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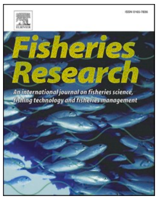

The effect of marine litter on fishery economic performance

Alice Sbrana [a,b,*], Simone Galli [a,b], Tommaso Russo [a,b]

[a] Laboratory of Experimental Ecology and Aquaculture, Department of Biology, University of Rome “Tor Vergata”, via della Ricerca Scientifica snc, Rome 00133, Italy
[b] CoNISMa, Piazzale Flaminio 9, Rome 00196, Italy

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ABSTRACT

Seabed plastic pollution seriously threatens marine biodiversity and ecosystem functioning by damaging marine organisms and disrupting ecosystems. Litter accumulation zones may overlap with fishing grounds for commercially important species, reducing productivity and yield. As studies have yet to be conducted on this topic, there is an urgent need to fill the knowledge gap on the impact of plastic pollution on fisheries and stock management. For these reasons, this study aimed to analyse the effect of seafloor plastic on fishing economic performance (as revenues) and commercially important species by mapping trawl areas and identifying litter hotspots on the seafloor. A model based on landing and Vessel Monitoring System data was employed to estimate the fishing grounds of the species, and a random forest machine-learning technique was used to identify seafloor litter hotspots. The findings demonstrate that seafloor plastic hotspots overlap with the fishing grounds, thus hurting economic productivity. The implications of this problem pose a significant threat to exposure and impact on certain species. Our findings indicate that seabed plastic pollution should be recognised as affecting fisheries administration and conservation approaches.

1. Introduction

Seafloor biodiversity refers to the variety of life forms that inhabit the ocean floor, ranging from shallow coastal areas to deep abyssal plains. It provides essential ecosystem services, including seafood production through fishing activities. Therefore, seafloor biodiversity plays a crucial role in maintaining the health and functioning of marine ecosystems and providing valuable resources for human well-being (Beauchard et al., 2023). However, various human activities, such as fishing, pollution, and climate change, directly or indirectly threaten seafloor biodiversity. Bottom trawling is considered one of the fishing industry’s most widespread and destructive practices. This method involves dragging heavy nets or gears along the seafloor, which scrapes and ploughs the sediment, causing damage to benthic organisms and habitats (Pusceddu et al., 2014). Bottom trawling reduces the biomass and diversity of seafloor communities and alters the sediment’s physical and chemical properties, affecting the biogeochemical cycles and the sequestration of carbon and nutrients (Bradshaw et al., 2021). Moreover, bottom trawling contributes to the accumulation of litter on the seafloor, as fishing gears often lose or discard plastic and metal items, such as nets, ropes, hooks, cans, and bottles (Canals et al., 2021). Seafloor litter pollution, determined by different human activities, including waste dispersal and fishing, has been observed to harm marine fisheries worldwide, directly and indirectly affecting them. For instance, the presence of marine litter in fishing nets can reduce their catching efficiency, cause damage to the nets, reduce the time available for fishing, increase repair costs, clog up equipment and require increased fuel (Beaumont et al., 2019; Ivar Do Sul and Costa, 2014; Mghili et al., 2023). Additionally, fisheries target species, along with their prey, are at risk of both lethal and sub-lethal harm due to plastic pollution, including reduced reproductive success and growth limitations, with the possibility of broader impacts at the population level (Galloway and Lewis, 2017; Sbrana et al., 2020; Sbrana et al., 2022) The combined effects of overfishing and seafloor litter could therefore have negative impacts on the productivity, sustainability, profitability and safety of the fishing and aquaculture industries (Beaumont et al., 2019). Despite growing awareness and concern about the effects of trawling and litter on the seabed, there are no studies on the combined effects of these two pressures and filling this knowledge gap would be a crucial task. Currently, different modelling approaches are available to carry out spatiotemporal analyses of fishing dynamics and to measure the direct effects of the presence of plastics on fish stocks (e.g. ingestion and reduced growth

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* Corresponding author at: Laboratory of Experimental Ecology and Aquaculture, Department of Biology, University of Rome “Tor Vergata”, via della Ricerca Scientifica snc, Rome 00133, Italy.

E-mail address: alice.sbrana@uniroma2.it (A. Sbrana).

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rates). However, studies have yet to examine the potential impact of litter accumulation on commercial stocks and the bio-economic performance of related fisheries. Furthermore, there is a need to develop and implement effective and innovative solutions to prevent, reduce, and manage the impacts of bottom trawling and seafloor litter on biodiversity, involving multiple stakeholders, such as fishers, managers, policymakers, scientists, and civil society. Strategies for managing and mitigating plastic pollution at sea require the development of a conceptual framework (Hardesty et al., 2019). This framework should consider the likelihood of organisms being exposed to litter hotspots and the potential impacts; it should also aim to balance the marine sector's environmental, social, and economic aspects (Hardesty et al., 2019). For these reasons, it is essential to elucidate the sources, distribution, and environmental impacts from a systems perspective, to understand the risks posed by marine debris (Hardesty and Wilcox, 2017). The application of risk assessment can clarify the species most vulnerable to risk and identify areas of highest concern. Risk assessments frequently represent the first stage in developing pollution regulations, improved resource management, and policies designed to preserve the environment and public health. To date, various research and studies have addressed the topic of risk assessment for plastic impact using a combination of numerical models, ingestion studies, and species distribution ranges (Compa et al., 2019), but very often these data are incomplete or fragmented. A functional approach to developing a risk assessment at sea could include the integration of fishing data, which can give us much information on the distribution of species of commercial interest and aggregation areas, which very often overlap with the species' feeding habits.

The aim of this work was to 1) assess the overlap between the areas of plastic accumulation on the seafloor and the commercial fishing grounds of demersal species exploited by bottom otter trawling; 2) assess the potential impact of plastic accumulation on fishing vessel yields; 3) examine the risk of plastic accumulation exposure on demersal stocks and assign an impact score using a spatial approach. For this study, a model of seabed litter distribution was used in conjunction with fishing metrics, including fishing effort, landings per unit effort, and revenues. These are crucial metrics for fisheries policy and decision-makers, as they demonstrate the economic return of fishing vessel operations. A spatial risk assessment analysis was conducted to inform fishermen, managers, and researchers about the demersal resources mainly affected by the accumulation of plastic litter and to indicate possible future field investigations. The analysis assumed that revenues are a good indicator of the economic performance of a fishery and used a model of the relationship between revenues and the amount of plastic litter.

