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Regional dynamic co-management for sustainable fisheries and ecosystem conservation: a pilot analysis in the Catalan Sea

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The complexity of coastal fisheries, which often involve many gears with cross-impacts on various species and life stages, requires a management system that is able to integrate these multiple interactions in order to gradually achieve sustainability. In this paper, we argue that regional co-management can appropriately address the complex interactions between fisheries, including those with other potentially conflicting human activities. Our results, notably obtained through a questionnaire to local fishers' representatives mainly on bottom trawl fisheries in the Catalan Sea region, show, however, that improved mutual understanding through effective communication and long-term collaboration between stakeholders, and in particular between fishers and scientists, is essential to ensure the successful implementation of fisheries co-management. In addition to balancing the voices of the many stakeholders, co-management needs to be further improved by developing multi-species, multi-gear and multi-use approaches to the oceans. This improvement could in turn support the effectiveness of co-decisions, as they would be based on the recognised administrative structure of co-management committees and sound scientific guidance that addresses both ecosystem protection and sustainable fisheries profitability. Dynamic management over time and space, using real-time essential fish habitat from operational oceanography, can help to make the co-management process more robust by improving collaboration between stakeholders and the effectiveness of measures in a changing environment. The decision-making, social and ecological components are described as integral and dependent parts of the co-management system, with priority given to mutual understanding between stakeholders. This integrated co-management framework is flexible enough to take into account regional complexity, but also national legislation and the EU Common Fisheries Policy, which all promote sustainable use of the oceans and protection of the ecosystem.

KEYWORDS

regional fisheries co-management, co-decision, real-time fish habitat, spatiotemporal measures, stakeholder engagement, complex fisheries, Mediterranean Sea, Catalan Sea

Introduction

Fisheries management in Europe faces a situation of exceptional complexity not found elsewhere in the world, not least because of shared responsibility among a large number of coastal states (Symes et al., 2003). The main shortcomings of current fisheries management may be overfishing, uncertainties in stock assessment, particularly in times of climate change, and a management framework that is often too remote (international or national vs. regional) from fishers to induce the necessary acceptance of measures. These shortcomings may all apply to Mediterranean Sea fisheries, given the general absence of TACs (total allowable catches) in trawl fisheries (except for blue and red shrimp, *Aristeus antennatus*, and giant red shrimp, *Aristaeomorpha foliacea* established in 2022, and for small-scale fisheries co-managed in the Catalan Sea area), the predominance of small- and medium-scale fisheries and the significant impact of warming water on this semi-enclosed marine ecosystem. The situation of the Northern Mediterranean fisheries may be critical even though the control of fishing effort associated with specific technical measures, such as gear regulation, the establishment of a minimum catch retention size and selective area and season closures, has been adopted by EU countries, as highlighted by Cardinale et al. (2017). These authors identify the ineffectiveness of the current effort control system, the continued lack of adherence to scientific advice and the inadequacies of existing national management plans as responsible for the relatively poor state of fisheries in the area. Similarly, the recent multi-annual plan for demersal fish stocks in the western Mediterranean (Regulation (EU), 2019), which aims to significantly reduce fishing time, has shown the need for improved selectivity, temporal and permanent closures and local co-management plans to protect juveniles and spawners and ensure sustainable socio-economic benefits (Sánchez Lizaso et al., 2020). In addition, Smith and Garcia (2014) highlight related contextual elements such as the high socio-economic complexity and low efficiency of the governance system, which are associated with the large number of small vessels operating on a small spatial scale, in addition to being from different countries sharing the same resources (as shown by Piroddi et al., 2015). Overall, the complexity of Mediterranean fisheries and the lack of confidence in management measures may largely contribute to explaining management failure.

In addition, essential fish habitats (EFH), such as those related to reproduction, are likely to change increasingly spatially and temporarily due to increased seasonal climate variability (Druon et al., 2021), making stock estimates and fishing impacts less predictable. EFH are the primary waters and substrates required by fish for spawning, breeding, feeding or growing to maturity, which are essential for population renewal. As the health of EFHs is vital to fisheries, several fisheries policies and legislation around the world have included the protection of EFHs, for example the FAO Code of Conduct for Responsible Fisheries (1995), the Magnuson-Stevens Act on Fisheries Conservation and Management (2007), the Nordic Council of Ministers (2016) and the EU Common Fisheries Policy (CFP) (European Commission, 2013). In particular, the CFP makes the conservation of EFH one of the pillars of the ecosystem approach to fisheries management (EAFM). The identification, protection and restoration of fish schools should help maintain productive fisheries and rebuild depleted stocks in the Mediterranean. Furthermore, dynamic fisheries management has been identified as one of the most innovative approaches to increasing the sustainability of marine resource exploitation and conservation (Lewison et al., 2015; Dunn et al., 2016; Maxwell et al., 2020). However, this requires that the complexity of Mediterranean fisheries be taken into account in order to build confidence in management.

Collaborative management, or co-management, has been defined as 'the sharing of power and responsibility between the government and local resource users' (Berkes et al., 1991). The World Bank has defined co-management as "the sharing of responsibilities, rights and duties between key stakeholders, in particular local communities and the nation state; a decentralised approach to decision-making that involves local users in the decision-making process on an equal footing with the nation state" (Soeftestad et al., 1999). Co-management thus refers to the notions of local or regional scale and shared responsibility. Furthermore, when applied to ecosystems, both co-management and EAFM are motivated by the common recognition that marine systems are dynamic and require a holistic approach to manage this complexity (Cucuzza et al., 2021 and below). The literature on EAFM and co-management indicates that traditional management approaches do not take this complexity into account and are often critical in their ability to maintain resilient fish stocks and marine ecosystems in the long term (Cucuzza et al., 2021 and in this paper). Regional co-decision based on EAFM between stakeholders (fishers, scientists, policy makers and NGOs) can therefore address the main barriers of traditional approaches by improving the necessary communication (and associated knowledge) at the local level to jointly agree on responsible decisions in response to complex systems. This local communication and common understanding between stakeholders appears to be essential for building mutual trust and acceptance of measures that can lead to increased compliance and successful management.

