strict voice when discussing alternative job opportunities for fishers so that overfishing and IUU fishing were under control (Figure 8). He said, "To reduce IUU fishing, the government must create more job opportunities, adapt existing rules and regulations, ensure strict monitoring, and build up the capacity of DOF officials."

A Navy officer said, "First, the monitoring system should be developed. An automatic identification system (AIS) should be introduced in larger fishing nets. The ship size should be different for mid-water and shallow-water fishing. All boats must have a communication system with the authorities responsible for fishing surveillance. Research on fishery resources and their management is vital. The capacities of the Navy and Coast Guard must be increased; simultaneously, the Coast Guard should be equipped with larger ships and helicopter support."

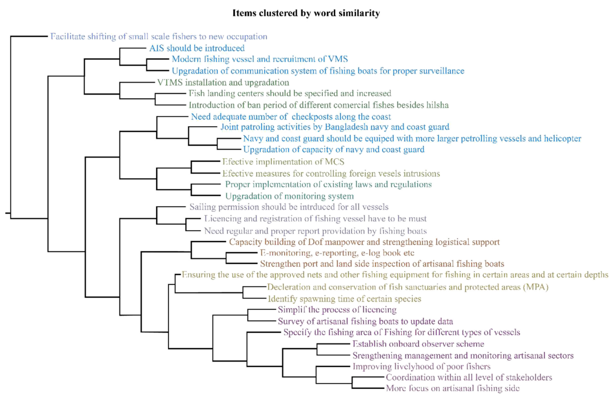



FIGURE 8
Cluster analysis of necessary needs for combating IUU fishing in BD using Pearson correlation coefficient (similarity matric) and clustered by word similarity.

## Discussions

Currently, IUU fishing is a serious and growing concern in the global fishing industry because it disrupts the conservation and management objectives of sustainable Fishing without permission in national, regional, and international waters is illegal According to a survey conducted by FAO, IUU fishing accounts for 20% (one in five) of all the fish captured in national and international waters worldwide (FAO, 2022). Currently, IUU fishing is widespread and prevalent in BD national waters. There are several causes of IUU fishing in BD that have recently taken place, such as violation of rules and regulations of fishing, using prohibited nets and illegal nets, fishing in a shallow depth, less or no catch information from mechanized wooden boats, no reports of bycatch discards and actual catch after a single voyage, lack of landing centers and catch reports from landing centers, intrusion of foreign fishers, especially during the ban season, who are more equipped and catch nontraditional medicinal fish, weak MCS for commercial vessels, lack of man force, and lack of necessary equipment for the Coastguard and navy to control IUU fishing (Present Study). Other studies have found similar results, such as foreign fishers being responsible for the most prolific IUU fishing (Le Gallic and Cox, 2006; Mackay et al., 2020; Song et al., 2020; Fujii et al., 2021). These findings demonstrate that IUU fishing is not limited to foreign vessels as initially assumed. Le Gallic and Cox (2006) discovered that domestic vessels account for a significant proportion of IUU fishing in the Southern Ocean. Song et al. (2020) and Mackay et al. (2020) discovered that, while foreign vessels contribute to IUU fishing, domestic vessels account for a substantial proportion globally. According to Fujii et al. (2021), IUU fishing in Southeast Asia involves domestic and foreign fishing vessels. Dayem and Kuwait fishermen noted that immigrant fishermen, especially those from Egypt, were the main perpetrators of IUU fishing in Kuwait, taking advantage of poor immigration control (Alqattan et al., 2020). When fishing vessels operate against the rules of a fishery, such as by taking too many vessels or fishing outside the designated seasons, this practice is known as IUU fishing. As many crab and lobster species, especially those in limited supply, are valuable, IUU fishermen have financial incentives to engage in this practice. Coastal fisheries in poorer nations are particularly susceptible to IUU fishing because governments often fail to regulate or implement national or international rules (for instance, owing to a lack of resources or ineffective levels of governance) (Force and Upton, 2006). Foreign fishing boats, typically Chinese or Korean, are particularly susceptible to the abuse of the marine resources of nations with weak or non-existent enforcement, such as Somalia, West Africa, and Madagascar (Petrossian et al., 2015). In the case of BD, the need for inland and marine fish conservation is addressed by the "Protection and Conservation of Fish Act 1950" and the "Marine Fisheries Ordinance of 1983." However, both laws lack adequate measures to stop and discourage unauthorized fishing. In addition, these statutes do not define IUU fishing as an offense. Although the Coast Guard Act of 2016's Section 10 refers to the constant role of law enforcement agencies in combating IUU fishing, several issues, such as the inspection of alleged foreign-flagged IUU vessels and the prevention of IUU catch products from entering ports, have not been addressed (Rahman and Rupom, 2020). In addition, owing to the lack of legal and administrative oversight, IUU fishing activities continued in BD's maritime zones. A large number of unregistered and unlicensed mechanical and non-mechanical fishing vessels in the BoB are causing gradual depletion of fish stocks. In addition, the conservation and proper management of marine fisheries are hampered by the violation of laws and regulations by commercial trawlers, which also puts pressure on fishery stock. Moreover, at present, no license fee is levied from unauthorized fishing vessels, and because of this, it is not possible to export the fish caught by such illegal fishing vessels to European Union countries; for this reason, revenue is not generated, and foreign exchange is not earned (DoF, 2014). Furthermore, fishing activities damage the marine environment and have detrimental effects on overall ecosystems, fisheries, and biodiversity. Moreover, fishing, legal and illegal, causes social conflicts between the two groups. If illegal fishing activities, such as IUU fishing, persist in the absence of an effective MCS, they are likely to become organized fishery crimes (DoF, 2019). Consequently, fish stocks will decrease and many fish species may vanish in the long run. Finally, the livelihoods of many small coastal fishing groups, including fishermen, vessel owners, exporters, and others involved in this sector, will be jeopardized, resulting in acute poverty and food insecurity, and sustainable development will also be impeded. Above all, the development of the Blue Economy, which is reliant on the sea, will be impeded. BD has a sizable coastal region rich in marine and aquatic biodiversity and is blessed with abundant natural resources. Fish production will increase if IUU fishing is curbed, boosting the GDP of the country. The IUU fishing hinders sustainable fishery management and the productivity of aquatic biological resources in a sustainable manner. There are many reasons for these threats, including poor MCS in the area, a lack of internal capacity to stop domestic fishing vessels from engaging in illegal fishing, a lack of coordination between relevant departments such as the DOF, a lack of checkpoints in the coastal belt for catch monitoring, a lack of technical support or facilities such as advanced RADAR, a lack of information about fisheries resources and fishing documentation, and poor or entirely no implementation of rules (SWOT analysis-Figure 9).

According to a three-year report commissioned by the government, IUU fishing has nearly eliminated the largest and most valuable species, including tiger prawns and Indian salmon (FAO, 2022). Fishers used to catch a variety of species but are no longer able to do so. Millions of underprivileged fishermen are affected by hilsa conservation, yet a substantial amount of the benefits go to industrial trawl operators, who capture tons of hilsa without much social benefit or taxable income for the government (Porras et al., 2017). The hilsa recovery has also begun to draw "super-trawlers" from other countries, which are outfitted with equipment to follow and target hilsa schools. The capacity of super trawlers is twice that of existing industrial vessels. Their size and engine power allow them to catch fast-moving hilsa, and they are outfitted with sonar technology to assist them in locating shoals (Islam and Walkerden, 2022).

To protect fishery resources, the government has formulated laws and policies regarding sustainable fishing. They are in the process of developing some laws, rules, and regulations to prevent IUU fishing in BD, such as the Marine Fisheries Act 2020 (Nakamura et al., 2022). The Marine Fisheries Act of 2020 is one of the many actions taken by the government to prevent IUU fishing. Laws were introduced to prevent IUU fishing in BD. In particular, the Marine Fisheries Act-2020 has already been passed under the MFSMU and FIQC, and fishing rules are currently proposed to combat IUU. Currently, patrolling activities are being carried out by DOF to prevent the illegal use of nets and comply with the Fisheries Protection Act. In addition, the ban period was 65 days during the breeding season of the hilsa. In addition, trawlers weighing more than 15 tons are registered, and those weighing less than 15 tons will be registered if the rules of the Marine Fisheries Act 2020 are implemented (this study). Mala (2020) said, "On January 29, 2020, the Marine Fisheries Bill 2020 was introduced to parliament. Marine Fisheries Ordnance-1983 will be replaced by the New Marine Fisheries Act 2020. Under the new IUU provisions, the Ministry of Fisheries and Livestock will have more authority to manage and monitor the maximum sustainable yield, establish permitted catch and hoarding limits, and conduct surveys on fish resources. The current ordinance has no legal provisions for issuing orders or instructions to stop illicit, unreported, or unregulated fishing. The country could unlock the potential of a blue economy with the help of the IUU and mariculture."

With limited exceptions, such as innocent passing, as defined by the 1982 United Nations Convention on the Law of the Sea, the proposed Act placed restrictions on the entry of foreign fishing vessels without a license. According to the proposed Act, registration is necessary for all automated fishing vessels, referred to as artisanal fishing vessels (Mala, 2020). One of the UN Nations' SDGs is to combat illegal fishing. Indicator 14.6.1 of the SDGs, which is related to SDG 14, 'Life Below Water,' is dedicated to evaluating progress toward the ambitious goal of eliminating IUU fishing by 2020 (Canton, 2021). BD experiences potential challenges in combating IUU fishing. However, time-consuming methods are required to overcome these issues. The livelihoods of fishermen will be severely impacted, and sustainable development will not be attained if the country fails to address this issue.

## Recommendations

Dealing with all these challenges and resolving them strictly and efficiently is necessary to control IUU fishing in BD. Government


FIGURE 9
SWOT analysis of IUU fishing in BD.

and national agencies can take several steps to control and stop IUU fishing in national waters. At present, in BD, ban period activities are being carried out by the DoF to protect jatka and mature hilsa fish, and benefits are being experienced after implementation. The Coast Guard only supports the proper implementation of the ban period's activities. This implementation system also needs to be introduced to other commercial fish or targeted fish at sea. For this purpose, the number of patrolling vessels and the workforce must be increased. The VTMS must be introduced, where VMS and AIS will be used for domestic and commercial vessels (all trawlers), and AIS will be used for boats and vessels in other fisheries. To protect critical species, it is essential to declare certain locations as fish sanctuaries. The spawning time/season of certain fish species should be identified, and a ban period should be implemented for each species. Sustainable fishing yield must be determined by the DoF. Furthermore, to control IUU fishing in BD, everything related to fishing must be included in a stable operative system. Fisher and trawler proprietors/owners must be aware of the harmful aspects of illegal nets with small mesh sizes. Rural people in the coastal areas of BD are less aware of the effects of illegal net use. Therefore, they need to be aware of this to protect the future. In addition, fish landing centers should be specified. All fishing trawlers must be registered through a proper survey and brought under the SP so that they can be controlled by the MFD. Further research is needed to resolve this issue. Government organizations and institutions can conduct research to combat IUU fishing. In this regard, national and international collaborations are essential. The country's MOFL needs to collaborate with other nations, such as the USA, UK, China, and Indonesia, to know how they are successful in this respect. The Ministry can arrange international seminars and conferences to better understand how they do so. Appropriate research is the only tool for appropriate fishery stock assessment and management, which is vital for sustainable governance.

Moreover, from a scientific standpoint, the government should assess all major stocks in the BoB. Additionally, the government can introduce MSP into existing MPA to boost declining fish resources. To reduce the pressure on inshore waters, scientists of the BFRI and MFD must explore deep-sea fisheries. To update the FRSS data collection system, the concerned departments must make appropriate plans. The SSF fishers must be motivated to follow rules and regulations. There is a need to determine the amount of support each fisherman needs during the lean period caused by bans and other restrictions. A holistic approach or research package based on a socio-ecological perspective is required to combat IUU fishing. In addition, nets smaller than 60 mm mesh size cannot be used in the sea because marine fish fry are generally much larger. Research on multi-fish species needs to be initiated, which will facilitate proper net selection for catching the desired fish, making it possible to reduce the number of bycatch fish. Research should be conducted on different marine fish species' breeding seasons and growth. Research on selecting the ban period for important fish species such as hilsa, Vetki, Indian salmon, and shrimp (tiger shrimp and lobster) should be carried out. The recommendations are summarized in the following figure (Figure 10):

## Conclusions

The consequences of IUU fishing include loss of revenue, environmental damage, economic loss for coastal communities, and reduction in fish stocks. This study focused on comprehensive knowledge of the historical patterns and current status of IUU fishing in the coastal and marine waters of BD. We recommend that relevant government and non-governmental organizations encourage and support coastal fishers to build resilience against IUU fishing effects and other human-made or natural threats to their existence. Such initiatives have allowed coastal fishermen to improve their lives and protect coastal waters. We also recommend strengthening the management and monitoring of artisanal sectors, as well as industrial fishing, training and motivation for stakeholders, coordination with all stakeholders, and effective implementation of MCS. We believe that this study will serve as a crucial guideline for sustainably managing fisheries and developing legislation, rules, and regulations to prevent


FIGURE 10
Recommendations to control IUU fishing in BD.