2. Material and methods

The investigated area is situated in the central Tyrrhenian Sea (FAO Geographical Sub Area 9 – Western Mediterranean Sea) along the coast of the Lazio region. This area has a narrow continental shelf, characterised by fine sands and muddy bottoms (Ardizzone et al., 2018). The coastal area is heavily populated with large urban centres, industrial settlements, and essential ports close to Rome. The Tiber River run-off significantly affects the chemical-physical traits of the area, and trophic characteristics are primarily determined by the river supply (Noce et al., 2013). During winter, the river Tiber discharge is carried along the coast and dispersed offshore by the strong Tyrrhenian Sea currents from the northwest. In contrast, during summer, weak sea breezes cause downwelling conditions that limit the river's fresh waters near the mouth (Inghilesi et al., 2008).

The study area was divided into 3785 individual spatial units using a grid of 1-square-kilometre cells. These units were used to analyse the spatial distribution of seafloor plastic and trawling fleet activities. Fishing productivity was then overlapped with the plastic accumulation zone to identify any spatial relationship and bio-economic impacts.

2.1. *Seafloor plastic data*

The number of seafloor plastics occurring in each grid cell was retrieved using the model described in Cau et al. (2024), an application of Random Forests (RF) on the western and central Mediterranean Sea. These data were available as shape files through the Mendeley Data platform (https://doi.org/10.17632/r2b6svy7h7.1) and were used to estimate the aggregated spatial distribution of marine litter. Input data used for the RF model were collected by the Mediterranean International Bottom Trawl Survey (MEDITS, Anonymous, 2017) from 2013 to 2020, according to the standardised official protocol (Fiorentino et al., 2013). The MEDITS protocol for monitoring marine litter (in agreement with the requirements of the Marine Strategy Directive Framework (Directive 2008/56/EC)) is based on a stratified random sampling design, providing reliable estimates for the area between 0 and 1000 m in depth. The total number of objects collected per category (plastics, wood, metals, glass, rubber, clothing, and paper) and sub-categories are then standardised according to the swept area, as the number of objects • km^{-2}.

2.2. *Modelling of fishing ground*

Fishing efforts were estimated by analysing data from the Vessel Monitoring System (VMS), a remote tracking device mandatory in European waters (EU regulation 404/2011) for fishing vessels with length overall (LOA) ≥ 12 m. The VMS data of 558,278 records describing the position, speed, and routes of 97 bottom otter trawling (OTB) operating in the central Tyrrhenian Sea between 2018 and 2020, were combined with landings data acquired from fishing logbooks, which contain information on landings by species and harbours stored by fishers (Gerritsen and Lordan, 2011). Therefore, the cross-analysis of VMS and Landings (Logbook) data estimated the seasonal Landing per Unit of Effort (kg of landing/m of vessel length•hours of fishing) for each cell c of the grid and each season t ($LPUE_{c,t}$), according to the modelling approach described in Russo et al. (2018). All these data have been collected within the Data Collection Framework for Fisheries (https://dcf.ec.europa.eu/index_en) and were provided by the Italian "Minister of Agriculture, Food Sovereignty and Forests". The LPUE of the different demersal species are considered in the further analysis of this study, as a proxy for the productivity of the different fishing grounds. Consistent with the relevant literature (Di Maio et al., 2022; Russo et al., 2019), we assumed that the quantity and composition of landings is a linear function of the amount of fishing effort and LPUE of the different species and that fishing effort is spatially distributed based on distance from the coast, depth, and the productivity of the different fishing areas.

2.3. *Bio-economic modelling*

The VMS dataset was processed in the following steps: firstly, data were interpolated on a vessel, cell and time basis, and each fishing trip was reconstructed according to the procedures described in Russo et al. (2011a); b), identifying and separating steaming, resting, or fishing (Russo et al., 2011a; b). Subsequently, landings data were combined with fishing set positions of each vessel, at a monthly scale, to determine the spatial and temporal *LPUE* of each cell (defined as the mean value for four distinct seasons: 1: January – March; 2: April – June; 3: July – September; 4: October – December).

Fishing grounds for individual species were identified by the SMART model (D'Andrea et al., 2020). This tool reconstructs the spatial and temporal flows of landings, from fishing grounds to commercial ports (Russo et al., 2018, 2014), as follows:

1) The expected landings (L) in kg per species, vessel, time, and species as:

$$L_{c,t,s,v} = LPUE_{c,t,s} \times Effort_{c,t,v}$$

where $LPUE_{c,t,s}$ is the LPUE in cell c in season t of species s and $Effort_{c,t,v}$ is the fishing effort of vessel v in cell c in season t.

2) The expected revenues in Euros per species:

$$Revenues_{c,t,s,v} = L_{c,t,s,v} \times Price_s$$

where $Price_s$ is the price, in Euros per kg, of species s.

The goodness-of-fit of the bio-economic model returned by SMART was tested by comparing the seasonal landings values predicted by the model for each vessel/species with those observed. Moreover, the values returned by the SMART application for economic parameters (landing values and revenues) were compared with the official values available for the fishing segments in the Annual Economic Report of the European Commission.

2.4. Fishing economic performance assessment

A Generalized Additive Model (GAM) with a Gaussian distribution was used to investigate the correlation between fishing economic performance (revenues) (response variable) as a function of fishing grounds productivity (using the LPUE as proxy), seafloor litter hotspots, fishing effort and seasonality (explanatory variables). GAMs are non-parametric regression techniques that allow modelling relationships between variables without specifying form for the underlying regression function. Using smooth functions as regressors gives GAMs greater flexibility over linear (or other parametric) types of models (Hastie and Tibshirani, 1986). GAMs were chosen among other statistical techniques because they represent the best compromise between the model's predictive ability and interpretability.