By combining different sources of information, this paper analyses the advantages and limitations of an existing regional co-decision process for the sustainable management of Catalan marine fisheries (see the detailed description and functioning of the co-management system in place in Catalonia, based on expert judgement and knowledge, in the Supplementary Information, hereafter SI). First, we gathered the perception of some experienced fishers' representatives on the current co-management system in Catalonia and on the potential use of species-specific real-time EFH to limit bycatch. Secondly, we present a new approach that inserts operational hake nursery avoidance mapping into the co-management system to mitigate bycatch of undersized fish and, as a concept, a multi-species habitat component, including target, unwanted and protected species. Finally, we make a series of recommendations to improve the fisheries co-management process by building mutual trust and developing an ecosystem dimension.

Material and methods

As the paper focuses on the perception of an existing fisheries co-management process from the perspective of fisher's representatives and on potential solutions using dynamic fisheries management, we describe the current process of the co-management system in the SI. In this section, we first describe the questionnaire sent to fisher's representatives, with particular reference to bottom-trawling activity, and then the use of near-real-time derived habitat prediction and mapping of hake nursery avoidance by this sector of the fishery. Finally, we detail the methodology of this tool for predicting and mitigating habitat derived from hake nurseries in real time.

It is important to note that the regional co-management committees in Catalonia are officially concerned with small-scale fisheries. Even though the fishing activity related to bottom trawling (blue and red shrimp and other demersal species) and purse seining (small pelagic species) is mainly under the competence of the Spanish national authorities, many important decisions for these fisheries result from a co-management approach associating the national and regional authorities after a consensus within the local actors in Catalonia is found. In this sense, the working processes are similar to other co-management committees and we have therefore included them in the assessment for the purposes of this scientific analysis.

Social component – questionnaire

In-depth face-to-face interviews were conducted with three experienced fishers' representatives (minimum 40 years, from fishers' guilds, "confraries de pescadors") who represent the largest fishing organisations in Catalonia, the Costa Brava region and the relevant fishers' guilds from the area of study (Northern Catalonia, Spain), covering most of the trawl fishing sector in this area as well as other sectors (purse seine and small-scale fishing). These representatives play a leading role in the management of the trawl fishery within their organisation. These interviews were used to gather their personal perceptions of the co-management process and the potential improvements in management that could result, given that these fishermen's representatives have a deep knowledge of the constraints of trawl fishing and the functioning of co-management. These key stakeholders constitute the study sample, i.e. a group of sample units selected for the purpose of answering the research question (Bernard and Gravlee, 2014). As a stakeholder in the social sciences, and more specifically in social anthropology, we refer to 'organisations or individuals with the power and authority to implement research, action or policy in a community under study' (Bernard and Gravlee, 2014).

The three fisher's representatives were selected on the basis of their important political role and power within the fisher's community. They are at the heart of the power and decision-making relationships within the fisher's guilds. In some cases, they occupy up to three different roles within the fishing community involving artisanal fisher, trawlers and seiners (fisher's guilds, the national federation of fisher's guilds and the regional federation of fisher's guilds of Girona, Costa Brava) or participate as the highest representatives of the co-management committees by taking part in the plenary meetings of all co-management committees. Therefore, this convenience sample provides particularly valuable sources of information for the purpose of this study. Furthermore, these relatively broad interviews with three key stakeholders made it possible to focus on specific points of interest for the research, with the aim of gathering synthetic information for an overall understanding of the research question. The alternative approach of interviewing many direct stakeholders (fishers) would have required additional analysis of the results according to different social profiles, which was not the objective of this study.

The same questions (detailed in the SI) were asked to explore their fishing activities (main species, mesh size, catch trends over the last decade) and what, in their view, are the advantages and disadvantages of the current co-management system and their propensity to use real-time information on hake nurseries to mitigate by-catch of undersized fish. The interviews lasted an average of one hour and the results were written up afterwards from the notes. This knowledge was complemented by information (e.g. participant observation) gathered by scientists (including several co-authors of this article) who participated in the co-management committees of the Cape Creus artisanal fisheries (since 2021), the cuttlefish fisheries in the Gulf of Roses and Pals (since 2020) and the sandeel fisheries (since 2012).

Dynamic habitat component

Habitat modelling of 0-group hake for use as information on bycatch mitigation of undersized fish

In this section, we present an updated version of an economically important nursery habitat (the 0-group hake nursery) from Druon et al. (2015), which forms the basis of a spatial indicator of real-time bottom trawl avoidance (see next section). European hake (*Merluccius merluccius* Linnaeus, 1758) is one of the main demersal species targeted by fisheries in the northwestern Mediterranean (reviewed by Oliver and Massutí, 1995). The most important nursery areas can be identified as Essential Fish Habitat (EFH) for hake recruitment in the Mediterranean, information needed to properly implement spatial fisheries management required by EU policies, and in particular to limit fishing mortality of recruits (Druon et al., 2015).

An ecological niche modelling (ENM) approach was developed to model the suitable habitat for the 0-group European hake (classes below 15 cm TL), in the Mediterranean Sea (Druon et al., 2015). The ENM was constructed by combining knowledge of biological traits of hake recruits (e.g. growth, settlement, mobility and feeding strategy) with patterns of selected ecological variables (fronts and chlorophyll-a concentration, bottom depth and seabed temperature) to highlight favourable nursery habitats. Positive biomass data of 0-group hake (kg.km^{-2}) from the Mediterranean bottom Trawl Surveys (MEDITS) and from the ICATMAR surveys (Catalan Research Institute for Marine Governance, n = 216) in the Catalan Sea were used from 2003 to 2020 (overlap with environmental data availability, n = 8,836) toestimate model performance, while only upper quartile biomass data (> 8.5 kg.km^{-2}, n = 2,161) contributed to calibrate the habitat model. The validation dataset consisted of additionally using the biomass data levels below this threshod (n = 6,698) to provide an overall habitat model performance. Daily chlorophyll-a (CHL, mg.m^{-3}) data were collected by the MODIS-Aqua ocean colour sensor (years 2003–2022; 1/24° resolution, ca. 4 km at the latitude of interest) using the Ocean Color Index (OCI) algorithm (Hu et al., 2012) and extracted from the NASA portal (https://oceancolor.gsfc.nasa.gov/l3/; reprocessing of July 2022). Small and large chlorophyll-a fronts were derived and refer to different levels of chlorophyll-a gradient values, with high levels of chlorophyll-a gradient assumed to correspond, when persistent, to productivity fronts with significant capacity to support well-developed food chains and foraging opportunities for predators (Olson et al., 1994; Polovina et al., 2001; Druon et al., 2019; Baudena et al., 2021), including demersal species (Druon et al., 2021). Monthly fields of seabed temperature (SBT) fields were extracted from the EU-Copernicus Marine Environment Monitoring Service Mediterranean model (MEDSEA_MULTIYEAR_PHY_006_004, https://marine.copernicus.eu/access-data) at a resolution of 1/16° (ca. 7 km at the latitude of interest), and linearly interpolated from monthly to daily values for estimating the daily habitat.