IUU fishing in BD. However, more research on this and related areas is needed to further improve the situation of fishers, obtain more data, and improve the surrounding processes to successfully combat IUU fishing in BD.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

## Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

Conceptualization, MM; Data curation, MM, DD, MH, SS; and A-AN; Formal analysis, MM, DD, MH, SS; and A-AN; Investigation, MM; Methodology, MM, PS; MU; Project administration, MM, and PS, MU; Resources, MM, and PS; Supervision, PS; Visualization, MM, DD, MH, SS; and A-AN; Writing—original draft, MM, DD, SS, MH, MU; and A-AN; Writing—review & editing, MM, MU, and PS. All authors have read and agreed to the published version of the manuscript.

## Funding

Open access funding was provided by the University of Helsinki.

## Acknowledgments

We extend our heartfelt gratitude to the fishermen and other invaluable stakeholders who generously participated in this research. Their valuable insights and contributions have been instrumental in enriching our study. We would also like to express our appreciation to Editage (www.editage.com) for their exceptional English language editing services, which have significantly enhanced the quality and clarity of our work. Additionally, we wish to acknowledge the remarkable efforts of Saif Mehjabin and Anik Karmakar, both talented individuals and dedicated undergraduate students from the Department of Oceanography at the University of Chittagong, Bangladesh. Saif Mehjabin's Adobe illustrations and Anik Karmakar's meticulous audio transcriptions have greatly augmented our research's visual and auditory aspects. We are immensely grateful for their valuable contributions.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1150213/full#supplementary-material

## References


Agnew, D. J., Pearce, J., Pramod, G., Peatman, T., Watson, R., Beddington, J. R., et al. (2009). Estimating the worldwide extent of illegal fishing. *PloS One* 4, e4570. doi: 10.1371/journal.pone.0004570

Alqattan, M. E. A., Gray, T. S., and Stead, S. M. (2020). The illegal, unreported and unregulated fishing in Kuwait: problems and solutions. *Mar. Policy.* 116, 103775. doi: 10.1016/j.marpol.2019.103775

Amrutha, V. N., and Geetha, S. N. (2020). A systematic review on green human resource management: implications for social sustainability. *J. Clean. Prod.* 247, 119131. doi: 10.1016/j.jclepro.2019.119131

Azad, A. K., and Pamment, C. (2020). Bangladesh Overfishing: almost all species pushed to brink. *BBC.* https://www.bbc.com/news/worldasia-52227735 [Accessed July 10, 2022].

Canton, H. (2021). *Food and agriculture organization of the united nations–FAO* (London: The Europa Directory of International Organizations (Routledge), 297–305.

Chaliluddin, M. A., Rahmah, A., Aprilla, R. M., Rizwan, T., Ikram, M., Satria, D., et al. (2021). "Management of environmentally friendly fishing gears based on the code of conduct for responsible fisheries in pidie district," in *IOP conference series. IOP conf. ser.: earth environ. sci*, vol. 674. (Aceh Besar, Indonesia: IOP Publishing), 012034. doi: 10.1088/1755-1315/674/1/012034

Chowdhury, M. S. N., Hossain, M. S., Das, N. G., and Barua, P. (2022). Small-scale fishermen along the naaf river, Bangladesh in crisis: a framework for management. *MJMS* 26, 149–169. doi: 10.58629/mjms.v26i2.181

DoF (2014) *[Annual report]*. Available at: http://www.fisheries.gov.bd/site/view/annual_reports/Annual-Report (Accessed July 12, 2022).

DoF (2019) *National plan of action to prevent, deter and eliminate illegal, unreported and unregulated (IUU)*. Available at: https://fisheries.portal.gov.bd (Accessed June 5, 2022).

Donlan, C. J., Wilcox, C., Luque, G. M., and Gelcich, S. (2020). Estimating illegal fishing from enforcement officers. *Sci. Rep.* 10, 12478. doi: 10.1038/s41598-020-69311-5

Doug, L. (2009). "SWOT analysis," in *Handbook of human performance technology 3rd edition*, vol. 1408. (San Francisco, USA: Principles, Practices, and Potential), 1.

Edhlund, B., and McDougall, A. (2019) *NVivo 12 essentials. lulu. com.* Available at: https://books.google.co.in/books?id=DiWGDwAAQBAJ&printsec=frontcover#v=onepage&q&f=false.

FAO. (2001) . *international plan of action to prevent, deter and eliminate illegal, unreported and unregulated fishing* (Rome, Italy). Available at: https://www.fao.org/fishery/en/ipoa-iuu (Accessed June 15, 2022).

FAO. (2007). *The state of world fisheries and aquaculture 2006* (Rome: FAO Fisheries and Aquaculture Department).

FAO. (2020). *The state of world fisheries and aquaculture 2020. sustainability in action* (Rome: Food and Agriculture Organization of the United Nations). doi: 10.4060/ca9229en.

FAO. (2022). *Illegal, unreported and unregulated (IUU) fishing*. Available at: https://www.fao.org/iuu-fishing/en/ (Accessed July 15, 2022).

Force, H. S. T., and Upton, S. (2006). *Closing the net: stopping illegal fishing on the high seas: final report of the ministerially-led task force on IUU fishing on the high seas.* IUU Fishing Coordination Unit, Department for Environment, Food and Rural Affairs. London SW1A 2HH. United Kingdom.

Fujii, I., Okochi, Y., and Kawamura, H. (2021). Promoting cooperation of monitoring, control, and surveillance of IUU fishing in the Asia-pacific. *Sustainability* 13, 10231. doi: 10.3390/su131810231

Ghose, B. (2014). Fisheries and aquaculture in Bangladesh: challenges and opportunities. *Ann. Aquaculture Res.* 1 (1), 1–5. doi: 10.47739/2379-0881/1001

Gürel, E. (2017). SWOT analysis: a theoretical review. *JISR* 10, 994–1006. doi: 10.17719/jisr.2017.1832

Hair, J. F., Ortinau, D. J., and Harrison, D. E. (2010). *Essentials of marketing research* Vol. 2 (New York, NY: McGraw-Hill: Irwin Publishing).

Helyar, S. J., Lloyd, H. A. D., de Bruyn, M., Leake, J., Bennett, N., and Carvalho, G. R. (2014). Fish product mislabelling: failings of traceability in the production chain and implications for illegal, unreported and unregulated (IUU) fishing. *PloS One* 9, e98691. doi: 10.1371/journal.pone.0098691

Islam, M. M., Shamsuzzaman, M. M., Hoque Mozumder, M. M., Xiangmin, X., Ming, Y., and Abu Sayed Jewel, M. (2017). Exploitation and conservation of coastal and marine fisheries in Bangladesh: do the fishery laws matter? *Mar. Policy.* 76, 143–151. doi: 10.1016/j.marpol.2016.11.026

Islam, R., and Walkerden, G. (2022). Livelihood assets, mutual support and disaster resilience in coastal Bangladesh. *Int. J. Disaster Risk Reduct.* 78, 103148. doi: 10.1016/j.ijdrr.2022.103148

Joseph, J., Squires, D., Bayliff, W., and Groves, T. (2010). "Addressing the problem of excess fishing capacity in tuna fisheries," in *Squires deditors. conservation and management of transnational tuna fisheries*. Eds. R. Allen and J. Joseph (California, USA: Wiley-Blackwell), 11–38.

Kadfak, A., and Linke, S. (2021). More than just a carding system: labour implications of the EU's illegal, unreported and unregulated (IUU) fishing policy in Thailand. *Mar. Policy.* 127, 104445. doi: 10.1016/j.marpol.2021.104445

Knauss, J. M. (2005). The growth of British fisheries during the industrial revolution. *Ocean Dev. Int. Law.* 36, 1–11. doi: 10.1080/00908320490508912

Kuperan, K. V., and Jahan, K. M. (2010). Noncompliance a major threat in fisheries management â€ experience from the artisanal coastal fisheries of Bangladesh. *J. Int. Stud.* 6, 97–113. doi: 10.32890/jis.6.2010.7911

Lambert, S. D., and Loiselle, C. G. (2008). Combining individual interviews and focus groups to enhance data richness. *J. Adv. Nurs.* 62(2), 228–237. doi: 10.1111/j.1365-2648.2007.04559.x

Le Gallic, B. L., and Cox, A. (2006). An economic analysis of illegal, unreported and unregulated (IUU) fishing: key drivers and possible solutions. *Mar. Policy.* 30, 689–695. doi: 10.1016/j.marpol.2005.09.008

Leroy, A., Galletti, F., and Chaboud, C. (2016). The EU restrictive trade measures against IUU fishing. *Mar. Policy.* 64, 82–90. doi: 10.1016/j.marpol.2015.10.013

Liddick, D. (2014). The dimensions of a transnational crime problem: the case of IUU fishing. *Trends Organ. Crim.* 17, 290–312. doi: 10.1007/s12117-014-9228-6

Lohrke, F. T., Mazzei, M. J., and Frownfelter-Lohrke, C. (2022). Should it stay or should it go? developing an enhanced SWOT framework for teaching strategy formulation. *J. Manage. Educ.* 46 (2), 345–382. doi: 10.1177/10525629211021143

Macfadyen, G., and Hosch, G. (2022) *The IUU fishing index 2021. Poseidon aquatic resource management limited and the global initiative against transnational organized crime*. Available at: https://globalinitiative.net/analysis/iuu-fishing-index-2021/ (Accessed September 20, 2022).

Mackay, M., Hardesty, B. D., and Wilcox, C. (2020). The intersection between illegal fishing, crimes at sea, and social well-being. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.589000

Mala, D. A. (2020). *Proposed marine fisheries act. focus on harnessing blue economy's potential. the financial express*. Available at: https://www.thefinancialexpress.com.bd/economy/focus-on-harnessing-blue-economys-potential-1581051032 (Accessed July 12, 2022).

Miller, D. D., Sumaila, U. R., Copeland, D., Zeller, D., Soyer, B., Nikaki, T., et al. (2016). Cutting a lifeline to maritime crime: marine insurance and IUU fishing. *Front. Ecol. Environ.* 14, 357–362. doi: 10.1002/fee.1293

Murshed-e-Jahan, K., Belton, B., and Viswanathan, K. K. (2014). Communication strategies for managing coastal fisheries conflicts in Bangladesh. *Ocean Coast. Manage.* 92, 65–73. doi: 10.1016/j.ocecoaman.2014.01.003

Nakamura, J. N., Amador, T., and Al Arif, A. (2022). *Legal report on the ecosystem approach to fisheries in Bangladesh – an analysis of the ecosystem approach to fisheries in selected national policy and legal instruments of Bangladesh* Vol. 57 (Rome: FAO EAF-Nansen Programme Report No). doi: 10.4060/cc2560en

NIC (2016) *Global implications of illegal, unreported, and unregulated (IUU) fishing*. Available at: https://www.dni.gov/index.php/newsroom/reports-publications/reports-publications-2016/item/1630-global-implications-of-illegal-unreported-and-unregulated-iuu-fishing (Accessed August 22, 2022).

Njifonjou, O., Satia, B., and Angaman, K. (2006). Fisheries co-management and poverty alleviation in the context of the sustainable livelihoods approach: a case study in the fishing communities of aby lagoon in cote d'Ivoire. *Int. J. Sustain. Dev. World Ecol.* 13, 448–458. doi: 10.1080/13504500609469694

Pant, P. (2019). SWOT analysis: a powerful tool of strategic competitive management effectiveness. *Adhyayan: A J. Manage. Sci.* 9 (02), 31–37. Retrieved from: http://smsjournals.com/index.php/Adhyayan/article/view/1982

Petrossian, G. A. (2018). A micro-spatial analysis of opportunities for IUU fishing in 23 western African countries. *Biol. Conserv.* 225, 31–41. doi: 10.1016/j.biocon.2018.06.011

Petrossian, G. A., Marteache, N., and Viollaz, J. (2015). Where do "undocumented" fish land? an empirical assessment of port characteristics for IUU fishing. *Eur. J. Crim. Policy Res.* 21, 337–351. doi: 10.1007/s10610-014-9267-1

Polacheck, T. (2012). Assessment of IUU fishing for southern bluefin tuna. *Mar. Policy.* 36, 1150–1165. doi: 10.1016/j.marpol.2012.02.019

Porras, I., Mohammed, E. Y., Ali, L., Ali, M. S., and Hossain, M. B. (2017). Power, profits and payments for ecosystem services in hilsa fisheries in Bangladesh: a value chain analysis. *Mar. Policy.* 84, 60–68. doi: 10.1016/j.marpol.2017.06.031

Rahman, M. A., and Rupom, R. S. (2020). IFAS and EFAS analysis of maritime region, Bangladesh: entwining strategical approach. *J. Bangladesh Inst. Plann.* 13, 39–45.