The GAM model, in which the cells/season represent the statistical units, was:

$$P_{c,t} = \sum_{s=1}^{S} s\left(LPUE_{c,s,t}\right) + s(FE_{c,t}) + s(PL_c) + s(Depth) + s(Distance\ coast) + Season + Species$$

where, $P_{c,t}$ was the revenue in cell c in season t, $LPUE_{c,s,t}$ was the LPUE of species s in cell c during season t, FE was the hours of fishing in cell c during season t, and PLc was the number of plastic litter in cell c. The function *s()* indicated the smoothed terms. With this model formulation, we wanted to investigate how the productivity of different fishing grounds (LPUE), their degree of exploitation (FE), and the degree of litter contamination (PL) interacted in determining the revenues (i.e., economic performance) of the fleet. The reasoning behind this model was that revenue was the result of the combination of environmental productivity (captured by LPUEs, which are a proxy for the characteristics of each fishing ground), the distribution of fishing effort (i.e., the exploitation strategy applied by fishers), and the amount of plastic waste on the bottom. The fishing effort relies on the productivity of the fishing grounds (LPUE), which, in turn, depends on the intensity of the fishing effort but also the level of pollution. Similarly, the distribution of waste is also partly influenced by fishing efforts.

2.5. Risk assessment

According to the International Organisation for Standardization (ISO), the risk is defined as a "combination of the probability of an event and its consequences". If the accumulation of plastic waste on the sea bottom has a (direct or indirect) negative effect on a given species exploited by the fishery, the risk of a given damage (quantifiable in terms of reduced productivity and thus lower catch and fewer revenues) occurring will depend proportionally on the number of waste and the amount of individuals of a given species permanently frequenting a polluted fishing area.

The study estimated the risk of demersal species' exposure to plastic pollution on the seabed. It assumed that the probability of a species being impacted increased with increasing productivity of the species (LPUE). The definition of potential impacts was objective and included all negative interactions resulting from the presence of plastic litter on the seabed, whether direct (e.g. ingestion) or indirect (due to reduced resource availability). Therefore, we assessed potential exposure to plastic litter, on a scale of 0 (low risk) to 1 (high risk), by multiplying the rescaled LPUE (i.e. within the range 0–1) for each species and the rescaled plastic debris field in a given cell, using the following formula:

$$\text{Risk of exposure} = LPUE \bullet Seafloor\ litter$$

These values were used to produce an Impact Score (IS) as an indicator of the probability that a species could be affected by the accumulation of waste on the seabed, as a proxy for impact risk. Therefore, the risk of exposure was divided by the number of total cells where the species was present (LPUE values > 0), as follows:

$$\text{IS} = \frac{Risk\ of\ exposure}{Total\ number\ of\ cells}$$

All the analyses were performed using R version 4.3.

3. Results

The spatial distribution map of seafloor litter by season highlighted the presence of plastic accumulation hotspots on the seabed, with mean values of 16392 no. of objects $\bullet$ km^{-2} and did not change among seasons. These are located mainly in the coastal area and have the highest values in the north of the Tiber River while decreasing offshore (Fig. 1). Revenues had seasonal variations, with a maximum peak of 2080.41 Euros in the winter season, mainly in the northern portion of the study area and offshore. While lower revenue values (up to 1562.36 Euros) were recorded for coastal cells in summer (Fig. 1S – 2S).

In the main text, LPUE data are reported exclusively for species that are significant in terms of landings and economic value, and for which assessments are regularly conducted (FAO, 2022). For other species, results are reported in supplementary material (Fig. 3S). The LPUE for the most key commercial species of the selected area is represented in Fig. 2. DPS had the highest values with a mean abundance of 1.54 kg of landing/m of vessel length•hours of fishing. Coastal areas presented high values of LPUE for most of the species, while for shrimp species (ARA, ARS, and NEP), high values of LPUE were associated with the offshore-deepest zone.

The GAM model explained 89 % of the total variance, and it adequately fits the observed data pattern (Table 1). All the explanatory variables significantly contributed ($p < 0.05$) to determining the economic performance (revenues) associated with the studied area (Table 1). In particular, revenue values increased with increasing LPUE (Fig. 3) until reached a plateau. Moreover, revenues decreased rapidly with the increase in the number of plastic (Fig. 3).

The risk of exposure in this study referred to the likelihood of a certain species encountering seafloor plastic. Fig. 4 & Fig. 4S highlighted several areas with significant concentrations of plastic debris and high species abundance (LPUE) values. High MUT, HKE, EOI, and DPS species abundances were found in coastal zones, together with significant litter concentrations. Notably, all of the species listed above are associated with a considerable degree of risk in the area north of Rome. Fig. 5 shows the impact scores (IS) for the key commercial species based on the risk of exposure. In particular, *Mullus barbatus* (MUT) had the highest exposure risk, followed by *Eledone cirrhosa* (EOI), *Illex coindetii* (SQM), *Merluccius merluccius* (HKE), *Parapenaeus longirostris* (DPS), *Lophius piscatorius* (MON), *Nephrops norvegicus* (NEP), *Aristeus antennatus* (ARA), *Aristaeomorpha foliacea* (ARS).

