Science of the Total Environment 922 (2024) 171282

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Identifying potential high-risk zones for land-derived plastic litter to marine megafauna and key habitats within the North Atlantic

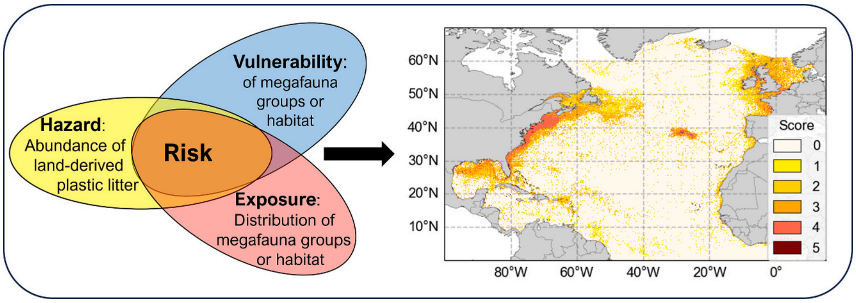
Samantha L. Garrard [a,*], James R. Clark [a], Nicola Martin [a], Sarah E. Nelms [b], Zara L.R. Botterell [b], Matthew Cole [a], Rachel L. Coppock [a], Tamara S. Galloway [c], Dannielle S. Green [d], Megan Jones [e], Pennie K. Lindeque [a], Heidi M. Tillin [a], Nicola J. Beaumont [a]

[a] *Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, United Kingdom*
[b] *Centre for Ecology and Conservation, University of Exeter, Penryn, TR10 9FE, United Kingdom*
[c] *Biosciences, Geoffrey Pope Building, University of Exeter, Stocker Road, Exeter EX4 4QD, United Kingdom*
[d] *Applied Ecology Research Group, School of Life Sciences, Anglia Ruskin University, Cambridge CB1 1PT, United Kingdom*
[e] *Marine Biological Association of the United Kingdom, The Laboratory, Citadel Hill, Plymouth, PL1 2PB, United Kingdom*

HIGHLIGHTS

- Risk of land-derived plastic to North Atlantic megafauna and habitats was assessed.
- Five high-risk zones (HRZs) were assigned through a Spatial Risk Assessment.
- Risk was driven by domestic sources in some HRZs and external sources in others.
- Litter from Caribbean islands is likely to be a significant source of plastic to HRZs.
- Identifying HRZs and sources of plastic could enable more efficient interventions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Damià Barceló

Keywords:
Marine plastic pollution
Land-derived plastic litter
North Atlantic
Marine megafauna
Biogenic habitats
Risk assessment

ABSTRACT

The pervasive use of plastic in modern society has led to plastic litter becoming ubiquitous within the ocean. Land-based sources of plastic litter are thought to account for the majority of plastic pollution in the marine environment, with plastic bags, bottles, wrappers, food containers and cutlery among the most common items found. In the marine environment, plastic is a transboundary pollutant, with the potential to cause damage far beyond the political borders from where it originated, making the management of this global pollutant particularly complex. In this study, the risks of land-derived plastic litter (LDPL) to major groups of marine megafauna – seabirds, cetaceans, pinnipeds, elasmobranchs, turtles, sirenians, tuna and billfish – and a selection of productive and biodiverse biogenic habitats – coral reefs, mangroves, seagrass, saltmarsh and kelp beds – were analysed using a Spatial Risk Assessment approach. The approach combines metrics for vulnerability (mechanism of harm for megafauna group or habitat), hazard (plastic abundance) and exposure (distribution of group or habitat). Several potential high-risk zones (HRZs) across the North Atlantic were highlighted, including the Azores, the UK, the French and US Atlantic coasts, and the US Gulf of Mexico. Whilst much of the modelled LDPL driving risk in the UK originated from domestic sources, in other HRZs, such as the Azores archipelago and the US

---

* Corresponding author.
E-mail address: sga@pml.ac.uk (S.L. Garrard).

https://doi.org/10.1016/j.scitotenv.2024.171282
Received 16 November 2023; Received in revised form 15 February 2024; Accepted 24 February 2024

Gulf of Mexico, plastic originated almost exclusively from external (non-domestic) sources. LDPL from Caribbean islands - some of the largest generators of marine plastic pollution in the dataset of river plastic emissions used in the study - was noted as a significant input to HRZs across both sides of the Atlantic. These findings highlight the potential of Spatial Risk Assessment analyses to determine the location of HRZs and understand where plastic debris monitoring and management should be prioritised, enabling more efficient deployment of interventions and mitigation measures.

1. Introduction

Plastic is a ubiquitous and semi-permanent pollutant in the world's oceans (Eriksen et al., 2023), with an estimated 19 to 23 Mt. of plastic waste entering the world's aquatic ecosystems in 2016 (Borrelle et al., 2020). This figure is predicted to triple by 2030 (Borrelle et al., 2020), with Eriksen et al. (2023) observing a rapid increase in ocean plastics between 2005 and 2022. Land-based sources of plastic litter are thought to account for approximately 80 % of marine plastic pollution, although this value varies with location and has a level of uncertainty as the source of plastic litter items cannot always be identified (Mehlhart and Blepp, 2012). A large portion of land-derived plastic litter (LDPL) consists of single-use consumer items such as carrier bags, plastic bottles, wrappers, food containers and cutlery (Morales-Caselles et al., 2021; UNEP, 2009), which are released into rivers or coastal zones, and transported through a combination of ocean currents, wind, and wave-induced Stokes drift (Chassignet et al., 2021; Van Sebille et al., 2020).

Plastic pollution is a transboundary issue, with plastics travelling between countries and regions via a complex network of ocean currents (Chassignet et al., 2021). This is particularly evident in the Arctic, where large concentrations of buoyant plastics are transported from the North Atlantic to the Barents Sea (Cózar et al., 2017); and the Seychelles, where models suggest that large amounts of terrestrial plastic debris arrives from Indonesia, over 4000 km away (Vogt-Vincent et al., 2023). Through modelling plastic dispersal, Hatzonikolakis et al. (2022) surmise that many national Marine Protected Areas (MPAs) in the Mediterranean Sea are highly contaminated with plastic originating from outside the host country's borders, whilst Macias et al. (2022) estimate that 30 % of all beach litter in Mediterranean countries originates from outside that country's borders.

Plastic pollution is harmful to marine biota through a variety of mechanisms including entanglement and ingestion (Kühn et al., 2015; Nelms et al., 2023; Tekman et al., 2019; UNEP, 2021). Ingestion can alter energetic balances, impact behaviour, or block or damage the intestinal tract, resulting in severe sub-lethal effects or even death (Kühn et al., 2015). Whilst abandoned, lost or otherwise discarded fishing gear (ALDFG) is the most common contributor to the entanglement of marine megafauna, LDPL has also been shown to pose a risk (Nelms et al., 2023). Over 4000 marine and coastal species are known to be affected by marine plastic debris (Tekman et al., 2019), with some taxa more sensitive to plastic pollution than others, and therefore at greater risk (Beaumont et al., 2019; Foley et al., 2018).

Coastal regions often have some of the highest plastic burdens (Harris et al., 2021), meaning that many shallow water or intertidal biogenic habitats, which have the potential to trap marine plastics, are at risk of entanglement or smothering (Fong et al., 2023; Lamb et al., 2018; Noman et al., 2024). These biogenic coastal habitats are highly valuable natural capital assets (Costanza et al., 2014), providing some of the most important ecosystem services available to humans, yet are degrading at an alarming rate (Barbier et al., 2011). LDPL poses an increasing threat to these habitats (Harris et al., 2021).

Addressing plastic pollution is considered an urgent issue (UNEP, 2019), yet current national policies only address a fraction of plastic pollution that enters the environment (March et al., 2022). In 2022, a UN Environment Assembly (UNEA) resolution to end plastic pollution was adopted by member states, with a mandate to draft a legally binding agreement by the end of 2024. This UNEA resolution aims to include a globally regulated approach to tackle plastic pollution along the entire length of international value chains, using a combination of national and global policies in which international cooperation will be key. It is likely to include components that address product design, consumption and waste management, curbing production of virgin plastic, and financial support for treaty implementation (Bergmann et al., 2022; March et al., 2022). As evidence grows, this resolution will adapt to ensure that interventions are placed to have the greatest impact on plastic abatement (March et al., 2022). However, even under a best case 'system change' scenario, Lau et al. (2020) estimated that significant quantities of plastic will still leak into the environment. Understanding where plastic is causing the most harm, and what countries that plastic originates from may help determine where potential intervention and mitigation measures may be directed.

Numerical modelling of plastic transport in the ocean, coupled with ecological data detailing species' distributions and vulnerability to plastic pollution can help assess plastic risk, yet studies of this type are still limited. Several studies have assessed the risk of marine plastics through mapping species' distributions or habitats against predicted plastic concentrations (Guerrini et al., 2019; Schuyler et al., 2016; Wilcox et al., 2013; Wilcox et al., 2015), with some taking it a step further by assessing species' sensitivity. Høiberg et al. (2022) mapped the prevalence of plastic entanglement for multiple marine megafauna species against the spatial distribution of floating plastic debris to develop a species sensitivity distribution, whilst Compa et al. (2019) used species life history traits to assess the sensitivity of multiple taxa in the Mediterranean, and coupled this with their home ranges and plastic exposure. Fabri-Ruiz et al. (2023) used the plastic: zooplankton ratio as a method of assessing risk to pelagic fish and marine megafauna in the Mediterranean.

In this study, we focus on one key fraction of plastic pollution in the North Atlantic; LDPL that enters the ocean via rivers. A particle tracking model was used to simulate the movement of plastic after it entered the ocean. We then mapped the recorded distribution of each of the major groups of marine megafauna - seabirds, cetaceans, pinnipeds, elasmobranchs, turtles, sirenians, tuna and billfish - and some of the most productive and biodiverse shallow-water (<30 m) biogenic habitats - coral reefs, mangroves, seagrass, saltmarsh and kelp beds- and used a Spatial Risk Assessment framework (Fig. 1) to assess potential high-risk zones (HRZs) in the North Atlantic. In this study we aimed to answer three key questions. 1) How sensitive are North Atlantic marine megafauna and key biogenic habitats to LDPL? 2) Where are the HRZs where LDPL is likely to have the highest impact on these groups/ habitats? 3) Which countries does the LDPL originate from in these identified HRZs?

The North Atlantic was chosen as a study site as our understanding of species' distributions (Moudrý and Devillers, 2020) and freshwater transport (Meijer et al., 2021) is more comprehensive than for other parts of the globe. We recognize that areas such as SE Asia are substantially higher emitters of plastic into the worlds' oceans (Meijer et al., 2021), however the current work has been developed as a 'proof of concept' study, which can be further refined and validated to incorporate other oceans.

2. Methods

2.1. Plastic vulnerability scores

Two workshops were held in February and March 2023 to discuss how to score the vulnerability of North Atlantic marine megafauna groups and biogenic habitats to LDPL. Vulnerability was defined as the susceptibility to interact with plastic in a way that has the potential to cause harm. The participants ($n = 10$) were scientific researchers (PhD level and above) with expertise in marine plastic pollution and/or marine sensitivity/ vulnerability assessments from UK universities and research institutions. Developing species and habitat vulnerability assessments that consider the diverse number of impacts evidenced to create systematic and comparable assessments for different levels of exposure was considered unfeasible. If we consider the full spectrum of size ranges of plastic (microplastics -macroplastics), a wide range of pathways that plastic can impact on species have been recognised (e.g. ingestion, trophic transfer, intergenerational ingestion, abrasion, shading, adhesion). The number of possible mechanisms of harm is therefore very large with variability and bias in the underlying evidence. Assessing a wide range of potential mechanisms of harm against different levels of plastic pollution is challenging due to lack of evidence to identify sensitivity thresholds and realistic hazard benchmarks. Instead, it was agreed that we would focus on macroplastic (>5 mm) LDPL and a metric would be developed to examine the evidence available for a reduced number of different mechanisms of harm that could be applied across a range of species and habitats, to provide a robust vulnerability assessment.

Marine megafauna groups can be negatively impacted by LDPL through two major mechanisms: ingestion and entanglement. Biogenic habitats can be negatively impacted by LDPL through two major mechanisms: entanglement and smothering. Here we define ingestion as the consumption of large (> 5 mm) LDPL, entanglement as constriction or restriction of parts or all of an organism that may lead to injury, abrasion, or subsequent infection by LDPL, and smothering as LDPL covering a species/ habitat so that it has reduced access to phototrophic or heterotrophic nutrition.

Assessing the vulnerability of species and habitats to LDPL is problematic due to the largely observational nature of the data. Whilst ingestion or entanglement rates can be extracted for some species such as the common bottlenose dolphin (*Tursiops truncatus*) (Høiberg et al., 2022) or the sperm whale (*Physeter macrocephalus*) (Lusher et al., 2018), species with low population numbers will be more rarely encountered and result in observation bias. For some species there is often only evidence of a mechanism of harm from only single or few observations of ingestion or entanglement, e.g. the whale shark (*Rhincodon typus*) (Abreo et al., 2019) or the black marlin (*Makaira indica*) (Fujieda et al., 2008). Therefore, the workshop participants decided that the quantity of peer-reviewed literature for megafauna groups as a whole and broad habitat types could be used as a proxy for the level of occurrence of a particular mechanism of harm (ingestion, entanglement, smothering), as the mechanisms were general, being based on traits expressed by the species group or habitat. Whilst the absence of evidence does not exclude occurrence, an increasing number of peer-reviewed publications would clearly establish that mechanism of harm as occurring for a particular megafauna group or biogenic habitat.

The abundance of peer-reviewed evidence was divided into four categories (0–3) with 0 = no evidence available, 1 = low (grey literature or evidence from ≤2 peer-reviewed papers), 2 = medium (evidence from 3 to 9 peer-reviewed papers), and 3 = high (evidence from ≥10 peer-reviewed papers). Evidence from 10+ peer-reviewed papers for a megafauna group/ biogenic habitat was considered substantial evidence of occurrence, although it must be noted that for some groups the quantity of evidence was considerably higher than this. This was complimented with a literature review of each mechanism for each megafauna group and biogenic habitat.

For the marine megafauna groups, peer-reviewed literature was searched for using a semi-systematic review approach in Google Scholar and Web of Science. Using Boolean terms, the term ‘plastic’ was searched with the mechanism of impact (ingest*/entangle*/smother*) AND common name (e.g cetacean/ dolphin/whale/porpoise) for each marine megafauna group. Only evidence of LDPL impacting an organism via the aforementioned mechanisms were recorded. Where evidence for a mechanism of harm was lacking, searches were repeated on Google to look for news reports/ photographic evidence of entanglement, ingestion or smothering. For habitats, evidence of LDPL causing entanglement or smothering (as defined above) were determined through literature review, as these mechanisms are often not mentioned directly in each study. Once it was established that LDPL led to a given mechanism of harm on a particular habitat, peer-reviewed papers documenting land-sourced plastic pollution on the habitat were searched for in Google Scholar and in Web of Science and counted as evidence of this mechanism. Literature was searched for across all ocean basins, as vulnerability scores were group/ habitat specific rather than region specific. For each group/ habitat, the abundance of evidence (0–3) for each mechanism of harm was summed to give a vulnerability score. Mechanisms of harm were summed to give a total out of six, as each mechanism has been shown to have the potential to cause mortality (e.g. Abreo et al., 2019; Daniel et al., 2023; Lamb et al., 2018; van Bijsterveldt et al., 2021), suggesting that mortality risk will increase with frequency of occurrence of either mechanism. Literature searches took place on April 6th 2023 and again on November 15th 2023.

