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Assessing the vulnerability of sensitive species in Mediterranean fisheries: insights from productivity-susceptibility analysis

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Mortality resulting from interactions with fishing gears represent an important threat to sensitive species globally. In this study, we address this issue by defining five species groups of marine megafauna (marine mammals, seabirds, demersal and pelagic elasmobranchs, and sea turtles), and conducting a productivity-susceptibility analysis (PSA) within the context of data-limited fisheries in the Mediterranean and Black Sea. Although there are significant differences among species within each group, this approach has been considered much more direct and functional for management purposes. The productivity (*P*) of each species group was determined by evaluating a set of attributes averaged across representative species within each group. Species groups' susceptibility (*S*) to bycatch was assessed through a comprehensive review of existing literature and expert judgment, considering a series of semi-quantitative attributes. Our analysis identified areas and fishing gears posing potential risks to the species groups assessed, highlighting that sea turtles and elasmobranchs face the potential risk of incidental captures from various fishing gears operating in both neritic (bottom trawls, set nets and bottom longlines) and pelagic (drifting longlines) environments. Marine mammals exhibit moderate risk across most fishing gears, with particular concern for the harbour porpoise *Phocoena phocoena relicta* in the Black Sea, primarily due to the interaction with set nets, which can severely impact entire population even capturing few specimens due the species low productivity. Seabirds face reduced impact with fishing activities, irrespective of the type of gear examined or the specific area under investigation. Overall, our study highlights the specific basins and fishing gears requiring focused management measures, mitigation strategies, and enhanced monitoring activities to mitigate the impacts of bycatch on vulnerable marine megafauna.

KEYWORDS

risk assessment, data-limited fisheries, pet species, bycatch, management measures, Mediterranean and Black Sea

Introduction

The incidental capture of sensitive species in commercial fishing, termed bycatch, poses an important threat to marine biodiversity and the conservation and welfare of megafauna on a global scale, with potential unexpected impacts on the functioning and resilience of entire ecosystems (ICES, 2022; Komoroske and Lewison, 2015). Bycatch of long-lived species with relatively low productivity, which includes many marine mammals, seabirds, elasmobranchs and sea turtles, as well as some finfish and cartilaginous fish, is a serious problem to their conservation (Lewison et al., 2014). Many of these species, classified as vulnerable and/or threatened (Protected, Endangered, and Threatened species, commonly known as PETs), provide essential marine ecosystem services, influencing the dynamics and community structure of multiple marine ecosystems (Lew, 2015). Effective management measures to minimize the impacts of fishing activities on marine biodiversity and PETs necessitate a comprehensive understanding of the extent of the problem. Therefore, monitoring programs, mandated by regional and other fisheries management bodies, have become increasingly common and mandatory in most countries worldwide and are essential steps towards minimizing these interactions and, more generally, conserving the marine ecosystems, as well as ensuring a sustainable fishery sector that provides long-term biological and socioeconomic benefits.

These programs employ various methods for data collection, including at-sea observers, port observers, vessel crew observers, fishers' logbooks, and remote electronic monitoring (REM). However, in many regions, including the Mediterranean and Black Seas, knowledge gaps persist regarding the extent of bycatch levels across different fishing gear. This is partly due to limitations in existing detection methods; for instance, logbooks may suffer from biases, such as consistent reporting from the same vessels and under-reporting by fishers, possibly due to perceived negative consequences (Moore et al., 2021; Wade et al., 2021; Virgili et al., 2024). Additionally, fishers frequently release animals alive, with unknown post-release survival rates, or discard them dead at sea despite regulations, making control and surveillance at landing sites ineffective for bycatch recording. Addressing these challenges is essential to develop more effective strategies for mitigating the impacts of bycatch on marine ecosystems and PETs.

The most reliable method for collecting bycatch information is represented by on-board observers and, recently, by the adoption of new technologies such as on-board cameras (Basran and Sigurðsson, 2021). In the Mediterranean, comprehensive programs for monitoring incidental catch using on-board observers with statistically robust sampling designs are not consistently implemented across all fisheries (Ligas, 2019). Additionally, to ensure data reliability, it is crucial to conduct a sufficient number of trips to achieve representation and an adequate level of certainty. Typically, coverage should fall within the range of 2 to 7 percent (FAO, 2009; Northridge and Fortuna, 2008), but the costs, in terms of personnel, vessels *etc.*, to reach this threshold are often unaffordable. Therefore, a minimum level of 0.5 percent is often accepted (James, 2016; FAO, 2019). However, bycatch, while common in certain fisheries (Lewison et al., 2014), remains relatively rare, necessitating large-scale and much frequent monitoring to accurately assess magnitude, frequency and risks. Consequently, these observations are often integrated with interviews and logbooks.

For over three decades, a series of GFCM Recommendations, monitoring programs (e.g. Marine Strategy Framework Directive - MSFD, European Commission 2008; Data Collection Framework (DFC), European Commission, 2017), research projects (e.g. Medbycatch project, LIFE projects, etc.), and initiatives by NGOs and companies have been implemented with varying levels of commitment across different countries and regions.

More recently, scientists have developed new Ecological Risk Assessments (ERAs) as an alternative to conventional stock assessments (Saldaña-Ruiz et al., 2022). ERAs aim to quantify the ecological risks for species or stocks exposed to fishing pressure and highlight specific issues that require enhanced management within harvest strategies. The risk assessment framework for data-limited fisheries includes Productivity and Susceptibility Analysis (PSA), a semi-quantitative methodology used to evaluate the overall vulnerability of target, non-target and vulnerable species to fishing activities (Milton, 2001; Griffiths et al., 2006; Faruque and Matsuda, 2021; Good et al., 2023). PSA relies on a set of pre-set measurable attributes and score rankings to estimate two important parameters: *1)* Productivity, which considers the species' capacity to sustain or recover from fishery-related impacts, and it is based on life history traits such as natural mortality rate and age at maturity; *2)* Susceptibility, which evaluates the species' exposure to impacts from specific fishing activities (Hobday et al., 2011). PSA is widely used to advise research priorities and management of bycaught stocks and populations needs (Hordyk and Carruthers, 2018).

This study aimed to identify areas representing a potential risk for five species groups of PET species (*i.e.* marine mammals, seabirds, pelagic and demersal elasmobranchs and sea turtles), in the Mediterranean and Black Seas, by calculating their vulnerability to the different fishing gears.

The fundamental question we want to answer is: "*Is the current level of knowledge truly insufficient to begin considering management measures to protect sensitive species?*"

Materials and methods

Data sources

The study area was defined as the entire Mediterranean and Black Sea (Figure 1). To enhance management guidance, we further subdivided the Mediterranean Sea into distinct sub-regions as outlined by the FAO-GFCM: Adriatic Sea, Central Mediterranean, Eastern Mediterranean, Western Mediterranean, and Black Sea (Carpentieri et al., 2021). According to the FAO list of vulnerable species in these areas (FAO, 2021), we selected a total of 78 relevant species to be assessed (Supplementary Material S1). We opted not to perform the Productivity and Susceptibility Analysis (PSA) at the level of individual species. Instead, we categorized them into specific species groups. These groups include sea turtles (ST), seabirds (SB), pelagic elasmobranchs (PE), demersal elasmobranchs (DE), and marine mammals (MM). We felt that this approach was much more general, direct and easy to understand, and could produce results directly useful for management purposes.

The main Mediterranean fishing gears having a potential effect on the bycatch of these groups of species were considered: bottom trawl (OTB), pelagic trawl (TM), drifting longline (LLD), set longline (LLS), set nets (GEN), and purse seine (PS). Other professional fishing gears (e.g. dredges, hand and underwater fishing, hand lines, *etc.*) were deemed to pose minimal or negligible risk in terms of catching PET species (Lucchetti et al., 2023), hence were excluded from the analysis.

Productivity and susceptibility analysis

The overall Vulnerability (*V*) is calculated as the combination of the Productivity (*P*) and Susceptibility (*S*).

Productivity is a parameter essentially related to the life-history characteristics of the species concerned. In order to establish dependable productivity scores, we focused on selecting the most prevalent and representative species, particularly those frequently