4. Discussion

This study investigated the impact of seafloor plastic litter on trawl

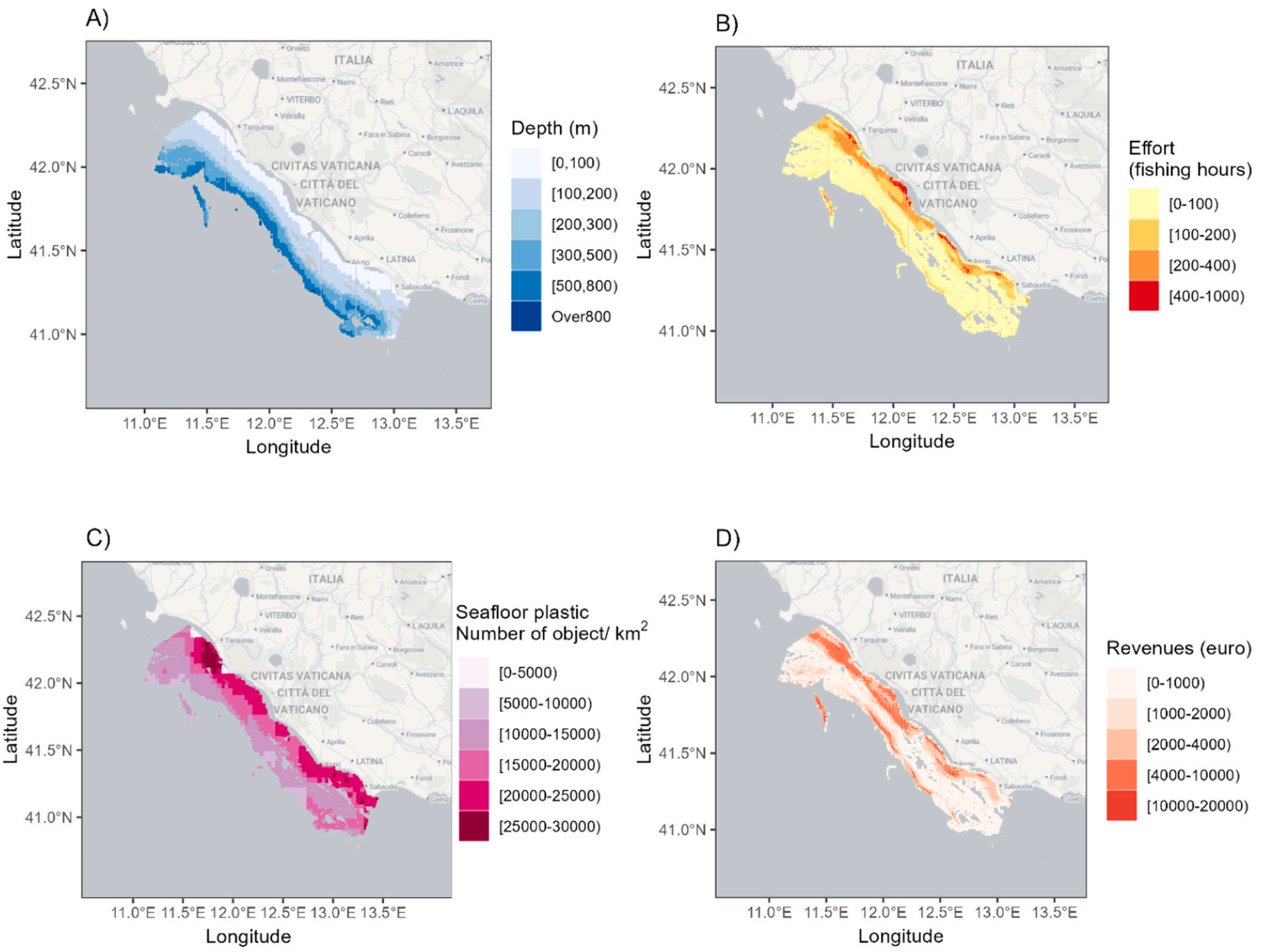

Fig. 1. Map of depth (A), fishing effort (B), seafloor litter (C) and revenues (D) of the studied area - central Tyrrhenian Sea (GSA 9).

productivity (measured in terms of revenues) in the central Tyrrhenian Sea and identified the commercial species at risk of exposure to plastic litter. The findings suggested that litter density above a certain threshold negatively affects revenues.

The distribution of plastic litter on the seafloor in our study was consistent with predicted patterns of litter accumulation along the Italian coast. Indeed, high-impact zones were found to be mainly concentrated in coastal areas and decreased offshore (Alomar et al., 2016; Critchell and Lambrechts, 2016; Passarello, 2017; Poeta et al., 2016; Scotti et al., 2021; Thiel et al., 2013). Sources of marine litter are primarily derived from the mainland, depending on population density, river inputs, industries, and harbours (Browne et al., 2011; Campanale et al., 2020; Pruter, 1987; Rech et al., 2014; Veiga et al., 2016). This is particularly evident in our study, where a densely populated area (population density of Rome 2231.5 inhabitants per square kilometre; ISTAT, 2024) with significant river run-off due to the presence of the Tiber River (Cesarini et al., 2023; Crosti et al., 2018; Inghilesi et al., 2008; Noce et al., 2013) was found to deliver the majority of plastic litter to the considered area.

The analysis of landing data has revealed that 16 species are fished in this area. Of these, nine are considered key species in commercial fisheries in terms of landings and economic values (FAO, 2022). The catch distribution identified in this study follows the general pattern of Lazio fishing activities; indeed, in this region, the trawling effort is evenly distributed on the platform and the continental slope. Smaller boats typically operate on the platform and target hake (*Merluccius merluccius* - HKE), red mullet (*Mullus barbatus* - MUT), Shortfin squid (*Illex coindetii* - SQM), and curled octopus (*Eledone cirrhosa* - EOI), while larger boats mainly operate on the slope, with an activity aimed at pink shrimp (*Parapenaeus longirostris* - DPS), red shrimp (*Aristaeomorpha foliacea* - ARS), blue shrimps (*Aristeus antennatus* - ARA) and Norway lobster (*Nephrops norvegicus* - NEP) (Cataudella and Spagnolo, 2011). This division of labour and targeting of resources is indicative of the physical capabilities of the fishing fleet, as well as the economic optimisation of fishing strategies in the region. It aligns with broader trends in Mediterranean fisheries, where species distribution, vessel type and fishing techniques are closely linked to maximise yield while responding to ecological constraints and market demand. The significance of slope fisheries is particularly notable, as they often yield species with higher economic value, playing a crucial role in sustaining the profitability of local fishing industries (Rinelli et al., 2013; Gorelli et al., 2016). This underscores the importance of spatially explicit management practices to ensure the sustainable exploitation of both platform and slope resources.