Water depth was extracted from the General Bathymetric Chart of the Oceans (http://www.gebco.net/) with a spatial resolution of 1/60° (about 2 km at the latitude of interest). The abiotic data were linearly interpolated to the habitat grid at 1/24° resolution (same grid as the CHL). Modelling differences from Druon et al. (2015) are detailed in the SI.

The preferred daily habitat of 0-group hake consists of 0 to 1 level of trophic proxies (small and large *CHL* gradient), a preferred range of surface chlorophyll-a content, water depth and bottom temperature, and 0 to 1 level of *SBT* standard deviation. The habitat model flow chart translates into the following equation, with a daily favourable habitat value of 0 to 1 for each grid cell:

$$0 - group\ Hake\ Habitat = C_g * C_r * B_r * D_r * T_r * stdT_l$$

where

C_g = linear function derived from the horizontal gradient of chlorophyll-a, from 0 to 1.

C_r = value 1 if within the suitable chlorophyll-a range, and 0 otherwise,

B_r = value 1 if within the suitable bathymetry range,

D_r = value 1 if within the suitable range of distance to the 200 m isodepth,

T_r = value 1 if within the suitable SBT range, and 0 otherwise,

$stdT_l$ = value 1 if *stdSBT*< *stdSBTintermediate*, with a 0 value where *stdSBT* > *stdSBTmax*, and 0 otherwise.

The latest habitat calibration (Table 1) is detailed in the SI. The performance of the model was evaluated with abundance data through matches between 0-group (TL< 15 cm) hake biomass levels (only positive values) and the habitat index for the calibration and validation data (high and low biomass levels,

TABLE 1 Habitat parameterisation of 0-group European hake that defines the environmental envelope, where *CHL*, *gradCHL* are the sea surface chlorophyll-a content and the horizontal gradient of the MODIS-Aqua sensor, respectively, *SBT* is the seabed temperature and *stdSBT* is the standard deviation of *SBT* over the last six months (the period between settlement of young juveniles on the seabed and recruitment).

Parameter values for suitable habitat	Minimum value	Intermediate value	Maximum value
CHL (mg.m^{-3})	0.11	NA	1.56
gradCHL (mg.m^{-3}.km^{-1})	0.00042	0.01218	NA
SBT (°C)	12.11	NA	15.72
stdSBT (°C)	NA	0.79	2.11
Bottom depth (m)	17.5	NA	311.5
Distance to the 200 m-isodepth (km)	0	NA	87.3

The preferred minimum and maximum levels correspond to the 3rd and 97th percentile values of high biomass hake recruits (above the third quartile value, > 8.5 kg.km^{-2}) for water depth and in the period from 0 to 5 months before sampling for the mean and standard deviation of SBT and using three clusters (same method as in Druon et al., 2015, see cluster analysis, Figure S1 in the SI). The intermediate value of gradCHL, which defines the minimum level corresponding to the maximum daily habitat of 1 (Cg see equation above), was identified using the minimum value and maximum slope of the cumulative distribution in the preferred range of gradCHL (see Figure S1 in the SI). The same method was used to identify the intermediate value of stdSBT, except that it corresponds to the maximum level of stdSBT for which stdT$_l$ has the maximum level of 1 (see equation above). NA, Not applicable.

respectively) using the MEDITS and ICATMAR surveys. The ICATMAR surveys are conducted throughout the year on a monthly basis and use the commercial codend (40 mm SM, square mesh) while the MEDITS surveys take place in spring with a 20 mm mesh codend (stretched mesh). These correspondences were presented as box plots of biomass by 10th percentile width of the recruit biomass.

The bottom trawling avoidance index in real-time

A daily bottom trawling avoidance index is calculated and mapped in real time to highlight to fishers the likely areas of active hake nurseries to be avoided. This avoidance index results from combining, with equal weight (Figure 2), the last seven days of estimated favourable habitat (real-time index, RTI) and a longer period (last four years, persistence index, PI) to take into account the minimum duration of viability of a nursery (at least three to four months) and to enhance the robustness of the prediction. The long-term period of the persistence index (four years) is long enough to identify the main nurseries and recent enough to take into account the current influence of climate change. This long-term component filters out short-term favourable habitats (e.g. of a few days or weeks) that may exceptionally occur in a given location and season, but which are not viable since relatively stable conditions of at least three to four months appear to be necessary for viable production of hake recruits. The PI persistence index therefore acts as a predictor of the expected duration of currently detected nurseries. The PI reaches a maximum value of 1 when the four-year average habitat is favourable for eight months per year, which is the maximum level observed. The daily bottom trawl avoidance index therefore gathers real-time information on the environmental conditions favourable to hake nurseries and their likely persistence over the season, given the occurrence in recent years (Figure 1).

The daily bottom trawl avoidance index is then translated into a simple three-colour map to facilitate identification by fishers of absolute avoidance (values above 0.7), areas to be preferentially avoided (values between 0.4 and 0.7) and areas to be preferentially selected for bottom trawling (values below 0.4). The daily map is sent to a list of users and updated online (https://fishreg.jrc.ec.europa.eu/web/fish-habitat).

Results

In the sections below we describe how the co-management system in Catalonia is perceived by fishers' representatives (questionnaire results mostly on the bottom trawling activities), while we detail the main characteristics of the current status and functioning of this system in the SI. We then describe the calculation and performance of a near-real-time mapping of hake nurseries as a bottom trawl avoidance index to mitigate by-catch of undersized fish, with a view to potential improvement through dynamic fisheries management (detailed in the next section).