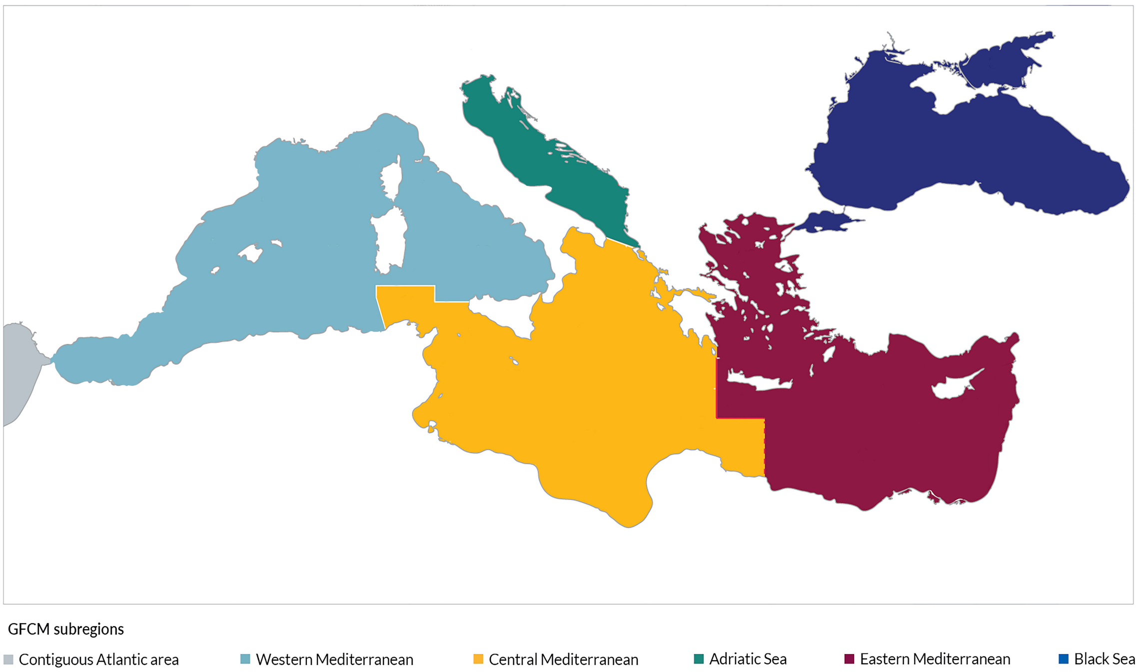

FIGURE 1
Study area. The map shows the division of the Mediterranean Sea and Black Sea into FAO-GFCM subregions (adapted from https://www.fao.org/gfcm/data/maps/gsas/en/).

interacting with fishing activities. We excluded those species whose presence in certain areas is doubtful and those whose spatial distribution is uncertain. We considered it speculative to make assumptions about the susceptibility of those species for which there are only sporadic "sightings." Within each group, given the thresholds established for each attribute, similar productivity values were obtained for the different species, which supported the idea of creating homogeneous groups.

Productivity attributes, which differ depending on the four relevant taxa (Elasmobranchs, Marine Mammals, Sea Birds, Sea Turtles), were selected following the methodology described by the MSC Fisheries Standard Toolbox (Good, 2019; MSC, 2023). Table 1 provides a summary of the selected attributes for each species group. Attributes were then scored for each species on a three-point risk scale using the cut-offs provided by MSC (2023): low (3), medium (2) or high (1) productivity. The scored life history data were compiled from scientific literature (peer-reviewed papers), technical reports or theses, and online databases *i.e.* FishBase and SeaLifeBase (Froese and Pauly, 2000). When multiple data were available, the median value was selected. In those cases, where a range of values was found, the most conservative value was chosen for scoring. If information for a given species was limited or absent, data was collected from a closely related species used as a proxy. If no proxies were available, a more conservative score of 3 (indicating low productivity and high risk) was assigned for missing attributes.

The species productivity score (P_S) was calculated as the arithmetic mean of the attribute scores, while the overall productivity of the groups (P_T) was determined as the arithmetic mean of the P_S scores within each species group of vulnerable species.

$$(P_S) = \frac{\sum_{i=1}^{n} X_i}{n} = \frac{X1 + X2 + X3 + \cdots Xn}{n}$$

Where X_1, X_2 …X_n are the different attributes and n the number of attributes.

$$(P_T) = \frac{\sum_{i=1}^{n} P_i}{n} = \frac{Ps1 + Ps2 + Ps3 + \cdots Psn}{n}$$

Where P_s1, P_s2… P_sn are the productivity scores for the different species within a species group.

Susceptibility is a parameter that highlights the degree to which the fishery can negatively impact the species. In the current study, we developed a two-fold approach to semi-quantitatively assess the susceptibility. First, the review on the bycatch of megafauna species, recently published by the FAO-GFCM (Carpentieri et al., 2021), was considered, gaining information on the bycatch estimates/rates (or the levels of bycatch reported in the document) considered as a *proxy* for susceptibility (susceptibility by bibliography = S_B) and classified from 1 to 3 (Low=1; Medium=2; High=3) according to the maximum bycatch level found for a specific species group in the Mediterranean basin (Table 2). The maximum bycatch level was chosen with a precautionary approach to the issue, in order to not exclude any potential risk of bycatch. The complementary method, consisted in determining susceptibility by experts' judgement. For this purpose, at least 2 authors per FAO-GFCM subregion were involved in the scoring of the susceptibility attributes for each species group. These attributes are reported in Table 2 and were considered for Susceptibility as a three-level score: low (1), medium (2) or high (3). Assuming that each attribute (y) had the same weight, the overall susceptibility calculated for each species group with this method (S_E) was calculated using the geometric mean of the obtained values for the different attributes.

TABLE 1 Productivity attributes and corresponding scoring thresholds assessed for each group of species according to MSC Fisheries Standard Toolbox (2023).

Species group	Productivity attribute	Scores		
		High (1)	Moderate (2)	Low (3)
Elasmobranchs (Both pelagic and demersal)	Average age at maturity	<5 years	5-15 years	>15 years
	Average maximum age	<10 years	10-25 years	>25 years
	Fecundity	>20000 eggs per year	100-20000 eggs per year	<100 eggs per year
	Average maximum size	<100 cm	100-300 cm	>300 cm
	Average size at maturity	<40 cm	40-200 cm	>200 cm
	Reproductive strategy	Broadcast spawner	Demersal egg layer	Viviparous/Ovoviviparous
Marine mammals	Trophic level	<2.75	2.75-3.25	>3.25
	Average age at maturity	<6 years	6-8 years	>8 years
	Fecundity (Mysticetes only)	>0.40	0.30-0.40	<0.30
	Fecundity (Odontocetes only)	>0.58	0.23-0.58	<0.23
Sea Birds	Average 'optimal' adult survival probability	<0.81	0.81-0.94	>0.94
	Fecundity	>1 chick/year	1 chick/year	<1 chick/year
Sea turtles	Average age at maturity:	<15 years	15-25 years	>25 years
	Fecundity	>150	100-150	<100

TABLE 2 Attributes used to estimate the susceptibility of each species group (modified and extended from MSC, 2023; *ad hoc* attributes developed).

		Scores		
Susceptibility attribute		Low (1)	Moderate (2)	High (3)
Areal overlap (Availability)[1] Overlap of the fishing effort and the species group distribution		<10% overlap	10-30% overlap	>30% overlap
Vertical overlap[1] The position of the species group within the water column relative to the fishing gear, and the position of the group within the habitat relative to the position of the gear		< Low overlap with fishing gear (low encounter rate)	Medium overlap with fishing gear	High overlap with fishing gear (high encounter rate)
Catchability[1] The probability of any species group to be incidentally captured by fishing gear. It is influenced by the selectivity of the gear and the behaviour of the species.		Low probability of being captured by the fishing gear	Moderate probability of being captured by the fishing gear	High probability of being captured by the fishing gear
Species presence[1] Abundance of a group of species in the assessed area, based on bibliography and expert judgement.		Most of the species in the group are rarely present in the area	Most of the species in the group are occasionally present in the area	Most of the species in the group are widespread in the area
Fishing effort[1] Fishing effort level of a specific gear		The area is not exploited by fishing gear	The area is moderately exploited by fishing gear	The area is extensively exploited by fishing gear
Bycatch rate[2]	Group			
The bycatch rate by species group derived from the FAO review	Sea turtles	< 5000 ind./year/subregion	5000 – 15000 ind./year/subregion	>15000 ind./year/subregion
	Seabirds	< 0.5 ind/survey effort	0.5 – 20 ind/survey effort	>20 ind/survey effort
	Pelagic elasmobranchs	<5 ind./year	5 – 50 ind./year	>50 ind./year
	Demersal elasmobranchs	<5 ind./year	5 – 50 ind./year	>50 ind./year
	Cetacean	< 0.02 ind./year	0.002 - 0.1 ind./year	>0.1 ind./year

[1]attributes used to estimate S_E; [2]attributes used to estimate S_B.

$$\text{Susceptibility by experts } (S_E) = \sqrt[n]{y1*y2*y3*\ldots*yn}$$

The final susceptibility value (S_T) was calculated as the arithmetic mean of S_B and S_E.

$$\text{Final susceptibility } (S_T) = \frac{S_B + S_E}{2}$$

Vulnerability is the result of combining productivity (P) and susceptibility (S) attributes to build a specific score that quantifies the potential risk of bycatch associated with a stock, species or group of species.

The vulnerability score (V) was estimated from the Productivity score (P_T) as:

$$\text{Vulnerability } (V) = \sqrt[2]{P_T^2 + S_T^2}$$

This relationship can be represented graphically to show that, at each point, V represents the graph's Euclidean distance from its origin. Potential risk scores can range from 1 (all scores are equal to 1) to 4.24 (all scores are equal to 3). The PSA plot was divided into three equal thirds, representing rank categories; low risk (Rank 1, $V< 2.64$), moderate risk, (Rank 2, $2.64 < V < 3.18$), and high risk (Rank 3, $V > 3.18$) (Hobday et al., 2011; MSC, 2023). We assessed the data quality for each attribute of P and S on a scale from 1 (indicating the best data) to 5 (representing no available data). This scoring was based on the principles outlined in Table 3. Additionally, we visually depicted this data quality in the PSA plots, where each vulnerability combination of group-fishing gear was linked to its corresponding relative data quality.

