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Quantifying the risk of plastic ingestion by ichthyofauna in the Balearic Islands (western Mediterranean Sea)

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ABSTRACT

This study investigates the risk plastic debris ingestion poses to coastal marine taxa in the Balearic Islands in the western Mediterranean Sea. Here, we use species observations and environmental data to model habitat maps for 42 species of fish. For each species, we then match estimates of habitat suitability against the spatial distribution of plastic debris to quantify plastic exposure, which we further combine with species-wise ingestion rates to map the risk of plastic ingestion. The results indicate that the risk of plastic ingestion is particularly high in the north-west and south-east regions and the risks varied strongly between species, with those at higher trophic levels being the most vulnerable overall. Extending this work to other coastal regions within the Mediterranean Sea and beyond will allow managers and policymakers to target the most appropriate areas and types of interventions for mitigating plastic pollution on coastal diversity in the marine environment.

1. Introduction

Marine ecosystems worldwide are vulnerable to impacts from human activities ranging from resource extraction, maritime transport, coastal development to terrestrial waste water input, among others (Coll et al., 2010). This combination of threats is leading to a decline in biodiversity worldwide, with plastic pollution identified as one of the seven main drivers of biodiversity loss (climate change, ocean acidification, hypoxia induced by eutrophication, seabed damage, overexploitation of biotic resources, invasive species, and marine plastic debris) (Woods et al., 2018).

Plastic pollution has been reported to cause adverse effects on the health and well-being of marine fauna through ingestion, entanglement and colonization (Jacobsen et al., 2010; Deudero and Alomar, 2015; Nauendorf et al., 2015) across different taxonomic groups: fish and elasmobranchs (Romeo et al., 2015; Solomando et al., 2020), invertebrates (Aliani and Molcard, 2003), mammals (Fossi et al., 2012, 2017), seabirds (Codina-García et al., 2013) and marine reptiles (Darmon et al., 2017; Tomás et al., 2002). Scientific literature in recent years has defined plastic ingestion as either direct, where marine organisms actively ingest plastic items, or indirect, for example through trophic transfer when ingesting prey. Ingestion of plastic can lead to toxic substances, (*e.g*: organochlorine pesticides, polychlorinated biphenyls) being transferred from benthic species (e.g. sea urchins) to species in higher trophic levels (e.g. Atlantic bluefin tuna *Thunnus thynnus)* (Feng et al., 2020; Guerranti et al., 2016; Rios-Fuster et al., 2021). Cases of entanglement, especially from derelict fishing gear, are increasingly common and have been reported in >40 species of marine mammals, reptiles, and elasmobranchs (Stelfox et al., 2016). Entanglement may also cause habitat loss through physical damage - especially in sessile species (Consoli et al., 2019) – as well as bycatch of non-target commercial species. These negative effects can result in direct and indirect economic costs to fisheries (NOAA Marine Debris Program, 2015). In addition to mortality resulting from plastic ingestion (and associated contaminants) and entanglement, sublethal effects on marine fauna can range from decreased physical function and health in organisms lower in the food chain, such as zooplankton, to increased toxicological stress, for example, in fin whales (Cole et al., 2013; Fossi et al., 2016). Concerns about the recent impacts of marine plastic debris on ecosystem health make it crucial to further identify the magnitude and severity of plastic-

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related threats in marine environments. Coastal ecosystems, which host key marine communities, are of special interest for studies on plastic impacts, especially since human pressures are generally more acute in coastal areas (Coll et al., 2012; Compa et al., 2019a).

Growing research has highlighted the Mediterranean Sea as a major global hotspot for marine plastic debris, both on the seafloor and on the sea surface (Deudero and Alomar, 2015; Lebreton et al., 2012; Macias et al., 2019; Spedicato et al., 2019). Identifying the levels of risk of marine stressors to which biodiversity is exposed is currently a focus of legislation in the European Union. This legislation aims for member states to achieve and maintain a Good Environmental Status (GES) of marine and coastal waters within the European Marine Strategy Framework Directive (MFSD) (Directive 2008/56/EC; Galgani et al., 2016). Furthermore, the European Parliament has recently approved the directive on reducing the impact of certain plastic products that are most commonly found on European beaches and in the environment by promoting sustainable alternatives (Directive 2019/904/EU).

In the western Mediterranean Sea, the Balearic Islands (Fig. 1A) form an archipelago located between southern Europe and northern Africa, lying between the northern current, which flows into the Balearic Basin from the northwestern Mediterranean region, and the Mesoscale gorge of Algeria, which flows from the Algerian Basin to the south of the islands (Lüdmann et al., 2012). In recent years, this area has become vulnerable to several impacts, ranging from various human activities such as tourism, recreational and commercial fisheries, and plastic pollution. The Balearic Islands are a hotspot for marine diversity and plastic ingestion has already been documented in several species of osteichthyes, elasmobranchs, crustaceans, and cephalopods (Alomar et al., 2020; Deudero et al., 2011). Furthermore, evidence of plastic debris ingestion by marine taxa of key commercial and ecological species has been reported in this area with ingestion values ranging from 16.8 to 68 % of sampled individuals, depending on the species considered (Rios-Fuster et al., 2019; Alomar et al., 2020; Nadal et al., 2016). Additionally, plastic debris has been identified on the seafloor of marine protected areas in the Balearic Island archipelago despite its protection status (Alomar et al., 2016; Compa et al., 2022) as well as in deep areas, exposed to fishing activities and up to 800 m depth and a distance of 21 nautical miles from the coast, giving further evidence of the potential transport of plastic debris to end-source areas (Alomar et al., 2020). In addition to seafloor debris, floating plastic debris on the sea surface is relatively common in the coastal waters of the Balearic Islands. To mitigate the presence of marine debris, the local government has been funding a boat service to perform a daily cleaning of floating plastics at sea during the summer months from 2005 onwards (Compa et al., 2019b). This latter study highlighted the existence of accumulation areas for floating plastic items within the coastal waters of the Balearic Islands, which were further characterized by sea surface net tows of floating microplastic particles in 2017 (Compa et al., 2020). The combined evidence of plastic ingestion by wild species and the presence of debris within all marine environments emphasizes the need for coastal management programs to protect marine diversity against this growing anthropogenic threat.