2.2. Mapping biogenic habitats and marine megafauna

Records of the distribution of shallow water biogenic habitats were

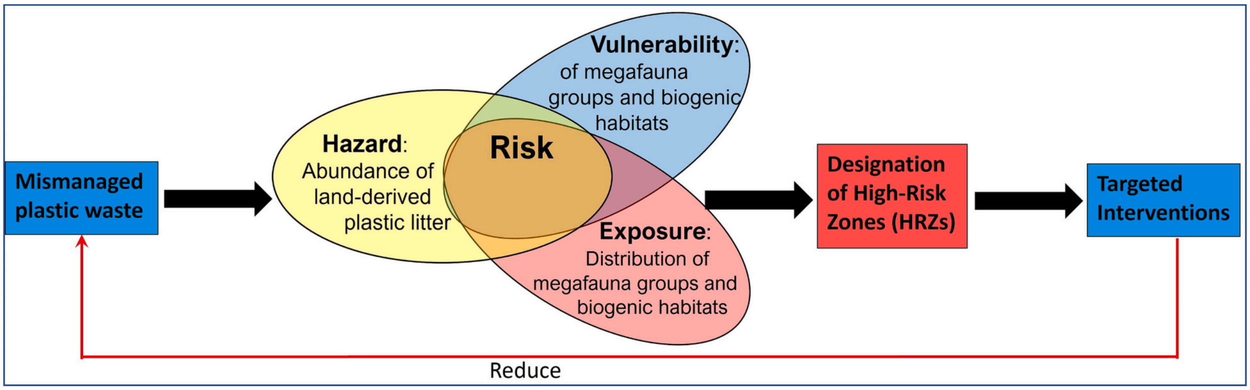


Fig. 1. Risk assessment framework to assess the spatial risk of land-derived plastic litter to marine megafauna and biogenic habitats, and the identification and of High-Risk Zones.

taken from the UNEP-WCMC ocean viewer, which hosts a variety of datasets from scientific and conservation organizations (https://data.unep-wcmc.org/). Data for the distribution of marine megafauna were taken from the Ocean Biogeographic Information System (OBIS) database (https://obis.org/). It is acknowledged that spatial and taxa bias occurs making it likely that the OBIS distribution data used in this study may be skewed towards certain geographic locations, where there is a significant number of records of marine megafauna sightings (Moudrý and Devillers, 2020). Low-middle income nations in the Gulf of Mexico and the Caribbean may be less well represented, and therefore their vulnerability and risk underestimated. However, OBIS is the most comprehensive database of marine species distribution available (De Pooter et al., 2017), hence it's application here as the best available source.

2.3. *Modelling river plastic emissions*

Modelled surface ocean plastic mass concentrations from Beaumont et al. (2024) are used. For inputs, the model used data on river plastic emissions for a set of countries bordering the North Atlantic Ocean, specifically Belgium (BE), Canada (CA), Denmark (DK), Dominican Republic (DO), France (FR), Germany (DE), Haiti (HT), Ireland (IE), Mexico (MX), Morocco (MA), Netherlands (NL), Portugal (PT), Spain (ES), Sweden (SE), United Kingdom (UK), and United States (US) (see Table S1, supplemental information for river emission values). The model was limited to these countries as 1) the North Atlantic and surrounding coastal waters play a dominant role in facilitating the transboundary movement of plastic from their rivers, and 2) consistent, recent macroplastic river data is available (Meijer et al., 2021). Countries such as Norway and other small island states/ overseas territories in the Antilles were excluded due to the lack of consistent river data (Beaumont et al., 2024).

Plastic transport pathways were simulated using the particle tracking model PyLag (Uncles et al., 2020). Simulated plastic particles were moved by a combination of surface ocean currents and direct wind forcing, with the latter incorporated using a wind factor of 0.02 in a downwind direction. This factor was found to provide a good fit to data for plastic bottles released off the SW Coast of the UK during the G7 summit (unpublished data) and is within the range of calibrated wind drift factors for bottles released in a study in Italy (Merlino et al., 2023). The model used daily surface ocean current data covering the period 2000–2014, which were taken from the 1/12° CMEMS Global Ocean Physics Analysis GLORYS12V1 dataset (Jean-Michel et al., 2021); and hourly surface winds covering the same period from the approximately ¼° ERA5 dataset (Hersbach et al., 2020).

Simulated plastic particles were released from river mouths at monthly intervals, starting at 12:00 h on 1st January 2000. The last release was performed at 12:00 h on 1st December 2014. The model was halted at 12:00 h on 1st January 2015. The model was configured to asymptote towards a steady state inventory corresponding to approximately half the annual influx of plastic from all countries included in the study by allowing particle weights – corresponding to the amount of plastic each particle represents – to decay exponentially in time. Decay coefficients were pulled from a uniform distribution, with fast rates of decay designed to account for plastics that tend to be rapidly lost from the ocean surface, while slower rates of decay account for plastics that remain at the ocean's surface for years to decades. The model was parameterized to produce a total inventory and spatial distribution of plastic that is consistent with past studies. See Beaumont et al. (2024) for a more complete discussion of this. In the model, beaching was not modelled explicitly; particles that crossed an ocean-land boundary during the simulation were reflected back into the domain.

2.4. *Risk assessment*

A risk assessment framework was developed based on the IPCC SREX risk analysis framework (IPCC, 2012), with risk defined as the likelihood of LDPL interacting with megafauna groups or habitats assessed in this study (hazard and exposure), leading to adverse ecological effects through the three main mechanisms of impact (vulnerability). We suggest that by developing this risk assessment framework, it is possible to identify potential high-risk zones (HRZs) where LDPL may be causing the most harm, and identify the countries of origin, so that targeted interventions can be made to reduce that risk (Fig. 1).

Hazard scores were mapped for each grid cell (1/12°) using the simulated plastic concentrations in the North Atlantic. Scores from 0 to 5 were assigned according to increasing order of magnitude of the plastic concentration in each grid cell, i.e., a score of 0 for 0–1 g km^{-2}, 1 for 1–10 g km^{-2}, 2 for 11–100 g km^{-2}, 3 for 101–1000 g km^{-2}, 4 for 1001–10,000 g km^{-2}, and 5 for >10,000 g km^{-2}. Plastic was scored in increasing orders of magnitude due to the log-logistic cumulative distribution of species' sensitivity found by Høiberg et al. (2022).

To assess exposure, distributions of marine megafauna groups and biogenic habitats were mapped as present (1) or absent (0), dependent on whether there were records available for presence in that grid cell (1/12°). Previous studies have shown that vulnerability is greatest where high species diversity and high plastic density overlap (Compa et al., 2019), therefore vulnerability scores for each group/ habitat present in each grid cell (1/12°) were added to give a total plastic vulnerability score, as it was assumed that with multiple groups/ habitats present, vulnerability would be cumulative.

Cumulative vulnerability scores were ranked (0–5) with grid cells with a value of zero added to the 0 category and the non-zero data split using the 50th, 75th, 90th and 99th percentiles to identify the cut off points for each category. Bounds for cumulative vulnerability scores were therefore 0, 1 for 1–4, 2 for 5–8, 3 for 9–13, 4 for 14–20 and 5 for 21+. Once the hazard, vulnerability and exposure were defined, risk of LDPL for each grid cell was computed as follows:

$$Risk = \sqrt{(V\mathrm{r} \times H\mathrm{p})}$$

where V_r = ranked vulnerability score and H_p = plastic hazard score.

We classified an HRZ as an area within a particular ocean EEZ with a risk score of 4 or above that covered an area >10,000km^2. A risk score of 4 or above was designated as high risk, as either vulnerability or hazard scores of 4 or above would be needed to generate risk scores of that value.

3. Results

3.1. *Hazard of LDPL across the North Atlantic*

By modelling the mass concentrations (g km^{-2}) of buoyant land-sourced plastic litter after 15 years of riverine input, we identified a number of key areas with medium to high plastic hazard scores (> 100 g km^{-2}; Fig. 2) including the US shelf and North Atlantic sub-tropical gyre, parts of the North East Atlantic, NW African shelf out to the Cape Verde Islands, the Gulf of Mexico and the Caribbean Sea.

Most of these are consistent with other ocean plastic models (Chenillat et al., 2021; Eriksen et al., 2014), although this model showed high concentrations of plastic along the NW African shelf out to the Cape Verde Islands, which differs from Chenillat et al. (2021) and Eriksen et al. (2014). In our model, this plastic mostly emanates from rivers associated with Morocco and, to a lesser extent, the disputed territory of Western Sahara. This difference is likely due to the different river emission datasets used; Chenillat et al. (2021) used river emissions data from Lebreton et al. (2017) which associates Morocco with a total flux of plastic from rivers to the ocean of <500 t per annum, whereas this study utilised the more updated river emissions dataset from Meijer et al. (2021) which calculated emissions for Morocco (including a small contribution from Western Sahara) as closer to 2000 t per annum.

Abundance of floating plastic litter in the German North Sea has been

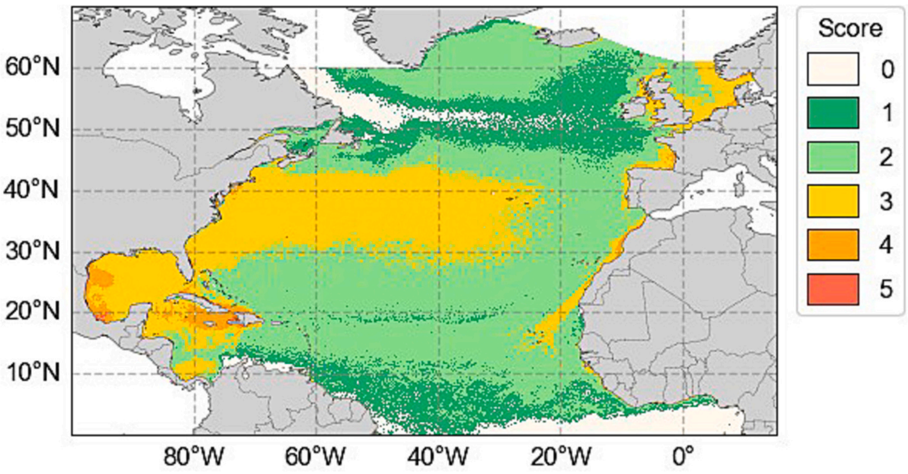


Fig. 2. Modelled mass concentration (g km^{-2}) of buoyant LDPL in the North Atlantic, with plastic hazard scored on a 0–5 basis based on LDPL mass increasing by an order of magnitude for each point. 0 for 0–1 g km^{-2}, 1 for 1–10 g km^{-2}, 2 for 11–100 g km^{-2}, 3 for 101–1000 g km^{-2}, 4 for 1001–10,000 g km^{-2}, and 5 for >10,000 g km^{-2}.

shown to be higher (Gutow et al., 2018) than measurements in other parts of the North Sea (Tekman et al., 2022), which is consistent with our model. And similarly, surface waters in the SE Bay of Biscay have been shown to contain extremely high concentrations of plastic, with a mean of 998 g km^{-2}, and up to 50,012 g km^{-2} (Basurko et al., 2022).

The accumulation of plastic in the North Atlantic sub-tropical gyre is consistent with observational studies (Cózar et al., 2017; Reisser et al., 2015; Wilcox et al., 2020) and modelling studies (Chenillat et al., 2021; Eriksen et al., 2014). High concentrations of plastic accumulation in the eastern Gulf of Mexico and around the Caribbean Islands of Haiti and the Dominican Republic are consistent with other models (Chenillat et al., 2021; Eriksen et al., 2014). There is a lack of data on floating macro litter in the Caribbean and the Gulf of Mexico, although high abundances of plastic can be found beached (Diez et al., 2019) or trapped in coastal habitats (Green and Webber, 1996).

3.2. LDPL vulnerability

Plastic vulnerability scores (Table 1) were derived from peer-reviewed evidence collected for each mechanism of harm (Table S2, supplemental information). This was complimented by a literature review of key literature on each mechanism of harm for each marine megafauna group and biogenic habitat.

Table 1
Plastic vulnerability scores for marine megafauna groups and biogenic habitats, based on the abundance of peer-reviewed evidence available each mechanism of harm (ingestion, entanglement or smothering). 0 = no evidence available, 1 = low (grey literature or evidence from ≤2 peer-reviewed papers), 2 = medium (evidence from 3 to 9 peer-reviewed papers), and 3 = high (evidence from ≥10 peer-reviewed papers). N/A = not applicable.

	Ingestion	Entanglement	Smothering	Total
Marine megafauna				
Seabirds	3	2	N/A	5
Cetaceans	3	2	N/A	5
Pinnipeds	2	2	N/A	4
Sirenians	2	1	N/A	3
Turtles	3	2	N/A	5
Elasmobranchs	3	2	N/A	5
Tuna and Billfish	3	1	N/A	4
Mean score	2.7	1.7	N/A	4.4
Biogenic habitats				
Seagrass	N/A	0	2	2
Kelp	N/A	0	0	0
Salt Marsh	N/A	0	2	2
Mangrove	N/A	3	3	6
Coral reef	N/A	3	3	6
Mean score	N/A	1.2	2	3.2

3.2.1. Seabirds

Seabirds have been used as biomonitors of plastic pollution due to their high susceptibility to plastic ingestion (van Franeker et al., 2011). In a study of seabirds in the NE Atlantic, 74 % of the 34 investigated species were recorded as having ingested plastic (O'Hanlon et al., 2017), whilst 60 % of all seabird species in the Bay of Biscay had ingested plastic (Franco et al., 2019). Seabirds have also been shown to feed plastic to their chicks, known as intergenerational transfer (Acampora et al., 2017; Young et al., 2009).

Ingested plastic can cause obstruction and physical damage to the gastrointestinal tract (Carey, 2011), leading to starvation (Pierce et al., 2004), organ damage (Rivers-Auty et al., 2023), and extensive scar tissue formation and plastic-induced fibrotic disease (Charlton-Howard et al., 2023). Ingestion is more common in surface-feeding birds due to floating particles of plastic being confused with prey items (Provencher et al., 2014), although diving birds are also susceptible (Tavares et al., 2017). Some seabird species actively select plastic while foraging and may consume a wide variety of plastic objects including fragments of larger products, bottle caps, plastic bags and wrappers, and sponges (Sileo et al., 1990), although hard, round plastic was most likely to be consumed (Hidalgo-Ruz et al., 2021). Seabirds from the order Procellariiformes appear particularly susceptible, with plastic ingestion found to be ubiquitous in shearwaters and fulmars for the NE Atlantic (O'Hanlon et al., 2017).

Seabird entanglement is primarily caused by ALDFG, although it can also be caused by other plastic debris (Costa et al., 2020). This can occur at sea, or through the incorporation of plastics in nests, where both chicks and adults can become entangled (Votier et al., 2011). Items that cause entanglement can include balloon and kite strings, bags, packing straps, six-pack straps, plastic lace and face masks (Fossi et al., 2018; Karris et al., 2023; Lucas, 1992; Massetti et al., 2021; Ryan, 2018; Wehle and Coleman, 1983).

Seabirds were given a vulnerability score of five, as evidence of ingestion of land-sourced plastic litter was high (3), whilst evidence of entanglement was medium (2).