Results

The analysis of the review conducted by FAO-GFCM (Carpentieri et al., 2021) yielded S_B (Supplementary Material S2) values for the different species groups based on 268 papers for sea turtles, 166 for seabirds, 334 for elasmobranchs, and 292 for marine mammals. Along with the expert judgement, who contributed to estimating the S_E (Supplementary Material S3), this analysis allowed identifying the relative vulnerability for each species group within the FAO-GFCM sub-regions (Supplementary Material S4).

In the Adriatic Sea (Figure 2A), demersal elasmobranchs resulted highly susceptible to various fishing gears. These include bottom trawls (V = 3.81), set nets (V = 3.64), and set longlines (V = 3.28). Additionally, sea turtles could face the risk of incidental catch from both bottom trawls (V = 3.37) and pelagic trawls (V = 3.21). Notably, also demersal elasmobranchs emerge as high vulnerable group in the Adriatic Sea, with a vulnerability score equal to 3.21 for set longlines. In contrast, sea birds consistently exhibit low vulnerability (V < 2.64), irrespective of the fishing gear used (Figure 2A).

In the central Mediterranean (Figure 2B), three groups of species are classified as high-risk (V > 3.18). Among these, demersal

TABLE 3 Assessment criteria for data quality in the present study according to Patrick et al. (2009).

Data quality score	Description
1	**Best Data**. Information based on collected data for the stock of interest.
2	**Adequate Data**. Information based on limited coverage and corroboration.
3	**Limited data**. Estimates with high variation and limited confidence. Species in other regions of the world.
4	**Very Limited Data**. Information based on expert opinion or on general literature reviews from a wide range of species (similar taxa).
5	**No data**

elasmobranchs are of utmost concern due to their elevated vulnerability to set nets (V=3.69), bottom trawls (V=3.65), and set longlines (V=3.46). Pelagic elasmobranchs exhibit similar sensitivity, particularly to fishing gear targeting large pelagic fish (e.g., tuna-like species or swordfish), such as pelagic longlines (V=3.69) and purse seines (V=3.21). Notably, pelagic longlines pose the highest potential risk to sea turtles in this region (V=3.27). Marine mammals consistently fall within the medium-risk category, regardless of the specific fishing gear under consideration. Additionally, similar to the evaluation conducted for the Adriatic region, seabirds exhibit the lowest level of risk. In fact, across all fishing gear types—except for pelagic trawl, which is categorized as medium risk (V=2.82)—the final vulnerability value remains below 2.49 (Figure 2B).

In the eastern and western Mediterranean, most group-gear combinations fall into the medium-risk category (with values ranging from 2.71 to 3.17; Figures 2C, D), while Elasmobranchs are a major area of concern. Demersal species face pressure from bottom trawling, set longlines, and nets, with V values ranging from 3.19 to 3.78. In the eastern Mediterranean, sea turtles, along with elasmobranchs, constitute the sole group that result in a high risk of incidental catch due to trawling activities (V=3.19). Interestingly, seabirds constitute the only group categorized in the lowest risk level in both basins, with the exception of drifting longlines, which present a moderate risk to this population in the Western Mediterranean (V=2.73).

In the Black Sea, demersal elasmobranchs were identified as being at elevated risk of incidental catch, primarily due to bottom trawling (V=3.72) and the impact of set nets (V=3.72), which also affects marine mammals' population (especially the harbour porpoises, *Phocoena phocoena relicta*, Figure 2E). The potential risk level associated with this group consistently falls within the medium range concerning the remaining fishing gear under consideration. The vulnerability of sea turtles was not evaluated due to their infrequent occurrence in the study area. Similarly, pelagic elasmobranchs were excluded from assessment because of the limited available information regarding these species in the Black Sea. In line with assessments across all Mediterranean areas, marine birds demonstrate a comparable trend.

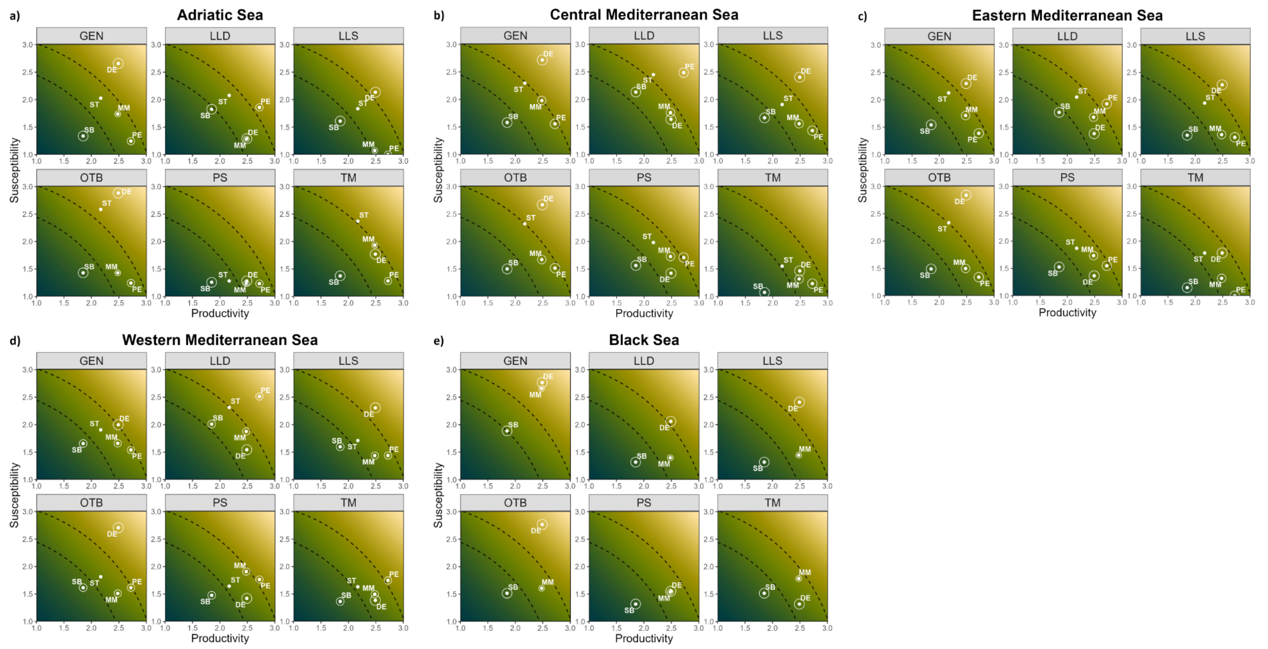

FIGURE 2
PSA in the FAO-GFCM sub-regions (Adriatic Sea, **A**; Central Mediterranean Sea, **B**; Eastern Mediterranean Sea, **C**; Western Mediterranean Sea, **D**; Black Sea, **E**) given different gear types. Sea turtles (ST), sea birds (SB), pelagic elasmobranchs (PE), demersal elasmobranchs (DE), and marine mammals (MM). Bottom trawl (OTB), pelagic trawl (TM; both pair trawl and single boat trawl), drifting longline (LLD), set longline (LLS), passive set net (GEN), and purse seine (PS). The size of external rings refers to the data quality: the larger the radius of the circle, the worse the data quality. Isopleths (dashed lines) delimit areas of equal relative Vulnerability: low risk (Rank 1, V< 2.64, green shaded), moderate risk, (Rank 2, 2.64 < V < 3.18, shaded), and high risk (Rank 3, V > 3.18, yellow shaded).

As concerns the quality of the collected data, marine turtles exhibited good data quality, while marine mammals demonstrated a lesser extent of data reliability (Figure 2). This discrepancy is attributed to the extensive conservation efforts focused on these species. Reliable estimates of bycatch or bycatch rates are available for these groups. The situation for elasmobranchs is more fragmented, as high-quality information is accessible only for specific regions. Regarding seabirds, a clearer understanding emerges primarily in the West Mediterranean, where standardized methodologies have been employed in several studies, providing valuable insights into bycatch rates.

To enhance accessibility, we visually summarized all these findings, including gear, species group, and sub-region details, in maps (Figure 3).

Discussion

Ecological Risk Assessment (ERA) methods, such as the PSA, are widely applied in data-limited fisheries to assess the potential vulnerability of species or groups of species impacted directly or indirectly by fisheries, and prioritize future research and management needs. Here we performed an ERA study using semi-quantitative Productivity-Susceptibility Analysis (PSA) to analyse the relative vulnerability of five species groups of species in the Mediterranean and Black Seas.