With increased reporting of plastic in the marine environment, one way to quantify the threat of a stressor to marine fauna is through risk assessment models. Such frameworks have previously been applied to quantify the threat of stressors such as plastic pollution or marine traffic worldwide and in the Mediterranean Sea for cetaceans, fish, sea turtles, and seabirds (Compa et al., 2019a; Guerrini et al., 2019; Pennino et al., 2017; Schuyler et al., 2016). Species-specific risk assessments for larger marine mammals, such as in Fossi et al., 2017, highlight the convergence areas between fin whale feeding grounds and plastic debris in the Pelagos Sanctuary, which was also confirmed with numerical models in Guerrini et al., 2019. Additionally, Compa et al., 2019a identified coastal regions as areas of high risk for marine diversity in the Mediterranean Sea and the 3D model highlighted coastal habitats to be especially vulnerable in the Western Mediterranean, Eastern Adriatic and the Aegean Sea (Soto-Navarro et al., 2021). Moreover, small-scale risk assessment from Alomar et al., 2020 highlights the overlap in seafloor plastic litter and ingestion in benthic and demersal species in the coastal region of the Balearic Islands.

In this study, our objective was to predict the exposure of coastal marine diversity to marine plastic in the coastal regions of the Balearic Islands archipelago. To assess this, a risk assessment framework scheme was followed that considers the following fourfold approach (Fig. 1B): 1) literature review of the literature on reports of marine species ingesting plastic debris, 2) development of habitat suitability maps for the

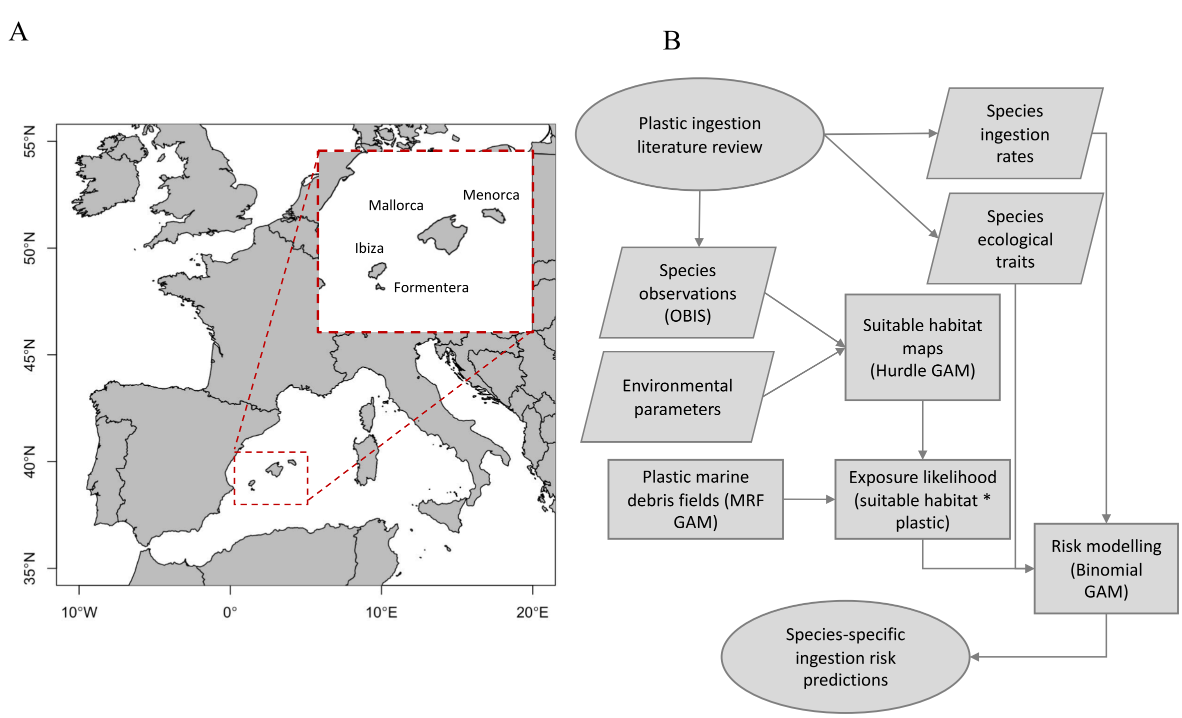

Fig. 1. The study area of the Balearic Islands (A) and conceptual framework of the risk assessment analytical strategy (B).

identified species in the region, 3) modelling of the distribution of coastal macroplastic debris from long-term empirical data, and 4) prediction of the risk of plastic ingestion by likelihood of exposure for each of the species (incorporating plastic ingestion rates and ecological traits).

2. Materials and methods

2.1. Literature review

A literature review of studies reporting the occurrence of ingestion in marine species was carried out using the Web of Science search engine and a combination of the following terms: 'microplastics and fish and Mediterranean' and 'marine debris and fish ingestion and Mediterranean' accessed on March 18, 2020. Given that only a regional area was the target, the Balearic Islands, the number of studies included in the four-fold modelling approach was broadened to include all studies throughout the Mediterranean Sea for fish, sharks, and rays indicating ingestion and number of individuals with plastic items in their stomach contents as well as the total number of individuals sampled. To consider ecological traits, the habitat of the species (pelagic and demersal) and their trophic levels, available data from "FishBase" (http://www.fishbase.org/search.php), were also considered for risk assessment. Additionally, it is important to mention that although the literature review identified many species, considering the western Mediterranean Sea is surrounded by non-English speaking countries, more observations published in other languages in addition to reporting from the gray literature were beyond the scope of this study, but could be included in future global assessments.