3.2.2. Cetaceans

Incidences of plastic ingestion in cetaceans is determined by analysis of the gastrointestinal tract of stranded animals (Lusher et al., 2015; Senko et al., 2020), although attributing cause of death can be challenging (Roman et al., 2021). Historical postmortems on 410 cetaceans stranded in the Irish Sea between 1990 and 2015 showed 13 contained LDPL with the most common item being plastic bags (Lusher et al., 2018). Plastic ingestion appears more common in recent analyses. Alexiadou et al. (2019 analysed the stomach contents of 34 cetaceans stranded in Greece, showing that nine had large plastic litter items in their stomach with gastric blockage confirmed to cause lethal effects in three (Alexiadou et al., 2019). In the south west Atlantic, over 8 % of cetaceans examined contained marine debris, with single-use plastics being the most common items (Padula et al., 2023). Sperm whales (*Physeter macrocephalus*) were the most at risk, with over 60 % containing plastic, and one individual containing 135 items, primarily plastic bags (Padula et al., 2023). The high risk of plastic ingestion by sperm whales has been found in other studies, with the most common LDPL items including plastic packaging, plastic bags, agricultural foil, and plastic bottles (de Stephanis et al., 2013; Hansen et al., 2016; Jacobsen et al., 2010; Unger et al., 2016; Walker and Coe, 1989). Baird and Hooker (2000) documented how ingestion of a black plastic sheet led to blockage of the oesophagus of a harbour porpoise (*Phocoena phocoena*) in Nova Scotia, leading to starvation and death. A Cuvier's beaked whale (*Ziphius cavirostris*), which initially exhibited unusually friendly behaviour before becoming stranded in the Mediterranean was found to contain four plastic bags/ food packaging items, which caused gastric blockage and are likely to have caused mortality (Gomerči et al., 2006). News articles can highlight how extreme some cases of plastic ingestion can be. A sperm whale washed ashore in Indonesia containing 6 kg of plastic including 115 plastic cups, 25 plastic bags, 4 plastic bottles, two flip-flops, a nylon sack and >1000 other pieces of plastic in its stomach (Marris, 2018), whilst another was unable to survive in Thailand after ingesting 80 plastic bags (Wills, 2018).

Most entanglement of cetaceans occurs in ALDFG (Simmonds, 2012; Solomando et al., 2022), although there have been incidences of entanglement in land-based litter including a plastic bag (Kelly, 2022), frisbees (Milman, 2020), synthetic clothing (Wells et al., 2008) and bailing twine (Balmer et al., 2019).

Cetaceans were given a vulnerability score of five, as evidence of ingestion of land-sourced plastic litter was high (3), whilst evidence of entanglement was medium (2).

3.2.3. *Pinnipeds*

Incidence of plastic ingestion in pinnipeds appears to be generally lower than for seabirds and cetaceans, although Bravo Rebolledo et al. (2013) found 12 % of seals in the Netherlands had plastic in their stomachs, with sheets and large threads being the most common items. In other studies plastic ingestion appears less prevalent, and Bourdages et al. (2020) found no evidence of plastic ingestion in seals harvested in the Canadian Arctic. On Macquarie Island, plastic particles were found in the scats of fur seals, although most of these would be classified as microplastics and are not considered in this study (Eriksson and Burton, 2003), whilst Ryan et al. (2016) found no plastic particles in the scat of fur seals on Southern Ocean Island. Denuncio et al. (2017) examined the gastrointestinal tract of 133 South American fur seals and found that young seals were most likely to ingest plastic. In total, three had ingested plastic bags, whilst another five had ingested fishing line. Pinzone et al. (2021) examined the gastrointestinal tract of 10 Arctic seals and eight hooded seals, with two plastic wrappings found in the GI tract of one hooded seal.

Pinnipeds, particularly juveniles, are highly susceptible to entanglement due to their inquisitive nature (Butterworth, 2016; Lucas, 1992), with sea lions appearing to be more so than seals (Kühn et al., 2015). Whilst reported pinniped entanglement is generally associated with ADLFG, there are a substantial number of accounts of pinnipeds becoming entangled in other circular plastics, including packing straps, plastic bags, burst balloons, rubber bands, frisbees, clothing, o-rings, windsocks and plastic rings from buckets (Butterworth, 2016; Henderson, 2001; Lucas, 1992; Page et al., 2004; Raum-Suryan and Suryan, 2022; Salazar-Casals et al., 2022; Waluda and Staniland, 2013). Entanglements can be caused by ALDFG or LDPL. For example, plastic bag entanglement accounted for 7 % of entanglement of fur seals off Kangaroo Island, Australia (Page et al., 2004), whilst 12 % of seal entanglement cases off the Dutch coast were in plastic other than fishing gear or fishing/ boating related debris such as frisbees, clothing, potato nets, rubber bands and tarpaulin (Salazar-Casals et al., 2022).

Pinnipeds were given a vulnerability score of four, as evidence of ingestion of land-sourced plastic litter was medium (2), and evidence of entanglement was medium (2).

3.2.4. *Sirenians*

Plastic ingestion has been documented in three out of the four species of Sirenia (Poeta et al., 2017), with plastic packaging being the most common type of LDPL (Beck and Barros, 1991). Of the 6893 manatees that died along the Florida coastline between 1993 and 2012, almost 10 % were documented as having ingested marine debris, with 37 cases of ingestion identified as the probable cause of death (Reinert et al., 2017). Ingestion was found to cause impaction, obstruction or perforation of the gastrointestinal tract (Reinert et al., 2017). Off the coast of Brazil, four of the 40 rehabilitated and released manatees were found to have later ingested plastic debris, being the cause of death in two of them (Attademo et al., 2015). Ingestion has also been observed in the Amazonian manatee (*Trichechus inunguis*) (Guterres-Pazin et al., 2012), and ingestion of a plastic bag has been known to cause death (Silva and Marmontel, 2009).

Florida manatees (*Trichechus manatus*) were most commonly entangled in ropes or nets, although they can also become entangled in other plastic debris such as packing straps (Reinert et al., 2017), basketball nets (Beck and Barros, 1991), and bicycle tyres (Moyer, 2020).

Sirenians were given a vulnerability score of three, as evidence of ingestion of land-sourced plastic litter was medium (2), and evidence of entanglement was low (1).

3.2.5. *Turtles*

Plastic ingestion in turtles has been documented in many studies, with all species now documented to ingest plastic (Kühn et al., 2015; Nelms et al., 2015). Much of that comprises single-use plastics, such as fragments of packaging and plastic bags/ wrappers (Choi et al., 2021; Petry et al., 2021; Santos et al., 2015). In the Gulf of Mexico, 65 % of the 189 green turtles (*Chelonia mydas*) necropsied in 2019 contained plastic in their gastrointestinal tracts (Choi et al., 2021), whilst 91 % of the 55 turtles necropsied in the Pacific had ingested plastic (Clukey et al., 2017). In the Azores, six of the seven green turtles necropsied had ingested plastic (Rodríguez et al., 2022). Wilcox et al. (2018) found a 50 % probability of turtle mortality once a turtle had collected 14 pieces of plastic in its gut.

Due to their complicated lifecycles, feeding modes and migratory behaviour, turtles are vulnerable to plastic ingestion and entanglement at multiple stages in their life (Duncan et al., 2017; Eastman et al., 2020). Oceanic convergence zones such as the subtropical gyres are important feeding zones for turtles, who may spend several years of their life in the open ocean, travelling between breeding and foraging areas (Hays and Scott, 2013). In the North Atlantic, the plastic debris may be entangled with the Sargassum-dominated macroalgal mats, which provide an important habitat for oceanic-stage neonatal turtles (Eastman et al., 2020). Petry et al. (2021) found that 88 % of juvenile green turtles had ingested plastics, with an average of 38 pieces per individual, whilst Eastman et al. (2020) found that 92 % of post-hatchling loggerhead turtles stranded in the Gulf of Florida had ingested plastic, with an average of 49 pieces per individual. In South Africa 24 of 40 stranded post-hatchling loggerhead turtles (*Caretta caretta*) had ingested plastic, with this being the cause of death for 11 of these, and contributing to the death of another five (Ryan et al., 2016). Ingestion appears to be biased towards certain shapes and colours of plastic, suggesting the plastic may be mistaken for food (Duncan et al., 2019).

Most entanglement of turtles occurs in ALDFG (Duncan et al., 2017; Rodríguez et al., 2022), although entanglement in plastic bags and other land-sourced items such as woven bags/ rope, weather balloons, '6 pack' drink rings, and kite string has been documented (Barreiros and Raykov, 2014; Casale et al., 2016; Chatto et al., 1995; Daniel et al., 2023; Duncan et al., 2017; Orós et al., 2016).

Turtles were given a vulnerability score of five, as evidence of ingestion of land-sourced plastic litter was high (3), and evidence of entanglement was medium (2).

3.2.6. *Elasmobranchs*

Macroplastic ingestion has been observed in elasmobranchs with a wide range of ecological traits from small, demersal species including *rays, dogfish and catsharks* (López-López et al., 2018; Morgan et al., 2021; Sbrana et al., 2022; Smith, 2018), to pelagic top predators, such as the longfin mako (*Isurus paucus*) (Gong et al., 2023), the porbeagle (*Lamna nasus*) (Joyce et al., 2002), the tiger shark (*Galeocerdo cuvier*) (Cliff et al., 2002), the bigeye thresher shark (*Alopias superciliosus*) (Benjamin et al., 2014), and the blue shark (*Prionace glauca*) (Bernardini et al., 2018; Fernández and Anastasopoulou, 2019), to indiscriminate filter feeders such as whale sharks (*Rhincodon typus*) (Abreo et al., 2019; Sampaio et al., 2018). Sharks appear to ingest a wide range of single-use items including packaging material and other sheet-like items, bottle caps, and plastic straws (Bernardini et al., 2018; Fossi et al., 2017; Gong et al., 2023).

There is growing evidence that land-based sources, such as circular plastic debris including plastic packaging straps, elastic bands, plastic bags, plastic rings, and even a car tyre can also cause elasmobranch entanglement (Afonso and Fidelis, 2023; Bird, 1978; Colmenero et al., 2017; Lombardi and Morton, 1993; Lucas, 1992; Parton et al., 2019; Sazima et al., 2002; Thiel et al., 2018).

Elasmobranchs were given a vulnerability score of five, as evidence of ingestion of land-sourced plastic litter was high (3), whilst evidence of entanglement was medium (2).

3.2.7. *Tuna and billfish*

Macroplastic ingestion has been documented in many tuna species including yellowfin (*Thunnus albacares*) (Chagnon et al., 2018; Fujieda et al., 2014; Manooch and Mason, 1983; Sajikumar et al., 2013), bluefin (*Thunnus thynnus*) (Romeo et al., 2015; Varela et al., 2022; Yick and Travers, 2022), blackfin (*Thunnus atlanticus*) (Manooch and Mason, 1983), the little tunny (*Euthynnus alletteratus*) (Manooch et al., 1985), skipjack (*Katsuwonus pelamis*) (Hyrenbach et al., 2021; Neto et al., 2020), bigeye (*Thunnus obesus*) (Fujieda et al., 2014), and albacore (*Thunnus alalunga*) (Hyrenbach et al., 2021; Romeo et al., 2015) tunas. Both swordfish (*Xiphias gladius*) (Romeo et al., 2015) and the black marlin (*Makaira indica*) (Fujieda et al., 2008) have been also been documented to ingest macroplastic litter. In the Mediterranean, Romeo et al. (2015) found that 32.4 % of bluefin tuna (*Thunnus thynnus*) and 12.5 % of swordfish (*Xiphias gladius*) caught in the Mediterranean contained macroplastic fragments in their stomachs (Romeo et al., 2015). Plastic objects were generally fragments or sheets (Hyrenbach et al., 2021), such as pieces of plastic bag (Sajikumar et al., 2013), sweet and food wrappers (Varela et al., 2022) and fragments of food containers (Yick and Travers, 2022).

Evidence of LDPL causing entanglement in tuna or billfish is rare, but an albacore was observed entangled in a plastic packaging band (Lucas, 1992).

Tunas and billfish were given a vulnerability score of four, as evidence of ingestion of land-sourced plastic litter was high (3), whilst evidence of entanglement was low (1).

3.2.8. *Seagrass*

Studies have shown that seagrass beds contain less plastic litter than mangroves and saltmarshes (Fong et al., 2023; Ouyang et al., 2022), although they do act as a trap for land-sourced plastic litter (Navarrete-Fernández et al., 2022). Macroplastic litter in seagrass beds has been documented in several studies across the globe (Abreo et al., 2018; Cozzolino et al., 2020; Fong et al., 2023; Gaboy et al., 2022; Navarrete-Fernández et al., 2022; Sanchez-Vidal et al., 2021), with plastic bags, wrappers and sheets common components of the litter, and abundance higher on the landward side (Gaboy et al., 2022; Navarrete-Fernández et al., 2022).

These items can smother seagrass beds by reducing the light available (Kaladharan et al., 2014). Shading by plastic has been shown to lead to reduced growth rate and shoot density in seagrass, with little recovery observed in the year after the removal of the plastic (Fitzpatrick and Kirkman, 1995). In a mesocosm experiment, macroplastic fragments added to sediments altered seagrass architecture and prevented vertical growth of rhizomes possibly reducing cover of seagrass in the longer term (Menicagli et al., 2021). Plastic can also reduce the decomposition rates of seagrass, which may reduce the functioning of the ecosystem (Litchfield et al., 2020). There is no evidence in the literature of plastic pollution causing entanglement, most likely due to the flexible nature of the shoots.

Seagrass was given vulnerability score of two, as there was medium (2) evidence that land-sourced plastic litter caused smothering. There was no evidence of entanglement.

3.2.9. *Kelp*

Whilst there is evidence that covering kelp with plastic can reduce the decomposition rate, which may reduce the functioning of kelp ecosystems (Litchfield et al., 2020), there was no evidence in the literature of plastic pollution causing entanglement or smothering, therefore kelp was given a vulnerability score of zero.

3.2.10. *Saltmarsh*

Saltmarshes are highly efficient at trapping debris (Yao et al., 2019), and have a higher abundance of plastic litter than seagrass beds and unvegetated habitats (Cozzolino et al., 2020). Plastic items can smother saltmarsh plants, reducing the light levels needed for growth (Mazarrasa et al., 2019; Viehman et al., 2011). Plastic bags placed in a saltmarsh have been shown to create anoxic conditions in the sediment, leading to reduced infaunal invertebrates, primary productivity, and flux of inorganic nutrients (Green et al., 2015). Macroplastic litter in saltmarsh has been documented in several studies across the globe (Cozzolino et al., 2020; Mazarrasa et al., 2019; Pinheiro et al., 2021; Podolsky, 1989; Tibbetts, 2015; Viehman et al., 2011; Yao et al., 2019).

Saltmarsh was given vulnerability score of two, as there was medium (2) evidence that land-sourced plastic litter caused smothering. There was no evidence of entanglement.

3.2.11. *Mangrove*

Mangroves occur in some of the most polluted coastlines in the world, with 54 % of mangroves situated <20 km from a river that discharges >1 t yr^{-1} of plastic (Harris et al., 2021). Mangroves contain more plastic litter than adjacent habitats such as seagrass beds, tidal flats and beaches (Martin et al., 2020; Ouyang et al., 2022), with plastic increasing with tree density (Hastuti et al., 2014; Martin et al., 2020). The structural complexity of their branches and aerial root system (pneumatophores) makes them highly susceptible to plastic entanglement and smothering (Walther and Bergmann, 2022), and plastics can be retained in mangroves for years (Ivar do Sul et al., 2014).

Large quantities of plastic litter have been found covering pneumatophores (specialised aerial root systems) and branches in mangrove systems (Cordeiro and Costa, 2010; Debrot et al., 2013; Fadare et al., 2022; Kesavan et al., 2021; Martin et al., 2019; Okuku et al., 2023; Paler et al., 2022; Sivasothi, 2002; Suyadi and Manullang, 2020), and is frequently found buried in mangrove sediments (Costa et al., 2011; van Bijsterveldt et al., 2021), where it causes the sediment to become anoxic (van Bijsterveldt et al., 2021). Single use plastics such as plastic bags and food wrappers are generally the most abundant type of plastic (De et al., 2022; Sivasothi, 2002).