The study revealed how different fishing gears imply a different potential risk of bycatch for different vulnerable species groups in relation to the different areas considered. Bottom trawling has been identified as one of the most potential impactful gear, as it poses a high vulnerability risk to many of the species groups here investigated, over different areas of the Mediterranean and Black Seas. These gears, being towed on the bottom at high speeds usually with small netting meshes, are non-selective and very efficient in catching all the species living near the bottom, including sea turtles, demersal sharks, rays, *etc.* (Casale et al., 2004; Lucchetti et al., 2021). In particular, loggerhead sea turtle, *Caretta caretta*, is known to concentrate in the shallow waters of the continental shelf during its demersal life stage, for feeding and wintering (Lucchetti et al., 2016a; Lucchetti et al., 2019; Vasapollo et al., 2019), thus

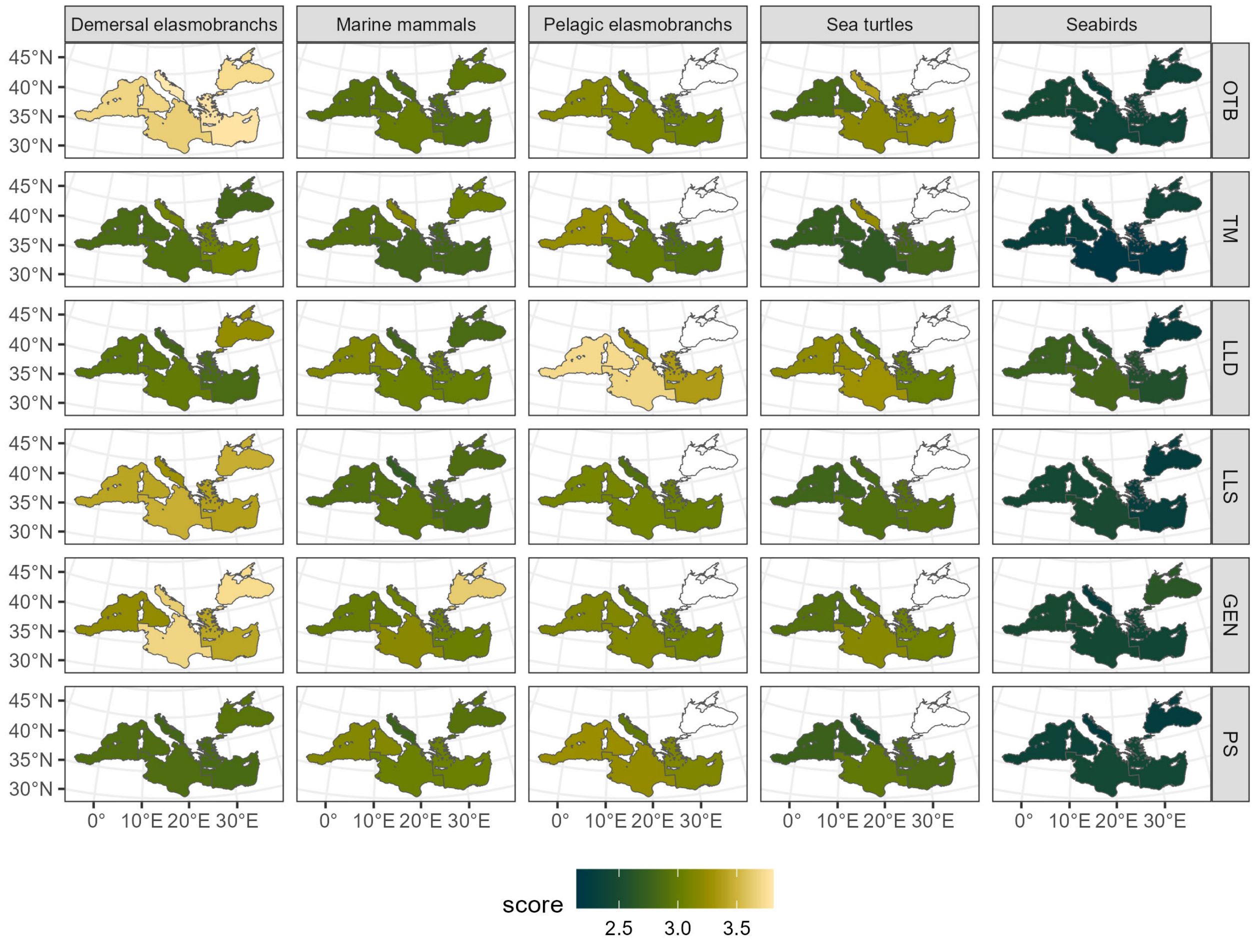

FIGURE 3
Spatial representation of the Productivity Susceptibility Analysis scores in the Mediterranean Sea sub-regions for each of the species groups (Sea turtles, ST; seabirds, SB; pelagic elasmobranchs, PE; demersal elasmobranchs, DE; and marine mammals, MM) and gears (Bottom trawl, OTB; paired- and single-boat pelagic trawl, TM; drifting longline, LLD; set longline, LLS; passive set net, GEN; and purse seine, PS). The white colour indicates those areas with no available data, or zero risk of interaction, whereas the other colours are described by the figure legend.

explaining the high risk to bottom trawls here detected for the species. Demersal sharks and rays, instead, can be affected by the gear in any time of their life stage (Di Lorenzo et al., 2022).

Pelagic trawl nets (TM) pose a potential risk to certain groups as ST and PE due to their operational methods (trawling in mid-water and close to the seabed, large water surface filtered during the towing *etc.*) coupled with the species behaviour. For example, sea turtles during their pelagic life stage (*i.e.* juveniles or migrating adults to egg-laying sites) can accidently enter inside the net during hauling and die by drowning (Lucchetti et al., 2017a; Pulcinella et al., 2019). Nonetheless, TM are mainly used only in the Adriatic Sea, where the assessments of bycatch are notably high, especially for sea turtles (Pulcinella et al., 2019; Bonanomi et al., 2022).

Drifting longlines pose a potential risk to all the investigated groups of sensitive species, wherever this gear is used. Since it is used at the surface or in mid-water, the gear can pose a risk to those groups that migrate or swim along the water column (especially PE, ST, and to a lesser extent to MM). A longline hook swallowed with the bait induces severe injuries in the bycaught species, since it pierces the oesophagus or penetrates even deeper, tearing the internal tissues. Once again, for sea turtles the interaction with this kind of fishing gear can occur during the pelagic life stage (Lucchetti et al., 2017b; Virgili et al., 2024), while for PE and MM in any time of their life cycle. The most potential at-risk area, we detected, is represented by the Western Mediterranean, where even seabirds are at risk with this type of gear, being attracted to longline as a source of food. For this group of sensitive species, however, a significant limit is represented by the shortage of available information and studies; therefore, the moderately high levels of risk observed in the Western Mediterranean could be linked to the fact that this is the only area where several studies have been conducted (García-Barcelona et al., 2010; Carpentieri et al., 2021). However, the risk of seabird bycatch with longlines is well-documented in other parts of the world (see Anderson et al., 2011 for a review); therefore, it is reasonable to expect that the extent of the problem may be underestimated in the Mediterranean.

Bottom longlines represent, according to our findings, a potential risk for demersal and pelagic elasmobranchs as well as for sea turtles in all the areas. The combination of bait presence attracting species, coupled with the small size of hooks used in these gears, makes them particularly effective and non-selective. As explained above for drifting longlines, hooks ingestion can have lethal consequences on the bycaught species, and in the case of sea turtles this interaction can occur during the demersal life stage of the species (Álvarez de Quevedo et al., 2010; Lucchetti et al., 2017b).

Set nets pose a potential risk to various groups of sensitive species, in particular to demersal elasmobranchs in all the investigated areas, and to marine mammals in the Black Sea, especially to *P. phocoena relicta* (Kratzer et al., 2021; Popov et al., 2023). However, the interactions (mainly depredation) between passive nets and marine mammals are a cause of concern throughout the Mediterranean basin, especially in the central sub-region (Li Veli et al., 2023), because the individuals trying to depredate the nets risk to get entangled and die by drowning.

Purse seine fishing is generally considered environmentally sustainable, because it does not damage the seabed and is selective for the schools of targeted fish. Indeed, a study conducted in the Western-Mediterranean Sea concluded that purse-seine fishery has only a slight impact on the main species of the pelagic ecosystem, due to the purse-seine slipping practices (Ruiz et al., 2021). However, the PSA analysis here showed that this gear poses a potential risk especially for pelagic elasmobranchs (the spatial and vertical overlap between this group of species and this fishery is high), while for all the other groups, the relative risk is generally low. By contrast, in the Western-Mediterranean Sea other authors found that the mainly affected species groups were instead seabirds and marine mammals (Wise et al., 2019; Ruiz et al., 2021).

Demersal elasmobranchs have emerged as the highest-risk group throughout the Mediterranean and Black Sea basins across nearly all the considered fishing gear types. This is ascribable to the presence of numerous species of demersal sharks and rays, which have broad geographic distributions and often have commercial value (Ragonese et al., 2013), thereby exposing them to intense fishing pressure. Because of the potential high risk posed by these gears to this groups, it would be necessary to identify key areas (e.g. nurseries area for demersal sharks) to be closed to fishing at least during certain times of the year, as it is being investigated for commercial species in the North Mediterranean (e.g. Colloca et al., 2015), but also as already investigated for sharks in different parts of the world (Heithaus, 2007; Kinney and Simpfendorfer, 2009; Barnett et al., 2019).

The identification and establishment of areas closed to fishing, such as marine protected areas (MPAs) and fisheries restricted areas (FRAs), could help reduce susceptibility by reducing the areal overlap between all species groups here considered and fishing effort. This could seem a good solution to reduce vulnerability of these species, which usually have high productivity values, meaning that they are particularly vulnerable to fishing activities due to intrinsic biological traits and thus less resilient. However, it is known that for socio-economic reasons, this solution is only feasible for small areas, which does little to resolve issues with species capable of long migrations. Also, when dealing with highly migratory species, a static approach is not always the best option. In fact, for some species, it would make sense to modulate the fishing closure periods only during specific times characterized by a high concentration of individuals of that species (Lewison et al., 2015). Furthermore, a dynamic management approach could also be more easily accepted by the fishing communities. For example, in some areas of the northern Adriatic, Sites of Community Importance have been established due to the presence of bottlenose dolphins and sea turtles (Fortuna et al., 2018). In these cases, a dynamic management of the areas and fishing activities could allow for greater compliance from fishers and increased effectiveness. But to implement such management, it is necessary to rely on a solid scientific foundation that is periodically updated, especially considering the significant climate changes underway that can rapidly alter both the global and local scenarios. Alternatively, measures could be introduced to reduce fishing effort, such as reducing the number of fishing vessels or decreasing the number of fishing days. Socio-economic factors make this solution impractical due to the implications for income and job losses.