Thereafter, the model used effectively detected changes in fishing productivity caused by plastic accumulations on the seabed. The Generalized Additive Model (GAM) indicates that litter on the seabed could reduce the revenues of commercial fishing activities. Indeed, a significant decline in revenue was observed as the quantity of plastic on the seafloor increased. This result could be attributed to several mechanisms:

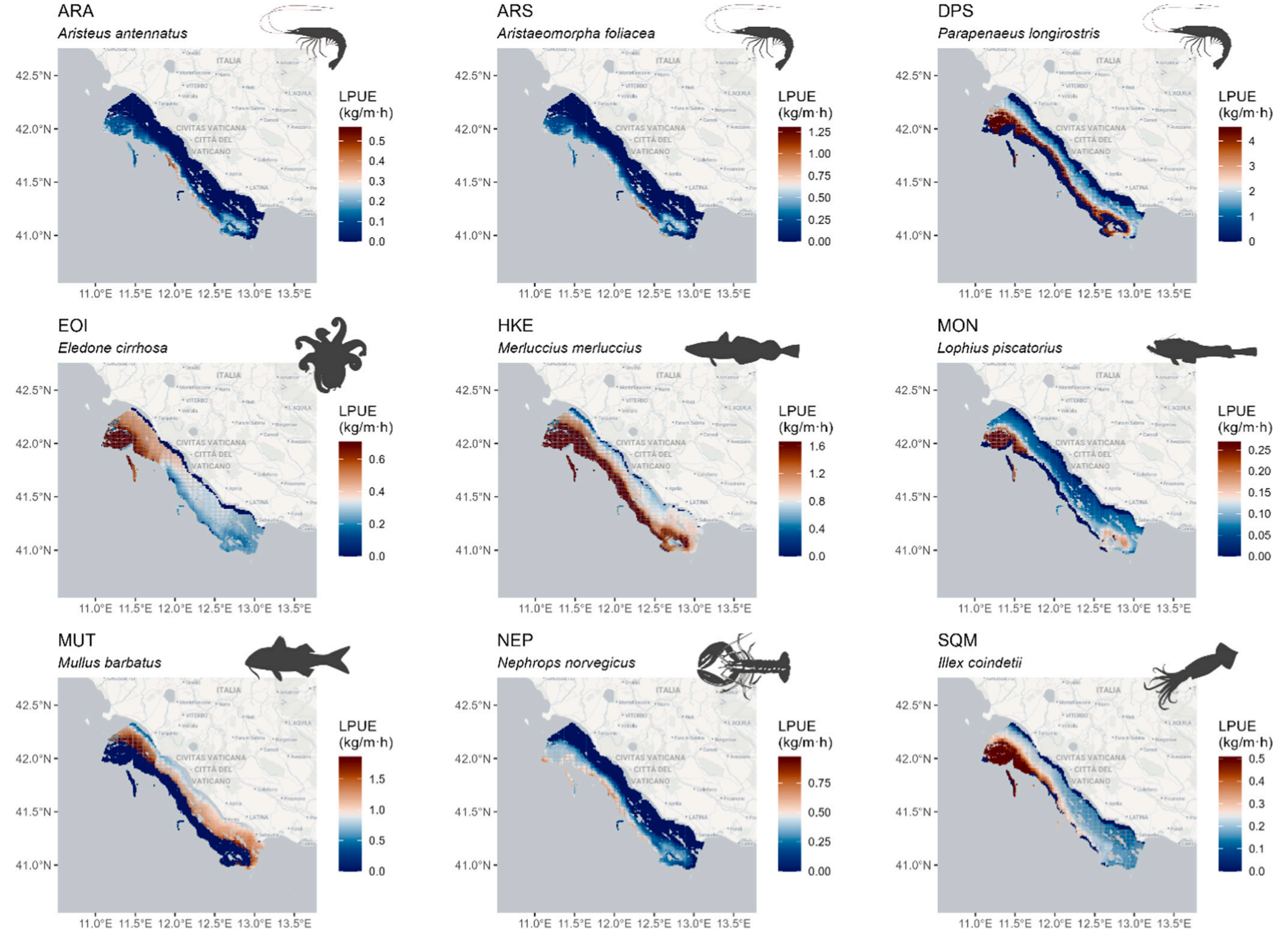

Fig. 2. Map of landing per unit effort (LPUE, kg of landing/m of vessel length/hours of fishing) for 9 important commercial trawling species in the central Tyrrhenian Sea (GSA 9).

1. Impact on marine resources: Pollution directly affects living resources, which indirectly reduces fishing productivity. Areas with high litter accumulation could probably exhibit lower fish abundance and reduced fish diversity, as plastic debris on the seabed disrupts essential habitats, negatively affecting fish populations and their reproduction cycles (Sbrana et al., 2020; Thushari and Senevirathna, 2020). It is possible to hypothesize that high levels of waste interfere with resource availability and could cause a decline in demersal resources. This decline could be due to direct impacts on the resource and secondary effects on the species (Nguyen & Brouwer, 2022). Plastic waste accumulating on the seabed can interfere with the activities of benthic organisms, such as their search for food, which can have secondary effects on their growth and survival. A previous study demonstrated that fishing effort and seafloor litter impact species composition and diversity. The adaptive traits of marine species played a critical role in their response to debris accumulation and fishing activities: mobile species appeared to use relocation strategies, sessile species showed flexibility in the face of disturbance, while epibiotic species relied on passive transport (Sbrana et al., 2024).
2. Impact on fishing operation: Pollution directly impairs fishing activities. The presence of marine litter in fishing nets can reduce their catch efficiency, cause damage to the gear, reduce the time available for fishing operations, inflate repair expenses, interfere with equipment functionality, and increase fuel consumption due to the added drag (Beaumont et al., 2019; Ivar Do Sul and Costa, 2014; Mghili et al., 2023). These economic and operational challenges underscore the multifaceted impact of marine litter on the fishing industry.

Both of these factors can act synergistically in reducing the economic profitability of fishing activities.

Further investigation is required to fully understand the non-linear effect of plastic litter abundance on revenues. Notably, trawling practices may contribute significantly to the redistribution of plastic waste, often displacing plastic hotspots on the seabed and intensifying the problem (Franceschini et al., 2019). It is reasonable to expect a certain level of litter abundance in areas with high trawling intensity, given that the activity itself may inadvertently increase seafloor litter. Conversely, it is less likely to observe high values of LPUE in areas without litter, especially in historically overexploited regions. This dynamic suggests a reciprocal influence between fishing intensity and the quantity of seafloor litter, where increased fishing activity contributes to plastic pollution. In turn, the presence of plastic negatively affects fish populations and, subsequently, fishing productivity.