Rangkuti, F. (2015). *Techniques for dissecting business case SWOT analysis* (Jakarta: P T. Gramedia Main).

Rangsipaht, S., and Thaipakdee, S. (2012). Using SWOT analysis to identify co-management schemes that enhance the livelihoods of small-scale fishers. *Fish People.* 3, 35–39.

Shamsuzzaman, M. M., and Islam, M. M. (2018). Analysing the legal framework of marine living resources management in Bangladesh: towards achieving sustainable development goal 14. *Mar. Policy.* 87, 255–262. doi: 10.1016/j.marpol.2017.10.026

Song, A. M., Scholtens, J., Barclay, K., Bush, S. R., Fabinyi, M., Adhuri, D. S., et al. (2020). Collateral damage? small-scale fisheries in the global fight against IUU fishing. *Fish Fish.* 21, 831–843. doi: 10.1111/faf.12462

Soyer, B., Leloudas, G., and Miller, D. (2018). Tackling IUU fishing: developing a holistic legal response. transnat. *Environ. Law.* 7, 139–163. doi: 10.1017/S2047102517000267

Sumaila, U. R. (2019). A carding system as an approach to increasing the economic risk of engaging in IUU fishing? *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00034

Sunny, A. R., Masum, K. M., Islam, N., Rahman, M., Rahman, A., Islam, J., et al. (2020). Analyzing livelihood sustainability of climate vulnerable fishers: insight from Bangladesh. *J. Aquac. Res. Dev.* 11, 6. doi: 10.35248/2155-9546.19.10.593

Viegas, M. D. C., Moniz, A. B., and Santos, P. T. (2014). Artisanal fishermen contribution for the integrated and sustainable coastal management – application of strategic SWOT analysis. *Proc. Soc. Behav. Sci.* 120, 257–267. doi: 10.1016/j.sbspro.2014.02.103

Watson, R. A., Cheung, W. W. L., Anticamara, J. A., Sumaila, R. U., Zeller, D., and Pauly, D. (2013). Global marine yield halved as fishing intensity redoubles. *Fish Fish.* 14, 493–503. doi: 10.1111/j.1467-2979.2012.00483.x

Widjaja, S., Long, T., and Wirajuda, H. (2020) *Illegal, unreported and unregulated fishing and associated drivers*. Available at: https://oceanpanel.org/publication/illegal-unreported-and-unregulated-fishing-and-associated-drivers/ (Accessed July 5, 2022).

Wijayanto, D. (2016). Fisheries development strategies of biak numfor regency, Indonesia. *Aquat. Procedia.* 7, 28–38. doi: 10.1016/j.aqpro.2016.07.004

frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 18 August 2023
DOI 10.3389/fmars.2023.1180920



OPEN ACCESS

EDITED BY
Pablo Pita,
University of Santiago de Compostela,
Spain

REVIEWED BY
Stephen Mangi,
MRAG Ltd., United Kingdom
Natali Lazzari,
University of Barcelona, Spain

*CORRESPONDENCE
Juan Carlos Villaseñor-Derbez
juancvd@stanford.edu

RECEIVED 06 March 2023
ACCEPTED 22 June 2023
PUBLISHED 18 August 2023

CITATION
Villaseñor-Derbez JC, Fulton S, Hernández-Velasco A and Amador-Castro IG (2023) Biomass accrual benefits of community-based marine protected areas outweigh their operational costs.
*Front. Mar. Sci.* 10:1180920.
doi: 10.3389/fmars.2023.1180920



# Biomass accrual benefits of community-based marine protected areas outweigh their operational costs

Juan Carlos Villaseñor-Derbez[1,2]*, Stuart Fulton[3], Arturo Hernández-Velasco[3] and Imelda G. Amador-Castro[3]

[1]Oceans Department, Stanford Doerr School of Sustainability, Stanford University, Pacific Grove, CA, United States, [2]Bren School of Environmental Science & Management, University of California Santa Barbara, Santa Barbara, CA, United States, [3]Comunidad y Biodiversidad A.C., Guaymas, Sonora, Mexico

The costs and benefits of customary top-down Marine Protected Areas (MPAs) have been studied at length. But the costs and benefits of community-based MPAs –an increasingly common tool in conservation and fisheries management– remain understudied. Here, we quantify the operational costs of maintaining community-based MPA monitoring programs in nine small-scale fishing communities in Mexico. We then compare these costs to the potential extractive use value of invertebrate and fish biomass contained in the reserves. We find that the annual monitoring costs (median: 1,130 MXN/ha; range: 23-3,561 MXN/ha) represent between 0.3% and 55% of the extractive use value of the biomass contained in the reserves (median: 21.31 thousand MXN/ha; 5.22 - 49/12 thousand MXN/ha). These results suggest that the direct monetary benefits of community-based marine conservation can outweigh the costs of monitoring programs, providing further support for these types of management schemes. While further research should explore other mechanisms that would allow fishers to leverage the non-extractive use value of reserves (*e.g.*, tourism) or the non-use value (*i.e.* existence value of biodiversity) to sustainably finance their conservation efforts, a stop-gap measure to ensuring long-term monitoring costs are covered might include limited extractive use of resources contained in the reserves.

KEYWORDS

**bottom-up conservation, small-scale fisheries, conservation financing, marine protected areas, sustainable development goals**

## 1 Introduction

Marine Protected Areas (MPAs) have become a common tool in the marine conservation and fisheries toolkit, particularly in tropical small-scale fisheries. A rich body of literature has studied the benefits that MPAs can have on fisheries through empirical evaluations (Moland et al., 2013; Lenihan et al., 2021) or numerical simulations

(Ovando et al., 2016; Millage et al., 2021), and can be largely summed up by increases in species richness, biomass, and catch-per-unit effort around MPA boundaries (Micheli et al., 2004; Lester et al., 2009; Lenihan et al., 2021; Medoff et al., 2022). Others have empirically evaluated how the costs of establishing MPAs scale with the duration of the planning phase and size of the MPA to be implemented (McCrea-Strub et al., 2011), or combined surveys and national statistics to estimate the recurrent annual expenditure of MPAs and calculate the budgetary requirements for a global network of MPAs (Balmford et al., 2004). A growing body of literature has focused on estimating the socioeconomic costs that MPAs place on resource users (Smith et al., 2010; Rees et al., 2013; Rees et al., 2021). Yet, few (if any) have jointly quantified the relationship between operational costs and socioeconomic benefits of the same MPA, and even fewer have performed such an analysis focusing on community-based MPAs.

Community-based MPAs are areas where fishers voluntarily eliminate fishing effort, or where fisher's input and knowledge is the main driver of the design, implementation, and management of the areas (White, 1989). An important distinction between these and customary top-down MPAs lies in the distribution of costs and benefits of conservation. Benefits of customary MPAs will mainly accrue to society in general, for example through leisure opportunities, food provisioning, and other ecosystem services (Potts et al., 2014; Leenhardt et al., 2015; Cabral et al., 2019; Johnson et al., 2019), while a smaller portion of the benefits may accrue to a subset of users [*e.g.* biomass spillover to fishers; Lenihan et al. (2021); Medoff et al. (2022)]. Their operational costs are also generally covered by society thorough national taxation, but we note that some private agents may disproportionately bear some of the opportunity costs [*e.g.* fishers that are displaced from their fishing grounds; Smith et al. (2010)]. In contrast, community-based MPAs are often implemented within traditional fishing grounds (some of which may be formal territorial user rights for fisheries - TURFs [Afflerbach et al. (2014); Gelcich et al. (2017); Villaseñor-Derbez et al. (2019)], which confer spatial property rights and often result in exclusive access regimes. Therefore, it follows that any benefits that arise from conservation interventions in these private areas will mainly accrue to those who hold the property rights (*i.e.* the fishers), rather than "society in general". Communities often resort to philanthropic sources in order to cover the operational costs of their MPAs, which has raised concerns about the long-term feasibility of such endeavors (Johannes, 2002; Ramutsindela et al., 2013; Mallin et al., 2019).

Marine reserves, also known as fully-protected MPAs, are a special type of MPA that do not allow extractive activities (Sala and Giakoumi, 2017). Over the past two decades, some Mexican fishing communities have implemented community-based marine reserves within their fishing grounds (Quintana and Basurto, 2021; Villaseñor-Derbez et al., 2022). Their documented success in maintaining biomass of fishery-relevant species (Smith et al., 2022) and biodiversity more broadly (Micheli et al., 2014; Munguía-Vega et al., 2015) has prompted ambitious commitments to expand coverage of community-based MPAs in Mexico. Yet, little is known about how the costs of implementing and maintaining them will stack up against the benefits that they may provide. Importantly, the existing reserves have received most of their financial support from philanthropic sources (although we recognize that government programs and the communities themselves have also provided *some* funding). The current funding model is therefore heavily dependent on philanthropic contributions, which cannot guarantee their long-term persistence. This highlights the need to study and develop alternative financing strategies that will be needed to maintain an expanded network of community-based marine reserves, and to better understand the benefits that they may provide.

One proposal discussed in the literature is to allow *some* amount of commercial fishing within the reserves, and use the proceeds to pay for their monitoring and enforcement. Such a set-up has been explored in the way of "Conservation Finance Areas" [*sensu* Millage et al. (2021)], where the authors show that in the absence of an exogenous budget it is always optimal to allow for *some* amount of fishing, and use the proceeds to pay for monitoring and enforcement. Here, we quantify the costs of implementing, monitoring, and maintaining community-based marine reserves in nine small-scale fishing communities in Mexico. We also leverage long-term fisheries and ecological monitoring data to estimate the monetary value of biomass contained in the reserves. We then compare these costs and benefits, and quantify the degree to which limited extraction of biomass contained in the reserves could help cover the costs of conservation. The main contributions of our paper are: We 1) provide the first cost estimates for maintaining community-based marine reserves, 2) quantify the economic benefits that they may provide, and 3) empirically confirm predictions made by previous theoretical work, and show that the value of the biomass within the reserves can help cover the costs of conservation.

# 2 Data and methods

## 2.1 Study area

We focus on nine systems of community-based marine reserves implemented in three distinct social-ecological systems (Figure 1). The first three reserve systems (El Rosario, Isla Natividad, and La Bocana) are located along the Pacific coast of the Baja California Peninsula, a temperate upwelling system dominated by kelp forests [mostly Giant Kelp (*Macrocystis pyrifera*) and Palm Kelp (*Ecklonia arborea*)]. This area is also known for their successful co-management strategies enabled by systems of TURFs and well-organized fishing cooperatives and federations of cooperatives who mainly target benthic invertebrate species (Lobster, Abalone, Sea Cucumber, Urchins) with a combination of set traps and hookah diving (McCay et al., 2014; McCay, 2017). The next three systems (Puerto Libertad, Isla San Pedro Mártir[1], and Isla San Pedro Nolasco) are located along the eastern coast of the Gulf of California, where the predominant habitats are rocky reefs and sandy bottoms. The system is subject to a variety of users with fewer

1 Isla San Pedro Mártir was implemented by the government with significant input from fishers. However, the monitoring program is still led by the a group of community members (Fulton et al., 2019b).

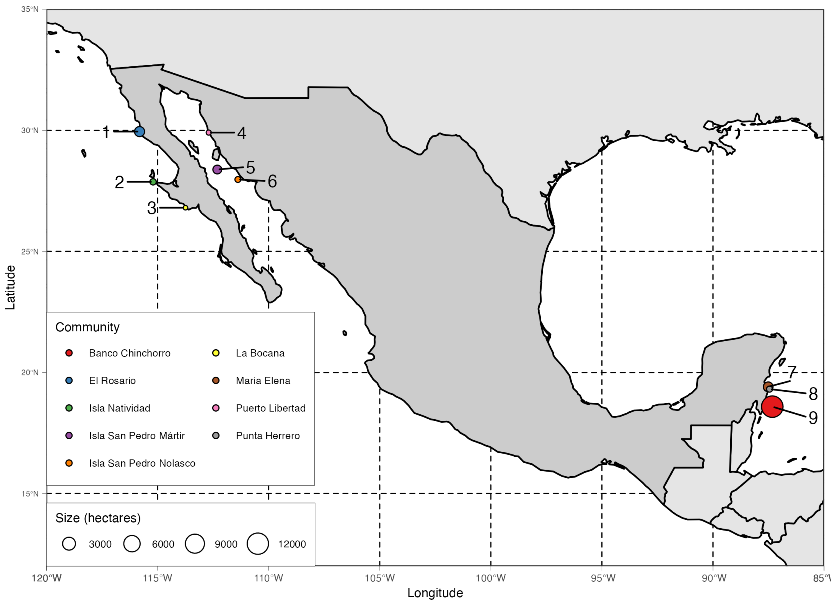



FIGURE 1
Map of general location of community-based marine reserves included in this analysis. Note that our sample includes three distinct regions: the Pacific coast of the Baja California peninsula, the Gulf of California, and the Mexican Caribbean. Color and numbers indicate the locations of the communities (1 = El Rosario, 2 = Isla Natividad, 3 = La Bocana, 4 = Puerto Libertad, 5 = Isla San Pedro Martir, 6 = Isla San Pedro Nolasco, 7 = Maria Elena, 8 = Punta Herrero, 9 = Banco Chinchorro).

exclusive access rights and more interactions with industrial fisheries (Amador-Castro et al., 2021). Here, fishers target finfish with a variety of fishing gear, while bivalves are collected *via* hookah diving. Finally, the last three reserve systems (Maria Elena, Punta Herrero, and Banco Chinchorro) are on the Caribbean coastline of the Yucatan Peninsula, where coral reefs and seagrass beds are the predominant habitat types. Fishers also operate under a system of cooperatives and TURFs rooted in historical land-based management practices (Méndez-Medina et al., 2015). They mainly target lobster, which they collect *via* free diving and hand-held nets and lassos in the open reef and artificial structures (Miller, 1982; Briones-Fourzán and Lozano-Álvarez, 2000). Our set of focal reserve systems are representative of the main marine habitat types, target species, fishing methods, and management regimes typically faced by small-scale fishers in Mexico.