Plastic covering roots or branches may lead to a physical impediment of gas exchange (Okuku et al., 2023), or prevent photosynthesis of the leaves (Kesavan et al., 2021), smothering the tree. Entanglement can cause physical damage to the pneumatophores and branches (De et al., 2022). Whilst mangroves are relatively resilient to partial smothering by plastic, large scale accumulation across the roots can lead to deterioration and tree death (van Bijsterveldt et al., 2021). Plastic abundance has been shown to negatively correlate with all aspects of mangrove health; seedling density, tree density, mean tree height and mean tree diameter (Suyadi and Manullang, 2020).

Mangroves were given vulnerability score of six, as there was high (3) evidence that land-sourced plastic litter caused both smothering and entanglement.

3.2.12. *Coral reefs*

Corals are unable to ingest large plastic litter, although microplastic ingestion is widespread (Allen et al., 2017; Hall et al., 2015; Reichert et al., 2018). Land-sourced plastic litter causing entanglement and smothering has been evidenced in many research papers (Abu-Hilal and Al-Najjar, 2009; Arindra Putra et al., 2021; De et al., 2022; Figueroa-Pico et al., 2016; Mueller et al., 2022; Mulochau et al., 2020; Richards and Beger, 2011; Santodomingo et al., 2021) as well as showing the negative impacts in laboratory studies (Mueller and Schupp, 2020). In the Gulf of Aqaba, the most common plastic items on the reef were single use items such as bags (61 %), bottles (24 %) and containers (13 %) (Abu-Hilal and Al-Najjar, 2009).

Tropical corals obtain their food through a combination of autotrophy and heterotrophy. They feed on bacteria and zooplankton and also contain symbiotic photosynthetic algae (zooxanthellae) which require sunlight to produce energy and supplement their nutrition (Houlbrèque and Ferrier-Pagès, 2009). If coral polyps are covered by plastic such as nappies, plastic bags etc., they will not be able to feed effectively by either mode and will bleach (Mueller and Schupp, 2020), and will eventually die from lack of nutrition (Richards and Beger, 2011).

Entanglement in ALDFG is thought to cause the most detrimental effects on coral reefs (de Carvalho-Souza et al., 2018), although Lamb et al. (2018) found that there was a 20-fold increase in the likelihood of coral disease (from four to 89 %) when mismanaged household waste became entangled in the reef and coral polyps were in contact with plastic. Corals with high levels of structural complexity (tabular and branching) are eight times more likely to impacted by plastics than those with lower complexity (Lamb et al., 2018). There is a significant relationship between habitat complexity and species richness due to increased niche diversity established (Gratwicke and Speight, 2005), and impacts on structurally complex corals will have a disproportionate effect on the organisms associated with the reef.

Coral reefs were given vulnerability score of six, as there was high (3) evidence that land-sourced plastic litter caused both smothering and entanglement.

3.3. *Vulnerability scores*

Evidence of ingestion of LDPL by marine megafauna was greater (mean score 2.7) than evidence of entanglement (mean score 1.7). Similarly, in marine biogenic habitats, evidence of smothering (mean score 2) was greater than evidence of entanglement (mean score 1.2), with entanglement only occurring in habitats with rigid strictures such as coral reefs and mangroves. Based on the current results of the cumulative vulnerability scores of the 12 marine megafauna taxa and biogenic habitats for each N Atlantic grid cell (1/12°), vulnerability to land-sourced buoyant plastic was generally higher along the continental shelf than the open ocean (Fig. 3). Continental shelves are generally much more biologically productive than open ocean (Yool and Fasham, 2001), providing rich feeding grounds for marine megafauna, although many species are widely dispersed throughout the ocean (Estes et al., 2016). The highest vulnerability scores were generally found adjacent to the coast, where multiple marine megafauna and biogenic habitats occurred in a single grid cell, but this was not always the case. The upwelling region of the US Atlantic shelf break was also shown to be an area of high vulnerability, due to the many groups of marine megafauna observed there.

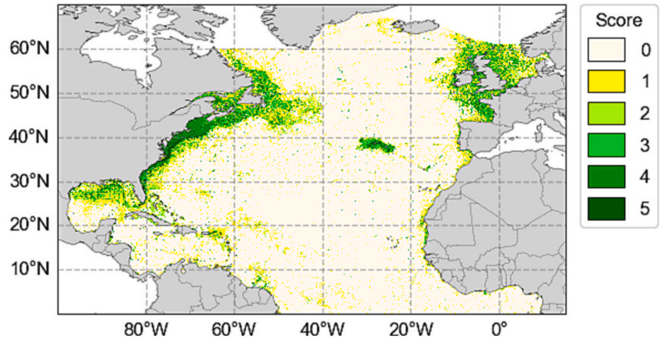


Fig. 3. Vulnerability scores for each grid cell, based on cumulative LDPL vulnerability scores for marine megafauna and key coastal biogenic habitats in the North Atlantic. Bounds for cumulative vulnerability scores were split using the 50th, 75th, 90th and 99th percentiles; 0, 1 for 1–4, 2 for 5–8, 3 for 9–13, 4 for 14–20 and 5 for 21 + .

Sheet-like plastics such as plastic bags and food wrappers were the most commonly ingested type of LDPL for most marine megafauna (Roman et al., 2021), except seabirds which were generally more at risk of ingesting hard plastic fragments (Hidalgo-Ruz et al., 2021). Most studies highlighted that entanglement was primarily caused by ALDFG, although there was some evidence of entanglement by LDPL for all marine megafauna groups, particularly in circular or rope-like plastic items such as packing straps, bailing twine and frisbees, with pinnipeds particularly at risk.

Biogenic habitats increased vulnerability along the coastline throughout the North Atlantic, with peer-reviewed evidence suggesting that coral reefs and mangroves may be the most at-risk habitats. Entanglement and smothering by plastic appear to be a significant threat for these habitats, with entanglement causing both breakage and disease in corals, and breakage in mangrove branches and roots. Smothering of corals and mangrove branches, roots or saplings by land-sourced plastic led to frequent mortality in corals, and a reduction in tree density in mangroves. In contrast, no evidence of plastic harm could be found for kelp beds at this current time, and they were assessed as the least sensitive.

3.4. *Plastic risk map, and identification of high-risk zones (HRZs)*

LDPL risk scores were ranked from 0 to 5, and HRZs classified as an area within a particular ocean EEZ with a risk score of 4 or above that covered an area $>$10,000 km^{-2}. Five HRZs were identified: 1) Atlantic USA EEZ, 2) US Gulf of Mexico, 3) UK EEZ, 4) French Atlantic EEZ, and 5) Portuguese Azores EEZ (Fig. 4). The Atlantic USA EEZ had an area of risk of four or above covering 383,380 km^{-2}, whilst the US Gulf of Mexico covered 98,441 km^{-2}, the UK EEZ covered 70,664 km^{-2}, the Portuguese Azores EEZ covered 62,903 km^{-2}, and the French Atlantic EEZ covered 38,587 km^{-2}.

Most of the areas highlighted as vulnerable to plastic pollution (Atlantic USA, the Azores, the UK and the French Atlantic) were calculated as HRZs (Fig. 5), although the Canadian North Atlantic became low risk, even though it had a high vulnerability score due to the presence of low volumes of plastic. In contrast, the USA section of the Gulf of Mexico had a higher hazard score than vulnerability score, due to the high concentrations of plastic in that area (Fig. 5). Greatest risk (5) was largely restricted to grid cells adjacent to coastlines, where biogenic

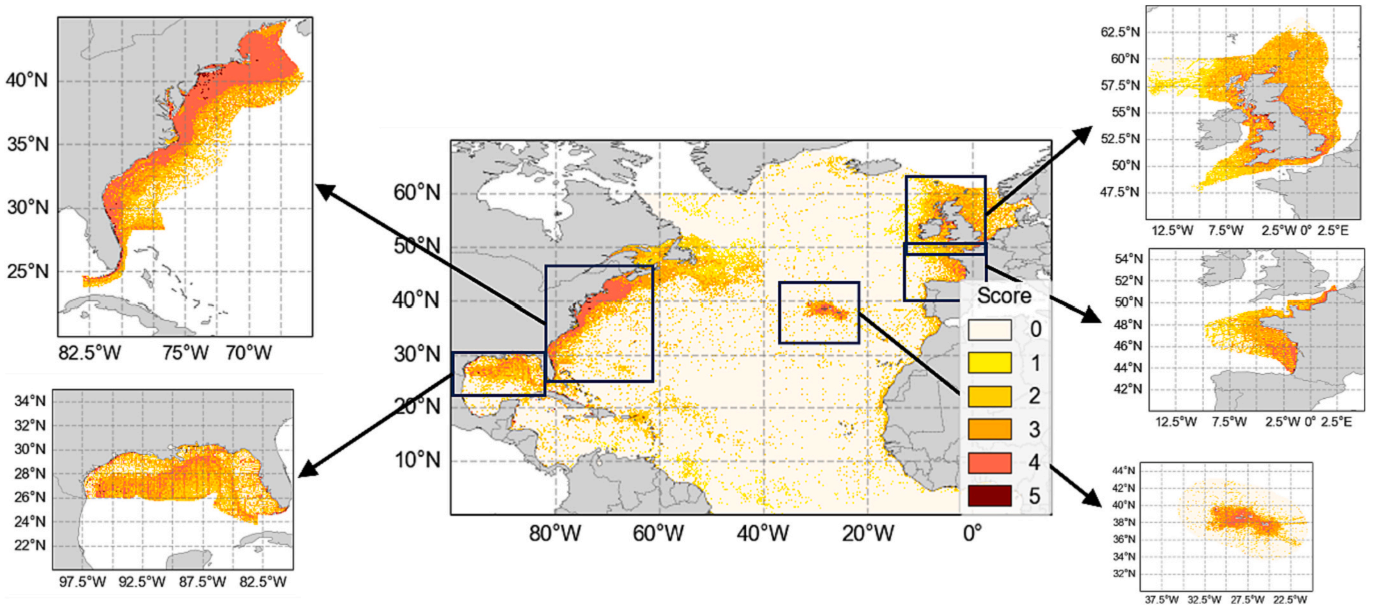


Fig. 4. Spatial risk assessment for land-derived plastic litter and risk to marine megafauna and key coastal biogenic habitats in the North Atlantic, including identification of five high risk zones: 1) the Atlantic USA EEZ, 2, the US Gulf of Mexico, 3) the UK EEZ, 4) the French Atlantic EEZ, and 5) the Portuguese Azores EEZ.

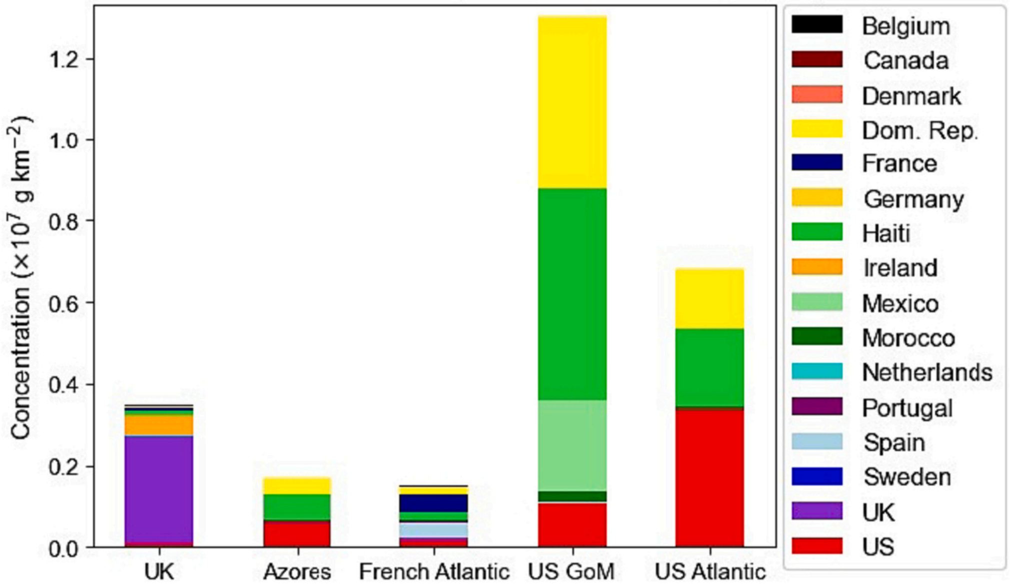


Fig. 5. Modelled mass concentrations and origins of land-derived plastic litter for each HRZ, by proportion from each country. UK = UK EEZ, Azores = Portuguese Azores EEZ, French Atlantic = French Atlantic EEZ, US GoM = US Gulf of Mexico, US Atlantic = US Atlantic EEZ.

habitats overlapped with marine megafauna distributions.

Separation of risk to biogenic habitats and marine megafauna show that the HRZs were largely dictated by risk to marine megafauna (Fig. S1, supplementary information), with areas of high risk for biogenic habitats (score ≥ 4) limited to tropical zones where mangroves and coral reefs were present. Individual risk maps for each megafauna group and biogenic habitat show that seabirds, cetaceans, turtles and elasmobranchs had the greatest risk scores, whilst seabirds, cetaceans, elasmobranchs and tuna and billfish risk had the greatest spatial extent (Fig. S2, supplementary information). Of the marine megafauna, sirenians had the least impact on spatial risk, due to their extremely low distribution.

3.5. Countries of origin

Through analysis of the modelled data, the countries of origin for simulated plastic debris were determined for each identified high-risk zone. In the model, 75 % of buoyant LDPL in the UK HRZ was assessed as domestic waste, whilst in comparison, >99 % came from external sources in the Azores; with 59 % coming from the Caribbean Islands (the Dominican Republic and Haiti) and 35 % from the US. In the French Atlantic, this was less pronounced, with most modelled buoyant LDPL coming from local sources in France and Spain (53 %), but a significant portion (37 %) came from the Caribbean Islands and the US. In the US Gulf of Mexico, most modelled buoyant LDPL (72 %) were from the Caribbean Islands and 8 % from Mexico, whilst in the Atlantic US, almost half of buoyant LDPL was domestic (49 %) and the other half from the Caribbean Islands (49 %), with very small contributions from elsewhere.

Modelled LDPL mass concentrations in HRZs were generally highest for those closest to Haiti and the Dominican Republic, with those further away modelled to contain less, although the UK contained more than the Azores or French Atlantic, due to the significant domestic input into the EEZ.

4. Discussion

Marine megafauna and biogenic habitats are threatened by many anthropogenic stressors including overexploitation, interactions with fishing gear, vessel traffic, coastal development, pollution, hypoxia, invasive species, and climate change (Avila et al., 2018; Lewison and Crowder, 2007). Under the IUCN estimated probability of species' extinction, 12 % of North Atlantic marine megafauna are expected to go extinct within the next 100 years (Pimiento et al., 2020), whilst the coverage of many biogenic habitats is decreasing (Eddy et al., 2021; Gedan et al., 2009; Waycott et al., 2009), and others are exhibiting signs of fragmentation and degradation (Bryan-Brown et al., 2020).

Plastic pollution may originate from one country, but the environmental harm occur within another country's jurisdictions. This study aimed to develop a methodology for assessing plastic risk to marine biodiversity at a large spatial scale (North Atlantic Ocean), by identification of HRZs and assessment of the origin of the plastic that is causing that risk. This initial risk assessment designated five HRZs (Fig. 5). Modelled data suggests that for two of those HRZs, the UK and the US Atlantic, prevention of land-sourced plastic leakage into the environment domestically will significantly lower the risk of ecological harm. For other HRZs including the Azores, the French Atlantic and the US Gulf of Mexico, international actions are needed.