In this study, LPUEs were used as an indicator of the availability of fisheries resources in the environment, and despite we did not directly assess the impacts of seafloor plastic on the species, we were able to identify varying levels of risk of exposure across different species and their abundances. Indeed, we assigned a probability of impact (IS) to each species based on their habitat preference and distribution in relation to the accumulation of seafloor litter. For example, the highest probability of exposure and impact from seafloor debris was found for

Table 1

Generalized Additive Model results used to identify the correlation between trawling revenues (response variable) and seafloor litter hotspots (explanatory variable). The model incorporated fishing hours, species-specific LPUE (Landings Per Unit of Effort, kg of landing/m of vessel length•hours of fishing), environmental variables (distance from the coast and depth) and seasons as significant factors affecting economic productivity.

Component	Term	Estimate	Std Error	t-value	p-value	
A. parametric coefficients	(Intercept)	5.399	0.007	750.318	0.0000	***
	SpeciesARS	0.603	0.008	75.030	0.0000	***
	SpeciesBOG	−5.012	0.019	−265.748	0.0000	***
	SpeciesCTC	−1.028	0.009	−113.070	0.0000	***
	SpeciesDPS	0.105	0.013	7.912	0.0000	***
	SpeciesEDT	−2.081	0.010	−209.069	0.0000	***
	SpeciesEOI	−0.833	0.008	−101.169	0.0000	***
	SpeciesHKE	−0.412	0.009	−44.337	0.0000	***
	SpeciesHOM	−3.787	0.011	−337.826	0.0000	***
	SpeciesMON	−1.734	0.009	−196.159	0.0000	***
	SpeciesMTS	−1.445	0.009	−153.352	0.0000	***
	SpeciesMUR	−2.182	0.009	−235.021	0.0000	***
	SpeciesMUT	−0.736	0.011	−69.866	0.0000	***
	SpeciesNEP	0.698	0.008	87.683	0.0000	***
	SpeciesOCC	−0.597	0.009	−67.304	0.0000	***
	SpeciesSQM	−0.913	0.008	−111.887	0.0000	***
	SeasonSpring	0.128	0.003	39.739	0.0000	***
	SeasonSummer	−0.134	0.004	−37.643	0.0000	***
	SeasonAutumn	−0.109	0.003	−34.377	0.0000	***
Component	**Term**	**edf**	**Ref. df**	**F-value**	**p-value**	
B. smooth terms	s(Litter)	1.998	2.000	4698.030	0.0000	***
	s(IS)	1.998	2.000	16,125.481	0.0000	***
	s(fishing.hours)	1.998	2.000	222,996.515	0.0000	***
	s(LPUE)	1.999	2.000	4007.685	0.0000	***
	s(dCoast)	1.994	2.000	127.906	0.0000	***
	s(Depth)	1.995	2.000	106.530	0.0000	***

Signif. codes: 0 < = ' *** ' < 0.001 < ' ** ' < 0.01 < ' * ' < 0.05
Adjusted R-squared: 0.771, Deviance explained 0.89
GCV: 2.573, Scale est: 2.764, N: 209488

Mullus barbatus (MUT). This species represents a significant component of the demersal assemblages inhabiting the Mediterranean continental shelf (Colloca et al., 2003; Esposito et al., 2014). Moreover, this species has a high commercial value, representing one of the primary targets of fishing activities in the Mediterranean Sea (Stergiou et al., 2003). Plastic exposure could be amplified by the feeding modalities that either increase or decrease a species' likelihood of ingesting plastic. *M. barbatus* could be highly susceptible to ingesting plastic as it is a demersal, sedentary species that exhibits fidelity to its benthic habitats (except for inter-depth migration related to reproduction), with a diverse diet including three major benthic invertebrate groups (polychaetes, decapods and small crustaceans) (Carreras-Aubets et al., 2012). For instance, several studies have documented the ingestion of plastic by this species (Anastasopoulou et al., 2018, Giani et al., 2019; Valente et al., 2022). In contrast, blue shrimp, *Aristeus antennatus* (ARA), and *Aristaeomorpha foliacea* (ARS) were found to be the species with the lowest risk of impact. These species are an essential component of the deep-sea food web and inhabit muddy bottoms of the continental slope, with a great abundance at around 1000 m depth (Sardà et al., 2004). The low-impact risk of the species was likely due to their distribution; indeed, we observed a high concentration of plastics in the coastal zone, while they were present in low concentration in the deeper areas.

Within the scope of this research, seafloor plastic data and LPUE (as a proxy of habitat suitability for each species examined) were used for the first time to map fishing grounds according to levels of anthropogenic contamination. This approach provides a novel framework for evaluating the spatial overlap between marine litter and fishing activities, highlighting areas where plastic pollution could pose significant threats to marine biodiversity and commercial fisheries. Previous studies have attempted to identify plastic exposure hotspots using numerical models of floating plastic, species distribution maps, and literature reviews of plastic ingestion (Compa et al., 2022, 2019). While these studies have contributed valuable insights, they predominantly focus on surface and water-column plastics, which exhibit higher mobility due to ocean currents, winds, and other environmental factors, potentially leading to less localized impacts. A key innovation of our research lies in using a spatial distribution model for plastic on the seafloor. Unlike floating plastic, which is subject to wide dispersal, seafloor plastic has limited mobility, remaining closely tied to its deposition sites. This characteristic allows for a stronger and more stable connection between plastic pollution and its impact on benthic habitats. It enables a more precise predictive model of its ecological and economic consequences. By incorporating high-resolution spatial data on plastic accumulation on the seabed, this research offers a more accurate representation of the intersection between anthropogenic contamination and fisheries productivity, contributing to the development of targeted management strategies. Additionally, this novel approach addresses the knowledge gap in understanding the long-term accumulation of plastic in benthic environments, which is often overlooked in studies focusing on surface plastics. Since seafloor plastic may interact with fishing gear, damage essential habitats, and alter benthic community structures, this methodology opens new pathways for assessing the localized effects of marine litter and designing mitigation measures tailored to high-contamination fishing grounds.