## 2.2 Estimating costs of monitoring

Most of these communities have monitored their reserves annually for at least a decade, which allows us to quantify the annual costs of monitoring reserves in each community. We extract information on the costs of the monitoring programs from past budgetary line items of each reserve system. Specifically, we consider payroll (community members participating in the monitoring campaign are compensated at a rate equivalent to an average day of fishing), boat rental, fuel costs, training in SCUBA diving and scientific monitoring, servicing of SCUBA gear, dive insurance, and other costs associated with common field work activities. For each reserve system, we first calculate the total costs of the annual monitoring program and then normalize it by total reserve area (hectares) to generate a cost-per-hectare metric commonly used in the literature [*e.g.* see Balmford et al. (2004)]. Additionally, it is necessary to standardize costs in this way so that we can compare them to our value-per-hectare metrics developed in the following section. However, whenever relevant, we will also report the absolute costs to reflect the true cost to each community.

## 2.3 Estimating benefits of conservation

We are concerned with estimating the extractive use value of biomass [*i.e.* the value derived from depleting the resource (Ninan, 2012)] contained in the reserves, and how this compares to the operational costs. To do this, we will combine a long-term data set of taxa-specific fisheries landings with *in situ* observations of biomass in the reserves and control sites (See Figure 2).

### 2.3.1 Ex-vessel prices

The ex-vessel price is the per-kilogram value of catch paid to fishers upon the first transaction (Melnychuk et al., 2017). We use monthly data from landing tickets reported to CONAPESCA (Mexico's fisheries management agency) between 2001 and 2019, which explicitly report the species or broad taxonomic group (*e.g.* sometimes the record might indicate "yellowtail jack" and sometimes simply "jack"), type of landed catch [*e.g.* total weight (recorded "peso vivo") or gutted weight], weight (in Kg) and value of the total catch (in Mexican Pesos; MXN).

We filter the data to keep only records for which type of catch is recorded as "peso vivo" (total weight), allowing us to exclude

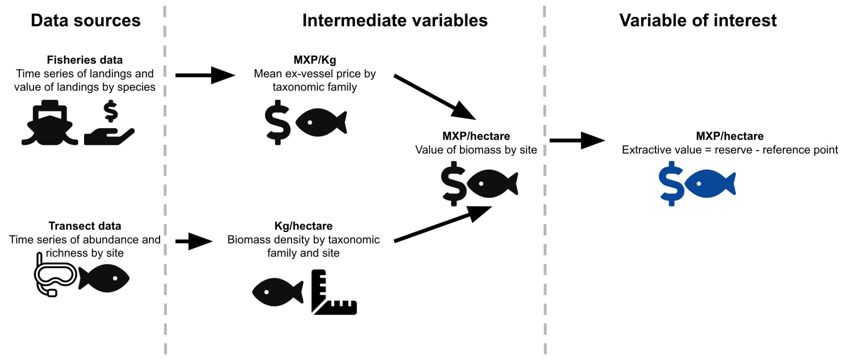



FIGURE 2
Pictorial representation of our methodological approach. The figure shows the data sources (left column), computed variables (middle column) and final variable of interest (right column).

records of products with any value-added processes (*e.g.* filleting, freezing, vacuum sealing, or gutting). Then, we match the reported species or group of species with their respective taxonomic families. For example, both "jack" and "yellowtail jack" would be matched with family Carangidae. We use the same price for families Serranidae and Polyprionidae that contain commercially similar species marketed as "groupers" and "sea bass" (translating from terms like *Mero, Pescada, Garropa*, and *Cabrilla*; See Table S1 for a list of main species groups and their respective taxonomic families). For each of these taxonomic families, we calculate the annual mean ex-vessel price (MXN/Kg) by dividing the total value of landed catch by total landed catch. We group our estimates at the family-year level to reduce errors due to species identification or variation in month-to-month price. We then use the Consumer Price Index from the OECD (OECD, 2023) to normalize all values to 2019 MXN, as:

$$\hat{p}_t = p_t \times \frac{CPI_t}{CPI_{2019}} \quad (1)$$

Where $\hat{p}_t$ is the adjusted ex-vessel price at time t, $p_t$ is the unadjusted ex-vessel price, $CPI_t$ is the Consumer Price index for year $t$, and $CPI_{2019}$ is the reference consumer price index, in this case for year 2019. Figure 3A shows a time-series of CPI-adjusted mean ex-vessel prices for 12 families of commercial interest in Mexican small-scale fisheries. Since we are concerned with evaluating the current value of the reserves, we must define what the ex-vessel price would be today. We calculate and use the mean ex-vessel price for each family across all years. This mean value better represents the expected ex-vessel price for a given product, compared to using the ex-vessel price from the latest year in record (*i.e.* 2019, which could introduce bias because the value of a particular group of species might have been abnormally high or abnormally low in 2019). The resulting estimates of ex-vessel price for each of the 12 families are shown in Figure 3B.

### 2.3.2 Biomass density

Each community has implemented annual ecological monitoring programs to track the performance of their reserves. Scientific divers (fishers, community members, and researchers) follow standardized methodologies to record the richness and abundance of fish and invertebrate species along standardized 30-by-2 m belt transects [between 5 and 20 m depth] in each reserve and pre-determined control sites (See Suman et al. (2010); Fulton et al. (2018); Fulton et al., (2019a) for additional details). For fish species, total length (in cm) is also recorded. Sampling effort varies across communities and time (*e.g.* due to weather events), but on average a total of 70 (± 38) invertebrate and 90 (± 43) fish transects were performed per community each year (See Figure S4 for more details on sampling effort).

We filter monitoring data to keep only species belonging to the 12 families of commercial interest (See Figure 3 and Table S1). For fish survey data, we exclude records from organisms with Total Length ≤ 20 cm to remove juveniles that could sum to a large biomass that is not of commercial size (See Reddy et al. (2013) for a discussion on market-driven size-selective harvesting and the 20 cm cut-off). We then use the standard length-weight relationship ($TW = a \times TL^{\beta}$) to calculate individual weight using species-specific $a$ and $b$ parameters obtained from FishBase (Froese and Pauly 2010), accessed using the "rfishbase" package in R [Fishbase version 23.01; Boettiger et al. (2012)]. When species-specific data were not available we used the genus-level median. Knowing the mass and number of individuals of each species recorded in each transect, we calculate the total biomass density for each family in each transect and then convert them to Kg/hectare.

The standardized invertebrate surveys do not record body length measurements for invertebrate species [abalone (Haliotidae), lobster (Panulidae), urchins (Strongylocentrotidae) and sea cucumber (Holoturoidea)]. Therefore, we use the species-specific minimum catch size or size at first capture and growth parameters retrieved from scientific literature to calculate individual weight (See Table S2). Other surveys have recorded carapace length of lobster (from a mark-and-recapture experiment in the Yucatan Peninsula) and diameter of abalone shells (during roving diver surveys in El Rosario, Isla Natividad, and La Bocana). These data show that 85.5% of lobster (total N = 173) and 80.24% of abalone (total N = 14,445) are larger than minimum catch sizes, and that the minimum catch sizes are consistently smaller than the mean sizes (Figure S1; See our discussion section for more information on the implications of this choice). As in the case of fish, we

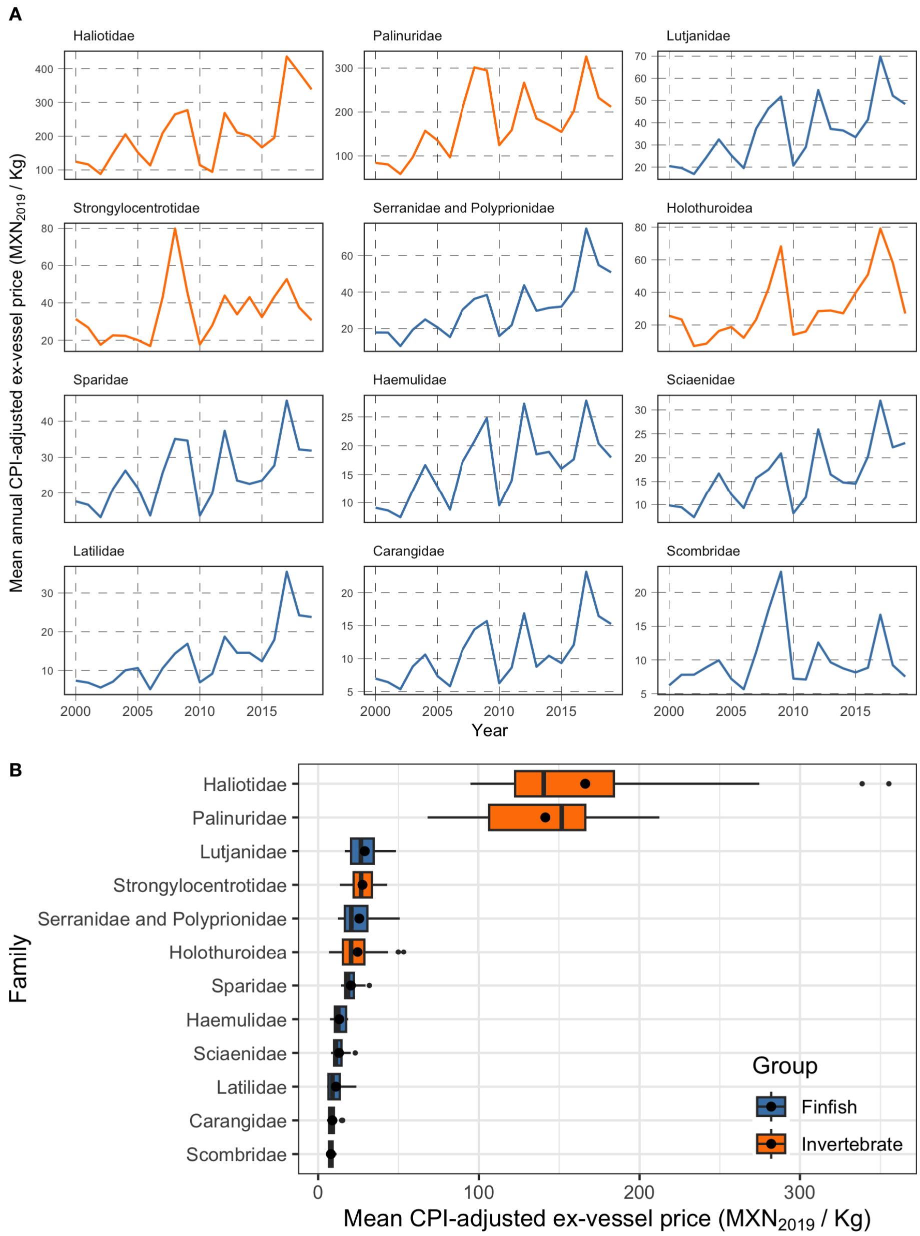



FIGURE 3
Ex-vessel prices for 12 taxonomic families of commercial importance to Mexican small-scale fisheries (2000 – 2019). Panel **(A)** shows mean annual ex-vessel prices, and panel **(B)** shows a boxplot of the ex-vessel price for each taxonomic family across all years. The vertical black line inside each box shows the median value, the black point within the bars shows the mean value (the one used in our analysis), the lower and upper edges of the bars correspond to the first and third quartiles. The upper error bar extends from the quartile to the largest value within 1.5 times the inter-quartile range, and the lower error bar extends from the edge of the first quartile to the smallest value at within 1.5 times the inter-quartile range. Data beyond the end of the whiskers are called “outlying” points and are plotted individually. Colors indicate whether the family contains finfish (blue) or invertebrates (orange).

calculate the total biomass density for each family in each transect and convert them to Kg/hectare. Fish and invertebrate will continue to be handled separately to avoid confounding our precise estimates of fish biomass with our lower-bound estimates of invertebrate biomass.