As reducing the vertical overlap or species presence in an area is impossible, the only possible solution is to reduce catchability and species mortality (even after release at sea), for example, through the development of alternative and more sustainable gears (Petetta et al., 2020, 2021) or through the use of mitigation systems (i.e. Bycatch Reduction Devices - BRDs) (Sartor et al., 2018; Lucchetti et al., 2019; Swimmer et al., 2020; De Santis et al., 2024; Virgili et al., 2024). In this sense, there are different initiatives such as the use of Turtle Excluder Device (TED) in trawler (Lucchetti et al., 2019), or the use of circle hooks in surface longline (Patterson et al., 2014) that could reduce bycatch and/or mortality on some PETs groups. In addition, the combination of mitigation systems, together with measures to avoid fishing during the species' peak activity hours, can significantly reduce catchability. For example, the use of tori-line, together with night setting, has been shown to significantly reduce seabird bycatch (Jiménez et al., 2020). Therefore, similar measures need to be developed to reduce bycatch from demersal sharks and further research is needed.

Concerning sea turtles, there are different BRDs suitable for different gears, which help mitigate the current high bycatch rates observed in most of the fisheries of the Mediterranean basin (Carpentieri et al., 2021; Virgili et al., 2024). The loggerhead sea turtle, *C. caretta*, is the most widespread sea turtle species in the basin, thus the most impacted; in contrast, data related to green turtle, *Chelonia mydas*, is more limited due to the narrower distribution range of the species (mainly Central and Eastern Mediterranean). The use ofTEDs in bottom trawls should be mandatory in areas where the vulnerability of sea turtles reaches the highest values. The PSA analysis revealed that these areas are the Adriatic Sea, the Central and Eastern Mediterranean. In longline fisheries, one solution resides in the use of circle hooks that are less likely ingested by large bycaught animals (also including pelagic elasmobranchs), thus decreasing bycatch or increasing survivability after release (Piovano et al., 2009; Virgili et al., 2024). The increase in fishing depth in the water column has significantly decreased the bycatch of sea turtle on surface longlines (Báez et al., 2019). In set nets fisheries, one promising solution to minimize sea turtle bycatch was found to be the use of lights, particularly UV-LED (Virgili et al., 2018).

Some BRDs developed for sea turtles are also useful to avoid the catch of large pelagic elasmobranchs, such as exclusion grids in bottom trawl (with some modifications compared to TED as narrower bar spacing (e.g. Brčić et al., 2015; De Santis et al., 2024), and circle hooks in longlines (Bull, 2007; Godin et al., 2012; Swimmer et al., 2020; Carbonara et al., 2023). The drifting longline was found to be the most impacting gear for this group, especially in the Central Mediterranean, where some large sharks (e.g., genus *Carcharhinus*) are still being targeted by specific fisheries (Echwikhi et al., 2014; Lucchetti et al., 2023). Urgent management actions are here required to reduce the effort on these species and/or introduce BRDs.

Concerning seabirds, in Western Mediterranean, bycatch mortality, especially due to longline fisheries, is reducing adult survival and affecting both sexes unequally, which may intensify bycatch impact on population viability (Cortes and Gonzalez-Solis, 2018). In a recent development, taking into account the high bycatch rate of the Balearic shearwater (*Puffinus mauretanicus*), the GFCM issued a crucial recommendation aimed at enhancing the conservation status of seabirds (GFCM, 2021). This recommendation outlines specific measures to reduce undesired interactions between fishing activities and seabirds, including *i)* the use of weighted lines that help sink hooks beyond the dive depths of seabirds, *ii)* streamer (tori) lines to scare them during longline deployment, *iii)* change in fishing practice such as night setting to reduce interactions with diurnal foraging seabirds or avoiding the discharge of offal and discards during the shooting and hauling of fishing gear. This guideline is applicable to all commercial fishing operations conducted in the entire Mediterranean Sea, where incidental capture of seabirds occurs during fishing activities.

Marine mammals have moderate vulnerability to all fishing gears except to set nets, especially in the Black Sea. Some BRDs are being investigated in relation to this gear, such as the use of acrylic glass spheres to improve acoustical visibility (Kratzer et al., 2021) or acoustic deterrents, namely pingers. The latter have been extensively tested in several fisheries of the Mediterranean and Black Seas (FAO, 2021) but, despite citizen science campaigns, their uptake by fishers is limited, while their effectiveness is controversial, with positive results in some areas e.g. (Monaco et al., 2020; Ceciarini et al., 2023) and less in others e.g (Cox et al., 2004; Buscaino et al., 2021). Some authors suggest that pingers may not be successful bycatch mitigation devices for all cetacean and pinniped species (Dawson et al., 2013). Concerning bottlenose dolphins (*Tursiops truncatus*), which is the most commonly observed species interacting with fisheries due to its wide and coastal distribution (Li Veli et al., 2023), pingers were found to deter depredation only in the short term, with null or opposite effect in the long term (Buscaino et al., 2021). In fact, they can act as 'dinner bell', with individuals of *T. truncatus* observed depredating set nets equipped with pingers (Snape et al., 2018). This might have discouraged fishers to use pingers available in the market. To this end, new pingers are being developed in the Life DELFI project (LIFE18 NAT/IT/000942), which are based on automatic recognition of dolphins approaching to fishing gears and they are planned to be more effective in producing alarming sounds that avoid dolphins' habituation.

Bycatch monitoring through on board observers only makes sense if a good percentage of the overall effort is monitored. Without intensive monitoring it is impossible to perceive whether, from year to year, there is an improvement or reduction of bycatch in the various fisheries. Over the last 10 years, megafauna monitoring techniques have evolved and bycatch risk assessment is now also conducted by cross-referencing megafauna observation data (e.g. from satellite tags or aerial surveys; e.g. (Pierantonio et al., 2023; Panigada et al., 2024) with fishing effort data (e.g. from AIS or VMS; Ferrà et al., 2018; Armelloni et al., 2021). However, aerial surveys provide a picture of the situation at a specific time (usually only one survey per year is carried out), thus they are not able to intercept individuals while they are submerged, etc.; on the other hand, VMS and AIS data are generally only available for large vessels, and by-catch information from small-scale coastal fisheries is largely lost. This information can also be supplemented by the Local Ecological Knowledge (LEK) *i.e.* gathering data by interviewing fishers (Goetz et al., 2014). Recently, machine learning algorithms have been suggested as a way to address some of the analytical challenges in estimating bycatch of protected species. This approach has the potential to enhance bycatch estimates, particularly for rare species (Long et al., 2024).

For this study, the FAO-GFCM subregions have been considered as reference areas, in order to maintain consistency with the management approach adopted in this area. These regions provide strategic and technical assistance to help countries effectively meet their commitments to the GFCM. However, due to the ecological and biogeographical characteristics of the different areas, the study of the vulnerability of various species to different fishing gears should be addressed in a more detailed manner at the level of GSAs (Geographical Sub-Areas), even though this would entail further fragmentation, including in any management measures.

The quality of the data collected is rated at level 2 (Adequate Data) only for two groups (marine turtles and mammals). For other groups, information derived from literature is fragmented and often linked to bycatch rates indicated by specific studies, rather than true estimates of bycatch. For elasmobranchs, for example, information is scattered across many sources, but a comprehensive basin-wide synthesis highlighting species-specific bycatch rates is lacking. Numerous scientific articles report on local issues with specific species and gear (see the review by Carpentieri et al., 2021). Here, we summarized bibliographic information and integrate it with expert input, but it is undeniable that the quality of the data needs to be improved. In such cases, with a precautionary approach, we described the worst-case scenario. For instance, regarding seabirds, the quality and quantity of available data are very poor, with the sole exception of the western Mediterranean. This is certainly due to the limited monitoring of this taxonomic group, but in this case, it may have created a bias in data analysis, highlighting a serious problem only in the area that is actually monitored. Expert input has only partially mitigated this issue. Therefore, the recommendation for this taxonomic group is to significantly increase monitoring efforts.

A final consideration should be made regarding the values of Productivity. Here, we used a scale and method proposed by MSC and internationally accepted. However, it should be considered that elasmobranchs exhibit a wide range of reproductive strategies, which should be considered when determining the fecundity cutoff. The number of eggs is positively correlated with increased mortality, reflecting the differences between r-selected and K-selected species. Viviparous species produce fewer eggs, but with significantly higher survival rates, making fecundity a less reliable indicator than suggested here. Therefore, for this group, we believe a revision of the scales and attributes proposed by MSC is necessary.

These results show that much still needs to be done in terms of data collection. Nevertheless, the path in the Mediterranean is being paved by the standardization initiatives of data collection undertaken by FAO-GFCM (FAO, 2019).