2.2. Habitat suitability modelling

For each of the species assessed found to have ingested plastic marine debris from the literature review ($n = 54$), habitat suitability maps were modelled following steps adopted from previous species distribution modelling approaches, which combine species observations and environmental data, as well as model evaluation techniques (Eese et al., 2005; Kaschner et al., 2013; Potts and Elith, 2006; Wintle, 2016). Species observations were acquired from the OBIS website using the openly available 'robis' package (Provoost and Bosch, 2018). Quality assurance was carried out to ensure that no duplicate entries from reported species observations were included. Although all species included in the bibliographic research on plastic ingestion are confirmed residents of the coastal area of the Balearic Islands, the study area for species observations acquired from the OBIS website was broadened using a 500 km buffer to include data found within the western Mediterranean Sea. The buffer area was grid into a cell size of 0.1° x 0.1° and OBIS observations were summed for each cell with presence observations. For cells without presence observations, we assigned background absence data to the fixed grid across the spatial extent (Phillips et al., 2009; VanDerWal et al., 2009).

To model the potential presence of species from observations when identifying suitable habitats in the Balearic Islands and western Mediterranean Sea, a two-part generalized additive model (GAM) with a zero-inflated Poisson model was used (Guisan et al., 2002; Hegel et al., 2010; Potts and Elith, 2006; Wood et al., 2017). These models can account for many zeros considering that either zero individuals can be found either due to lack of habitat suitability or that individuals are present but not found at the time of observation (Zuur et al., 2009). This included a two-item list of a zero-inflated Poisson model with the first linear predictor controlling for the potential presence of the species and the second linear predictor controlling the mean conditional on the presence of the species modelled with the first linear predictor (Wood, 2017; Wood et al., 2017). For the first part of the model, the following environmental predictors were used and rescaled to a cell size of 0.1° x 0.1°: mean sea surface temperature June–August from 2012 to 2017 (SST, °C), mean Chlorophyll-a for June to August from 2012 to 2017 (Chl-a; mg/m^3), sea surface salinity (SSS), slope of the seabed (°), bathymetry (m) and latitude and longitude of the observation (°) and distance to the coast (m) (see Fig. 2 and SI Table 1 for further description of each predictor). We include Chl-a concentration and mean SST to predict potential habitat of species during the summer months (June to August). To accommodate the large number of zeros, low order penalties were used for each covariate and a Duchon spline was used for the isotropic smooth on the spatial data. For the second part (control of the mean condition), a logit model predicting each species' presence, the mean distance to all grid cells with species data was incorporated as a smooth. For each species, the convergence of the model was checked and the predictions were projected onto a grid of 0.1^o by 0.1^o and clipped for the coastal range of the Balearic Islands using a 5 km buffer of the coastline of the Balearic Islands and rescaled to range from 0 to 1.

2.3. Modelling of plastic marine debris

Data on floating marine plastic debris collected between 2005 and 2017 along the coastal areas of the Balearic Islands were used to model the plastic debris field. The modelling approach is based on previous work analysing and understanding the quantities and patterns of floating coastal plastic debris along the Balearic Island (Compa et al., 2019a). This program during which the debris was collected consists of daily surveys from June to September (inclusive) onboard 23 to 33 boats, varying yearly. Coastal floating macro-debris data from the annual monitoring surveys conducted by the regional Balearic Government include nearshore surveys (up to 500 m from the coastline) and offshore (from 500 m to 5 km off the coast). Although the monitoring program includes different categories of floating marine debris, only plastic items were included in this study. For a full descriptive analysis of survey methodologies, see Compa et al. (2019b).

A GAM with a smooth Gaussian Markov Random Fields (GMRF) was used to create the plastic marine debris field for this study. GMRFs have recently been used for climate models to test for spatial dependencies (Nosedal-Sanchez et al., 2016). The yearly size of the surveyed area, wave height, and average onshore wind direction were considered smooth effects while island and month were included as fixed factors (Compa et al., 2019b) (see SI Table 2 for details). To determine which scenario of the onshore wind component best explained the distribution of plastic marine debris around the Balearic Islands, a full model was run that included GMRFs and year for five wind scenarios: average onshore wind direction for the previous day, 3 days, 5 days, 7 days, and 10 days. A null model without onshore wind and a hindcasting approach were applied following previous risk assessment methodologies (Wilcox et al., 2015). The best model was identified as the one having the lowest AIC (Akaike Information Criterion) value. Furthermore, the model was restricted to selecting only one wind predictor, using a correlation matrix to select the wind predictor with the highest standardized regression coefficient for each offshore wind and the residuals of the null model (model without any predictors). The relationship between the abundance of floating plastic marine debris (kg km^{-2}) and the covariates (see SI Table 2) including the best onshore wind coefficient was examined. Although coastal marine debris was collected throughout the time period, offshore marine debris was only collected from 2005 to 2010, therefore daily predictions were made for the years 2011 to 2017. The results of the prediction model were rescaled to sum to one across each 0.1° × 0.1° cell.