### 2.3.3 Establishing the economic value of the reserves

We now proceed to match ex-vessel prices (MXN/Kg) and biomass density (Kg/ha) for each corresponding family, multiply them to obtain the economic value of the biomass of each family, and then sum across all families to obtain the total per-hectare value of invertebrate or fish biomass (MXN/ha) in the transect. Finally, we calculate the expected per-hectare value of each reserve and control site by taking the average across all transects.

We are interested in determining the immediate[2] extractive value of the biomass in the reserves that fishers would perceive by extracting *some* of the biomass within their reserves. For each reserve, we identify the historical minimum observed in control sites (within the TURFs and fishing grounds, where fishing is allowed) or the reserve sites before they were implemented (when fishing was still allowed) and use them as a reference points (Table S3). We define the extractive value of a reserve as the difference between the value of biomass in the reserve today and value of biomass from the reference point (See Figure 2). This definition of reference points assumes that historical values are both economically and ecologically valuable. We ground this assumption on previous findings from fisheries economics (Gordon, 1954; Costello et al., 2012) and community-based management literature (Gelcich et al., 2008; Gelcich et al., 2015). Greater detail is provided in the discussion section, but it broadly implies two things: 1) That even if a reserve contains high amounts of valuable biomass, only some of it can be extracted (extraction can only be up to the reference point). And 2) that if the value of biomass within the reserve today is lower than the reference point, then no extraction can take place and the economic value of the reserve is zero (even if there is biomass within the reserve).

We can estimate the extractive value of biomass within the reserves *via* a simple difference-in-means estimation using a linear regression of the form:

$$Y_{it} = \alpha + \Delta P_{it} + \epsilon_{it} \qquad (2)$$

Where $Y_{it}$ represents the economic value of biomass in transect $i$ at time $t$, $P_{it}$is dummy variable that indicates whether an observation comes from the historical reference point (*i.e.* $P_{it} = 0$) or current value (*i.e.* $P_{it} = 1$), and $\epsilon_{it}$ is an idiosyncratic error term. The interpretation of the coefficients is also convenient: $\alpha$ is the mean value of biomass across all transects in the reference point, and the coefficient of interest, $\Delta$, captures the difference in mean value of biomass between the current value ($P_{it} = 1$) and the reference point ($P_{it} = 0$). The null hypothesis is that there is no difference between the value of biomass in the reserves today, and the mean value of biomass in the reserves at the reference point (*i.e.* $H_0 : \Delta = 0$). We estimate $\alpha$ and $\Delta$ for each system of reserves using ordinary least squares with heteroskedastic-robust standard errors (White, 1980). All data were analyzed in R [R version 4.2.3; R Core Team (2023)] using RStudio (RStudio 2023.03.0; Build 386).

# 3 Results

We divide our results into three brief subsections and leave further interpretation of the results and extended lines of inference for the discussion section. We first report normalized and total costs of monitoring the reserves in each community. We then focus on the temporal patterns observed in fish and invertebrate value of biomass within reserve and control sites, followed by a description of current (2019) value and extractive value of biomass in the reserves. Finally, we turn to our main goal of comparing the costs of monitoring with the potential extractive value of biomass.

2 *i.e.* we do not account for the value of escapement and subsequent somatic growth and reproduction.

## 3.1 Costs of monitoring

The annual costs of monitoring the reserves studied here range from 23 MXN/ha to 3,561 MXN/ha, with a median value of 1,130 MXN/ha (Figure 4A). La Bocana had the highest per-unit-area costs because they have the smallest reserves (at just 59.76 ha), while Banco Chinchorro has the lowest per-unit-area costs because they have the largest reserve area (12,257 ha). In absolute terms, however, the annual median is of 212,854 MXN/ha (ranging from 95,500 to 458,474 MXN), with the highest value observed for El Rosario and the lowest value observed for Isla San Pedro Martir (Figure 4B).

## 3.2 Value of biomass

### 3.2.1 General temporal trends in valuable biomass

The first pattern worth noting is the temporal prevalence of the source of value for each reserve's community (Figure 5). Fish biomass is consistently more valuable than invertebrate biomass in Banco Chinchorro, Isla San Pedro Martir, Isla San Pedro Nolasco, and Puerto Libertad. Conversely, invertebrate biomass contributes consistently more than fish biomass to the value of reserves in El Rosario and Isla Natividad. In Punta Herrero and María Elena, the values of fish and invertebrate biomass contribute similarly to reserve value. The second temporal pattern of interest is that the value of biomass does not strictly increase in time.

### 3.2.2 Present-day (2019) value of biomass in reserves

All numeric results in this section are reported in thousands of Mexican pesos per hectare (thousand MXN/ha) and accompanied by the standard error around the point estimate. Monitoring data show that the reserves in Isla Natividad (56.3 ± 14.45; mean ± standard error), Punta Herrero (22.9 ± 15.4), and El Rosario (16.54 ± 2.8) have the most valuable mean invertebrate biomass (Figure 6A). On the other hand, the least valuable invertebrate biomass was observed for Isla San Pedro Martir (0.27 ± 0.09), Puerto Libertad (0.75 ± 0.3), and Banco Chinchorro (2.60 ± 1.3). However, when compared against the baseline values identified in the time series (Figure 5, See also Table S3), we find that the extractive value of invertebrate biomass is highest in Isla Natividad (24.9 ± 16.3), Punta Herrero (20.7 ± 15.9), and Isla San Pedro Nolasco (5.3 ± 1.6; Figure 6B). The extractive valuable of invertebrate biomass is lowest in El Rosario where the current (2019) value of biomass was at an all-time low (Figure 5 and Table 1). These patterns are largely driven by spiny lobster (*Panulirus argus* in the Caribbean and *P. interruptus* in the Pacific, Figure S2), which are the most abundant and second most valuable species (after abalone; Figure 3).

The most valuable finfish biomass was observed in Puerto Libertad (51.9 ± 19.9), Isla San Pedro Mártir (40.1 ± 12.7), and Punta Herrero (30.5 ± 20.9). Conversely, Isla Natividad (5.53 ± 1.44), El Rosario (8.64 ± 1.91), and La Bocana (11.7 ± 4.59) had the least valuable finfish biomass. The three communities with the highest valued reserves also exhibit the highest extractive values: Punta Herrero (28.4 ± 23.3) and Isla San Pedro Mártir (27.8 ± 13.8), and Puerto Libertad (20.9 ± 21.4). The lowest value that would

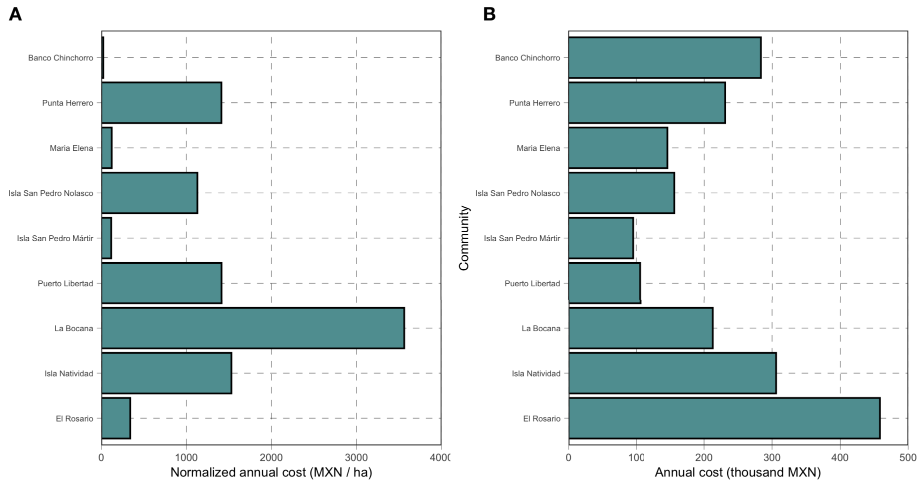



FIGURE 4
Monitoring costs for nine systems of community-based marine reserves in Mexico. Panel **(A)** shows the costs normalized by the total reserve area, while panel **(B)** shows the total annual costs.

allow for some extraction of finfish was observed for La Bocana (3.2 ± 5.14), Isla Natividad (3.41 ± 1.74), and Banco Chinchorro (4.67 ± 5.09). A summary of current total value of biomass, reference point value of biomass, and extractive value of biomass are found in Table 1.

## 3.3 Costs and benefits of conservation

We find that the costs of monitoring the reserves represent 0.3-55.5% of the extractive value of the reserves, with a median value of 5.5% (Table 2). While Punta Herrero is the community with the

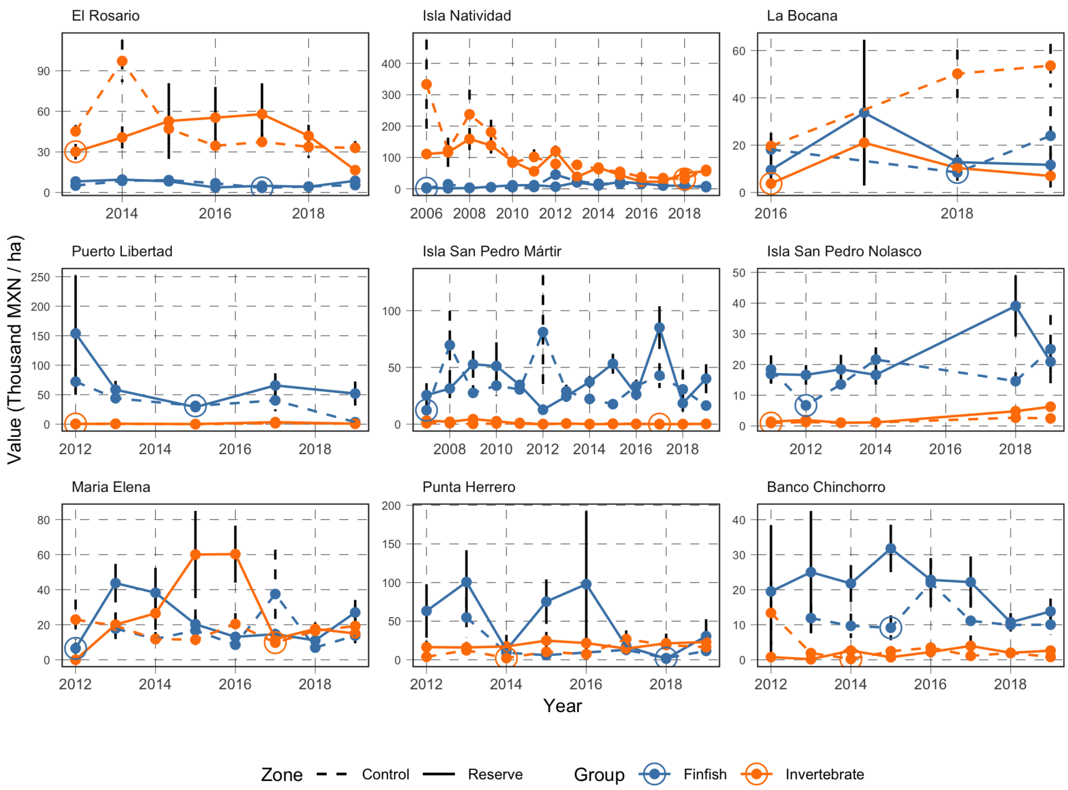



FIGURE 5
Time series of value of biomass contained in the reserve (solid line) and control sites (dashed line) for finfish (blue) and invertebrate (orange) species. The large circle markers indicate the reference value (historical low) used as benchmark when determining the potential extractive value of each reserve (See Table S3 for details).