Mismanaged waste is often correlated with developing economies, which lack the funding for initiatives to reduce their mismanaged waste (Bundhoo, 2018). Of the countries in this study where simulated plastic was released for modelling plastic transport, the Caribbean nations of Haiti and the Dominican Republic have the highest proportion of mismanaged waste, with over 90 % of waste estimated to be mismanaged (Brooks et al., 2020). A portion of this plastic can then be transported across the ocean to the Azores archipelago, or the French Atlantic, where sensitive marine megafauna and biogenic habitats will be negatively impacted. This mismanaged plastic waste is also likely to cause significant harm to local biota within the Caribbean and Gulf of Mexico. Whilst species' density records are particularly rich for areas such as the NE Atlantic, the Azores and the N Atlantic costal shelf of the USA, species' distribution records are less dense for other parts of our study area including the Gulf of Mexico and the Caribbean (Moudrý and Devillers, 2020), which may lead to an underestimation of ecological risk for these areas.

Designation of HRZs does not mean that lower risk areas are risk free. For example, Kelly et al. (2023) demonstrated ingestion of LDPL in northern bottlenose whales off the coast of Nova Scotia, an area identified as having a risk score of less than four. However, given the wide extent of the plastic pollution the identification of HRZs is useful to provide a focus for initial intervention to enable the identification of the most efficient mitigation actions.

The vulnerability to LDPL will vary widely within a group of taxa, with some species and populations particularly sensitive to plastic and others less so, depending on their traits and conservation status. Traits can be biological (e.g., feeding type, size, longevity) or ecological (e.g., habitat preferences, motility) and the extent to which they are under threat from other anthropogenic activities. Risk will also depend on the type and abundance of plastic that animals are exposed to at each life history stage/habitat, and their current extinction risk (IUCN red list). As such it is recognised that within the megafauna and habitat groups identified here there will be variability in the degree of impact, and it is recommended that now a framework has been devised that a next step for this Spatial Risk Assessment approach would be to provide more detail on these species specific impacts.

For the purpose of this study, gathering the available evidence on each mechanism of harm, whilst rudimentary, was deemed sufficient to give a relative score of between 0 and 6 for most marine megafauna and biogenic habitats which are well studied/ have a widescale distribution. It must be noted that the vulnerability score for sirenians (which have a small distribution and for which research is limited: Wirsing et al., 2022) may be underestimated, although this is unlikely to have a significant impact on the designation of HRZs, due to their limited impact on the plastic risk map (see Fig. S2 for individual risk maps, supplemental information).

It is critical to note that attempts to model the distribution of plastic in the ocean face multiple challenges, many of which are yet to be resolved. While many of the processes likely to impact the movement and fate of plastic in the ocean have been identified and discussed (Van Sebille et al., 2020), the diversity of plastic litter types and the frequent absence of robust data for both parameterising models and validating their outputs mean simulation outputs remain indicative. Still, models have been shown to reproduce several observed patterns, including the accumulation of plastic in sub-tropical gyres (Cózar et al., 2014; Eriksen et al., 2014; van Sebille et al., 2015); and remain our current best tool for connecting sources of plastic pollution to potential hotspots and areas most at risk from associated negative impacts. We acknowledge that our estimates of plastic distribution contain uncertainties, and future work should be focussed on reducing biases in models, guided by targeted observations which include identification of plastic origins.

Høiberg et al. (2022) similarly assessed that marine mammal entanglement risk was greater in coastal areas/ continental shelves, although they also found that these species were at high risk of entanglement in the North Atlantic gyre. This is likely because the gyres often contain derelict fishing gear such as synthetic ropes and nets (Morales-Caselles et al., 2021), which pose a high risk of entanglement to marine megafauna (Høiberg et al., 2022). As our study focussed on LDPL, these marine-based items were not taken into consideration in this study. Whilst buoyant LDPL poses a significant risk to marine megafauna and biogenic habitats, the risk of entanglement is greater for ALDFG, and this marine plastic source must not be underestimated. Future development of this framework is recommended to take in account these wider forms of plastic pollution.

Rising levels of plastic pollution have prompted the resolution of the UN Marine Environment Assembly (UNEA) to draft a legally binding global plastics treaty by 2024, which will include financial mechanisms to tackle plastic pollution including domestic and international funding and extended producer responsibility (UNEP, 2023). A key aspect of these discussions will be where the weight of the interventions will lie, and the potential distribution of costs and benefits between countries. There are limited resources available to tackle this global pollutant and so their efficient distribution will be critical. The proposed Risk Assessment Framework and designation of HRZ has potential to inform the development and application of a Plastics Treaty by clarifying both the areas most requiring of intervention, and the primary sources of the impacts in these areas. This research provides a first attempt at understanding and identifying HRZs for multiple taxa to a particular plastic type, and examining the country of origin.

Declaration of generative AI in scientific writing

The authors would like to declare that no generative artificial intelligence (AI) and AI-assisted technologies have been used in the writing process.

CRediT authorship contribution statement

Samantha L. Garrard: Conceptualization, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **James R. Clark:** Conceptualization, Formal analysis, Methodology, Software, Validation, Writing – review &

editing. **Sarah E. Nelms:** Methodology, Writing – review & editing. **Zara L.R. Botterell:** Methodology, Writing – review & editing. **Matthew Cole:** Methodology, Writing – review & editing. **Rachel L. Coppock:** Methodology, Writing – review & editing. **Tamara S. Galloway:** Methodology, Writing – review & editing. **Dannielle S. Green:** Methodology, Writing – review & editing. **Megan Jones:** Writing – review & editing. **Pennie K. Lindeque:** Methodology, Writing – review & editing. **Heidi M. Tillin:** Methodology, Writing – review & editing. **Nicola J. Beaumont:** Formal analysis, Methodology, Software, Validation, Visualization.

Declaration of competing interest

The authors would like to declare that there are no financial or personal relationships with other people or organizations that could inappropriately influence (bias) this work.

Data availability

No data was used for the research described in the article.

Acknowledgements

This research was conducted as part of the project 'The Economics of Marine Plastic Pollution- What are the benefits of International Cooperation?' funded by the Economic and Social Research Council (ESRC: ES/S002448/1). SLG was supported by a Daphne Jackson Fellowship. Authors would also like to acknowledge funding support from a number of Natural Environmental Research Council grants (NE/V009354/1, NE/V005448/1, NE/S003975/1 and NE/V007351). We would like to thank the anonymous reviewers, whose comments greatly improved this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171282.

References

Abreo N, Macusi E, Jimenez L. A survey of subtidal anthropogenic marine debris (AMD) in Mayo Bay. Mati City, Davao Oriental 2018. Philippine Journal of Science 147: 597–600.

Abreo, N.A.S., Blatchley, D., Superio, M.D., 2019. Stranded whale shark (Rhincodon typus) reveals vulnerability of filter-feeding elasmobranchs to marine litter in the Philippines. Mar. Pollut. Bull. 141, 79–83. https://doi.org/10.1016/j.marpolbul.2019.02.030.

Abu-Hilal, A., Al-Najjar, T., 2009. Marine litter in coral reef areas along the Jordan Gulf of Aqaba, Red Sea. J. Environ. Manage. 90, 1043–1049. https://doi.org/10.1016/j.jenvman.2008.03.014.

Acampora, H., Newton, S., O'Connor, I., 2017. Opportunistic sampling to quantify plastics in the diet of unfledged black legged kittiwakes (*Rissa tridactyla*), northern fulmars (*Fulmarus glacialis*) and great cormorants (*Phalacrocorax carbo*). Mar. Pollut. Bull. 119, 171–174. https://doi.org/10.1016/j.marpolbul.2017.04.016.

Afonso AS, Fidelis L. The fate of plastic-wearing sharks: Entanglement of an iconic top predator in marine debris. Marine Pollution Bulletin 2023; 194 Part A, September 2023, 115326. Doi:https://doi.org/10.1016/j.marpolbul.2023.115326.

Alexiadou, P., Foskolos, I., Frantzis, A., 2019. Ingestion of macroplastics by odontocetes of the Greek seas, eastern Mediterranean: often deadly! Mar. Pollut. Bull. 146, 67–75. https://doi.org/10.1016/j.marpolbul.2019.05.055.

Allen, A.S., Seymour, A.C., Rittschof, D., 2017. Chemoreception drives plastic consumption in a hard coral. Mar. Pollut. Bull. 124, 198–205. https://doi.org/10.1016/j.marpolbul.2017.07.030.

Arindra Putra, M.G., Zamani, N., Natih, N., Harahap, S., 2021. Relationship between characteristics of marine debris and how it impacts to coral reef at three islands in DKI Jakarta. Indonesia. Jurnal Ilmiah Perikanan dan Kelautan 13, 11–19. https://doi.org/10.20473/jipk.v13i1.18896.

Attademo, F.L.N., Balensiefer, D.C., Freire, AcdB, de Sousa, G.P., da Cunha, F.A.G.C., Luna, FdO, 2015. Debris ingestion by the Antillean manatee (*Trichechus manatus manatus*). Mar. Pollut. Bull. 101, 284–287. https://doi.org/10.1016/j.marpolbul.2015.09.040.

Avila, I.C., Kaschner, K., Dormann, C.F., 2018. Current global risks to marine mammals: taking stock of the threats. Biol. Conserv. 221, 44–58. https://doi.org/10.1016/j.biocon.2018.02.021.

Baird, R.W., Hooker, S.K., 2000. Ingestion of plastic and unusual prey by a juvenile harbour porpoise. Mar. Pollut. Bull. 40 (8), 719–720. https://doi.org/10.1016/S0025-326X(00)00051-5.

Balmer, B., Zolman, E., Bolton, J., Fauquier, D., Fougeres, E., George, R.C., et al., 2019. Ranging patterns and exposure to cumulative stressors of a *Tursiops truncatus* (common bottlenose dolphin) in Georgia. Southeast. Nat. 18.1.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecological monographs 81, 169–193. https://doi.org/10.1890/10-1510.1.

Barreiros, J.P., Raykov, V.S., 2014. Lethal lesions and amputation caused by plastic debris and fishing gear on the loggerhead turtle *Caretta caretta* (Linnaeus, 1758). Three case reports from Terceira Island, Azores (NE Atlantic). Mar. Pollut. Bull. 86, 518–522. https://doi.org/10.1016/j.marpolbul.2014.07.020.

Basurko, O.C., Ruiz, I., Rubio, A., Beldarrain, B., Kukul, D., Cózar, A., et al., 2022. The coastal waters of the south-East Bay of Biscay a dead-end for neustonic plastics. Mar. Pollut. Bull. 181, 113881 https://doi.org/10.1016/j.marpolbul.2022.113881.

Beaumont, N.J., Aanesen, M., Austen, M.C., Börger, T., Clark, J.R., Cole, M., et al., 2019. Global ecological, social and economic impacts of marine plastic. Mar. Pollut. Bull. 142, 189–195. https://doi.org/10.1016/j.marpolbul.2019.03.022.

Beaumont N, Börger T, Clark J, Hanley N, Johnston R, Meginnis K, et al. Significant benefits from international cooperation over marine plastic pollution. Nature (submitted) 2024. Doi:10.21203/rs.3.rs-3328986/v1.

Beck, C.A., Barros, N.B., 1991. The impact of debris on the Florida manatee. Mar. Pollut. Bull. 22, 508–510. https://doi.org/10.1016/0025-326X(91)90406-I.

Benjamin, D., Rozario, J., Jose, D., Kurup, M., 2014. Plastic ingestion by bigeye thresher shark *Alopias superciliosus* off Ratnagiri southwest coast of India. Int. J. Environ. Sci. 5, 277–281. https://doi.org/10.6088/ijes.2014050100024.

Bergmann, M., Almroth, B.C., Brander, S.M., Dey, T., Green, D.S., Gundogdu, S., et al., 2022. A global plastic treaty must cap production. Science 376, 469–470. https://doi.org/10.1126/science.abq0082.

Bernardini, I., Garibaldi, F., Canesi, L., Fossi, M.C., Baini, M., 2018. First data on plastic ingestion by blue sharks (*Prionace glauca*) from the Ligurian Sea (North-Western Mediterranean Sea). Mar. Pollut. Bull. 135, 303–310. https://doi.org/10.1016/j.marpolbul.2018.07.022.

Bird, P.M., 1978. Tissue regeneration in three Carcharhinid sharks encircled by embedded straps. Copeia 1978, 345–349. https://doi.org/10.2307/1443580.

Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., et al., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369, 1515–1518. https://doi.org/10.1126/science.aba3656.

Bourdages, M.P.T., Provencher, J.F., Sudlovenick, E., Ferguson, S.H., Young, B.G., Pelletier, N., et al., 2020. No plastics detected in seal (Phocidae) stomachs harvested in the eastern Canadian Arctic. Mar. Pollut. Bull. 150, 110772 https://doi.org/10.1016/j.marpolbul.2019.110772.

Bravo Rebolledo, E.L., Van Franeker, J.A., Jansen, O.E., Brasseur, S.M.J.M., 2013. Plastic ingestion by harbour seals (Phoca vitulina) in the Netherlands. Mar. Pollut. Bull. 67, 200–202. https://doi.org/10.1016/j.marpolbul.2012.11.035.

Brooks A, Jambeck J, Mozo-Reyes E. Plastic waste management and leakage in Latin America and the Caribbean. Technical Note N° IDB-TN-02058 2020.

Bryan-Brown, D.N., Connolly, R.M., Richards, D.R., Adame, F., Friess, D.A., Brown, C.J., 2020. Global trends in mangrove forest fragmentation. Sci. Rep. 10, 7117. https://doi.org/10.1038/s41598-020-63880-1.

Bundhoo, Z.M.A., 2018. Solid waste management in least developed countries: current status and challenges faced. J. Mater. Cycles Waste Manage. 20, 1867–1877. https://doi.org/10.1007/s10163-018-0728-3.

Butterworth, A., 2016. A review of the welfare impact on pinnipeds of plastic marine debris. Frontiers in marine. Science 3. https://doi.org/10.3389/fmars.2016.00149.

Carey, M.J., 2011. Intergenerational transfer of plastic debris by short-tailed shearwaters (*Ardenna tenuirostris*). Emu - Austral Ornithology 111, 229–234. https://doi.org/10.1071/MU10085.

Casale, P., Freggi, D., Paduano, V., Oliverio, M., 2016. Biases and best approaches for assessing debris ingestion in sea turtles, with a case study in the Mediterranean. Mar. Pollut. Bull. 110, 238–249. https://doi.org/10.1016/j.marpolbul.2016.06.057.

Chagnon, C., Thiel, M., Antunes, J., Ferreira, J.L., Sobral, P., Ory, N.C., 2018. Plastic ingestion and trophic transfer between Easter Island flying fish (*Cheilopogon rapanouiensis*) and yellowfin tuna (*Thunnus albacares*) from Rapa Nui (Easter Island). Environ. Pollut. 243, 127–133. https://doi.org/10.1016/j.envpol.2018.08.042.

Charlton-Howard, H.S., Bond, A.L., Rivers-Auty, J., Lavers, J.L., 2023. 'Plasticosis': Characterising macro- and microplastic-associated fibrosis in seabird tissues. J. Hazard. Mater. 450, 131090 https://doi.org/10.1016/j.jhazmat.2023.131090.

Chassignet, E.P., Xu, X., Zavala-Romero, O., 2021. Tracking marine litter with a Global Ocean model: where does it go? Where does it come from? Frontiers in marine. Science 8. https://doi.org/10.3389/fmars.2021.667591.

Chatto, R., Guinea, M., Conway, S., 1995. Sea turtles killed by flotsam in northern Australia. Mar. Turt. Newsl. 69, 17–18.