2.4. Quantifying species-specific ingestion risk

Species-specific habitat suitability maps and plastic debris distribution maps were then used to map the risk of exposure to plastic items within the spatial range of each species. The likelihood of exposure was evaluated for each species by multiplying the habitat suitability of each species and the rescaled plastic debris field within a cell using the

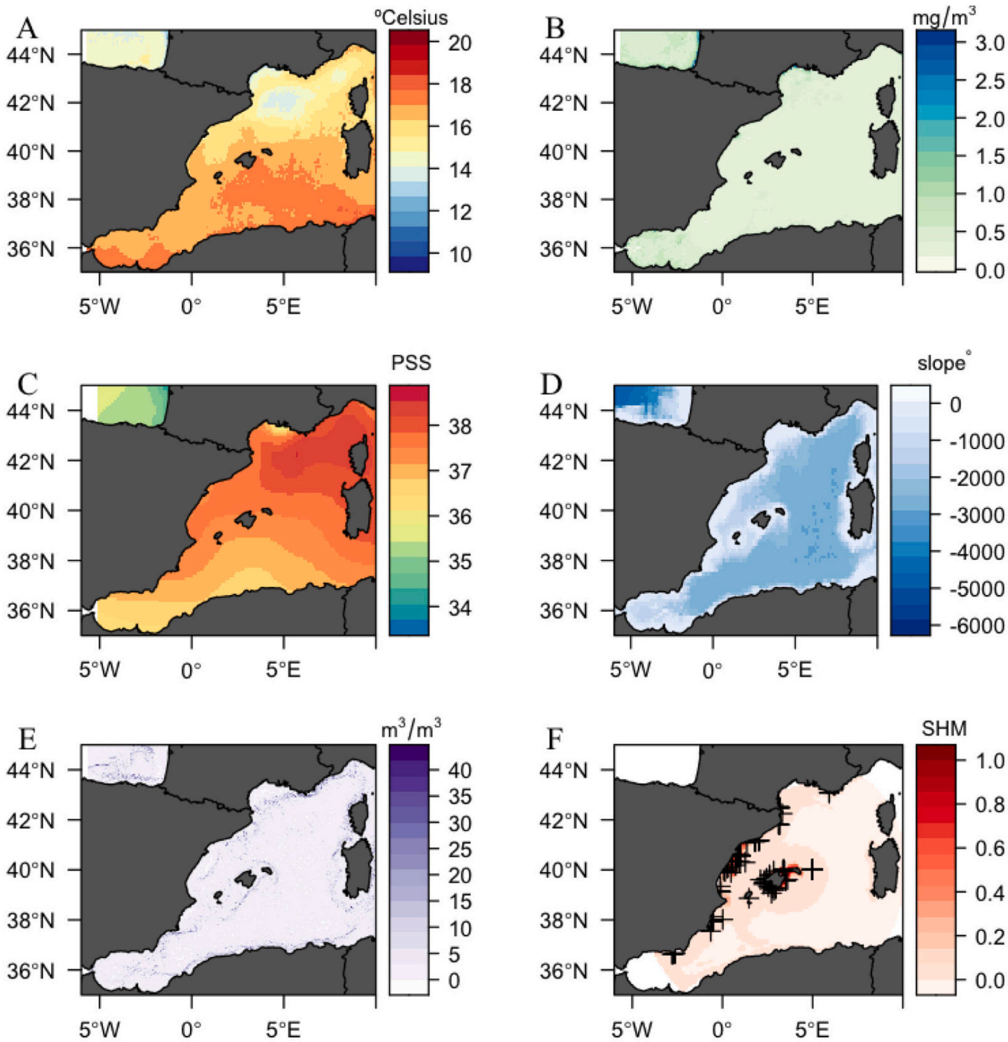

Fig. 2. Input data used in the modelling for habitat suitability for each of the selected species using a two part generalized additive model with a 500 km buffer surrounding the Balearic Islands: A) average sea surface temperature for June–August from 2012 to 2017 (NASA); B) average chlorophyll-a concentrations for June–August from 2012 to 2017 (NASA); C) sea surface salinity; D) bathymetry; E) slope; F) crosses indicate OBIS species observations for an example species *Chelidonichthys lucerna* and suitable habitat predictions for the example species *Chelidonichthys lucerna* incorporating the predictions at a 0.1° × 0.1° spatial grid. For further details of environmental data, please see SI Table 1.

Table 1
Summary of the backward stepwise approach for the Generalized Additive Model evaluated ingestion rates, plastic threat and ecological traits.

Model	AIC	Deviance explained	R-squared adjusted
M1: ingestion rates ~ median threat + trophic level + habitat	256.5	89.20 %	0.87
M2: ingestion rates ~ average threat + trophic level + habitat	393.9	74.40 %	0.65
M3: ingestion rates ~ median threat	513.3	59.80 %	0.58
M4: ingestion rates ~ average threat	578.7	52.90 %	0.51
M5: ingestion rates ~ 1	1060.7	<0.1 %	<0.1

Table 2
Summary of the results from the binomial Generalized Additive Model for the survey area considering habitat as a fixed term and the smooth terms for median plastic exposure and trophic level.

Parametric coefficients	Estimate	Std. error	Z value	*p*-Value
Intercept	2.9	0.25	11.94	<2e-16***
Habitat Pelagic	−0.01	0.25	−0.01	0.99

Smooth terms	Estimated df	Chi.sq	p-Value
Plastic threat (median)	8.94	118.9	<2e-16***
Trophic level	8.97	194.8	<2e-16***

following formula: habitat suitability * plastic debris fields. After quantifying exposure, the next step was to quantify the risk of plastic ingestion for each species considering exposure within the coastal region of the Balearic Islands and the ingestion rates and ecological traits of each species. We follow the IPCC definition of risk as a 'potential for adverse consequences' (Reisinger et al., 2020), here the ingestion of plastic debris as a combination of exposure and species vulnerability. For risk quantification, two modelling scenarios were explored, one with the average exposure for each species and the other with the median exposure for each species calculated across the coastal range for each species. A GAM with binomial distribution was used to determine the risk of ingestion of marine plastic debris for each species by considering the number of individuals with plastic in their gastrointestinal tract as the response variable for each exposure risk scenario, as well as incorporating ecological traits, such as habitat and trophic level of each species. The type of habitat for each species/scenario (demersal or pelagic) was considered a fixed effect and has been identified as an important predictor of risk (Compa et al., 2019a; Schuyler et al., 2016), while the trophic level of each species can indicate the possible transfer of marine plastic debris from one consumer to another (Rios-Fuster et al., 2019). A backward stepwise approach was considered and the best-fit model with the lowest AIC was used to predict the risk of exposure to ingestion of marine plastic debris.