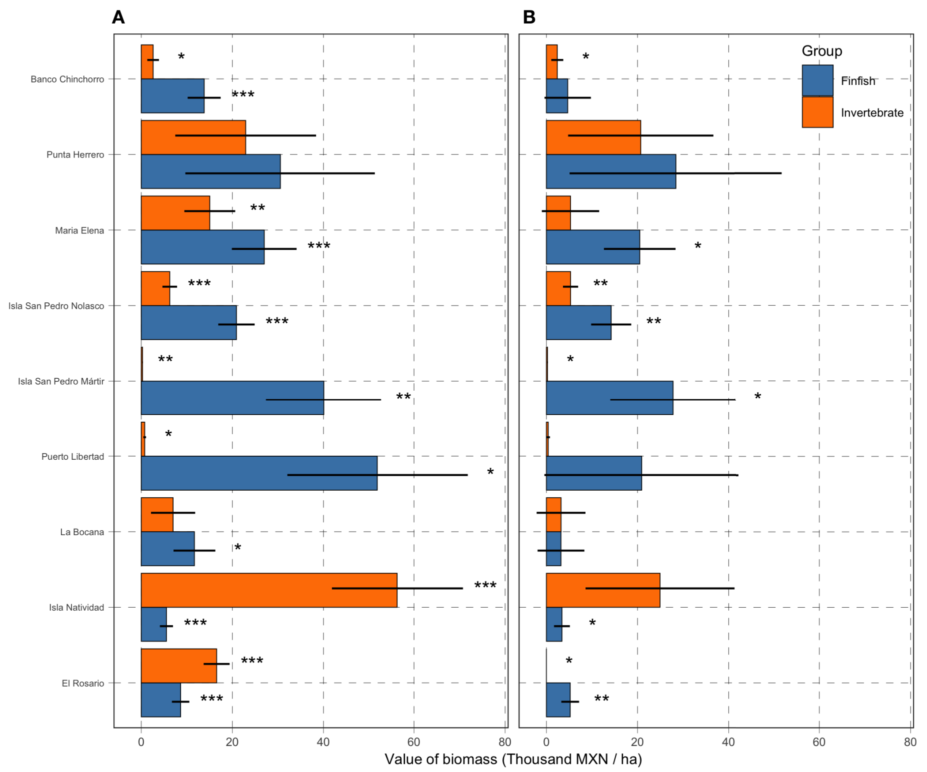



FIGURE 6
Value of biomass in thousands of MXN per hectare. Panel **(A)** shows the total value per hectare of reserve, and error bars show Standard Errors. Panel **(B)** shows the extractive value (*i.e.* the $\Delta$ coefficient in Equation 2), calculated as the difference between values on the left and the reference point (Table S3). Asterisks indicate statistical significance (***: $p < 0.001$; **: $p < 0.01$; and *: $p < 0.1$) on whether the coefficient is different from zero.

most valuable reserves (at 49.12 thousand MXN/ha for finfish and invertebrates combined), it is only the fourth most expensive with costs 1,412 MXN/ha (Figure 4). In this case, the cost of monitoring the reserve is 2.88% of the extractive value of biomass contained in the reserves. El Rosario has the least valuable reserves (5.22 thousand MXN/ha), but the costs of monitoring are only 6.51% of this value (339.89 MXN/ha). The most expensive reserves to monitor are in La Bocana (3,561 MXN/ha), where total extractive value of biomass is one of the lowest (6.410 thousand MXN/ha), and thus costs are 55.57% of extractive value of the reserve. The lowest monitoring costs correspond to Banco Chinchorro (23 MXN/ha), and while this community also has the third lowest valuable reserves (7.06 thousand MXN/ha), costs represent 0.33% of the value of biomass.

## 4 Discussion

We begin by providing further interpretation to our results and discussing them in the context of fisheries management and marine conservation in Mexico. We then discuss potential shortcomings in our analysis as it relates to our approach to estimating invertebrate

TABLE 1 Value of biomass (thousand MXN/ha) for marine reserves in each community.

| Community | Group | Total value | Historical min | Extractive value | Proportion |
|---|---|---|---|---|---|
| El Rosario | Finfish | 8.64 (+ 1.91)*** | 3.42 (+ 0.34)*** | 5.22 (+1.95)** | 60.44% |
| | Invertebrate | 16.55 (+2.85)*** | 30.16 (+5.73)*** | | 0.00% |
| Isla Natividad | Finfish | 5.53 (+ 1.44)*** | 2.12 (+ 0.94)* | 3.41 (+1.74)* | 61.71% |
| | Invertebrate | 56.3 (+14.45)*** | 31.36 (+7.49)*** | 24.94 (+ 16.35) | 44.30% |
| La Bocana | Finfish | 11.67 (+ 4.59)* | 8.47 (+2.06)*** | 3.2 (+5.14) | 27.38% |
| | Invertebrate | 6.99 (+4.85) | 3.78 (+2.11)* | 3.21 (+5.36) | 45.98% |

*(Continued)*

TABLE 1 Continued

| Community | Group | Total value | Historical min | Extractive value | Proportion |
|---|---|---|---|---|---|
| Puerto Libertad | Finfish | 51.94 (+19.87)* | 31.03 (+7.25)*** | 20.91 (+21.36) | 40.27% |
| | Invertebrate | 0.76 (+ 0.3)* | 0.36 (+0.23) | 0.4 (+0.38) | 52.50% |
| Isla San Pedro Mártir | Finfish | 40.07 7 (+12.7)** | 12.28 (+4.97)* | 27.8 ( 13.77)* | 69.37% |
| | Invertebrate | 0.28 (+0.1)** | 0.04 (+0.04) | 0.24 ( + 0.1)* | 85.71% |
| Isla San Pedro Nolasco | Finfish | 20.9 (+ 4)*** | 6.68 (+ 1.75)*** | 14.22 (+4.4)** | 68.03% |
| | Invertebrate | 6.26 (+ 1.61)*** | 0.96 (+0.38)* | 5.3 (+ 1.66)** | 84.71% |
| Maria Elena | Finfish | 26.99 (+7.11)*** | 6.51 (+3.06)* | 20.49 (7.86)* | 75.89% |
| | Invertebrate | 15.04 (+ 5.58)** | 9.75 (+ 2.81)** | 5.29 (+6.29) | 35.16% |
| Punta Herrero | Finfish | 30.54 (+20.86) | 2.12 2 (+0.21)*** | 28.42 (+ 23.33) | 93.05% |
| | Invertebrate | 22.92 (+15.46) | 2.21 (1.39) | 20.71 (+15.94) | 90.34% |
| Banco Chinchorro | Finfish | 13.81 (+3.62)*** | 9.14 (+3.53)* | 4.67 (+5.09) | 33.83% |
| | Invertebrate | 2.6 (+1.28)* | 0.22 (+0.22) | 2.38 (+1.32)* | 91.53% |

The columns with numeric values show the total value of biomass contained within the reserve, the historical minimum observed, and the extractive value (difference between total and historical). The last column shows the proportion of the total. Numbers in parentheses are robust standard errors, and asterisks indicate statistical significance (***: $p < 0.001$; **: $p < 0.01$; and *: $p < 0.1$).

TABLE 2 Extractive value (summing value of invertebrate and fish biomass) and monitoring costs for reserves in each community.

| Community | Extractive value (Thousand MXN / ha) | Monitoring costs (MXN / ha) | Costs as % of Value |
|---|---|---|---|
| El Rosario | 5.22 | 339.86 | 6.51% |
| Isla Natividad | 28.35 | 1529.47 | 5.39% |
| La Bocana | 6.41 | 3561.81 | 55.57% |
| Puerto Libertad | 21.31 | 1414.15 | 6.64% |
| Isla San Pedro Mártir | 28.03 | 116.43 | 0.42% |
| Isla San Pedro Nolasco | 19.52 | 1130.09 | 5.79% |
| Maria Elena | 25.78 | 122.54 | 0.48% |
| Punta Herrero | 49.12 | 1412.80 | 2.88% |
| Banco Chinchorro | 7.06 | 23.12 | 0.33% |

Note that value of biomass is presented in thousands of pesos per hectare, while monitoring costs is in pesos per hectare.

biomass, our measure of extractive value of biomass, and the omission of ancillary economic benefits of marine reserves. We then end with suggestions for further directions in research.

## 4.1 Interpretation and contextualization of results

Our compilation of cost data shows that the median normalized monitoring cost for community-based MPAs is 1,130 MXN/ha (min: 23 MXN/ha; max: 3,561 MXN/ha), which is higher than what has been reported for customary top-down MPAs around the world, and much larger than the budget typically available for top-down MPAs in Mexico (Figure 7). For example, Balmford et al. (2004) reported a median value of annual recurrent expenses of 155 MXN/ha (they report 775 USD/km$^2$) for a survey on 85 MPAs worldwide, while Hayashida et al. (2021) find that Mexican MPAs receive just 0.17 MXN/ha. If one considers community-based MPAs to receive an optimal amount of funding, one would conclude that many top-down MPAs worldwide –and particularly those in Mexico– remain underfunded (Gill et al., 2017). A counter argument may be that community-based MPAs are simply too costly. Regardless of how one perceives these costs, our analysis shows that the extractive value of biomass often makes up for the large costs. And, importantly, previous work has shown that the financial investment in these long-term monitoring programs has resulted in a series of co-benefits, from allowing fishers to record and understand environmental shocks and resource recovery (Micheli et al., 2012; Smith et al., 2022), to empowering community leaders and promoting social cohesion (Fulton et al., 2019a; Quintana et al., 2020; Quintana et al., 2021).

Our analysis of value of biomass in reserves suggests that, generally, total and extractive value are correlated. However, it

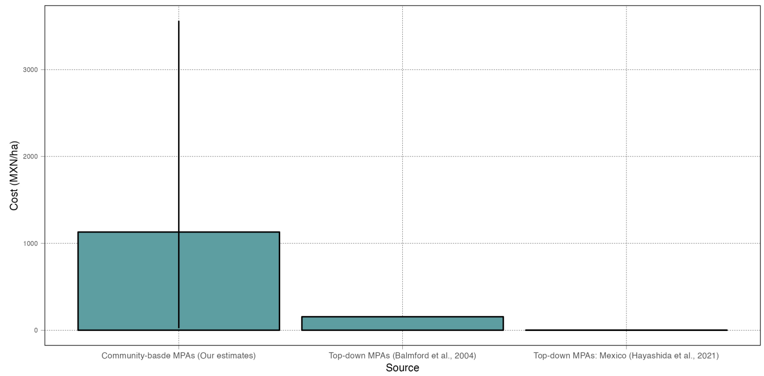



FIGURE 7
Comparison of per-hectare monitoring costs (MXN/ha). Each column shows the median estimate from our analysis (first column) or from two other relevant sources in the literature. The bars show the range (min, max).

also highlights the large variability in the value of extractive biomass for finfish and invertebrate species, even within the same community. We can more easily visualize these idiosyncratic responses in Figure 8. While some communities have reserves that have high values of extractive biomass for both groups of species (*e.g.* Punta Herrero), the extractive value of reserves in most communities is unequally made up from either group. These heterogeneous responses are to be expected since these reserves were designed with the goal of bolstering the biomass of different species targeted by each community. For example, the value of extractive biomass of invertebrate species from reserves in the Gulf of California were relatively low, but these communities largely target finfish and bivalve species. Conversely, in the Pacific, the most important species are abalone (Halliotidae) and spiny lobster (Palinuridae), which make a large portion of the total extractive biomass in the reserves (Figure S2).

## 4.2 Potential shortcomings and recommendations

One of the main limitations of our study is that the standardized invertebrate surveys do not record the size of commercially-relevant organisms, which we attempt to mitigate by taking two steps. First, we assumed that the size of all organisms of each invertebrate species were as big as the minimum catch size. Using the minimum catch sizes assumes most organisms are smaller than they truly are (Figure S1). In our case, this produces a conservative (*i.e.* lower-bound) estimate of the total biomass, but we note that this may not always be the case elsewhere. And secondly, we kept our estimates of fish biomass separate from our estimates of invertebrate biomass to avoid confounding the total value of the reserves. We chose to still report the invertebrate data due to their importance for some of the communities, but highlight the potential sources of uncertainty

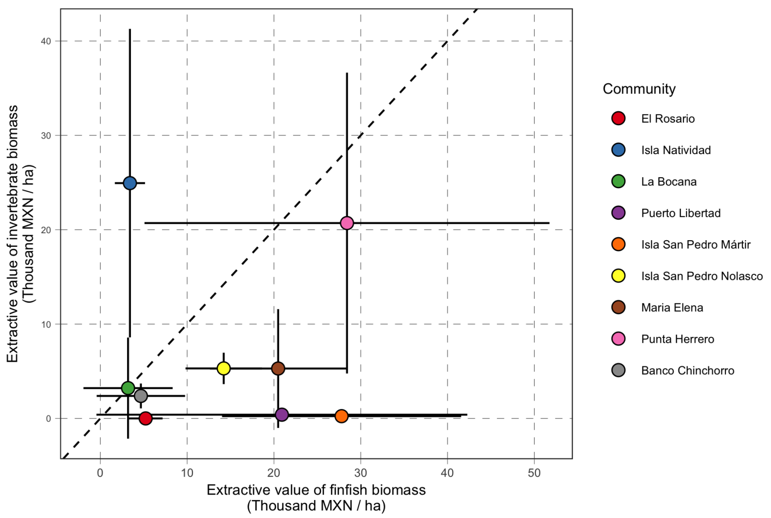



FIGURE 8
Comparison of extractive value of finfish biomass (x-axis; Thousand MXN/ha) and extractive value of invertebrate biomass (y-axis; Thousand MXN/ ha). The dashed red line indicates a 1:1 line. Communities above that line are those with reserves where most of the value comes from invertebrate biomass, while communities below the line are those with reserves where the value comes from finfish biomass.

to the reader. Going forward, we recommend that the monitoring protocols be modified in order to capture this crucial information.