Conclusions

Over the past two decades, escalating concerns surrounding fisheries' bycatch have catalysed numerous conservation initiatives and scientific endeavours. Despite these efforts, achieving a comprehensive understanding of the extent, magnitude, and spatial distribution of bycatch has proven challenging, hindering the development of effective management strategies. We are aware that the approach of using five broad species groups, which differ in biology and ecology, has its limitations (there is variability even among species within the same group). However, we believe that the results presented this way are much more direct and useful for management purposes (providing management recommendations at the level of individual species would be less practical). Beginning with the fundamental query "*Is the current level of knowledge truly insufficient to begin considering management measures to protect sensitive species?*", we advocate for a precautionary approach to safeguard Mediterranean biodiversity and advocate for the conservation of vulnerable species. We assert that actionable steps can be taken using available data, with Productivity and Susceptibility Analysis (PSA) serving as a versatile tool to integrate region-specific insights into fisheries and management activities. PSAs may assist in identifying potential risks in data-limited circumstances and in prioritizing actions, such as data collection or management measures, to mitigate those risks. While there is scientific evidence regarding the impact of different types of fishing gear on marine turtles and marine mammals in various areas, this is not as clear for elasmobranchs and seabirds. For elasmobranchs, the main task will be to systematize the available information to derive bycatch rates by gear type and area. For seabirds, the available information is mostly qualitative, making it essential to increase data collection efforts. A crucial second step will be to identify not only the areas but also the seasonality of interactions between fishing gear and various groups of vulnerable species. This would allow for the development of dynamic management measures that could significantly reduce the problem without completely disrupting fishing activities. An additional and fundamental step will be to refine and finally introduce the use of bycatch mitigation systems in Mediterranean fisheries. It will be necessary to make a significant leap from solutions predominantly used in scientific research to concrete measures to be adopted in professional fishing practices. Some technical solutions, such as the use of circle hooks in longline fishing, or changes in fishing practices (such as the night setting; Swimmer et al., 2020) represent a minimal change to standard fishing practices and should be evaluated over the long term (Swimmer et al., 2020). In some cases, simple technical solutions, such as avoiding the use of very large mesh sizes or trammel nets (at least during certain times of the year), could reduce bycatch with minimal effort (Lucchetti et al., 2017a). Other solutions, such as the use of TEDs in trawl nets, represent a substantial but very promising change, at least in certain areas (Lucchetti et al., 2016b; Lucchetti et al., 2019; Vasapollo et al., 2019). These could be introduced at least in areas where turtle-fishing interactions are evident or in regions where restrictions are already in place, such as Fishery Restricted Areas (FRAs). Regarding seabirds, the use of relatively simple solutions, such as bird lines in longline fishing, should definitely be tested and encouraged. For dolphins, there are no solutions that are 100% effective; therefore, a multi-faceted approach should be adopted, and systems of alert (or new pingers) based on dolphin recognition through artificial intelligence should be promoted (Li Veli et al., 2023).

Thus, PSA can serve as a decision-making tool for progressively enhancing the sustainability of seafood products as exemplified by this study. Although monitoring activities can and should be improved and increased, all the information to be able to "decide" already exists. Our study, synthesising data from numerous sources across Mediterranean and Black Sea regions, unequivocally identifies areas and fishing gears posing risks of bycatch for various species groups. Thus, attention must be directed toward these areas and gears to minimize species mortality and enhance the survival of discarded individuals while ensuring fisheries profitability. This involves investing in *a)* technological innovations in fishing gears and BRDs, especially critical areas and gears, *b)* management efforts enforcing technical measures on gears, fishing closures and time closures to be implemented dynamically, based on the seasonality, the presence of species, and actual emergencies, and *c)* new monitoring techniques such as Remote Electronic Monitoring (REM).

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 approval was not required for the study involving animals in accordance with the local legislation and institutional requirements because No authorization or ethics board approval was required.

Author contributions

DL: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. JB: Writing – review & editing. GBg: Data curation, Investigation, Writing – review & editing. Gbo: Data curation, Writing – review & editing. MB: Writing – review & editing. PCb: Writing – review & editing. RF: Writing – review & editing. CF: Writing – review & editing. GG: Writing – review & editing. HM: Writing – review & editing. ALi: Writing – review & editing. MM: Writing – review & editing. GM: Writing – review & editing. MP: Writing – review & editing. AP: Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. JS: Writing – review & editing. KT: Writing – review & editing. MV: Writing – review & editing. ALu: Writing – original draft, Writing – review & editing.

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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.

The author(s) 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

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1411033/full#supplementary-material

References

Álvarez de Quevedo, I., Cardona, L., De Haro, A., Pubill, E., and Aguilar, A. (2010). Sources of bycatch of loggerhead sea turtles in the western Mediterranean other than drifting longlines. *ICES J. Mar. Sci.* 67, 677–685. doi: 10.1093/icesjms/fsp278

Anderson, O. R. J., Small, C. J., Croxall, J. P., Dunn, E. K., Sullivan, B. J., Yates, O., et al. (2011). Global seabird bycatch in longline fisheries. *Endang Species Res.* 14, 91–106. doi: 10.3354/esr00347

Armelloni, E. N., Tassetti, A. N., Ferrà, C., Galdelli, A., Scanu, M., Mancini, A., et al. (2021). AIS data, a mine of information on trawling fleet mobility in the Mediterranean Sea. *Mar. Policy* 129, 104571. doi: 10.1016/j.marpol.2021.104571

Báez, J. C., García-Barcelona, S., Camiñas, J. A., and Macías, D. (2019). Fishery strategy affects the loggerhead sea turtle mortality trend due to the longline bycatch. *Fish. Res.* 212, 21–28. doi: 10.1016/j.fishres.2018.11.032

Barnett, A., McAllister, J. D., Semmens, J., Abrantes, K., Sheaves, M., and Awruch, C. (2019). Identification of essential habitats: Including chimaeras into current shark protected areas. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 29, 865–880. doi: 10.1002/aqc.3087

Basran, C. J., and Sigurðsson, G. M. (2021). Using case studies to investigate cetacean bycatch/interaction under-reporting in countries with reporting legislation. *Front. Mar. Sci.* 8, 779066. doi: 10.3389/fmars.2021.779066

Bonanomi, S., Moro, F., Colombelli, A., Pulcinella, J., and Fortuna, C. M. (2022). A 14-year time series of marine megafauna bycatch in the Italian midwater pair trawl fishery. *Sci. Data* 9, 51. doi: 10.6084/m9.figshare.17152577

Brčić, J., Herrmann, B., De Carlo, F., and Sala, A. (2015). Selective characteristics of a shark-excluding grid device in a Mediterranean trawl. *Fish. Res.* 172, 352–360. doi: 10.1016/j.fishres.2015.07.035

Bull, L. S. (2007). Reducing seabird bycatch in longline, trawl and gillnet fisheries. *Fish Fish.* 8, 31–56. doi: 10.1111/j.1467-2979.2007.00234.x

Buscaino, G., Ceraulo, M., Alonge, G., Pace, D. S., Grammauta, R., Maccarrone, V., et al. (2021). Artisanal fishing, dolphins, and interactive pinger: A study from a passive acoustic perspective. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 31, 2241–2256. doi: 10.1002/aqc.3588

Carbonara, P., Prato, G., Niedermüller, S., Alfonso, S., Neglia, C., Donnaloia, M., et al. (2023). Mitigating effects on target and by-catch species fished by drifting longlines using circle hooks in the South Adriatic Sea (Central Mediterranean). *Front. Mar. Sci.* 10. doi: 10.3389/fmars.2023.1124093

Carpentieri, P., Nastasi, A., Sessa, M., and Srour, A. eds. (2021). Incidental catch of vulnerable species in Mediterranean and Black Sea fisheries: a review. *General Fisheries Commission for the Mediterranean. Studies and Reviews.* No. 101. Rome, FAO. 317 pp. doi: 10.4060/cb5405en

Casale, P., Laurent, L., and De Metrio, G. (2004). Incidental capture of marine turtles by the Italian trawl fishery in the north Adriatic Sea. *Biol. Conserv.* 119, 287–295. doi: 10.1016/j.biocon.2003.11.013

Ceciarini, I., Franchi, E., Capanni, F., Consales, G., Minoia, L., Ancora, S., et al. (2023). Assessment of interactive acoustic deterrent devices set on trammel nets to reduce dolphin–fishery interactions in the Northern Tyrrhenian Sea. *Sci. Rep.* 13, 20680. doi: 10.1038/s41598-023-46836-z

Colloca, F., Garofalo, G., Bitetto, I., Facchini, M. T., Grati, F., Martiradonna, A., et al. (2015). The seascape of demersal fish nursery areas in the North Mediterranean Sea, a first step towards the implementation of spatial planning for trawl fisheries. *PloS One* 10, 1–25. doi: 10.1371/journal.pone.0119590

Cortes, V., and Gonzalez-Solis, J. (2018). Seabird bycatch mitigation trials in artisanal demersal longliners of the Western Mediterranean. *PloS One* 13, e0196731. doi: 10.1371/journal.pone.0196731

Cox, T. M., Read, A. J., Swanner, D., Urian, K., and Waples, D. (2004). Behavioral responses of bottlenose dolphins, *Tursiops truncatus*, to gillnets and acoustic alarms. *Biol. Conserv.* 115, 203–212. doi: 10.1016/S0006-3207(03)00108-3

Dawson, S. M., Northridge, S., Waples, D., and Read, A. J. (2013). To ping or not to ping: the use of active acoustic devices in mitigating interactions between small cetaceans and gillnet fisheries. *Endanger. Species Res.* 19, 201–221. doi: 10.3354/esr00464

De Santis, L. J., Bonanomi, S., Bueloni, E., Petetta, A., Annibale, O., Finotto, L., et al. (2024). Performance of sorting grids on catching elasmobranchs in a multispecies Mediterranean bottom trawl fishery. *Estuar. Coast. Shelf Sci.* 296, 108594. doi: 10.1016/j.ecss.2023.108594

Di Lorenzo, M., Calò, A., Di Franco, A., Milisenda, G., Aglieri, G., Cattano, C., et al. (2022). Small-scale fisheries catch more threatened elasmobranchs inside partially protected areas than in unprotected areas. *Nat. Commun.* 13, 4381. doi: 10.1038/s41467-022-32035-3

Echwikhi, K., Saidi, B., and Bradai, M. N. (2014). Elasmobranchs longline fisheries in the Gulf of Gabès (southern Tunisia). *J. Mar. Biol. Assoc. United Kingdom* 94, 203–210. doi: 10.1017/S0025315413000726

European Commission. (2008). EU 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. *Off. J. Eur. Commun.* L164, 19–40.