For the best-fit model, the risk of ingestion between each species and the study area was calculated and determined by scaling the risk to the ingestion of marine plastic debris from 0 (lowest risk) to 1 (highest risk), providing a risk indicator for each species studied (Schuyler et al., 2016). The sum of the risk of all species determined the combined risk in marine diversity in coastal areas of the Balearic Islands. All analyses were performed using R version 3.2.3 (Team, 2014).

3. Results

3.1. Habitat and exposure modelling

Of the 54 initial species identified in the literature search, habitat suitability was produced for 42 species of fish, sharks, and rays that occur in the study region (SI Table 3). Each of the identified species was individually modelled and prediction maps were developed considering all environmental parameters for each species, integrating Chl-a, SSS, SST, depth, and the average distance of observations for habitat suitability maps (Fig. 2). In Fig. 2E, we have visualized the results for the suitable habitat of the *Chelidonichthys lucerna* fish species overlapped with the OBIS observations. The variability for each habitat model was species-specific, and the deviance explained for each model ranged from 21 % for *Phycis blennoides* to 91 % for *Phycis phycis* (SI Table 3). An example of the results from the GAM model for the species *Boops boops* can be found in SI Table 4. The sum of species diversity in the Balearic Islands varied and ranged from 3.3 to 23.6 species considering their suitable habitats, making it evident where the hotspots of marine diversity were identified along the northern and southern coasts of Mallorca (Fig. 3B).

When modelling the long-term floating macro-debris data, the most parsimonious model included all the predictor covariates and the average onshore wind direction for the previous 3 days (SI Table 2). In addition, calm seas with very low wave height improved the conditions for sea cleaning boats to function. Onshore wind was positively correlated with the increase in plastic debris collected.

3.2. Exposure

In this study, exposure (suitable habitat * plastic debris) indicates the probability that each species will encounter plastic debris during the summer months. There were areas of the Balearic Islands where high species diversity coincided with areas of high accumulation of plastic debris accumulation (Fig. 3A-C and 3D-F). While the northern region of Mallorca had high species diversity and high concentrations of plastic debris, the southern coasts of Mallorca and Menorca had high species diversity and low concentrations of plastic debris. The interlacing of each species and the field of plastic debris allowed us to identify areas of high exposure throughout the coastal region of the Balearic Islands, especially in the southern regions of Menorca and the northern bays of Mallorca (Fig. 3H and I). When considering exposure, the results indicate that between 1.7 and 21.8 of the identified species (42 species) are exposed to plastic marine debris within the 5-km coastal boundary in the Balearic Islands, especially in the coastal area of northern Mallorca and southern Menorca, coinciding with areas of high abundances of floating debris.

3.3. Quantifying risk

The risk of ingestion across taxa was assessed by combining ingestion rates from the literature, the exposure model, and ecological traits. Here we used a backward stepwise approach for both the average and median exposure of encountering marine debris (Table 1). The best-fit model included the median exposure model for plastic marine debris (GAM M1, AIC = 256.5) rather than the average encounter model (GAM M2, AIC =

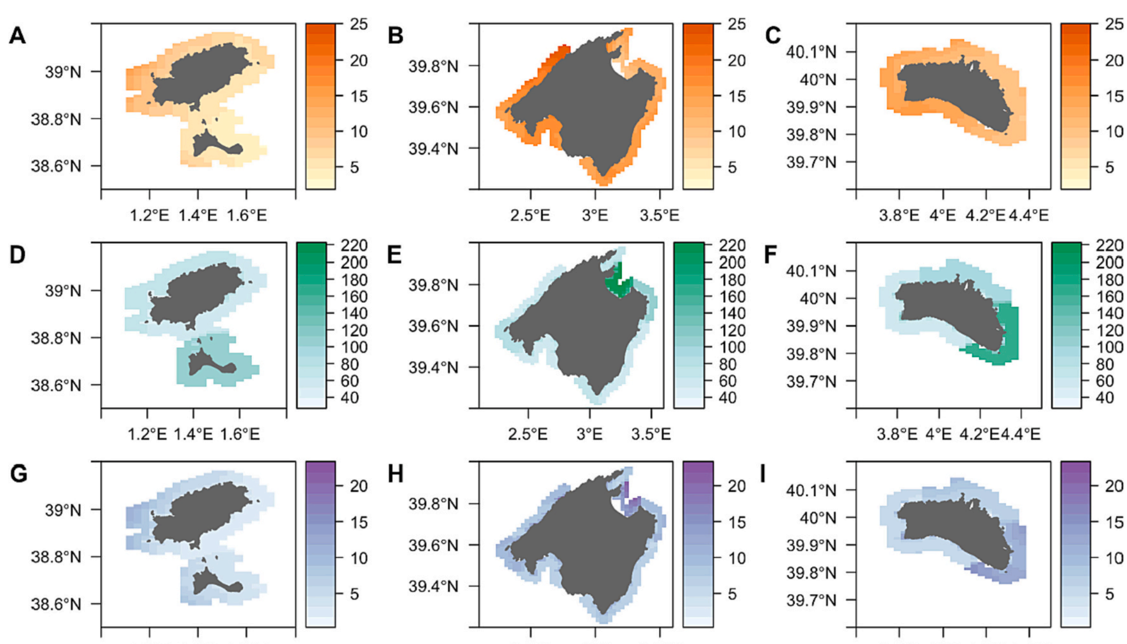

Fig. 3. A, B, C: Summed map of habitat suitability integrating all considered species ($n = 42$), with each species' individual suitability values rescaled from 0 to 1. D, E, F: Near- and offshore predictions of plastic concentration (kg/km^2) estimated by a GAM incorporating a Markov Random Field (original data: floating plastics debris collected over the 2005–2017 period). G, H, I: Summed map of plastic exposure likelihood, with each species' individual likelihood values rescaled from 0 to 1.