Our definition of the reference points for the value of biomass assumes they are viable minimums that can be used as benchmarks to determine the value of the reserves. This is a critical assumption that shapes the main results of our study and therefore warrants some attention. We posit that the historical minimums can be used as baselines if they are economically and ecologically viable. We consider them to be economically viable because these are values that we have observed under fishing operations, and that values at or below the observed minima may not be profitable. If it were, standard economic theory predicts that fishers would have fished more and the observed values would have been even lower (Gordon, 1954; Costello et al., 2012). We also consider them to be ecologically viable because these communities operate under well-enforced TURF-managed or limited entry fisheries, which are known to foster higher biomass density of target species than areas operating under open access, and sometimes similar to fully protected no-take zones (Gelcich et al., 2008; Gelcich et al., 2015). In summary, if fishers are willing and able to harvest populations down to historically observed densities, these values are economically viable. And since TURFs are known to have ecologically viable biological densities, even the minimum values we observe are also ecologically viable. In some instances, an alternative may be to use the second lowest value as a conservative reference point (See Figure S5). We note that these assumptions may not hold in places operating under complete open access, severely overfished areas, when destructive or low-selectivity fishing methods are employed, or in particularly vulnerable ecosystems. Regardless of the chosen metric, future research attempting to use a similar approach should carefully scrutinize the data, question the validity of the assumptions, and incorporate best-available knowledge when identifying viable minimums.

Another methodological choice that warrants discussion is that of normalizing the costs of monitoring by reserve area. This is a common approach in the literature [*e.g.* Balmford et al. (2004); McCrea-Strub et al. (2011)], but fails to account for the fact that the programs should also monitor control sites. In absence of a polygon, a control site does not have an "area" assigned to them and it is difficult to incorporate their cost into our calculations. However, monitoring these control sites allows for robust before-after-control-impact evaluation of the reserves (Ferraro and Pattanayak, 2006; Villaseñor-Derbez et al., 2018; Kerr et al., 2019), and gives fishers the opportunity to monitor their fishing grounds. Thus, allowing some fishing within the reserves and using the proceeds to fund a monitoring program that surveys the reserves and control sites could ensure long-term sustainability of the reserves and the fishery as a whole (Millage et al., 2021; Bergseth et al., 2023).

### 4.3 Potential future directions

It is important to consider other ways of valuing the biomass contained in the reserves, for example, by valuing the economic benefit of any spillover of commercially important species. Such analyses have been undertaken in similar ecosystems, but for top-down MPAs [*e.g.* Goñi et al. (2008); Di Lorenzo and Mantua (2016); Lenihan et al. (2021)]. Future research could explore and quantify the spillover benefits (if any) provided by these reserves. Another way to assign a monetary value to the reserves could hinge on the non-extractive use of the biomass (Ninan, 2012). For example, one of the species found in Isla Natividad and El Rosario is the giant sea bass (*Stereolepis gigas*). The per-kilogram value of the species is 31.41 MXN/Kg (Tab S1), but Guerra et al. (2018) estimate the average value of *S. gigas* to recreational divers in the order of 46 million MXN per year (they report US$2.3 million). Finally, one might consider the non-use value of the reserves, which would refer to the intrinsic existence value of the biomass and biodiversity contained in them, or society's willingness to pay to protect the reserve. For traditional top-down MPAs the link may be clear: funding comes from taxpayers' money. But, under community-based marine reserves, fishers bear all the costs while providing a public benefit. Future research could explore mechanisms that would allow fishers to monetize and capture the public good that arises from their conservation interventions (Gelcich et al., 2019).

Our results suggest that allowing some level of biomass to be extracted from the reserves could help cover the costs of the monitoring programs in some communities. As an example, one of the communities included in our study (which has asked to remain anonymous) conducted limited extraction (three days of fishing) of one high-value species from one of their reserves to create liquidity during the COVID-19 pandemic. The reported earnings show that this limited extraction could have covered the biological monitoring of all the community's reserves for nearly a decade (Hernández-Velasco et al., 2020). Extracting accumulated biomass to fund long-term monitoring of reserves is likely a controversial proposal, especially when accounting for the well-documented benefits of full-protection (Lester et al., 2009; Sala et al., 2018). However, one must consider that the true choice is not between a fully-protected area and a partial-take area, but between a self-financed partial-take area, an externally-funded no-take area, or no conservation at all. Evidence from rotational closures suggest that alternating between protection and harvest can have long-term benefits (Plagányi et al., 2015), but further research should focus on evaluating biomass before and after any extraction occurs and determine whether this can be sustained in the long-term.

## 5 Conclusion

Our analysis determined the costs and potential benefits of the extractive use value of the invertebrate and fish biomass contained in marine reserves from nine small-scale fishing communities in Mexico. We show that community-based marine reserves accumulate enough commercially-important biomass to allow for some limited extraction, and that the proceeds could help cover the costs of monitoring the reserves and control sites. The creation of a marine reserve monitoring fund operated by the fishing organization and periodically funded from proceeds of limited (and monitored) biomass extraction could be a viable option to ensure the long-term financial sustainability of community-based marine reserves.

## Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://github.com/jcvdav/reserve_economic_value.

## Author contributions

JV-D conceived the project, analyzed data, and wrote the first draft. SF secured funding, conceived the project, and edited the drafts. AH-V and IA-C collected the data, helped secure funding, and edited the drafts. All authors contributed to the article and approved the submitted version.

## Funding

Authors of this paper were supported by the Walton Family Foundation (00104754), Summit Foundation (20220233), Packard Foundation (2021-73213), Sandler Family Foundation (20220429), Marisla Foundation (20220131), the National Science Foundation (2108566 and 2206739), and Oceans 5.

## Acknowledgments

This study would have not been possible without the efforts of members of the fishing communities mentioned herein who have undertaken underwater monitoring in their marine reserves over multiple years. We are grateful for helpful feedback provided by two reviewers.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1180920/full#supplementary-material

## References

Afflerbach, J. C., Lester, S. E., Dougherty, D. T., and Poon, S. E. (2014). A global survey of "TURF-reserves", territorial use rights for fisheries coupled with marine reserves. *Global Ecol. Conserv.* 2, 97–106. doi: 10.1016/j.gecco.2014.08.001

Amador-Castro, I. G., Melo, F. J. F.-R., and Torre, J. (2021). Marine diversity in the biosphere reserve of the most oceanic island in the gulf of california: San pedro mártir. *Zookeys* 1062, 177–201. doi: 10.3897/zookeys.1062.67964

Balmford, A., Gravestock, P., Hockley, N., McClean, C. J., and Roberts, C. M. (2004). The worldwide costs of marine protected areas. *Proc. Natl. Acad. Sci. U. S. A.* 101, 9694–9697. doi: 10.1073/pnas.0403239101

Bergseth, B. J., Arias, A., Barnes, M. L., Caldwell, I., Datta, A., Gelcich, S., et al. (2023). Closing the compliance gap in marine protected areas with human behavioural sciences. *Fish Fish* 24(4), 695–704. doi: 10.1111/faf.12749

Boettiger, C., Temple Lang, D., and Wainwright, P. (2012). rfishbase: exploring, manipulating and visualizing FishBase data from R. *J. Fish Biol* 81(6), 2030–2039. doi: 10.1111/j.1095-8649.2012.03464.x

Briones-Fourzán, P., and Lozano-Álvarez, E. (2000). "The spiny lobster fisheries in mexico," in *Spiny lobsters: fisheries and culture* (Oxford, United Kingdom: Fishing News Books, Blackwell Science), 169–188.

Cabral, R. B., Halpern, B. S., Lester, S. E., White, C., Gaines, S. D., and Costello, C. (2019). Designing MPAs for food security in open-access fisheries. *Sci. Rep.* 9, 1–10. doi: 10.1038/s41598-019-44406-w

Costello, C., Ovando, D., Hilborn, R., Gaines, S. D., Deschenes, O., and Lester, S. E. (2012). Status and solutions for the world's unassessed fisheries. *Science* 338, 517–520. doi: 10.1126/science.1223389

Di Lorenzo, E., and Mantua, N. (2016). Multi-year persistence of the 2014/15 north pacific marine heatwave. *Nat. Clim. Change* 6, 1042–1047. doi: 10.1038/nclimate3082

Ferraro, P. J., and Pattanayak, S. K. (2006). Money for nothing? a call for empirical evaluation of biodiversity conservation investments. *PloS Biol.* 4, e105. doi: 10.1371/journal.pbio.0040105

Froese, R., and Pauly, D. Editors. (2010). *FishBase.* World Wide Web electronic publication. www.fishbase.org, ( 02/2023 ). https://www.fishbase.se/summary/citation.php

Fulton, S., Caamal-Madrigal, J., Aguilar-Perera, A., Bourillón, L., and Heyman, W. D. (2018). Marine conservation outcomes are more likely when fishers participate as citizen scientists: case studies from the mexican mesoamerican reef. *Citizen Science: Theory Pract.* 3(1), 7, pp. 1–12. doi: 10.5334/cstp.118

Fulton, S., Hernández-Velasco, A., Suarez-Castillo, A., Fernández-Rivera Melo, F., Rojo, M., Sáenz-Arroyo, A., et al. (2019a). "From fishing fish to fishing data: The role of artisanal fishers in conservation and resource management in mexico," in *Viability and Sustainability of Small-Scale Fisheries in Latin America and The Caribbean*. Eds. S. Salas, M. J. Barragán-Paladines and R. Chuenpagdee (Cham: Springer International Publishing), 151–175.

Fulton, S., López-Sagástegui, C., Weaver, A. H., Fitzmaurice-Cahluni, F., Galindo, C., Fernandez-Rivera Melo, F., et al. (2019b). Untapped potential of citizen science in mexican small-scale fisheries. *Front. Mar. Sci.* 517. doi: 10.3389/fmars.2019.00517

Gelcich, S., Cinner, J., Donlan, C. J., Tapia-Lewin, S., Godoy, N., and Castilla, J. C. (2017). Fishers' perceptions on the chilean coastal TURF system after two decades: problems, benefits, and emerging needs. *Bull. Mar. Sci.* 93, 53–67. doi: 10.5343/bms.2015.1082

Gelcich, S., Godoy, N., Prado, L., and Castilla, J. C. (2008). Add-on conservation benefits of marine territorial user rights fishery policies in central chile. *Ecol. Appl.* 18, 273–281. doi: 10.1890/06-1896.1

Gelcich, S., Martínez-Harms, M. J., Tapia-Lewin, S., Vasquez-Lavin, F., and Ruano-Chamorro, C. (2019). Comanagement of small-scale fisheries and ecosystem services. *Conserv. Lett.* 12, e12637. doi: 10.1111/conl.12637

Gelcich, S., Peralta, L., Donlan, C. J., Godoy, N., Ortiz, V., Tapia-Lewin, S., et al. (2015). Alternative strategies for scaling up marine coastal biodiversity conservation in chile. *Marit. Stud.* 14, 5. doi: 10.1186/s40152-015-0022-0

Gill, D. A., Mascia, M. B., Ahmadia, G. N., Glew, L., Lester, S. E., Barnes, M., et al. (2017). Capacity shortfalls hinder the performance of marine protected areas globally. *Nature* 543, 665–669. doi: 10.1038/nature21708

Goñi, R., Adlerstein, S., Alvarez-Berastegui, D., Forcada, A., Reñones, O., Criquet, G., et al. (2008). Spillover from six western mediterranean marine protected areas: evidence from artisanal fisheries. *Mar. Ecol. Prog. Ser.* 366, 159–174. doi: 10.3354/meps07532

Gordon, H. S. (1954). The economic theory of a Common-Property resource: The fishery. *J. Polit. Econ.* 62, 124–142. doi: 10.1086/257497

Guerra, A. S., Madigan, D. J., Love, M. S., and McCauley, D. J. (2018). The worth of giants: The consumptive and non-consumptive use value of the giant sea bass (stereolepis gigas). *Aquat. Conserv.* 28, 296–304. doi: 10.1002/aqc.2837

Hayashida, H., Cisneros, A., and Palmeros, M. (2021) *esLas extensas áreas marinas "desprotegidas" de méxico*. Available at: https://causanatura.org/wiki-cn/las-extensas-areas-marinas-desprotegidas-de-mexico (Accessed 2023-3-1).

Hernández-Velasco, A., Flores, A., Précoma de la Mora, M., and Romero, A. (2020). *Reporte: Pesca en una reserva marina como medida de adaptación ante cambios*. (Guaymas, Sonora, Mexico: Comunidad y Biodiversidad).