European Commission. (2017). *Regulation (EU) 2017/1004 of the European Parliament and of the Council of 17 May 2017 on the establishment of a Union framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the common fisheries policy and repealing Council Regulation (EC) No 199/2008 (recast).* 1–21, OJ L 157, 20.6.2017.

FAO. (2009). *Technical Guidelines for Responsible Fisheries*. No. 1, Suppl. 2. Rome, FAO. 2009. 49p.

FAO. (2019). *Monitoring the incidental catch of vulnerable species in Mediterranean and Black Sea fisheries: Methodology for data collection* (Rome: FAO). FAO Fisheries and Aquaculture Technical Paper No. 640.

FAO. (2021). Fishing operations. Guidelines to prevent and reduce bycatch of marine mammals in capture fisheries. *FAO Technical Guidelines for Responsible Fisheries* No.1, Suppl. 4. Rome. doi: 10.4060/cb2887en

Faruque, H., and Matsuda, H. (2021). Assessing the vulnerability of bycatch species from Hilsa gillnet fishing using productivity susceptibility analysis: Insights from Bangladesh. *Fish. Res.* 234, 105808. doi: 10.1016/j.fishres.2020.105808

Ferrà, C., Tassetti, A. N., Grati, F., Pellini, G., Polidori, P., Scarcella, G., et al. (2018). Mapping change in bottom trawling activity in the Mediterranean Sea through AIS data. *Mar. Policy* 94, 275–281. doi: 10.1016/j.marpol.2017.12.013

Fortuna, C. M., Cañadas, A., Holcer, D., Brecciaroli, B., Donovan, G. P., Lazar, B., et al. (2018). The coherence of the European Union marine natura 2000 network for wide-ranging charismatic species: A Mediterranean case study. *Front. Mar. Sci.* 5. doi: 10.3389/fmars.2018.00356

Froese, R., and Pauly, D. (Eds.) (2000). *FishBase 2000: concepts, design and data sources* (Los Baños, Laguna, Philippines: ICLARM). 344 p.

García-Barcelona, S. G., Ortiz De Urbina, J. M., de la Serna, J. M., Alot, E., and Macías, D. (2010). Seabird bycatch in Spanish Mediterranean large pelagic longline fisheries 2000-2008. *Aquat. Living Resour.* 23, 363–371. doi: 10.1051/alr/2010022

GFCM. (2021). *Recommendation GFCM/44/2021/13 on the mitigation of fisheries impacts for conservation of seabirds in te Mediterranean Sea. [Online]*. General Fisheries Commission for the Mediterranean. Available online at: https://www.fao.org/gfcm/decisions/en/.

Godin, A. C., Carlson, J. K., and Burgener, V. (2012). The effect of circle hooks on shark catchability and at-vessel mortality rates in longlines fisheries. *Bull. Mar. Sci.* 88, 469–483. doi: 10.5343/bms.2011.1054

Goetz, S., Read, F. L., Santos, M. B., Pita, C., and Pierce, G. J. (2014). Cetacean–fishery interactions in Galicia (NW Spain): results and management implications of a face-to-face interview survey of local fishers Sabine. *ICES J. Mar. Sci.* 71, 604–617. doi: 10.1093/icesjms/fst149

Good, S. (2019). Review of the MSC productivity susceptibility analysis for out-of-scope species. *Marine Stewardship Council.* 70 pp.

Good, S. D., Gummery, M., McLennan, S., Dewar, K., Votier, S. C., and Phillips, R. A. (2023). Evaluating the appropriateness of risk-based approaches to assess the sustainability of fishery impacts on seabirds. *Endanger. Species Res.* 51, 161–172. doi: 10.3354/esr01251

Griffiths, S. P., Brewer, D. T., Heales, D. S., Milton, D. A., and Stobutzki, I. C. (2006). Validating ecological risk assessments for fisheries: assessing the impacts of turtle excluder devices on elasmobranch bycatch populations in an Australian trawl fishery. *Mar. Freshw. Res.* 57, 395–401. doi: 10.1071/MF05190

Heithaus, M. R. (2007). Nursery areas as essential shark habitats: a theoretical perspective, in: American Fisheries Society Symposium. *Am. Fish. Soc.* p, 3.

Hobday, A. J., Smith, A. D. M., Stobutzki, I. C., Bulman, C., Daley, R., Dambacher, J. M., et al. (2011). Ecological risk assessment for the effects of fishing. *Fish. Res.* 108, 372–384. doi: 10.1016/j.fishres.2011.01.013

Hordyk, A. R., and Carruthers, T. R. (2018). A quantitative evaluation of a qualitative risk assessment framework: Examining the assumptions and predictions of the Productivity Susceptibility Analysis (PSA). *PloS One* 13, e0198298. doi: 10.1371/journal.pone.0198298

ICES. (2022). Working Group on Bycatch of Protected Species (WGBYC). *ICES Scientific Reports*. 4 (91), 265. doi: 10.17895/ices.pub.21602322

James, M. A. (2016). *EU-MARE 2014/19 Strengthening regional cooperation in the area of fisheries data collection (fishPi)* (Marine Alliance for Science and Technology for Scotland (MASTS). 2016. 617 p.

Jiménez, S., Domingo, A., Winker, H., Parker, D., Gianuca, D., Neves, T., et al. (2020). Towards mitigation of seabird bycatch: large-scale effectiveness of night setting and Tori lines across multiple pelagic longline fleets. *Biol. Conserv.* 247, 108642. doi: 10.1016/j.biocon.2020.108642

Kinney, M. J., and Simpfendorfer, C. A. (2009). Reassessing the value of nursery areas to shark conservation and management. *Conserv. Lett.* 2, 53–60. doi: 10.1111/j.1755-263X.2008.00046.x

Komoroske, L. M., and Lewison, R. L. (2015). Addressing fisheries bycatch in a changing world. *Front. Mar. Sci.* 2, 83. doi: 10.3389/fmars.2015.00083

Kratzer, I. M. F., Brooks, M. E., Bilgin, S., Özdemir, S., Kindt-Larsen, L., Larsen, F., et al. (2021). Using acoustically visible gillnets to reduce bycatch of a small cetacean: first pilot trials in a commercial fishery. *Fish. Res.* 243, 106088. doi: 10.1016/j.fishres.2021.106088

Lew, D. K. (2015). Willingness to pay for threatened and endangered marine species: A review of the literature and prospects for policy use. *Front. Mar. Sci.* 2. doi: 10.3389/fmars.2015.00096

Lewison, R. L., Crowder, L. B., Wallace, B. P., Moore, J. E., Cox, T., Zydelis, R., et al. (2014). Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proc. Natl. Acad. Sci. U. S. A.* 111, 5271–5276. doi: 10.1073/pnas.1318960111

Lewison, R., Hobday, A. J., Maxwell, S., Hazen, E., Hartog, J. R., Dunn, D. C., et al. (2015). Dynamic ocean management: identifying the critical ingredients of dynamic approaches to ocean resource management. *BioScience* 65, 486–498. doi: 10.1093/biosci/biv018

Ligas, A. (2019). *Strengthening Regional Cooperation in the Area of Fisheries Biological Data Collection in the Mediterranean and Black Sea (STREAM)*, EU Project MARE/2016/22 – SI2.770115. Final Report. [Online]. Available online at: https://www.coispa.it/it/progetti/41/stream-strengthening-regional-cooperation-in-the-area-of-fisheries-biological-data-collection-in-the-mediterranean-and-black-sea.htm.