Perception of bottom trawl fishing associations on co-management systems and potential EFH use

The context of the fishery reported by the three experienced representatives of fishing associations mainly associated with bottom trawling highlights that, among the target species, there is an overall perception of a reduction over the last decade in landings of hake of all sizes, relatively stable catches of blue and red shrimp (*Aristeus antennatus*) and anglerfish, and a substantial increase in recent years in thermophilic (warm water) deep-water rose shrimp (*Parapenaeus longirostris*). It is worth noting that the first spatio-temporal closure of the fishery has been implemented since 2014, in particular to protect hake nurseries (Recasens et al., 2016; Sala-Coromina et al., 2021; Tuset et al., 2021). Currently, twenty permanent protected fishing areas have been established along the Catalan coast, representing 462 km^2 (BOE-A-2020-5163)[1]. The objective of these protected areas is to recover different habitats on the shelf and slope that are intensively exploited.

The three representatives of the bottom trawl fishing associations agreed that fishers and scientists have complementary knowledge of fish distribution and reproduction, recognising that scientists have a greater knowledge of biological processes but often little knowledge of the field and the practical constraints of fisheries. All participants agreed on the need for co-management, but also on the improvements to be made. One of the main challenges highlighted by two of the three representatives was the low number of fishers involved in the co-management process compared to scientists and fisheries administrators. Co-management is therefore perceived as being mainly driven by the administration and scientists, whereas fishers claim a more active role in this process and "are not mere

[1] Orden APA/423/2020, de 18 de mayo, por la que se establece un plan de gestión para la conservación de los recursos pesqueros demersales en el mar Mediterráneo"

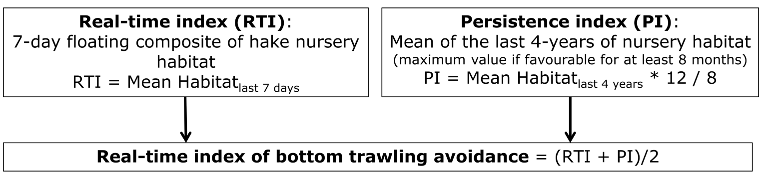

FIGURE 1
Flowchart of the calculation of the daily real-time bottom trawl avoidance index to be used by fishers to limit by-catch of 0-group hake. The avoidance index is composed of the average, with equal weight, of a real-time index (RTI, average of hake nursery habitat over the last 7 days) and a persistence index (PI, average of habitat over the last 4 years, with a maximum value reached after 8 months of favourable habitat).

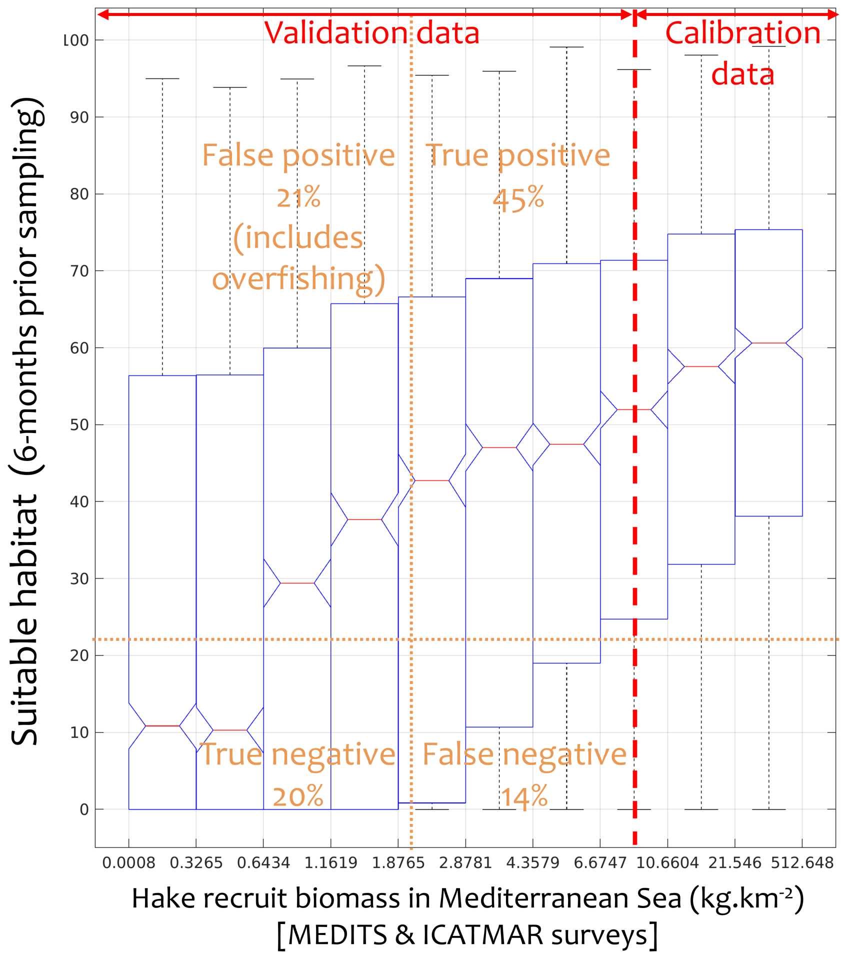

FIGURE 2
Distribution of matches between 0-group (Total Length< 15 cm) hake biomass (only positive values) and habitat index for data using MEDITS (2003-2019) and ICATMAR (2018-2020) surveys distributed by 10% bins (n = 8,836, Spearman's r = 0.29, p< 0.001) noting that calibration data represent biomass levels above 8.51 kg. km^{-2} (75th percentile value, n = 2,161) and that the validation data are below this biomass level (n = 6,698). In each box, the central red mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentile values, respectively. When the notches (narrowing of the box around the median) in the box plot do not overlap, one can conclude with 95% confidence that the true medians differ. The whiskers extend to the most extreme data points not considered outliers (1.5 times the interquartile range, i.e., 99.65% for a normal distribution). Considering the entire data set, the sum of true positive and true negative matches is 65%, while false negatives including the potential effect of fishing are 21% and false negatives are 14% for a central biomass level of 1.95 kg.km^{-2} and habitat of 23% (beige line segments). The correct matchups are thus overall, above 65% as including part of the false positive (21%) due to overfishing.

spectators of endless discussion sessions". They generally acknowledge the work of the scientists who participate in the co-management committees and feel that there is a need for more frequent interaction with the scientists, but preferably in a process of continuous collaboration (partnership type). One representative complained about the lack of knowledge of some NGOs about fisheries. Reducing the administrative burden was also mentioned.