Chenillat, F., Huck, T., Maes, C., Grima, N., Blanke, B., 2021. Fate of floating plastic debris released along the coasts in a global ocean model. Mar. Pollut. Bull. 165, 112116 https://doi.org/10.1016/j.marpolbul.2021.112116.

Choi, D.Y., Gredzens, C., Shaver, D.J., 2021. Plastic ingestion by green turtles (Chelonia mydas) over 33 years along the coast of Texas, USA. Mar. Pollut. Bull. 173, 113111 https://doi.org/10.1016/j.marpolbul.2021.113111.

Cliff, G., Dudley, S., Ryan, P., Singleton, N., 2002. Large sharks and plastic debris in KwaZulu-Natal. South Africa. Marine and Freshwater Research 53, 575–581. https://doi.org/10.1071/MF01146.

Clukey, K.E., Lepczyk, C.A., Balazs, G.H., Work, T.M., Lynch, J.M., 2017. Investigation of plastic debris ingestion by four species of sea turtles collected as bycatch in pelagic

Pacific longline fisheries. Mar. Pollut. Bull. 120, 117–125. https://doi.org/10.1016/j.marpolbul.2017.04.064.

Colmenero, A.I., Barria, C., Broglio, E., Garcia-Barcelona, S., 2017. Plastic debris straps on threatened blue shark *Prionace glauca*. Mar. Pollut. Bull. 115, 436–438. https://doi.org/10.1016/j.marpolbul.2017.01.011.

Compa, M., Alomar, C., Wilcox, C., van Sebille, E., Lebreton, L., Hardesty, B.D., et al., 2019. Risk assessment of plastic pollution on marine diversity in the Mediterranean Sea. Sci. Total Environ. 678, 188–196. https://doi.org/10.1016/j.scitotenv.2019.04.355.

Cordeiro, C.A.M.M., Costa, T.M., 2010. Evaluation of solid residues removed from a mangrove swamp in the São Vicente estuary, SP. Brazil. Marine Pollution Bulletin 60, 1762–1767. https://doi.org/10.1016/j.marpolbul.2010.06.010.

Costa, M., Silva-Cavalcanti, J., Barbosa, C., Portugal, J., Barletta, M., 2011. Plastics buried in the inter-tidal plain of a tropical estuarine ecosystem. J. Coast. Res. 339–343.

Costa, R.A., Sá, S., Pereira, A.T., Ângelo, A.R., Vaqueiro, J., Ferreira, M., et al., 2020. Prevalence of entanglements of seabirds in marine debris in the central Portuguese coast. Mar. Pollut. Bull. 161, 111746 https://doi.org/10.1016/j.marpolbul.2020.111746.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Chang. 26, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

Cózar, A., Echevarría, F., González-Gordillo, J.I., Irigoien, X., Úbeda, B., Hernández-León, S., et al., 2014. Plastic debris in the open ocean. Proc. Natl. Acad. Sci. 111, 10239–10244. https://doi.org/10.1073/pnas.1314705111.

Cózar, A., Martí, E., Duarte, C.M., García-de-Lomas, J., van Sebille, E., Ballatore, T.J., et al., 2017. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the thermohaline circulation. Sci. Adv. 3, e1600582 https://doi.org/10.1126/sciadv.1600582.

Cozzolino, L., Nicastro, K.R., Zardi, G.I., de los Santos CB., 2020. Species-specific plastic accumulation in the sediment and canopy of coastal vegetated habitats. Sci. Total Environ. 723, 138018 https://doi.org/10.1016/j.scitotenv.2020.138018.

Daniel, J.T., Costidis, A.M., Barco, S.G., 2023. Fatal entanglements of sea turtles caused by widely deployed weather instruments. Mar. Pollut. Bull. 193, 115108 https://doi.org/10.1016/j.marpolbul.2023.115108.

de Carvalho-Souza, G.F., Llope, M., Tinôco, M.S., Medeiros, D.V., Maia-Nogueira, R., Sampaio, C.L.S., 2018. Marine litter disrupts ecological processes in reef systems. Mar. Pollut. Bull. 133, 464–471. https://doi.org/10.1016/j.marpolbul.2018.05.049.

De Pooter, D., Appeltans, W., Bailly, N., Bristol, S., Deneudt, K., Eliezer, M., et al., 2017. Toward a new data standard for combined marine biological and environmental datasets - expanding OBIS beyond species occurrences. Biodivers Data J, e10989. https://doi.org/10.3897/BDJ.5.e10989.

de Stephanis, R., Giménez, J., Carpinelli, E., Gutierrez-Exposito, C., Cañadas, A., 2013. As main meal for sperm whales: plastics debris. Mar. Pollut. Bull. 69, 206–214. https://doi.org/10.1016/j.marpolbul.2013.01.033.

De, K., Sautya, S., Gaikwad, S., Mitra, A., Nanajkar, M., 2022. Characterization of anthropogenic marine macro-debris affecting coral habitat in the highly urbanized seascape of Mumbai megacity. Environ. Pollut. 298, 118798 https://doi.org/10.1016/j.envpol.2022.118798.

Debrot, A.O., Meesters, H.W.G., Bron, P.S., de León, R., 2013. Marine debris in mangroves and on the seabed: largely-neglected litter problems. Mar. Pollut. Bull. 72, 1. https://doi.org/10.1016/j.marpolbul.2013.03.023.

Denuncio, P., Mandiola, M.A., Pérez Salles, S.B., Machado, R., Ott, P.H., De Oliveira, L.R., et al., 2017. Marine debris ingestion by the south American Fur seal from the Southwest Atlantic Ocean. Mar. Pollut. Bull. 122, 420–425. https://doi.org/10.1016/j.marpolbul.2017.07.013.

Diez, S.M., Patil, P.G., Morton, J., Rodriguez, D.J., Vanzella, A., Robin, D., Marine pollution in the Caribbean: not a minute to waste, et al., 2019. Washington. D.C, World Bank Group.

Duncan, E.M., Botterell, Z.L.R., Broderick, A.C., Galloway, T.S., Lindeque, P.K., Nuno, A., et al., 2017. A global review of marine turtle entanglement in anthropogenic debris: a baseline for further action. Endanger. Species Res. 34, 431–448. https://doi.org/10.3354/esr00865.

Duncan, E.M., Arrowsmith, J.A., Bain, C.E., Bowdery, H., Broderick, A.C., Chalmers, T., et al., 2019. Diet-related selectivity of macroplastic ingestion in green turtles (*Chelonia mydas*) in the eastern Mediterranean. Sci. Rep. 9, 11581. https://doi.org/10.1038/s41598-019-48086-4.

Eastman, C.B., Farrell, J.A., Whitmore, L., Rollinson Ramia, D.R., Thomas, R.S., Prine, J., et al., 2020. Plastic ingestion in Post-Hatchling Sea turtles: assessing a major threat in Florida near shore waters. Frontiers in marine. Science 7. https://doi.org/10.3389/fmars.2020.00693.

Eddy, T.D., Lam, V.W., Reygondeau, G., Cisneros-Montemayor, A.M., Greer, K., Palomares, M.L.D., et al., 2021. Global decline in capacity of coral reefs to provide ecosystem services. One Earth 4, 1278–1285. https://doi.org/10.1016/j.oneear.2021.08.016.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., et al., 2014. Plastic pollution in the World's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PloS One 9, e111913. https://doi.org/10.1371/journal.pone.0111913.

Eriksen, M., Cowger, W., Erdle, L.M., Coffin, S., Villarrubia-Gómez, P., Moore, C.J., et al., 2023. A growing plastic smog, now estimated to be over 170 trillion plastic particles afloat in the world's oceans—urgent solutions required. PloS One 18, e0281596. https://doi.org/10.1371/journal.pone.0281596.

Eriksson, C., Burton, H., 2003. Origins and biological accumulation of small plastic particles in fur seals from Macquarie Island. AMBIO: A journal of the human. Environment 32, 380–384. https://doi.org/10.1579/0044-7447-32.6.380.

Estes, J.A., Heithaus, M., McCauley, D.J., Rasher, D.B., Worm, B., 2016. Megafaunal impacts on structure and function of ocean ecosystems. Annu. Rev. Env. Resour. 41, 83–116. https://doi.org/10.1146/annurev-environ-110615-08562.

Fabri-Ruiz, S., Baudena, A., Moullec, F., Lombard, F., Irisson, J.O., Pedrotti, M.L., 2023. Mistaking plastic for zooplankton: risk assessment of plastic ingestion in the Mediterranean Sea. Sci. Total Environ. 856, 159011 https://doi.org/10.1016/j.scitotenv.2022.159011.

Fadare, O.O., Akinbile, A.A., Makinde, O.W., Ogundele, K.T., Ajagbe, E.F., Ilechukwu, I., 2022. Spatiotemporal variations in marine litter along the Gulf of Guinea coastline, Araromi seaside. Nigeria. Marine Pollution Bulletin 183, 114048. https://doi.org/10.1016/j.marpolbul.2022.114048.

Fernández, C., Anastasopoulou, A., 2019. Plastic ingestion by blue shark Prionace glauca in the South Pacific Ocean (south of the Peruvian Sea). Mar. Pollut. Bull. 149, 110501 https://doi.org/10.1016/j.marpolbul.2019.110501.

Figueroa-Pico, J., Valle, D.M.-D., Castillo-Ruperti, R., Macías-Mayorga, D., 2016. Marine debris: implications for conservation of rocky reefs in Manabi, Ecuador (se Pacific coast). Mar. Pollut. Bull. 109, 7–13. https://doi.org/10.1016/j.marpolbul.2016.05.070.

Fitzpatrick, J., Kirkman, H., 1995. Effects of prolonged shading stress on growth and survival of seagrass *Posidonia australis* in Jervis Bay, New South Wales. Australia. Marine Ecology Progress Series 127, 279–289.

Foley, C.J., Feiner, Z.S., Malinich, T.D., Höök TO, 2018. A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. Sci. Total Environ. 631-632, 550–559. https://doi.org/10.1016/j.scitotenv.2018.03.046.

Fong, J., Lee, S.H.R., Sun, Y., Lim, C.L., Tan, Y.A.J., Tan, Y.H., et al., 2023. Litter traps: A comparison of four marine habitats as sinks for anthropogenic marine macro-litter in Singapore. Mar. Pollut. Bull. 196, 115645 https://doi.org/10.1016/j.marpolbul.2023.115645.

Fossi, M.C., Baini, M., Panti, C., Galli, M., Jiménez, B., Muñoz-Arnanz, J., et al., 2017. Are whale sharks exposed to persistent organic pollutants and plastic pollution in the Gulf of California (Mexico)? First ecotoxicological investigation using skin biopsies. Comp. Biochem. Physiol., Part C: Toxicol. Pharmacol. 199, 48–58. https://doi.org/10.1016/j.cbpc.2017.03.002.

Fossi, M.C., Panti, C., Baini, M., Lavers, J.L., 2018. A review of plastic-associated pressures: cetaceans of the Mediterranean Sea and eastern Australian shearwaters as case studies. Frontiers in marine. Science 5. https://doi.org/10.3389/fmars.2018.00173.

Franco, J., Fort, J., García-Barón, I., Loubat, P., Louzao, M., del Puerto, O., et al., 2019. Incidence of plastic ingestion in seabirds from the Bay of Biscay (southwestern Europe). Mar. Pollut. Bull. 146, 387–392. https://doi.org/10.1016/j.marpolbul.2019.06.077.

Fujieda, S., Uchiyama, M., Azuma, T., Fukuda, R., Arita, Y., 2008. Ingestion case of plastics by black marlin *Makaira indica* and lancetfish *Alepisaurus ferox* caught in the East Indian Ocean. Mem. Fac. Fish. Kagoshima Univ 57, 47–48.

Fujieda, S., Higashi, M., Habano, M., Azuma, T., Arita, Y., Makino, H., 2014. Ingestion of plastic debris by tuna caught in the North Pacific Ocean. Journal of Japan Driftological Society 12, 47–48.

Gaboy, S.M.M., Guihawan, J.Q., Leopardas, V.E., Bacosa, H.P., 2022. Unravelling macroplastic pollution in seagrass beds of Iligan City, Mindanao. Philippines. Marine Pollution Bulletin 185, 114233. https://doi.org/10.1016/j.marpolbul.2022.114233.

Gedan, K.B., Silliman, B.R., Bertness, M.D., 2009. Centuries of human-driven change in salt marsh ecosystems. Ann. Rev. Mar. Sci. 1, 117–141.

Gomerčić, H., Đuras Gomerčić, M., Gomerčić, T., Lucić, H., Dalebout, M., Galov, A., et al., 2006. Biological aspects of Cuvier's beaked whale (*Ziphius cavirostris*) recorded in the Croatian part of the Adriatic Sea. Eur. J. Wildl. Res. 52, 182–187. https://doi.org/10.1007/s10344-006-0032-8.

Gong, Y., Huang, X., Li, Z., Shen, Y., Li, Y., Zhu, J., et al., 2023. Plastic ingestion and trophic transfer in an endangered top predator, the longfin mako shark (*Isurus paucus*), from the tropical western Pacific Ocean. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-023-25532-5.

Gratwicke, B., Speight, M.R., 2005. The relationship between fish species richness, abundance and habitat complexity in a range of shallow tropical marine habitats. J. Fish Biol. 66, 650–667. https://doi.org/10.1111/j.0022-1112.2005.00629.x.

Green, S., Webber, M., 1996. A survey of the solid waste pollution in Kingston harbour mangroves, near port royal. Jamaica. Caribb. Mar. Stud. 5, 14–22.

Green, D.S., Boots, B., Blockley, D.J., Rocha, C., Thompson, R., 2015. Impacts of discarded plastic bags on marine assemblages and ecosystem functioning. Environ. Sci. Technol. 49, 5380–5389. https://doi.org/10.1021/acs.est.5b00277.

Guerrini, F., Mari, L., Casagrandi, R., 2019. Modeling plastics exposure for the marine biota: risk maps for fin whales in the Pelagos sanctuary (North-Western Mediterranean). Frontiers in marine. Science 6. https://doi.org/10.3389/fmars.2019.00299.

Guterres-Pazin, M.G., Rosas, F.C., Marmontel, M., 2012. Ingestion of invertebrates, seeds, and plastic by the Amazonian manatee (Trichechus inunguis)(Mammalia, Sirenia). Aquat. Mamm. 38, 322.

Gutow, L., Ricker, M., Holstein, J.M., Dannheim, J., Stanev, E.V., Wolff, J.-O., 2018. Distribution and trajectories of floating and benthic marine macrolitter in the South-Eastern North Sea. Mar. Pollut. Bull. 131, 763–772. https://doi.org/10.1016/j.marpolbul.2018.05.003.

Hall, N.M., Berry, K.L.E., Rintoul, L., Hoogenboom, M.O., 2015. Microplastic ingestion by scleractinian corals. Mar. Biol. 162, 725–732. https://doi.org/10.1007/s00227-015-2619-7.

Hansen, M., Alstrup, A., Hansen, J., Al-Sabi, M., Nonnemann, B., Jensen, L., et al., 2016. Stranding of two sperm whales (Physeter macrocephalus) in the “North Sea trap” at Henne Strand. Denmark. Aquatic Mammals 42, 35–41. https://doi.org/10.1578/AM.42.1.2016.35.

Harris, P.T., Westerveld, L., Nyberg, B., Maes, T., Macmillan-Lawler, M., Appelquist, L.R., 2021. Exposure of coastal environments to river-sourced plastic pollution. Sci. Total Environ. 769, 145222 https://doi.org/10.1016/j.scitotenv.2021.145222.