Li Veli, D., Petetta, A., Barone, G., Ceciarini, I., Franchi, E., Marsili, L., et al. (2023). Fishers' Perception on the interaction between dolphins and fishing activities in Italian and Croatian waters. *Diversity*. 15 (2), 133. doi: 10.3390/d15020133

Long, C. A., Ahrens, R. N. M., Jones, T. T., and Siders, Z. A. (2024). A machine learning approach for protected species bycatch estimation. *Front. Mar. Sci.* 11. doi: 10.3389/fmars.2024.1331292

Lucchetti, A., Bargione, G., Petetta, A., Vasapollo, C., and Virgili, M. (2019). Reducing sea turtle bycatch in the Mediterranean mixed demersal fisheries. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00387

Lucchetti, A., Carbonara, P., Colloca, F., Lanteri, L., Spedicato, M. T., and Sartor, P. (2017a). Small-scale driftnets in the Mediterranean: Technical features, legal constraints and management options for the reduction of protected species bycatch. *Ocean Coast. Manage.* 135, 43–55. doi: 10.1016/j.ocecoaman.2016.11.002

Lucchetti, A., Petetta, A., Bdioui, M., Gökçe, G., Saber, M., Sacchi, J., et al. (2023). *Catalogue of fishing gear in the Mediterranean and Black Sea region* (Rome: FAO Fisheries and Aquaculture Technical Paper). doi: 10.4060/cc7260en

Lucchetti, A., Pulcinella, J., Angelini, V., Pari, S., Russo, T., and Cataudella, S. (2016a). An interaction index to predict turtle bycatch in a Mediterranean bottom trawl fishery. *Ecol. Indic.* 60, 557–564. doi: 10.1016/j.ecolind.2015.07.007

Lucchetti, A., Punzo, E., and Virgili, M. (2016b). Flexible Turtle Excluder Device (TED): an effective tool for Mediterranean coastal multispecies bottom trawl fisheries. *Aquat. Living Resour.* 201, 1–12. doi: 10.1051/alr/2016016

Lucchetti, A., Vasapollo, C., and Virgili, M. (2017b). An interview-based approach to assess sea turtle bycatch in Italian waters. *PeerJ* 5, e3151. doi: 10.7717/peerj.3151

Lucchetti, A., Virgili, M., Vasapollo, C., Petetta, A., Bargione, G., Li Veli, D., et al. (2021). An overview of bottom trawl selectivity in the Mediterranean Sea. *Mediterr. Mar. Sci.* 22, 566–585. doi: 10.12681/mms.26969

Milton, D. A. (2001). Assessing the susceptibility to fishing of populations of rare trawl bycatch: sea snakes caught by Australia's Northern Prawn Fishery. *Biol. Conserv.* 101, 281–290. doi: 10.1016/S0006-3207(00)00232-9

Monaco, C., Aguilera, R., Camiñas, J. A., Laspina, M., Molina, M., Said, A., et al. (2020). "Interactions between cetaceans and small-scale fisheries in the Mediterranean. Conclusive Report," *Published by Low Impact Fishers of Europe.* 24 pp. doi: 10.13140/RG.2.2.20562.89284

Moore, J. E., Heinemann, D., Francis, T. B., Hammond, P. S., Long, K. J., Punt, A. E., et al. (2021). Estimating bycatch mortality for marine mammals: concepts and best practices. *Front. Mar. Sci.* 8, 752356. doi: 10.3389/fmars.2021.752356

MSC (2023). *Marine Stewardship Council. Fisheries Standard Toolbox v1.1.* Available online at: https://www.msc.org/docs/default-source/default-document-library/for-business/programdocuments/fisheries-program-documents/msc-fisheries-standard-toolbox.pdf?sfvrsn=5788a3ef_33.

Northridge, S. P., and Fortuna, C. M. (2010). Protocol for data collection on bycatch and depredation in the ACCOBAMS region. A standardised methodology for use in the collection of data on Cetacean bycatch and depredation of nets. In *Report of the INTERNATIONAL WORKSHOP ON BYCATCH WITHIN THE ACCOBAMS AREA* (pp. 1-37). General Fisheries Council of the Mediterranean.

Panigada, S., Pierantonio, N., Araùjo, H., Di-Mèglio, N., Dorèmus, G., Gonzalvo, J., et al. (2024). The ACCOBAMS survey initiative : the first synoptic assessment of cetacean abundance in the Mediterranean Sea through aerial surveys. *Front. Mar. Sci.* 10, 1270513. doi: 10.3389/fmars.2023.1270513

Patrick, W. S., Spencer, P., Ormseth, O. A., Cope, J. M., Field, J. C., Kobayashi, D. R., et al. (2009). Use of productivity and susceptibility indices to determine stock vulnerability, with example applications to six US fisheries. *U.S. Dep. Commer.*, NOAA Tech. Memo. NMFS-F/SPO-101, 90 p.

Patterson, H., Hansen, S., and Larcombe, J. (2014). *A review of shark bycatch mitigation in tuna longline fisheries*. Canberra, July. CC BY 3.0. 32 pp.

Petetta, A., Vasapollo, C., Virgili, M., Bargione, G., and Lucchetti, A. (2020). Pots vs trammel nets: A catch comparison study in a Mediterranean small-scale fishery. *PeerJ* 8, e9287. doi: 10.7717/peerj.9287

Petetta, A., Virgili, M., Guicciardi, S., and Lucchetti, A. (2021). Pots as alternative and sustainable fishing gears in the Mediterranean Sea: an overview. *Rev. Fish Biol. Fish.* 31, 773–795. doi: 10.1007/s11160-021-09676-6

Pierantonio, N., Panigada, S., and Lauriano, G. (2023). Quantifying abundance and mapping distribution of loggerhead turtles in the Mediterranean sea using aerial surveys: implications for conservation. *Diversity* 15 (12), 1159. doi: 10.3390/d15121159

Piovano, S., Swimmer, Y., and Giacoma, C. (2009). Are circle hooks effective in reducing incidental captures of loggerhead sea turtles in a Mediterranean longline fishery? *Aquat. Conserv.: Mar. Freshw. Ecosyst.* 19, 779–785. doi: 10.1002/aqc.1021

Popov, D., Meshkova, G., Vishnyakova, K., Ivanchikova, J., Paiu, M., Timofte, C., et al. (2023). Assessment of the bycatch level for the Black Sea harbour porpoise in the light of new data on population abundance. *Front. Mar. Sci.* 10. doi: 10.3389/fmars.2023.1119983

Pulcinella, J., Bonanomi, S., Colombelli, A., Fortuna, C. M., Moro, F., Lucchetti, A., et al. (2019). Bycatch of loggerhead turtle (Caretta caretta) in the Italian Adriatic midwater pair trawl fishery. *Front. Mar. Sci.* 6, 365. doi: 10.3389/fmars.2019.00365

Ragonese, S., Vitale, S., Dimech, M., and Mazzola, S. (2013). Abundances of demersal sharks and chimaera from 1994-2009 scientific surveys in the central Mediterranean Sea. *PloS One* 8, e74865. doi: 10.1371/journal.pone.0074865

Ruiz, J., Louzao, M., Oyarzabal, I., Arregi, L., Mugerza, E., and Uriarte, A. (2021). The Spanish purse-seine fishery targeting small pelagic species in the Bay of Biscay: landings, discards and interactions with protected species. *Fish. Res.* 239, 105951. doi: 10.1016/j.fishres.2021.105951

Saldaña-Ruiz, L. E., Flores-Guzmán, A., Cisneros-Soberanis, F., Cuevas-Gómez, G. A., Gastélum-Nava, E., Rocha-Tejeda, L., et al. (2022). A risk-based assessment to advise the responsible consumption of invertebrates, elasmobranch, and fishes of commercial interest in Mexico. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.866135

Sartor, P., Li Veli, D., De Carlo, F., Ligas, A., Massaro, A., Musumeci, C., et al. (2018). Reducing unwanted catches of trammel nets: Experimental results of the "guarding net" in the caramote prawn, Penaeus kerathurus, small-scale fishery of the Ligurian sea (Western Mediterranean). *Sci. Mar.* 82, 131–140. doi: 10.3989/scimar.2018.82S1

Snape, R. T. E., Broderick, A. C., Çiçek, B. A., Fuller, W. J., Tregenza, N., Witt, M. J., et al. (2018). Conflict between dolphins and a data-scarce fishery of the European Union. *Hum. Ecol.* 46, 423–433. doi: 10.1007/s10745-018-9989-7

Swimmer, Y., Zollett, E., and Gutierrez, A. (2020). Bycatch mitigation of protected and threatened species in tuna purse seine and longline fisheries. *Endangered Species Res.* 43, 517–542. doi: 10.3354/esr01069

Vasapollo, C., Virgili, M., Petetta, A., Bargione, G., Sala, A., and Lucchetti, A. (2019). Bottom trawl catch comparison in the Mediterranean Sea: Flexible Turtle Excluder Device (TED) vs traditional gear. *PloS One* 14, e0216023. doi: 10.1371/journal.pone.0216023

Virgili, M., Petetta, A., Barone, G., Li Veli, D., Bargione, G., and Lucchetti, A. (2024). Engaging fishers in sea turtle conservation in the Mediterranean Sea. *Mar. Policy* 160, 105981. doi: 10.1016/j.marpol.2023.105981

Virgili, M., Vasapollo, C., and Lucchetti, A. (2018). Can ultraviolet illumination reduce sea turtle bycatch in Mediterranean set net fisheries? *Fish. Res.* 199, 1–7. doi: 10.1016/j.fishres.2017.11.012

Wade, P. R., Long, K. J., Francis, T. B., Punt, A. E., Hammond, P. S., Heinemann, D., et al. (2021). Best practices for assessing and managing bycatch of marine mammals. *Front. Mar. Sci.* 8, 757330. doi: 10.3389/fmars.2021.757330

Wise, L., Galego, C., Katara, I., Marçalo, A., Meirinho, A., Monteiro, S. S., et al. (2019). Portuguese purse seine fishery spatial and resource overlap with top predators. *Mar. Ecol. Prog. Ser.* 617, 183–198. doi: 10.3354/meps12656