Johannes, R. E. (2002). The renaissance of community-based marine resource management in oceania. *Annu. Rev. Ecol. Syst.* 33, 317–340. doi: 10.1146/annurev.ecolsys.33.010802.150524

Johnson, D. N., van Riper, C. J., Chu, M., and Winkler-Schor, S. (2019). Comparing the social values of ecosystem services in US and australian marine protected areas. *Ecosystem Serv.* 37, 100919. doi: 10.1016/j.ecoser.2019.100919

Kerr, L. A., Kritzer, J. P., and Cadrin, S. X. (2019). Strengths and limitations of before–after–control–impact analysis for testing the effects of marine protected areas on managed populations. *ICES Journal of Marine Science* 76 (4), 1039–1051. doi: 10.1093/icesjms/fsz014

Leenhardt, P., Low, N., Pascal, N., Micheli, F., and Claudet, J. (2015). "Chapter 9 - the role of marine protected areas in providing ecosystem services," in *Aquatic Functional Biodiversity*. Eds. A. Belgrano, G. Woodward and U. Jacob (San Diego: Academic Press), 211–239.

Lenihan, H. S., Gallagher, J. P., Peters, J. R., Stier, A. C., Hofmeister, J. K. K., and Reed, D. C. (2021). Evidence that spillover from marine protected areas benefits the spiny lobster (panulirus interruptus) fishery in southern california. *Sci. Rep.* 11, 2663. doi: 10.1038/s41598-021-82371-5

Lester, S. E., Halpern, B. S., Grorud-Colvert, K., Lubchenco, J., Ruttenberg, B. I., Gaines, S. D., et al. (2009). Biological effects within no-take marine reserves: a global synthesis. *Mar. Ecol. Prog. Ser.* 384, 33–46. doi: 10.3354/meps08029

Mallin, M.-A. F., Stolz, D. C., Thompson, B. S., and Barbesgaard, M. (2019). In oceans we trust: Conservation, philanthropy, and the political economy of the phoenix islands protected area. *Mar. Policy* 107, 103421. doi: 10.1016/j.marpol.2019.01.010

McCay, B. J. (2017). Territorial use rights in fisheries of the northern pacific coast of mexico. *Bull. Mar. Sci.* 93, 69–81. doi: 10.5343/bms.2015.1091

McCay, B. J., Micheli, F., Ponce-Díaz, G., Murray, G., Shester, G., Ramirez-Sanchez, S., et al. (2014). Cooperatives, concessions, and co-management on the pacific coast of mexico. *Mar. Policy* 44, 49–59. doi: 10.1016/j.marpol.2013.08.001

McCrea-Strub, A., Zeller, D., Rashid Sumaila, U., Nelson, J., Balmford, A., and Pauly, D. (2011). Understanding the cost of establishing marine protected areas. *Mar. Policy* 35, 1–9. doi: 10.1016/j.marpol.2010.07.001

Medoff, S., Lynham, J., and Raynor, J. (2022). Spillover benefits from the world's largest fully protected MPA. *Science* 378, 313–316. doi: 10.1126/science.abn0098

Melnychuk, M. C., Clavelle, T., Owashi, B., and Strauss, K. (2017). Reconstruction of global ex-vessel prices of fished species. *ICES J. Mar. Sci.* 74, 121–133. doi: 10.1093/icesjms/fsw169

Méndez-Medina, C., Schmook, B., and McCandless, S. R. (2015). The punta allen cooperative as an emblematic example of a sustainable small-scale fishery in the mexican caribbean. *Marit. Stud.* 14, 12. doi: 10.1186/s40152-015-0026-9

Micheli, F., De Leo, G., Butner, C., Martone, R. G., and Shester, G. (2014). A risk-based framework for assessing the cumulative impact of multiple fisheries. *Biol. Conserv.* 176, 224–235. doi: 10.1016/j.biocon.2014.05.031

Micheli, F., Halpern, B. S., Botsford, L. W., and Warner, R. R. (2004). Trajectories and correlates of community change in no-take marine reserves. *Ecol. Appl.* 14, 1709–1723. doi: 10.1890/03-5260

Micheli, F., Saenz-Arroyo, A., Greenley, A., Vázquez, L., Espinoza Montes, J. A., Rossetto, M., et al. (2012). Evidence that marine reserves enhance resilience to climatic impacts. *PloS One* 7, e40832. doi: 10.1371/journal.pone.0040832

Millage, K. D., Villaseñor-Derbez, J. C., Bradley, D., Burgess, M. G., Lenihan, H. S., and Costello, C. (2021). Self-financed marine protected areas. *Environmental Research Letters* 16(12), 125001. doi: 10.1088/1748-9326/ac3439

Miller, D. L. (1982). "Construction of shallow water habitat to increase lobster production in mexico," in *Gulf and Caribbean Fisheries Institute*, vol. 34, pp. 168–79.

Moland, E., Olsen, E. M., Knutsen, H., Garrigou, P., Espeland, S. H., Kleiven, A. R., et al. (2013). Lobster and cod benefit from small-scale northern marine protected areas: inference from an empirical before–after control-impact study. *Proc. R. Soc. B: Biol. Sci.* 280, 20122679. doi: 10.1098/rspb.2012.2679

Munguía-Vega, A., Sáenz-Arroyo, A., Greenley, A. P., Espinoza-Montes, J. A., Palumbi, S. R., Rossetto, M., et al. (2015). Marine reserves help preserve genetic diversity after impacts derived from climate variability: Lessons from the pink abalone in baja california. *Global Ecol. Conserv.* 4, 264–276. doi: 10.1016/j.gecco.2015.07.005

Ninan, K. N. (2012). *The economics of biodiversity conservation: valuation in tropical forest ecosystems* (New York, USA: Routledge).

OECD (2023) *enPrices - inflation (CPI) - OECD data*. Available at: https://data.oecd.org/price/inflation-cpi.htm (Accessed 2023-2-18).

Ovando, D., Dougherty, D., and Wilson, J. R. (2016). Market and design solutions to the short-term economic impacts of marine reserves. *Fish Fish.* 17(4), 939–954. doi: 10.1111/faf.12153

Plagányi, É.E., Skewes, T., Murphy, N., Pascual, R., and Fischer, M. (2015). Crop rotations in the sea: Increasing returns and reducing risk of collapse in sea cucumber fisheries. *Proc. Natl. Acad. Sci. U. S. A.* 112, 6760–6765. doi: 10.1073/pnas.1406689112

Potts, T., Burdon, D., Jackson, E., Atkins, J., Saunders, J., Hastings, E., et al. (2014). Do marine protected areas deliver flows of ecosystem services to support human welfare? *Mar. Policy* 44, 139–148. doi: 10.1016/j.marpol.2013.08.011

Quintana, A. C. E., and Basurto, X. (2021). Community-based conservation strategies to end open access: The case of fish refuges in mexico. *Conserv. Sci. Pract.* 3(1), e283. doi: 10.1111/csp2.283

Quintana, A., Basurto, X., Rodriguez Van Dyck, S., and Weaver, A. H. (2020). Political making of more-than-fishers through their involvement in ecological monitoring of protected areas. *Biodivers. Conserv.* 29, 3899–3923. doi: 10.1007/s10531-020-02055-w

Quintana, A. C. E., Giron-Nava, A., Urmy, S., Cramer, A. N., Domínguez-Sánchez, S., Dyck, R.-V., et al. (2021). Positive social-ecological feedbacks in community-based conservation. *Front. Mar. Sci.* 8, 428. doi: 10.3389/fmars.2021.652318

Ramutsindela, M., Spierenburg, M., and Wels, H. (2013). *Sponsoring nature: Environmental philanthropy for conservation* (London: Routledge).

R Core Team (2023). *R: A language and environment for statistical computing.* (Vienna, Austria: R Foundation for Statistical Computing)

Reddy, S. M. W., Wentz, A., Aburto-Oropeza, O., Maxey, M., Nagavarapu, S., and Leslie, H. M. (2013). Evidence of market-driven size-selective fishing and the mediating effects of biological and institutional factors. *Ecol. Appl.* 23, 726–741. doi: 10.1890/12-1196.1

Rees, S. E., Ashley, M., Evans, L., Mangi, S., Sheehan, E. V., Mullier, T., et al. (2021). An evaluation of the social and economic impact of a marine protected area on commercial fisheries. *Fish. Res.* 235, 105819. doi: 10.1016/j.fishres.2020.105819

Rees, S. E., Attrill, M. J., Austen, M. C., Mangi, S. C., and Rodwell, L. D. (2013). enA thematic cost-benefit analysis of a marine protected area. *J. Environ. Manage.* 114, 476–485. doi: 10.1016/j.jenvman.2012.10.048

Sala, E., and Giakoumi, S. (2017). No-take marine reserves are the most effective protected areas in the ocean. *ICES J. Mar. Sci.* 75, 1166–1168. doi: 10.1093/icesjms/fsx059

Sala, E., Lubchenco, J., Grorud-Colvert, K., Novelli, C., Roberts, C., and Sumaila, U. R. (2018). Assessing real progress towards effective ocean protection. *Mar. Policy* 91, 11–13. doi: 10.1016/j.marpol.2018.02.004

Smith, A., Aguilar, J. D., Boch, C., De Leo, G., Hernández-Velasco, A., Houck, S., et al. (2022). Rapid recovery of depleted abalone in Isla Natividad, Baja California, Mexico. *Ecosphere* 13(3), e4002. doi: 10.1002/ecs2.4002

Smith, M. D., Lynham, J., Sanchirico, J. N., and Wilson, J. A. (2010). Political economy of marine reserves: Understanding the role of opportunity costs. *Proc. Natl. Acad. Sci.* 107, 18300–18305. doi: 10.1073/pnas.0907365107

Suman, C. S., Saenz-Arroyo, A., Dawson, C., and Luna, M. C. (2010). *Manual de Instrucción de Reef Check California: Guia de instrucción para el monitoreo del bosque de sargazo en la Peninsula de Baja California* (Pacific Palisades, CA, USA: Reef Check Foundation).

Villaseñor-Derbez, J. C., Aceves-Bueno, E., Fulton, S., Suarez, A., Hernández-Velasco, A., Torre, J., et al. (2019). An interdisciplinary evaluation of community-based TURF-reserves. *PloS One* 14, e0221660. doi: 10.1371/journal.pone.0221660

Villaseñor-Derbez, J. C., Amador-Castro, I. G., Hernández-Velasco, A., Torre, J., and Fulton, S. (2022). Two decades of Community-Based marine conservation provide the foundations for future action. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.893104

Villaseñor-Derbez, J. C., Faro, C., Wright, M., Martínez, J., Fitzgerald, S., Fulton, S., et al. (2018). A user-friendly tool to evaluate the effectiveness of no-take marine reserves. *PloS One* 13, e0191821. doi: 10.1371/journal.pone.0191821

White, H. (1980). A Heteroskedasticity-Consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica* 48, 817–838. doi: 10.2307/1912934

White, A. T. (1989). "Two community-based marine reserves: lessons for coastal management," in *Coastal area management in Southeast Asia: Policies, management strategies and case studies* (Society in New York), vol. 138. Available at: https://www.jstor.org/publisher/econosoc.

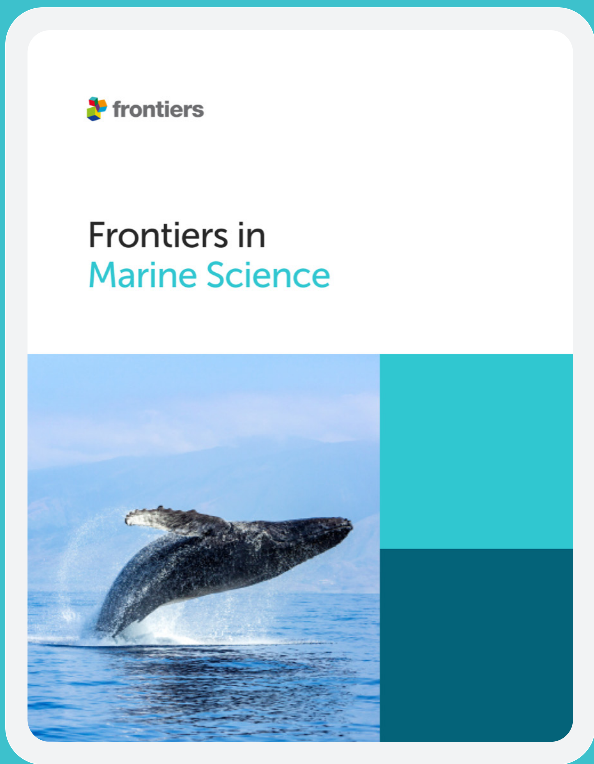
# Frontiers in Marine Science

**Explores ocean-based solutions for emerging global challenges**

The third most-cited marine and freshwater biology journal, advancing our understanding of marine systems and addressing global challenges including overfishing, pollution, and climate change.

## Discover the latest Research Topics

See more →





**Frontiers**

Avenue du Tribunal-Fédéral 34
1005 Lausanne, Switzerland
frontiersin.org

**Contact us**

+41 (0)21 510 17 00
frontiersin.org/about/contact