5. Conclusion

A distinct separation between plastic debris and fishing activities was identified in the study area. Such categorization simplifies the recognition of areas characterized by different levels of accumulation and serves as a primary reference for understanding the spatial distribution of marine debris and fishing activities. This research could provide

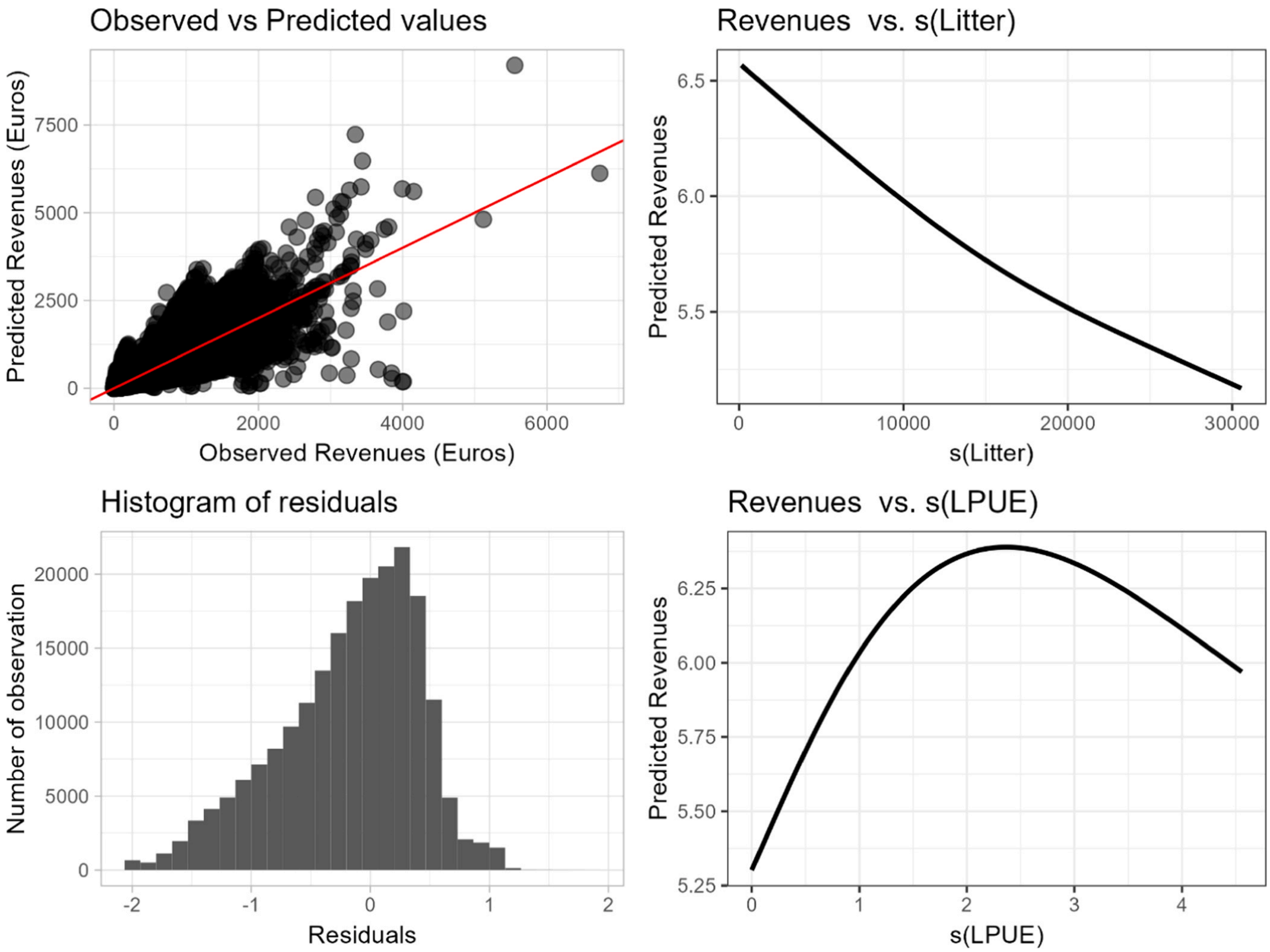

Fig. 3. Summary of the Generalized Additive Model (GAM) results used to identify the correlation between trawling revenues (response variable) and seafloor litter hotspots (Litter - explanatory variable), and incorporating fishing hours, species-specific LPUE (Landings Per Unit of Effort), and seasons as significant factors affecting economic productivity. The results comprise a comparison of the observed and GAM-predicted values of trawling revenues in Euros, a histogram depicting the model residuals, and an analysis of the effects of fishing hours and seafloor litter on revenues.

essential information for designing effective conservation and management strategies to mitigate the impact of litter on marine ecosystems in the Lazio region. The proposed mapping of litter hotspots provided valuable tools for ongoing monitoring efforts, in line with European directives, and highlighted the need for adapted approaches based on habitat type and spatial distribution. Seafloor litter was found to seriously endanger the sustainability and profitability of commercial fishing, along with the health and well-being of the species. Our research has identified areas and species that are at high risk of exposure and impact. The goal of the study was to encourage new research to focus sampling and monitoring efforts in targeted areas where the risk of impact has been assessed. Future research could investigate whether these species are directly or indirectly contaminated, which is important for assessing and monitoring the impact of marine litter (MSFD descriptor 10). The implications of these findings extended beyond scientific inquiry and reached into the field of resource management in the Lazio region. Recognizing waste as a potential threat to economic productivity may encourage fishing community participation in waste monitoring and removal efforts (Forleo and Romagnoli, 2023). Additionally, the study recommended establishing a threshold level of seafloor litter density as a practical approach to ensuring the sustainability and profitability of commercial fishing operations in the face of evolving environmental challenges. Therefore, this study provided practical insights for policymakers, stakeholders, and the fishing community providing a framework for further research, collaboration, and innovation to protect the delicate balance of the central Tyrrhenian Sea’s marine environment.

CRediT authorship contribution statement

Sbrana Alice: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Galli Simone:** Writing – original draft, Methodology, Data curation. **Russo Tommaso:** Writing – original draft, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation.