A fishers' representative felt that the administration was not fully implementing the ecosystem approach to fisheries management. He would have liked to see all components of the food chains taken into account, including plankton, small pelagic and demersal fish, and large pelagic species such as tuna. The co-management process should also improve the selection of time-area closures of fisheries and in particular its seasonal component. In addition, this representative felt that an integrated co-management plan taking into account all species and regional fleets would be preferable to co-management divided by species and fleet (e.g. cuttlefish by artisanal fishers) in order to reduce conflicts between fleets (e.g. artisanal fishers versus trawlers). Another representative pointed out that in the future, fishers are less likely to cooperate in the co-management process if regulations become stricter and if they are not compensated for their efforts (e.g. time spent on interviews and sampling done for scientists), especially considering the important funding given by the EU to administration.

In particular, the co-management committee for artisanal fisheries in Cape Creus has highlighted conflicts between small-scale fishers and the tourism and energy sectors, mainly over access to sites and competition for resources. Conflicts involve recreational fishers (especially spearfishers), recreational boaters (especially jet skis), scuba divers (Gómez et al., 2021) and, recently, offshore wind farm projects that directly interact with the closed fishing zone established by fishers, scientists and the administration to protect hake nurseries (Tuset et al., 2021; Lloret et al., 2022). In particular, the exclusion of professional fishers from certain areas of MPAs is seen as particularly problematic.

All trawler representatives expressed support for joint development and use of real-time maps to avoid hake nursery areas, but also emphasized the need for daily presence of scientists at sea or in port for monitoring. Again, long-term collaboration was seen as a key element to a successful relationship with scientists. Although all three representatives focused on issues when asked about possible future solutions for increasing the sustainability of fisheries under an ecosystem-based management approach (requests for assistance including financial support), one had clear ideas about how the current system could be improved. Following the decline in hake landings after the introduction of fixed fishery closures in 2015, this representative suggested replacing them with dynamic closures in "(a) areas where hake spawn and (b) areas where hake grow."

Predictive performance of the hake nurseries core habitat

Model performance is illustrated using both calibration data, i.e., biomass levels above the 75th percentile value (8.51 kg.km^{-2}, n = 2,161), and validation data below this biomass level (n = 6,698) (Figure 2) from the MEDITS and ICATMAR studies. The hake recruit biomass index increased with the habitat suitability index for both calibration and validation data with a Spearman's r of 0.29 (n = 8,836) (p< 0.001). An overall quantitative performance of the habitat model at the Mediterranean Sea scale was provided by a simple binary statistical classification (an error matrix) that separates the positive and negative true/false of the model into four spaces. The maximum rate of correct matches (sum of true positives and true negatives) of 65% is obtained for a central point delimiting these four spaces at a habitat suitability index value of 23% and a biomass limit of 41st percentile value (1.95 kg.km^{-2}; Figure 2). False negatives from the model accounted for 14% of the data, while false positives accounted for 21%, the latter including the potential effect of fishing in nurseries (hake biomass less than expected from the habitat). Therefore, overall, including the potential effect of the 0-group hake fishing, the habitat model identifies about 65-80% of biomass levels above 1.95 kg.km^{-2} with a habitat level above 23% suitability.

The four-year average potential habitat for 0-group hake (2019-2022, Figures 3A, C) highlights recurring favourable areas in the outer shelf and shelf break of most of the northern Mediterranean Sea and particularly in the Catalan Sea and Gulf of Lions. The overall absolute trend in favourable habitat for 2003-2022 in the Mediterranean Sea is negative (-3.9% of favourable habitat per decade, Figure S7 in the SI), with regional negative levels in the Catalan Sea that are moderate (up to -8% per decade compared to up to -20% per decade in the Strait of Sicily area, southern Adriatic Sea, and the Aegean Sea), with the only positive trend areas being the central Gulf of Lions (+5% per decade) and the west-central Adriatic Sea (+10% per decade). The trend levels in the Catalan Sea are between 0 and -8% per decade.

Daily index of bottom trawling avoidance

An example of a real-time bottom trawl avoidance index using three-colour mapping (red is an active nursery to be avoided, orange is uncertain, and green is probably not active) is made available one day after the time period under consideration (i.e., one day late, Figure 3B), providing useful information to fishers to potentially limit the capture of young juvenile hake.

Perspectives of the use of essential habitat in co-management

In this section, we first describe the new concept of combining habitats of different species to optimise fishing while reducing the impact on the ecosystem, and then explain how this single or multi-species habitat could be added to co-management to increase mutual trust and acceptance.

As an improvement over the above single-species habitat avoidance, a multi-species habitat combining target, undesirable, and protected species is proposed to deepen the co-decision process towards EAFM through the increased use of objective spatial information and updated environmental information (Figure 4). Species-specific weighting factors, jointly decided by the management committee, ensure that management objectives are met. The resulting habitats for target (H_T), non-target (H_U), and protected (H_P) species are calculated using the maximum weighted habitat value for each category to fully account for the single-species habitat variability that must be met to achieve the priority objectives. Multispecies habitat for fishers (H_{man}) is then calculated as weighted target habitat (H_T) minus weighted undesirable species habitat (H_U) and minus weighted protected species habitat (H_P). We estimated that if negative H_{man} values are actively avoided, values greater than 0 to 0.5 are preferentially avoided, and H_{man} values above 0.5 are targeted, management objectives should be met. In practice, weighting factors for targeted and protected species should be between 0.5 and 1 to be effective in terms of priority objectives, while they should be less than 0.5 for undesired species, which should only be an adjustment variable in the overall equation.