393.9), which explained >89 % of the deviance (Table 1). Even if ecological traits were not included (M3 and M4), between 50 and 60 % of the variance was explained by the model. In comparison, if the model did not include exposure or ecological traits, the model described <0.1 % of the variance.

For the best-fit model (M1), the trophic level (range = 2.8–4.5; median trophic level 3.5) was found to be a significant contributor in determining the risk of species to plastic debris ingestion (GAM, $p < 0.001$) (Table 2). Although the demersal species had a slightly higher risk of plastic ingestion, no significant differences were found between the pelagic and demersal habitats (GAM, $p > 0.05$).

The overall risk of plastic ingestion among the marine species modelled indicated a varying risk of between 25.9 and 38.9 species susceptible to plastic ingestion in the coastal region of the Balearic Islands (Fig. 4E). Spatially, areas of higher risk were found in Menorca and Mallorca islands compared to Ibiza and Formentera islands. There was variability between the risk of plastic ingestion among species, with some species at a higher risk, such as *Chelidonichthys lucerna* and *Trigla lyra*, while others, such as *Epigonus telescopus,* were found to be at a lower risk (SI Table 3). Pelagic species such as *Brama brama* had a very high median risk of plastic ingestion across its suitable habitat range (0.95), especially in the southern coast of Mallorca (Fig. 4A). In terms of trophic levels, species such as the golden gray mullet *Chelon auratus* and the boque *Boops boops* that had lower trophic levels (2.8) had median risks of 0.87 and 08.4. The black-mouthed catshark *Galeus melastomus* and the velvet belly lantern shark *Etmopterus spinax* had trophic levels ranging from 4.1 to 4.2 with very high median risks of 0.98 and 0.97. Species of high commercial value, such as *Sparus aurata* (median = 0.40) were found to have a slightly lower risk of plastic ingestion throughout the region, especially in the south-west coast of Mallorca and throughout Ibiza (Fig. 4B) and large migratory species, such as *Thunnus alalunga,* were at a high risk of ingesting plastics (median = 0.98) in the waters of Mallorca (Fig. 4C). Another commercially important species, *Trachurus mediterraneus* (median = 0.98) was also at high risk of ingesting plastic in its suitable habitat range (Fig. 4D). In general, the results indicate that, whether migratory or resident, most species are at high risk of ingesting plastic debris when feeding in the coastal waters of the Balearic Islands.

4. Discussion

Previous work has identified species that represent endangered, commercially, ecologically, and culturally important fish, sharks, and rays that are under threat from plastic ingestion. Most assessments have relied on the numerical modelling of plastic items using ocean currents and hydrodynamical models (Guerrini et al., 2019), however with this study, we improve and build on previous modelling approaches by incorporating empirical data from a long-term coastal monitoring

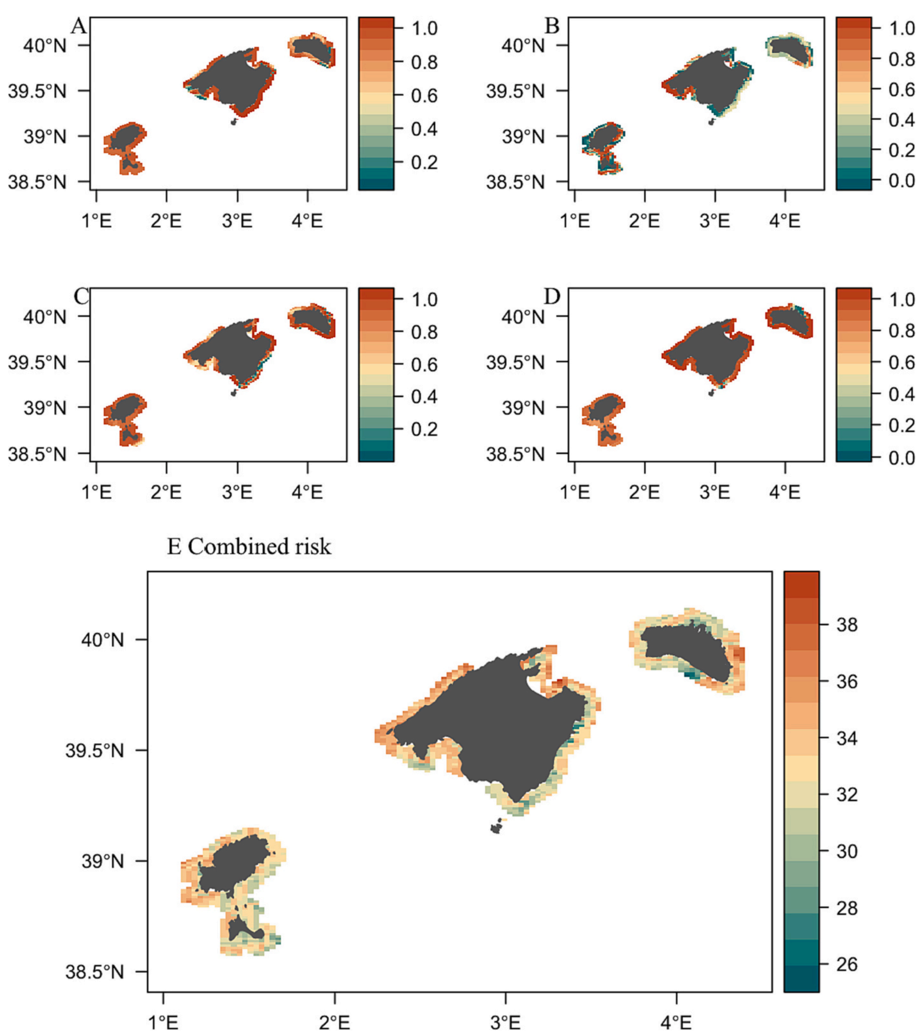

Fig. 4. Example maps of risk of ingestion of plastic debris for four selected species from the Generalized Additive Model binomial model: A) *Brama brama*, B) *Sparus aurata*, C) *Thunnus alalunga* and D) *Trachurus mediterraneus* and E) map of overall coastal risk (summed) of ingesting marine plastic debris in the Balearic Islands during summer months.

program which validate model predictions.