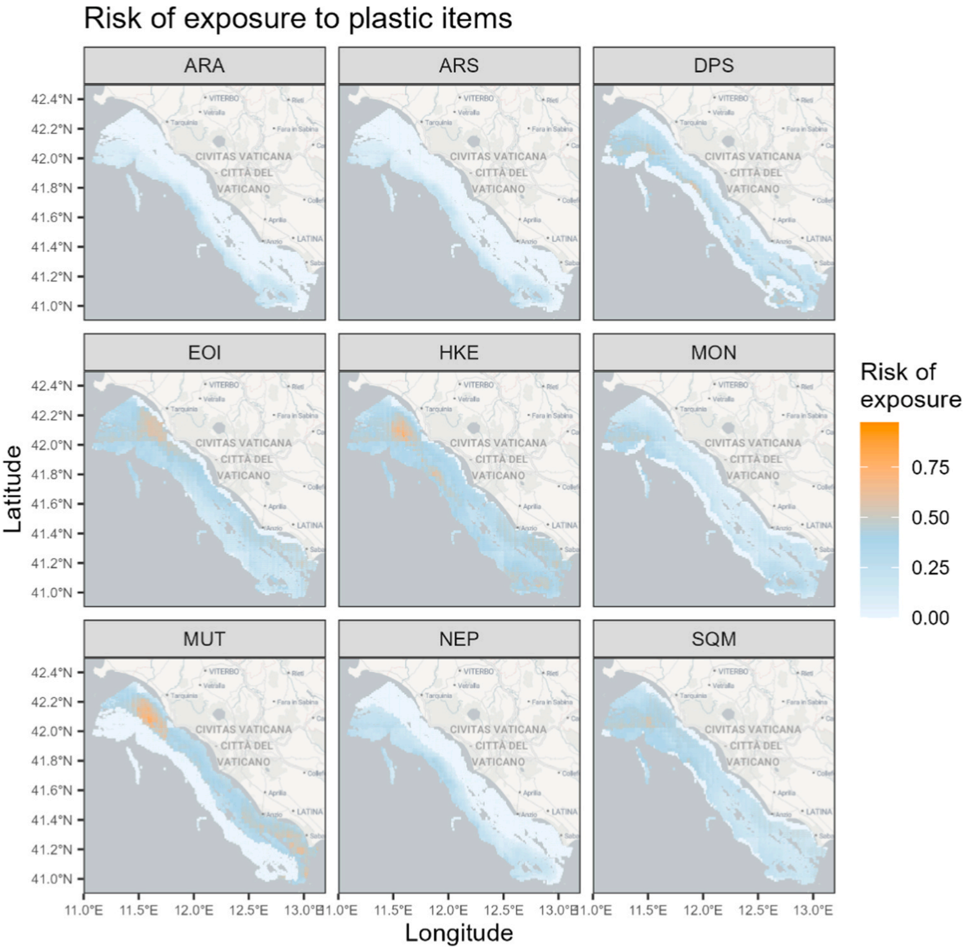

Fig. 4. Maps of risk of exposure to seafloor plastic for 9 commercial important trawling species in the central Tyrrhenian Sea (GSA 9). This was achieved by multiplying the LPUE of each species and the plastic litter cells.

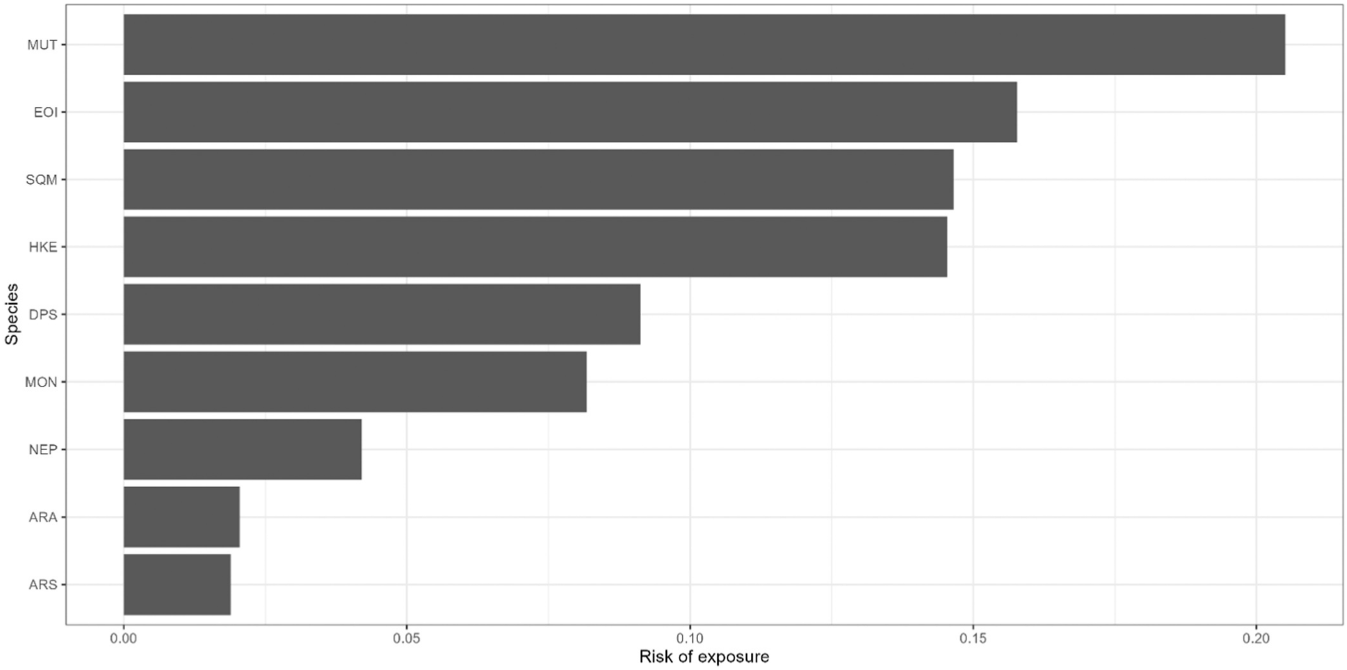

Fig. 5. Impact score (IS) results. IS was considered an indicator of the probability that a species could be affected by the accumulation of waste on the seabed for 9 commercial important trawling species in the central Tyrrhenian Sea (GSA 9).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2025.107346.

Data Availability

This study utilized metadata prepared within the activities of the Italian Workplan for the EU Data Collection Framework. Access to these data is governed by EU Regulation 2017/1004. To request access, contact the "Direzione Generale della Pesca Marittima e dell'Acquacoltura" at the Italian Ministry of Agriculture, Food Sovereignty and Forests (MASAF). A data request template is available at the DCF-Italian website (https://dcf-italia.cnr.it/#/dati).

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