In addition to the current operation of ICATMAR and co-management committees (adaptive management measures on an annual or multi-year scale), we propose to add an EFH component to enhance the benefits of the co-decision process by using real-time objective spatial information to improve resource and ecosystem protection. Real-time updated single-species avoidance mapping is first proposed as an existing product for fishers to better respect the EFH of a target species, namely 0-group (nursery) hake. Real-time information will optimize both the nurseries' level of protection and the later spillover effect. A step forward in the approach is suggested, as a prospect for improvement, to use a multi-species

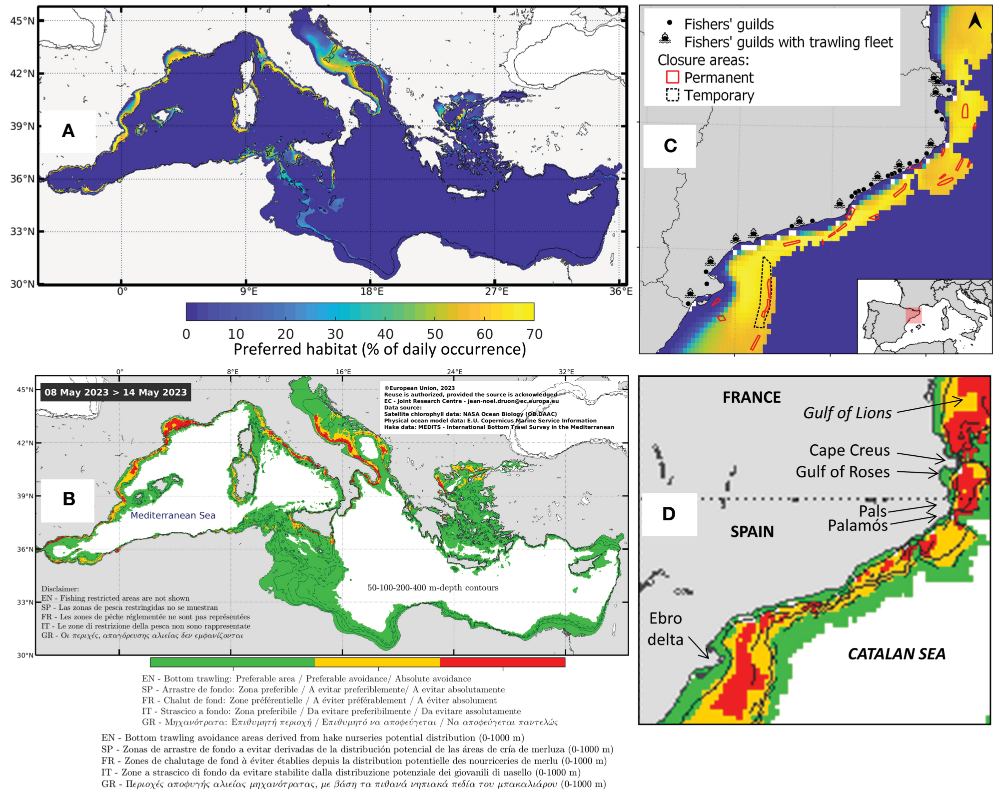

FIGURE 3
(A) Average potential 0-group hake habitat for 2018-2021, and **(B)** an example of a bottom trawl avoidance index derived in real time and updated daily to inform fishers of likely active hake nurseries (red colour) for the period May 8-14, 2023, made available on May 15, 2023 (updated in near real-time at https://fishreg.jrc.ec.europa.eu/web/fish-habitat/index.html) and **(C, D)** zoom-in equivalent maps of **(A, B)** in the Catalan Sea with the highlight of fishing restricted areas in **(C)**. See also the high and low habitat seasons and inter-annual variability for the hake nurseries on Figures S5 and S6 in the SI.

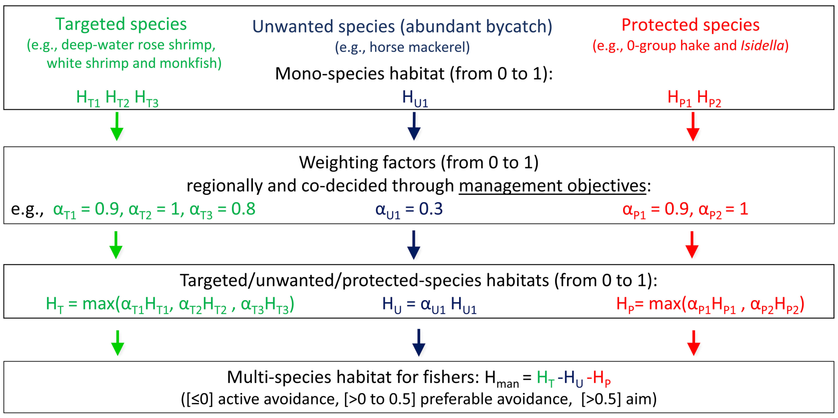

FIGURE 4
Flowchart of multi-species habitat estimation including, for example, three target species, one undesirable species, and two protected species. The resulting target (H_T)/undesirable (H_U)/protected (H_P) species habitat is calculated using the maximum weighted single-species habitat, with weighting factors determined within the co-management committee based on priority objectives.

habitat product combining target, unwanted and protected species (Figure 5). Each weight used to combine these species-specific habitats would be jointly decided within the co-management committee based on agreed upon priority protection objectives. This multi-species habitat component could also be used for the evaluation of closure areas and their potential redefinition in an adaptive co-management context.

These additional environmental components in the co-decision process would thus promote necessary adaptation to climate change and maintain capitalized trust and accountability.

Discussion

The results of our questionnaire (social component) to fisher's representatives on the existing fisheries co-management process in Catalonia (decision-making component detailed in the SI), mainly representing bottom trawling, highlighted the remaining problems and potential solutions. The mentioned issues mainly relate to the lack of perceived opinion, mutual understanding and trust, while potential solutions include long-term collaboration in the field, improved communication and the use of dynamic EFH to limit bycatch (ecological component). Finally, we presented a new approach that inserts a multi-species habitat component into the co-management system, including target, unwanted and protected species with jointly decided combined weights, in order to provide relevant spatio-temporal information to best protect fishers' profitability and the ecosystem while building mutual trust.