The bibliographic review identified 54 species inhabiting the coastal regions of the Balearic Islands, of which habitat suitability maps were developed for 42 of those species. By developing suitable habitat maps for this regional area, we were able to assign a quantifiable measure, which is an improvement to general presence/absence species distribution maps (Compa et al., 2019a; Schuyler et al., 2016; Wilcox et al., 2015). Potential hotspots for marine diversity were identified along the northwest coast of Mallorca and the southeast coast of Menorca, which coincides with persistent hotspot areas for fish habitat in this region (Tugores et al., 2019).

The modelling approach used to assess the spatial distribution of debris (plastic debris field) has improved on previous models by incorporating the effect of onshore wind and the neighbourhood structures over the discrete sampling areas. For example, during several days of offshore wind, no debris was found (SI Fig. 1), indicating that continuous offshore wind forces debris away from the coast and strong onshore winds displace debris closer to coastal areas. The Balearic Islands are known for onshore thermal winds, especially during the summer months, where the sea breeze only intensifies during morning hours, also known locally as ‘s'embat’ (Jiménez et al., 2016, 2015). Additionally, the modelling approach of our research allowed predictions to be made considering the large spatio-temporal data set provided on coastal plastic marine debris for the Balearic Island archipelago. Although this is the first time that GMRFs have been applied to model the distribution of plastic marine debris, such models have previously been preferentially applied to air pollution models to measure fine particulate matter (Sarafian et al., 2019). Here, by integrating empirical data collected from a long-term marine debris monitoring program and considering several predictor variables (onshore wind, time, island, etc.), we were able to provide a plastic debris map for the risk modelling approach of plastic ingestion rather than relying on numerical model simulations. This is an improvement over previous risk assessment models that have relied on numerical or theoretical simulations. Furthermore, since this study uses plastic collection data acquired daily over a large region and an extended period of time, predicted debris concentrations for the nearshore coastal areas are likely more accurate than those produced by simpler numerical models, which may fail to capture the complexity of nearshore hydrodynamics.

Additionally, it is essential to highlight the importance of using long-term empirical plastic data, not just in terms of modelling concentrations. Coffin et al. (2021) indicates that modelling marine plastics, specifically microplastics, does not fit within traditional risk-based regulatory frameworks because of their persistence and extreme diversity such as size, shape, and chemical properties associated with pollutants, which may result in high levels of uncertainty regarding exposure estimates and the negative consequences derived from exposure. Previous studies have highlighted the wide range of contaminants associated with marine plastics such as organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) and their effects on marine species (Moore, 2008; Rios-Fuster et al., 2021), although these studies are often species specific and more research is needed on the effects of plastics across different taxonomic groups under controlled laboratory studies to better understand their impacts on wild species.

By integrating our exposure, species-specific suitable habitat maps and the plastic debris field, we identified the best model to predict each species that encounters plastic throughout its range. The median exposure coincides with previous risk assessment models for marine diversity in the Mediterranean Sea (Compa et al., 2019a) and for risk assessments in sea turtles worldwide (Schuyler et al., 2016). In the present study, the final model to quantify the risk of plastic ingestion considered the integration of ecological parameters into the model, the trophic level and habitat, in combination with the median rate of plastic encounter. This is important because research has highlighted that exposure to plastic ingestion is variable according to sampling areas and the trophic level of species (Sbrana et al., 2020). For example, microplastic ingestion in species from the eastern Mediterranean region is higher than in the western coast (Alomar et al., 2020) and species with a more predator strategy ingest a more diverse variety of plastic items, including fibers and fragments than species with a filter feeder strategy (Compa et al., under review).

Trophic levels allow for conceptual and quantitative understanding of the roles of different species in different systems (Yodzis, 2001). Here, we found that species with higher trophic levels were potentially at a higher risk of ingesting plastics than species with lower trophic levels. Plastics have been reported to enter the digestive system of species through active predation of marine plastic by misidentifying marine plastic for food or through the transfer of plastics already ingested by prey, passing plastic from one trophic level to the next (Carson, 2013; Nelms et al., 2018). Furthermore, Rios-Fuster et al., 2019 reported microplastics in whole undigested sardines within the diet contents of Mediterranean horse mackerel while Farrell and Nelson, 2013 identified the translocation of microplastics to different tissues of crabs that ingested mussels spiked with microspheres. Taking this into account, further studies in both wild and controlled laboratory studies are needed to examine the impact across food webs, especially predator-prey relationships and species-specific plastic transfer.

The extensive bibliographic review in the Mediterranean basin indicated that pelagic species ingest higher amounts of plastic debris than demersal species, as suggested by the results of the present study, which has also been highlighted by other authors in other regions (Fossi et al., 2018; Lusher et al., 2013; Rummel et al., 2016) but again there is high variability in plastics ingestion between species. Similarly to previous studies, species habitats are a significant factor when determining exposure risk to marine plastic debris, and it has been illustrated in previous risk models for different taxonomic groups such as seabirds, sea turtles, and across marine diversity (Good et al., 2020; Schuyler et al., 2016; Wilcox et al., 2015). The results of the present study indicate that although they do not show significant habitat differences with pelagic species, demersal species are at a slightly higher risk of ingesting plastic debris, according to previous risk assessments across the Mediterranean Sea (Compa et al., 2019a) and also with field data where demersal and benthic organisms are ingesting larger amounts of plastics (Neves et al., 2015). Multi-species analyses are needed to truly identify and better understand how the physical characteristics of marine plastics, as well as associated chemicals, affect and contribute to the overall impact on marine organisms (Bucci et al., 2020; Fossi et al., 2018).