Hastuti, A.R., Yulianda, F., Wardiatno, Y., 2014. Spatial distribution of marine debris in mangrove ecosystem of Pantai Indah Kapuk. Jakarta. International Journal of Bonorowo Wetlands 4, 94–107.

Hatzonikolakis, Y., Giakoumi, S., Raitsos, D.E., Tsiaras, K., Kalaroni, S., Triantaphyllidis, G., et al., 2022. Quantifying transboundary plastic pollution in marine protected areas across the Mediterranean Sea. Frontiers in marine. Science 8. https://doi.org/10.3389/fmars.2021.762235.

Hays, G.C., Scott, R., 2013. Global patterns for upper ceilings on migration distance in sea turtles and comparisons with fish, birds and mammals. Funct. Ecol. 27, 748–756. https://doi.org/10.1111/1365-2435.12073.

Henderson, J.R., 2001. A pre- and post-MARPOL annex V summary of Hawaiian monk seal entanglements and marine debris accumulation in the northwestern Hawaiian islands, 1982–1998. Mar. Pollut. Bull. 42, 584–589. https://doi.org/10.1016/S0025-326X(00)00204-6.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al., 2020. The ERA5 global reanalysis. Q. J. Roy. Meteorol. Soc. 146, 1999–2049. https://doi.org/10.1002/qj.3803.

Hidalgo-Ruz, V., Luna-Jorquera, G., Eriksen, M., Frick, H., Miranda-Urbina, D., Portflitt-Toro, M., et al., 2021. Factors (type, colour, density, and shape) determining the removal of marine plastic debris by seabirds from the South Pacific Ocean: is there a pattern? Aquatic Conservation: Marine and Freshwater Ecosystems 31, 389–407. https://doi.org/10.1002/aqc.3453.

Høiberg, M.A., Woods, J.S., Verones, F., 2022. Global distribution of potential impact hotspots for marine plastic debris entanglement. Ecol. Indic. 135, 108509 https://doi.org/10.1016/j.ecolind.2021.108509.

Houlbrèque, F., Ferrier-Pagès, C., 2009. Heterotrophy in tropical Scleractinian corals. Biol. Rev. 84, 1–17. https://doi.org/10.1111/j.1469-185X.2008.00058.x.

Hyrenbach, K.D., McGinnis, Z., Page, K., Rapp, D., Horgen, F.D., Lynch, J.M., 2021. Assessment of plastic ingestion by pole-caught pelagic predatory fish from O’ahu, Hawai’i. Aquat. Conserv. Mar. Freshwat. Ecosyst. 31, 408–419. https://doi.org/10.1002/aqc.3507.

IPCC. Summary for Policymakers. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, et al., editors. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp., 2012, pp. 1–19.

Ivar do Sul, J.A., Costa, M.F., Silva-Cavalcanti, J.S., MCB, Araújo, 2014. Plastic debris retention and exportation by a mangrove forest patch. Mar. Pollut. Bull. 78, 252–257. https://doi.org/10.1016/j.marpolbul.2013.11.011.

Jacobsen, J.K., Massey, L., Gulland, F., 2010. Fatal ingestion of floating net debris by two sperm whales (*Physeter macrocephalus*). Mar. Pollut. Bull. 60, 765–767. https://doi.org/10.1016/j.marpolbul.2010.03.008.

Jean-Michel, L., Eric, G., Romain, B.-B., Gilles, G., Angélique, M., Marie, D., et al., 2021. The Copernicus global 1/12 oceanic and sea ice GLORYS12 reanalysis. Front. Earth Sci. 9, 698876.

Joyce, W.N., Campana, S.E., Natanson, L.J., Kohler, N.E., Pratt Jr., H.L., Jensen, C.F., 2002. Analysis of stomach contents of the porbeagle shark (*Lamna nasus* Bonnaterre) in the Northwest Atlantic. ICES J. Mar. Sci. 59, 1263–1269. https://doi.org/10.1006/jmsc.2002.1286.

Kaladharan, P., Asokan, P., Koya, M., Bhint, H., 2014. Plastic debris in the stomach of a Longman’s beaked whale, *Indopacetus pacificus* (Longman, 1926) stranded off Sutrapada, Veraval, Saurashtra coast, India. J. Mar. Biol. Assoc. India 56, 92–94.

Karris, G., Savva, I., Kakalis, E., Bairaktaridu, K., Espinosa, C., Smith, M.S., et al., 2023. First sighting of a pelagic seabird entangled in a disposable COVID-19 facemask in the Mediterranean Sea. Mediterr. Mar. Sci. 24, 50–55.

Kelly, B., 2022. An Assessment of Plastic Ingestion in Selected Australian Pinniped Species. Macquarie University.

Kelly, N.E., Feyrer, L., Gavel, H., Trela, O., Ledwell, W., Breeze, H., et al., 2023. Long term trends in floating plastic pollution within a marine protected area identifies threats for endangered northern bottlenose whales. Environ. Res. 227. https://doi.org/10.1016/j.envres.2023.115686.

Kesavan, S., Xavier, K.A.M., Deshmukhe, G., Jaiswar, A.K., Bhusan, S., Shukla, S.P., 2021. Anthropogenic pressure on mangrove ecosystems: quantification and source identification of surficial and trapped debris. Sci. Total Environ. 794, 148677 https://doi.org/10.1016/j.scitotenv.2021.148677.

Kühn, S., Bravo Rebolledo, E.L., van Franeker, J.A., 2015. Deleterious effects of litter on marine life. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 75–116. https://doi.org/10.1007/978-3-319-16510-3_4.

Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., et al., 2018. Plastic waste associated with disease on coral reefs. Science 359, 460–462. https://doi.org/10.1126/science.aar3320.

Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., et al., 2020. Evaluating scenarios toward zero plastic pollution. Science 369, 1455–1461. https://doi.org/10.1126/science.aba9475.

Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., 2017. Reisser J. c. Communications 8, 15611. https://doi.org/10.1038/ncomms15611.

Lewison, R.L., Crowder, L.B., 2007. Putting longline bycatch of sea turtles into perspective. Conserv. Biol. 21, 79–86. https://doi.org/10.1111/j.1523-1739.2006.00592.x.

Litchfield, S.G., Schulz, K.G., Kelaher, B.P., 2020. The influence of plastic pollution and ocean change on detrital decomposition. Mar. Pollut. Bull. 158, 111354 https://doi.org/10.1016/j.marpolbul.2020.111354.

Lombardi, J., Morton, M., 1993. Dusky shark injured by plastic packing strap encirclement off North Carolina. Journal of the Elisha Mitchell Scientific Society 109, 180–182.

López-López, L., Preciado, I., González-Irusta, J.M., Arroyo, N.L., Muñoz, I., Punzón, A., et al., 2018. Incidental ingestion of meso- and macro-plastic debris by benthic and demersal fish. Food Webs 14, 1–4. https://doi.org/10.1016/j.fooweb.2017.12.002.

Lucas, Z., 1992. Monitoring persistent litter in the marine environment on Sable Island. Nova Scotia. Marine Pollution Bulletin 24, 192–199. https://doi.org/10.1016/0025-326X(92)90529-F.

Lusher, A.L., Hernandez-Milian, G., O’Brien, J., Berrow, S., O’Connor, I., Officer, R., 2015. Microplastic and macroplastic ingestion by a deep diving, oceanic cetacean: the True’s beaked whale Mesoplodon mirus. Environ. Pollut. 199, 185–191. https://doi.org/10.1016/j.envpol.2015.01.023.

Lusher, A.L., Hernandez-Milian, G., Berrow, S., Rogan, E., O’Connor, I., 2018. Incidence of marine debris in cetaceans stranded and bycaught in Ireland: recent findings and a review of historical knowledge. Environ. Pollut. 232, 467–476. https://doi.org/10.1016/j.envpol.2017.09.070.

Macias, D., Stips, A., Hanke, G., 2022. Model based estimate of transboundary litter pollution on Mediterranean coasts. Mar. Pollut. Bull. 175, 113121 https://doi.org/10.1016/j.marpolbul.2021.113121.

Manooch, C.S., Mason, D.L., 1983. Comparative food studies of yellowfin tuna, *Thunnus albacares*, and blackfin tuna, *Thunnus atlanticus* (Pisces: Scombridae) from the southeastern and gulf coasts of the United States. Brimleyana 9, 33–52.

Manooch, C.S., Mason, D.L., Nelson, R.S., 1985. Foods of little tunny *Euthynnus alletteratus* collected along the southeastern and gulf coasts of the United States. Nippon Suisan Gakkaishi 51, 1207–1218.

March, A., Roberts, K.P., Fletcher, S., 2022. A new treaty process offers hope to end plastic pollution. Nature Reviews Earth & Environment 3, 726–727. https://doi.org/10.1038/s43017-022-00361-1.

Marris, S., 2018. Dead whale had 115 plastic cups in its belly. Sky News. https://news.sky.com/story/dead-whale-had-115-plastic-cups-in-its-belly-11558642.

Martin, C., Almahasheer, H., Duarte, C.M., 2019. Mangrove forests as traps for marine litter. Environ. Pollut. 247, 499–508. https://doi.org/10.1016/j.envpol.2019.01.067.

Martin, C., Baalkhuyur, F., Valluzzi, L., Saderne, V., Cusack, M., Almahasheer, H., et al., 2020. Exponential increase of plastic burial in mangrove sediments as a major plastic sink. Science. Advances 6, eaaz5593. https://doi.org/10.1126/sciadv.aaz5593.

Massetti, L., Rangel-Buitrago, N., Pietrelli, L., Merlino, S., 2021. Litter impacts on marine birds: the Mediterranean northern gannet as case study. Mar. Pollut. Bull. 171, 112779 https://doi.org/10.1016/j.marpolbul.2021.112779.

Mazarrasa, I., Puente, A., Núñez, P., García, A., Abascal, A.J., Juanes, J.A., 2019. Assessing the risk of marine litter accumulation in estuarine habitats. Mar. Pollut. Bull. 144, 117–128. https://doi.org/10.1016/j.marpolbul.2019.04.060.

Mehlhart G, Blepp M. Study on land sourced litter in the marine environment. Review of sources and literature. Olko Institut report http://www. kunststoffverpackungen.de/show. php 2012.

Meijer, L.J.J., van Emmerik, T., van der Ent, R., Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science. Advances 7, eaaz5803. https://doi.org/10.1126/sciadv.aaz5803.

Menicagli, V., Balestri, E., Vallerini, F., De Battisti, D., Lardicci, C., 2021. Plastics and sedimentation foster the spread of a non-native macroalga in seagrass meadows. Sci. Total Environ. 757, 143812 https://doi.org/10.1016/j.scitotenv.2020.143812.

Merlino, S., Locritani, M., Guarnieri, A., Delrosso, D., Bianucci, M., Paterni, M., 2023. Marine litter tracking system: A case study with open-source technology and a citizen science-based approach. Sensors 23, 935. https://doi.org/10.3390/s23020935.

Milman, O., 2020. Endangered animals get entangled in plastics that riddle US oceans – study. The Guardian.

Morales-Caselles, C., Viejo, J., Martí, E., González-Fernández, D., Pragnell-Raasch, H., González-Gordillo, J.I., et al., 2021. An inshore–offshore sorting system revealed from global classification of ocean litter. Nature Sustainability 4, 484–493. https://doi.org/10.1038/s41893-021-00720-8.

Morgan, E., Hutchinson, D., Gaion, A., 2021. Plastic ingestion by the small-spotted catshark (Scyliorhinus canicula) from the south west coast of the United Kingdom. Bull. Environ. Contam. Toxicol. 106, 910–915. https://doi.org/10.1007/s00128-021-03129-3.

Moudrý, V., Devillers, R., 2020. Quality and usability challenges of global marine biodiversity databases: an example for marine mammal data. Eco. Inform. 56, 101051 https://doi.org/10.1016/j.ecoinf.2020.101051.

Moyer, M., 2020. Resourceful Florida manatee frees self after lengthy bicycle tire entanglement. Orlando Weekly https://www.orlandoweekly.com/news/resourceful-manatee-frees-self-after-lengthy-bicycle-tire-entanglement-28417402.

Mueller, J.S., Schupp, P.J., 2020. Shading by marine litter impairs the health of the two indo-Pacific scleractinian corals Porites rus and Pavona cactus. Mar. Pollut. Bull. 158, 111429 https://doi.org/10.1016/j.marpolbul.2020.111429.

Mueller, J.S., Bill, N., Reinach, M.S., Lasut, M.T., Freund, H., Schupp, P.J., 2022. A comprehensive approach to assess marine macro litter pollution and its impacts on corals in the Bangka Strait, North Sulawesi. Indonesia. Marine Pollution Bulletin 175, 113369. https://doi.org/10.1016/j.marpolbul.2022.113369.

Mulochau, T., Lelabousse, C., Séré, M., 2020. Estimations of densities of marine litter on the fringing reefs of Mayotte (France – South Western Indian Ocean) - impacts on coral communities. Mar. Pollut. Bull. 160, 111643 https://doi.org/10.1016/j.marpolbul.2020.111643.

Navarrete-Fernández, T., Bermejo, R., Hernández, I., Deidun, A., Andreu-Cazenave, M., Cózar, A., 2022. The role of seagrass meadows in the coastal trapping of litter. Mar. Pollut. Bull. 174, 113299 https://doi.org/10.1016/j.marpolbul.2021.113299.

Nelms, S.E., Duncan, E.M., Broderick, A.C., Galloway, T.S., Godfrey, M.H., Hamann, M., et al., 2015. Plastic and marine turtles: a review and call for research. ICES Journal of Marine Science 73, 165–181. https://doi.org/10.1093/icesjms/fsv165.

Nelms, S.E., Clark, B.L., Duncan, E.M., Germanov, E., Godley, B.J., Parton, K.J., et al., 2023. Plastic pollution and marine megafauna: recent advances and future directions. Plastic Pollution in the Global Ocean 97–138. https://doi.org/10.1142/9789811259111_0005.

Neto, J.G.B., Rodrigues, F.L., Ortega, I., Rodrigues, LdS, Lacerda, AldF, Coletto, J.L., et al., 2020. Ingestion of plastic debris by commercially important marine fish in southeast-South Brazil. Environ. Pollut. 267, 115508 https://doi.org/10.1016/j.envpol.2020.115508.

Noman, M.A., Adyel, T.M., Macreadie, P.I., Trevathan-Tackett, S.M., 2024. Prioritising plastic pollution research in blue carbon ecosystems: A scientometric overview. Sci. Total Environ. 914, 169868 https://doi.org/10.1016/j.scitotenv.2024.169868.

O'Hanlon, N.J., James, N.A., Masden, E.A., Bond, A.L., 2017. Seabirds and marine plastic debris in the northeastern Atlantic: A synthesis and recommendations for monitoring and research. Environ. Pollut. 231, 1291–1301. https://doi.org/10.1016/j.envpol.2017.08.101.

Okuku, E.O., Kombo, M., Mwalugha, C., Owato, G., Otieno, K., Mbuche, M., et al., 2023. Are tropical mangroves a sink for litter leaking from land-and sea-based sources? Evidence from selected Kenyan mangroves. Mar. Pollut. Bull. 187, 114590 https://doi.org/10.1016/j.marpolbul.2023.114590.

Orós, J., Montesdeoca, N., Camacho, M., Arencibia, A., Calabuig, P., 2016. Causes of stranding and mortality, and final disposition of loggerhead sea turtles (*Caretta caretta*) admitted to a wildlife rehabilitation center in gran Canaria Island, Spain (1998-2014): a long-term retrospective study. PloS One 11, e0149398.