Conditions of efficient fisheries co-management

Although the number of active fishing units in EU Mediterranean fisheries has decreased by 30% over the period 1995-2016 (from about 51,000 to 36,000 vessels, Maynou, 2020 and herein), these fisheries remain complex due to the number and size of vessels involved, the diversity of fishing gears and target species, the number of countries and the variety of socio-economic and cultural contexts (Smith and Garcia, 2014; FAO-GFCM, 2022). Our results (illustrated by the Catalan co-management system) confirm that stakeholder involvement and commitment are essential in such a complex system of studying and managing fish stocks and protecting their EFH, as they promote shared understanding, acceptance, responsibility and mutual trust (Figure 5). Despite the efforts made in Catalonia to communicate effectively for mutual understanding in a well-developed regional co-management system, part of the fishing community still perceives a lack of representativeness among stakeholders in the co-decision process. Although the questionnaire was addressed to representatives mainly focusing on bottom trawling, in particular to inquire about the potential benefits of using real-time EFH mapping, the results suggest that only long-term continuous collaboration in the field (at sea or in port) with scientists can create the mutual understanding and trust that is necessary for their voice to be heard in the co-decision process. Regular communication also promotes the confrontation and inclusion of complementary scientific and fisheries knowledge that is desirable in a co-management process (Herrera-Racionero et al., 2019). This

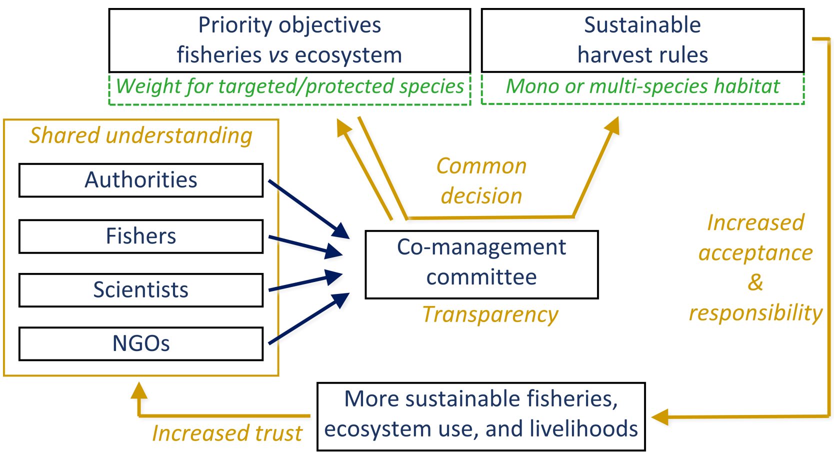

FIGURE 5
The virtuous cycle of the co-decision process in ecosystem-based fisheries management reinforces i) the complementarity between the decision-making, socio-economic and biological components and ii) the behavioural benefits (beige colour). The flow chart describes the current management system in the Catalan area, with the exception of the use of a single or multi-species habitat (green dotted line) that would strengthen the management system. A multi-species habitat, which would be based on combined habitats using weights for target, undesirable, and protected species, would be commonly decided as a priority goal by stakeholders in the co-management committee.

regular face-to-face communication on the basis of effective mutual understanding reinforces the need to limit the number of actors, thus developing fisheries co-management on a limited geographical scale. This should also facilitate the management of complex situations involving conflicting use of the marine environment, where professional and recreational fisheries, tourism activities and offshore energy projects overlap, which is even more relevant for small-scale fisheries (SSF) and areas with marine protected areas (e.g. Cape Creus) due to their social and ecological vulnerability.

New governance approaches to local fisheries management have demonstrated the capabilities of bottom-up, transdisciplinary and cross-sectoral collaborative models to effectively engage stakeholders in research and management of marine issues (Gómez and Köpsel, 2022) and to develop management plans that can regulate activity down to small-scale fishing gear (Lloret et al., 2020). Complex co-management commitments can facilitate the difficult coexistence of different stakeholders (e.g. between scuba divers, recreational and professional fishers) who may have different interests (Gómez et al., 2006; Lloret and Riera, 2008; Lloret et al., 2012; Gómez et al., 2021), such as the artisanal fisheries management plan that was approved in 2022 in Cape Creus through an agreement between all participating stakeholders. Voluntary guidelines to ensure the sustainability of artisanal fisheries (SSF guidelines) have been proposed to establish regulations in coastal MPAs taking into account the spatial, ecological and cultural specificities of artisanal fisheries that are not reflected in national and European legislation (Gómez and Lloret, 2017). The SSF guidelines, by recognizing small-scale fisheries' tenure rights as a way to promote small-scale fishers' stewardship over resources, can contribute to achieving the objectives of sustainable resource (co)management (Gómez and Lloret, 2017). Regardless of the complexity of fisheries, co-management therefore requires an effective communication system to foster mutual understanding between stakeholders and a robust scientific information system, the latter also promoting the former. Seasonal disturbances induced by climate change having recently created more unusual fishing conditions, the need for effective collaboration between fishers and scientists is likely reinforced (Herrera-Racionero et al., 2019).

Contribution of the dynamic and ecosystem approaches to fisheries management

In particular, our results highlight that co-management can be effective in finding balanced decisions for the management of diverse and spatially interacting coastal activities (e.g. small-scale fisheries, tourism) and for more offshore fisheries. In the case of offshore trawl fisheries, the protection of nursery areas for heavily exploited stocks such as hake in the Catalan Sea is a valuable tool for fisheries management (Maynou et al., 2003), as its implementation has improved recruitment and spillover effects (Sala-Coromina et al., 2021). Compared to static spatial closures, one of the main advantages of real-time dynamic ocean management is that the area targeted for mitigation can be considerably smaller and more efficient (Hazen et al., 2018; Pons et al., 2022, see also the high and low habitat seasons and inter-annual variability for the hake nurseries on Figures S5, S6 in the SI). The use of near-real-time spatial information on the most important and spatially variable nurseries by bottom trawlers appears to offer an effective tool for mitigating the capture of undersized hake (< 20 cm) by low-selectivity gear and fostering collaboration with scientists. On the other hand, the protection of hake spawners mainly inhabiting the continental slope and submarine canyons is important to safeguard the reproductive potential of hake stocks that suffer from overfishing by bottom longliners (Oliver and Massutí, 1995; Lleonart and Maynou, 2003). Hake management must therefore take into account time-area measures for the different fishing gears. This is particularly important as all hake stocks in the Mediterranean have been estimated to be overexploited and a reduction in fishing mortality has been recommended (FAO-GFCM, 2022). The situation becomes more complex if more species or life stages are to be considered in an EAFM approach, such as required under the EU Common Fisheries Policy (CFP) since January 2014 (European Commission, 2013). The presented multi-species habitat framework, which proposes to attach a positive weight to exploited species and a negative weight to the habitat or nurseries of protected species, as well as a low weight (positive or negative) to undesirable species (Figure 4), should allow a given allocation of fishing effort (in space and time) to be best guided by metier. Such an implementation could increase selectivity, and thus ecosystem protection, while improving acceptance as species habitat weights would be transparently agreed among stakeholders and aligned with priority management objectives. Accessibility of information and tools increases transparency and dissemination of information, thus promoting dialogue and trust between stakeholders (Kelly et al., 2022). As multi-species fisheries are highly adaptive to regulatory changes, a multi-species approach would avoid any unintended displacement of effort and/or changes in targeting practices that would undermine the management objectives of the wider ecosystem (Abbott and Haynie, 2012). In other words, combining and providing multi-species habitats with different management objectives is likely to result in clearer, more effective and accepted management measures. Such a programme could include culturally important species to stimulate the interest and engagement of the local population (Freitas et al., 2020).