Overall, the calculated risk of plastic exposure/ingestion was quite high for most species and the risk extended throughout their coastal range, which likely has not only individual but potentially population-level impacts on affected taxa. Using the approach in this study, we identified areas of concern where species are at risk of ingesting plastics, including the northwestern coast of Mallorca and the eastern coast of Menorca. The north-western coast of Mallorca has also been suggested as a sensitive and vulnerable area to plastic pollution when simultaneously evaluating seafloor plastics and microplastic ingested in species of the same area (Alomar et al., 2020). Furthermore, species from the eastern coast of Menorca were also found to ingest higher amounts of microplastics than other deep sea species from the Balearic Islands (Alomar et al., 2020). Building on the results of previous research is necessary, including distribution maps that regional governments can use to refine management and conservation plans that protect species and habitats from further harm due to anthropogenic activities such as plastic pollution. Many species showing a high risk of plastic ingestion occupy regional waters of the Balearic islands seasonally, particularly those that spawn in this area, such as the pelagic fish species *Thunnus thynnus* (median risk of plastic ingestion = 0.81) (Druon et al., 2011), which has shown to have an increased risk of ingesting marine debris when entering these coastal areas. Furthermore, several of these species are currently considered endangered or almost threatened by the IUCN red list category. Other species that live closer to the seafloor, such as *Pagellus bogaraveo* (median risk of plastic ingestion = 0.97), currently listed as Near Threatened (IUCN), were found to be at relatively high risk of plastic ingestion. *Pagellus bogaraveo* is an omnivorous species primarily feeding on crustaceans, molluscs and small fish, all of which could be mistaken for microplastics. A congener of *Pagellus bogaraveo*, *Pagellus acarne*, was found to be one of the species ingesting the highest amounts of microplastics of the 45 species analyzed in the same study area (Alomar et al., 2020). Consequently, by having species-specific exposure maps, the protection of more exposed and affected species can serve as an umbrella in conservation efforts of other species; this way ecologically important species will indirectly benefit from protective measures.

Future studies would benefit from the integration of other threats to marine fauna, such as marine traffic, exploitation of marine resources, and fishing activities in addition to the coastal population and river discharge. Additional measures derived from potential threats to plastic debris, such as entanglement in lost, abandoned, or discarded fishing gear, are also relevant and should be considered when evaluating the risk of marine diversity to plastic exposure, as it has been directly linked to species mortality (Gilman, 2016). This is of particular concern, especially on a global scale, since increased gear loss has been associated with increased fishing effort (Richardson et al., 2019). The increased coastal population is also another major concern, especially when considering the seasonal flux of tourism, as areas in the Mediterranean Sea have seen an increase of up to 4.7 times more marine debris during the high season, along with an increased waste production of up to 75 % (Grelaud and Ziveri, 2020; Zorpas et al., 2015). In the Balearic Islands, during the summer months of June, July, and August 2019, almost 8 million tourists, more than four times the current 1.5 million residents (https://www.caib.es/ibestat), visited the archipelago, having a potential impact on natural resources and coastal ecosystems in the short, medium, and long term. Consequently, this increase in human capacity has the potential to increase the input of sewage including debris into marine systems, as the capacities of waste management systems are exceeded in many urban areas during the summer season.

Several species considered in this study are currently at risk of extinction, according to the IUCN Red List. A common reason for a species to enter the IUCN red list has been as a consequence of habitat loss or overfishing (Yan et al., 2021). Plastic ingestion and entanglement are currently not listed as threats on this globally accepted threat list. It is also worth considering an integrative approach that combines plastic entanglement and ingestion, as such an approach could provide a more in-depth understanding of how marine debris impacts biodiversity in oceans and coastal environments around the world.

The marine spatial planning legislation within the European Union (EU) calls for the identification of risks associated with human activities in habitats, in addition to the requirement of EU member states to address marine debris so that it does not cause any harm to ecosystems and ensures a Good Environmental Status (GES) of marine and coastal waters by 2020 (Descriptor 10, MSFD). In the Balearic Islands, efforts to mitigate these threats and preserve biodiversity range from the creation and amplification of Marine Protected Areas to the application of legislation related to debris (terrestrial) and contaminated grounds (refer to Ley 8/2019, de 19 de *febrero, de residuos and suelos contaminados of las Illes Balears* (BOE-A-2019-5577, 2020). In this sense, several areas have been identified as marine reserves, national and natural parks and natural areas of national interest in addition to Sites of Community Importance (SCI), Special Areas of Conservation (SAC) and Special Protection Areas (SPA) from the European Commission Habitats Directive (92/43/EEC) and Natura 2000 Management Plan. Considering several of these areas that are currently being managed, often the implemented measures do not specifically address plastic pollution. Taking into account the results of this study, risk maps can be a useful tool for managers to include in spatial management plans.

5. Conclusions

From this study, we observed that marine diversity is sensitive to plastic exposure in the Balearic Islands, especially in the northern coastal area of Mallorca. These risk maps highlight the areas of greatest concern, identifying target areas where mitigation measures can be carried out, especially when resources are limited. Studies such as this emphasize the need for coordinated conservation studies and initiatives between regional, subregional, national, and international governments to effectively develop measures to protect marine biodiversity from plastic pollution.

CRediT authorship contribution statement

MC: Conceptualization, methodology, formal analysis, writing – original draft.

CA: Conceptualization, methodology, formal analysis, writing, reviewing and editing.

DM: Methodology, writing, reviewing and editing.

DH: Methodology, formal analysis, writing, reviewing and editing.

CW: Methodology, formal analysis, writing, reviewing and editing.

SD: Conceptualization, methodology, supervision, funding acquisition, writing, reviewing and editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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