Recommendations for the co-management process

In this section, we describe more specific recommendations for the fisheries co-management process, acknowledging the general theoretical context provided by Ostrom's (1990) list of principles for managing the commons (as amended by Cox et al., 2010): i) well-defined user and resource boundaries, ii) congruence between both rules of appropriation and provision with local conditions, iii) collective choice arrangements, iv) community oversight of its members and the resource, v) graduated sanctions, vi) conflict resolution mechanisms, vii) minimal recognition of rights, and viii) interlocking enterprises.

In the particular case of fisheries, it is important that co-management of commercial fisheries moves from monospecific to holistic co-management that integrates different gears targeting different species and possibly life stages of the same species (e.g. trawlers targeting smaller individuals and small-scale fisheries targeting larger ones) and natural habitat distributions. While the EAFM has been a requirement of the EU-CFP since 2014, current fisheries management is still dominated by conventional single-species advice (European Commission, 2022). For coastal species, co-management initiatives should also take into account other stakeholders that may have interests in the same species or areas as professional fishers, such as recreational fishers and scuba divers. Only such integrative co-management of shared stocks and activities can effectively minimise conflicts between professional fishers and between professional fishers and other stakeholders, and improve the overall welfare achieved through the use of common resources.

Our conclusions on the benefits of co-management are fully aligned with those of a recent EC report on EAFM implementation within the CFP (European Commission, 2022): "The advisory process should build on a transdisciplinary knowledge base, integrating various interdisciplinary scientific and local indigenous (e.g. fisher) knowledge to consider the full social-ecological system. Including context and stakeholder interests in decision-making can enhance the feasibility, appropriateness and impact of chosen management measures". It is recommended to involve more fishers and scientists in the co-management process. Sometimes fishers are reluctant to participate in meetings, and not all scientists respond positively to these processes due to lack of time or interest in work that differs from their routine tasks (fishing at sea or research in their laboratories, respectively). Research governing bodies and fishers' associations should therefore attach great importance to the time spent between scientists and fishers on board and in port. Greater engagement of decision-makers and managers would also increase interactions with scientists and other stakeholders (Röckmann et al., 2015; Macher et al., 2021), which may reveal opportunities and constraints in the consultative process (European Commission, 2022). The cement of mutual understanding and trust between fishers, scientists, NGOs and the administration is probably the shared time and knowledge exchange. Near-real-time scientific information on species vulnerable to fishing or on multispecies habitats, combined with feedback from fishers in the field, can be a central element in building this trust between communities that have mostly different backgrounds. The long-term voluntary collaboration of both parties, scientists and fishers, should be greatly facilitated by the respective governing structures. Fishers and scientists should then benefit from each other's complementary knowledge (field and academic), and their integration should lead to more objective management and improved sustainability.

Furthermore, it should be stressed that co-management processes should be seen as a flexible system that allows for adaptation. There is always a delicate and often changing balance between stakeholders that needs to be maintained to satisfy the mutual interests of all parties. Therefore, the co-management process should consider (if necessary) rebalancing theory, practice, outcomes and participants. Co-management should lead to the joint development of regulations that should promote the recovery of fish stocks and the ecological and economic sustainability of fisheries, while avoiding conflicts with other economic sectors. This requires the support of the administration to facilitate and accompany the co-management process. The adoption of a dynamic ocean management should in parallel further help to reduce conflicts in complex systems (Maxwell et al., 2020). Overall, a flexible and dynamic co-agreed system should favours compliance and successful ocean management.

From a broader perspective, fisheries co-management should be aligned with maritime spatial planning (MSP) for all activities at sea, which takes into account other activities such as recreational fishing, recreational boating, aquaculture, tourist cruises and, more recently, offshore wind energy. Co-management remains a challenge with recent offshore uses, such as offshore fisheries or wind farms, which often conflict with fisheries interests and marine habitat conservation objectives. This is particularly the case when offshore wind farms are proposed to be built over closed fishing areas aimed at restoring fish stocks and areas of exceptional ecological value, as is the case at Cap Creus/Gulf of Roses (reviewed by Lloret et al., 2022). As MSP should theoretically enable the management of any sustainable activity at sea - in space and time - as part of the blue economy, in which fisheries are integrated, MSP should be the general framework for the co-management process in which habitat information, including real-time information, can be used among the other layers. Within such a framework, activities at sea could be organised in space and time within a single integrated system that would accommodate the best available scientific data (biological, social and economic) in order to achieve as far as possible, the environmental, social and economic objectives of the coastal community and to achieve good environmental status (GES) for all descriptors of the EU Marine Strategy Framework Directive (MSFD). In practice, a dynamic MSP system would allow, in an area designated for a given activity (e.g. fishing), to identify in real-time and communicate to stakeholders which areas are subject to restrictions (voluntary or mandatory) based on essential habitat information (e.g. avoidance of nurseries). The use of different and innovative analytical methods, including artificial intelligence, could also be promoted in order to co-decide on the best possible scenario for the sustainable use of maritime space and resources.

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://data.jrc.ec.europa.eu/.

Author contributions

Data: J-ND, JL, LR, JS-C, SG. Analysis: J-ND, JS-C, JL, SG. Manuscript: J-ND, JL, LR, JS-C, SG, JG, ST, LB. Review: J-ND, JL, LR, JS-C, SG, JG, ST, LB. All authors contributed to the article and approved the submitted version.

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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

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1197878/full#supplementary-material

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