Ouyang, X., Duarte, C.M., Cheung, S.-G., Tam, N.F.-Y., Cannicci, S., Martin, C., et al., 2022. Fate and effects of macro- and microplastics in coastal wetlands. Environ. Sci. Technol. 56, 2386–2397. https://doi.org/10.1021/acs.est.1c06732.

Padula, A.D., Machado, R., Milmann, L., de León, M.C., Gana, J.C.M., Wickert, J.C., et al., 2023. Marine debris ingestion by odontocete species from the Southwest Atlantic Ocean: absence also matter. Mar. Pollut. Bull. 186, 114486 https://doi.org/10.1016/j.marpolbul.2022.114486.

Page, B., McKenzie, J., McIntosh, R., Baylis, A., Morrissey, A., Calvert, N., et al., 2004. Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after government and industry attempts to reduce the problem. Mar. Pollut. Bull. 49, 33–42. https://doi.org/10.1016/j.marpolbul.2004.01.006.

Paler, M.K.O., Tabañag, I.D.F., Siacor, F.D.C., Geraldino, P.J.L., Walton, M.E.M., Dunn, C., et al., 2022. Elucidating the surface macroplastic load, types and distribution in mangrove areas around Cebu Island, Philippines and its policy implications. Sci. Total Environ. 838, 156408 https://doi.org/10.1016/j.scitotenv.2022.156408.

Parton, K.J., Galloway, T.S., Godley, B.J., 2019. Global review of shark and ray entanglement in anthropogenic marine debris. Endanger. Species Res. 39, 173–190.

Petry, M.V., Araújo, L.D., Brum, A.C., Benemann, V.R.F., Finger, J.V.G., 2021. Plastic ingestion by juvenile green turtles (Chelonia mydas) off the coast of southern Brazil. Mar. Pollut. Bull. 167, 112337 https://doi.org/10.1016/j.marpolbul.2021.112337.

Pierce, K.E., Harris, R.J., Larned, L.S., Pokras, M.A., 2004. Obstruction and starvation associated with plastic ingestion in a northern gannet Morus bassanus and a greater shearwater Puffinus gravis. Mar. Ornithol. 32, 187–189.

Pimiento, C., Leprieur, F., Silvestro, D., Lefcheck, J.S., Albouy, C., Rasher, D.B., et al., 2020. Functional diversity of marine megafauna in the Anthropocene. Sci. Adv. 6, eaay7650 https://doi.org/10.1126/sciadv.aay7650.

Pinheiro, L.M., Carvalho, I.V., Agostini, V.O., Martinez-Souza, G., Galloway, T.S., Pinho, G.L.L., 2021. Litter contamination at a salt marsh: an ecological niche for biofouling in South Brazil. Environ. Pollut. 285, 117647 https://doi.org/10.1016/j.envpol.2021.117647.

Pinzone, M., Nordøy, E.S., Eppe, G., Malherbe, C., Das, K., Collard, F., 2021. First record of plastic debris in the stomach of a hooded seal pup from the Greenland Sea. Mar. Pollut. Bull. 167, 112350 https://doi.org/10.1016/j.marpolbul.2021.112350.

Podolsky, R.H., 1989. Entrapment of sea-deposited plastic on the shore of a gulf of Maine Island. Mar. Environ. Res. 27, 67–72. https://doi.org/10.1016/0141-1136(89)90019-6.

Poeta, G., Staffieri, E., Acosta, A.T.R., Battisti, C., 2017. Ecological effects of anthropogenic litter on marine mammals: A global review with a "black-list" of impacted taxa. Hystrix, the Italian Journal of Mammalogy 28, 253–264. https://doi.org/10.4404/hystrix-00003-2017.

Provencher, J.F., Bond, A.L., Hedd, A., Montevecchi, W.A., Muzaffar, S.B., Courchesne, S.J., et al., 2014. Prevalence of marine debris in marine birds from the North Atlantic. Mar. Pollut. Bull. 84, 411–417. https://doi.org/10.1016/j.marpolbul.2014.04.044.

Raum-Suryan KL, Suryan RM. Entanglement of Steller Sea Lions in Marine Debris and Fishing Gear on the Central Oregon Coast from 2005–2009. Oceans. 3. MDPI, 2022, pp. 319–330.

Reichert, J., Schellenberg, J., Schubert, P., Wilke, T., 2018. Responses of reef building corals to microplastic exposure. Environ. Pollut. 237, 955–960. https://doi.org/10.1016/j.envpol.2017.11.006.

Reinert, T.R., Spellman, A.C., Bassett, B.L., 2017. Entanglement in and ingestion of fishing gear and other marine debris by Florida manatees, 1993 to 2012. Endanger. Species Res. 32, 415–427.

Reisser, J., Slat, B., Noble, K., du Plessis, K., Epp, M., Proietti, M., et al., 2015. The vertical distribution of buoyant plastics at sea: an observational study in the North Atlantic gyre. Biogeosciences 12, 1249–1256. https://doi.org/10.5194/bg-12-1249-2015.

Richards, Z.T., Beger, M., 2011. A quantification of the standing stock of macro-debris in Majuro lagoon and its effect on hard coral communities. Mar. Pollut. Bull. 62, 1693–1701. https://doi.org/10.1016/j.marpolbul.2011.06.003.

Rivers-Auty, J., Bond, A.L., Grant, M.L., Lavers, J.L., 2023. The one-two punch of plastic exposure: macro- and micro-plastics induce multi-organ damage in seabirds. J. Hazard. Mater. 442, 130117 https://doi.org/10.1016/j.jhazmat.2022.130117.

Rodríguez, Y., Vandeperre, F., Santos, M.R., Herrera, L., Parra, H., Deshpande, A., et al., 2022. Litter ingestion and entanglement in green turtles: an analysis of two decades of stranding events in the NE Atlantic. Environ. Pollut. 298, 118796 https://doi.org/10.1016/j.envpol.2022.118796.

Roman, L., Schuyler, Q., Wilcox, C., Hardesty, B.D., 2021. Plastic pollution is killing marine megafauna, but how do we prioritize policies to reduce mortality? Conserv. Lett. 14, e12781 https://doi.org/10.1111/conl.12781.

Romeo, T., Pietro, B., Pedà, C., Consoli, P., Andaloro, F., Fossi, M.C., 2015. First evidence of presence of plastic debris in stomach of large pelagic fish in the Mediterranean Sea. Mar. Pollut. Bull. 95, 358–361. https://doi.org/10.1016/j.marpolbul.2015.04.048.

Ryan, P.G., 2018. Entanglement of birds in plastics and other synthetic materials. Mar. Pollut. Bull. 135, 159–164. https://doi.org/10.1016/j.marpolbul.2018.06.057.

Ryan, P.G., Cole, G., Spiby, K., Nel, R., Osborne, A., Perold, V., 2016. Impacts of plastic ingestion on post-hatchling loggerhead turtles off South Africa. Mar. Pollut. Bull. 107, 155–160. https://doi.org/10.1016/j.marpolbul.2016.04.005.

Sajikumar, K., Ragesh, N., Remya, R., Mohamed, K., 2013. Occurrence of Plastic Debris in the Stomach of Yellowfin Tuna (*Thunnus albacares*) from the Arabian Sea: A Cause for Concern. Technical and Extension Series, Marine Fisheries Information Service, p. 13.

Salazar-Casals A, de Reus K, Greskewitz N, Havermans J, Geut M, Villanueva S, et al. Increased Incidence of Entanglements and Ingested Marine Debris in Dutch Seals from 2010 To 2020. Oceans. 3. MDPI, 2022, pp. 389–400.

Sampaio CLS, Leite L, Reis-Filho JA, Loiola M, Miranda RJ, de Anchieta C.C. Nunes J, et al. New insights into whale shark Rhincodon typus diet in Brazil: an observation of ram filter-feeding on crab larvae and analysis of stomach contents from the first stranding in Bahia state. Environ. Biol. Fishes 2018; 101: 1285–1293. Doi:https://doi.org/10.1007/s10641-018-0775-6.

Sanchez-Vidal, A., Canals, M., de Haan, W.P., Romero, J., Veny, M., 2021. Seagrasses provide a novel ecosystem service by trapping marine plastics. Sci. Rep. 11, 254. https://doi.org/10.1038/s41598-020-79370-3.

Santodomingo, N., Perry, C., Waheed, Z., Hussein, Syed, MAb, Rosedy A, Johnson KG., 2021. Marine litter pollution on coral reefs of Darvel Bay (East Sabah, Malaysia). Mar. Pollut. Bull. 173, 112998. DOI : https://doi.org/10.1016/j.marpolbul.2021.112998.

Santos, R.G., Andrades, R., Boldrini, M.A., Martins, A.S., 2015. Debris ingestion by juvenile marine turtles: an underestimated problem. Mar. Pollut. Bull. 93, 37–43. https://doi.org/10.1016/j.marpolbul.2015.02.022.

Sazima, I., Gadig, O.B.F., Namora, R.C., Motta, F.S., 2002. Plastic debris collars on juvenile carcharhinid sharks (*Rhizoprionodon lalandii*) in Southwest Atlantic. Mar. Pollut. Bull. 44, 1149–1151. https://doi.org/10.1016/s0025-326x(02)00141-8.

Sbrana, A., Cau, A., Cicala, D., Franceschini, S., Giarrizzo, T., Gravina, M.F., et al., 2022. Ask the shark: blackmouth catshark (*Galeus melastomus*) as a sentinel of plastic waste on the seabed. Mar. Biol. 169, 98. https://doi.org/10.1007/s00227-022-04084-1.

Schuyler, Q.A., Wilcox, C., Townsend, K.A., Wedemeyer-Strombel, K.R., Balazs, G., van Sebille, E., et al., 2016. Risk analysis reveals global hotspots for marine debris ingestion by sea turtles. Glob. Chang. Biol. 22, 567–576. https://doi.org/10.1111/gcb.13078.

Senko, J.F., Nelms, S.E., Reavis, J.L., Witherington, B., Godley, B.J., Wallace, B.P., 2020. Understanding individual and population-level effects of plastic pollution on marine megafauna. Endanger. Species Res. 43, 234–252.

Sileo, L., Sievert, P., Samuel, M.D., Fefer, S.I., 1990. Prevalence and characteristics of plastic ingested by Hawaiian seabirds. Second International Conference on Marine Debris 665–681.

Silva, A., Marmontel, M., 2009. Ingestão de lixo plástico como provável causa mortis de peixe-boi amazônico (Trichechus inunguis Natterer, 1883). Scientific Magazine UAKARI 5, 105–112.

Simmonds, M.P., 2012. Cetaceans and marine debris: the great unknown. Journal of Marine Biology 2012, 684279. https://doi.org/10.1155/2012/684279.

Sivasothi, N., 2002. Battling the curse of marine litter. Nature Watch 10.

Smith, L.E., 2018. Plastic ingestion by Scyliorhinus canicula trawl captured in the North Sea. Mar. Pollut. Bull. 130, 6–7. https://doi.org/10.1016/j.marpolbul.2018.03.001.

Solomando, A., Pujol, F., Sureda, A., Pinya, S., 2022. Evaluating the presence of marine litter in cetaceans stranded in the Balearic Islands (Western Mediterranean Sea). Biology-Basel 11. https://doi.org/10.3390/biology11101468.

Suyadi, Manullang, C.Y., 2020. Distribution of plastic debris pollution and it is implications on mangrove vegetation. Mar. Pollut. Bull. 160, 111642 https://doi.org/10.1016/j.marpolbul.2020.111642.

Tavares, D.C., de Moura, J.F., Merico, A., Siciliano, S., 2017. Incidence of marine debris in seabirds feeding at different water depths. Mar. Pollut. Bull. 119, 68–73. https://doi.org/10.1016/j.marpolbul.2017.04.012.

Tekman MB, Peter C, Gutow. and Bergmann M (2019): litterbase.org: An Online Portal for Marine Litter and Microplastics and their Impacts on Marine Life, Side Event @ Arctic Frontiers, Tromso, 20 January 2019–25 January 2019.

Tekman, M.B., Gutow, L., Bergmann, M., 2022. Marine debris floating in Arctic and temperate Northeast Atlantic waters. Frontiers in marine. Science 9. https://doi.org/10.3389/fmars.2022.933768.

Thiel, M., Luna-Jorquera, G., Álvarez-Varas, R., Gallardo, C., Hinojosa, I.A., Luna, N., et al., 2018. Impacts of marine plastic pollution from continental coasts to subtropical gyres—fish, seabirds, and other vertebrates in the SE Pacific. Frontiers in marine. Science 5. https://doi.org/10.3389/fmars.2018.00238.

Tibbetts, J.H., 2015. Managing marine plastic pollution: policy initiatives to address wayward waste. Environ. Health Perspect. 123, A90–A93. https://doi.org/10.1289/ehp.123-A90.

Uncles, R., Clark, J., Bedington, M., Torres, R., 2020. On sediment dispersal in the Whitsand Bay marine conservation zone: neighbour to a closed dredge-spoil disposal site. Marine protected areas. Elsevier 599–629.

UNEP. Marine litter: a global challenge. 2009. Nairobi: UNEP. 232 pp.

UNEP, 2019. In: Notten, P. (Ed.), Addressing Marine Plastics: A Systemic Approach - Recommendations for Action. United Nations Environment Programme, Nairobi, Kenya.

UNEP, 2021. From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution. United Nations Environmental Program, Nairobi, Kenya.

UNEP. Zero draft text of the international legally binding instrument on plastic pollution, including in the marine environment 2023.

Unger, B., Rebolledo, E.L.B., Deaville, R., Gröne, A., Ijsseldijk, L.L., Leopold, M.F., et al., 2016. Large amounts of marine debris found in sperm whales stranded along the North Sea coast in early 2016. Mar. Pollut. Bull. 112, 134–141. https://doi.org/10.1016/j.marpolbul.2016.08.027.

van Bijsterveldt, C.E.J., van Wesenbeeck, B.K., Ramadhani, S., Raven, O.V., van Gool, F.E., Pribadi, R., et al., 2021. Does plastic waste kill mangroves? A field experiment to assess the impact of macro plastics on mangrove growth, stress response and survival. Sci. Total Environ. 756, 143826 https://doi.org/10.1016/j.scitotenv.2020.143826.

van Franeker, J.A., Blaize, C., Danielsen, J., Fairclough, K., Gollan, J., Guse, N., et al., 2011. Monitoring plastic ingestion by the northern fulmar *Fulmarus glacialis* in the North Sea. Environ. Pollut. 159, 2609–2615. https://doi.org/10.1016/j.envpol.2011.06.008.

van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., van Franeker, J.A., et al., 2015. A global inventory of small floating plastic debris. Environ. Res. Lett. 10, 124006 https://doi.org/10.1088/1748-9326/10/12/124006.

Van Sebille, E., Aliani, S., Law, K.L., Maximenko, N., Alsina, J.M., Bagaev, A., et al., 2020. The physical oceanography of the transport of floating marine debris. Environ. Res. Lett. 15, 023003.

Varela, J.L., Medina, A., Déniz, S., Abascal, F.J., 2022. Feeding of Atlantic bluefin tuna Thunnus thynnus around the Canary Islands assessed from stomach content and stable isotope analyses. Mar. Ecol. Prog. Ser. 686, 177–186.

Viehman, S., Vander Pluym, J.L., Schellinger, J., 2011. Characterization of marine debris in North Carolina salt marshes. Mar. Pollut. Bull. 62, 2771–2779. https://doi.org/10.1016/j.marpolbul.2011.09.010.

Vogt-Vincent, N.S., Burt, A.J., Kaplan, D.M., Mitarai, S., Turnbull, L.A., Johnson, H.L., 2023. Sources of marine debris for Seychelles and other remote islands in the western Indian Ocean. Mar. Pollut. Bull. 187, 114497 https://doi.org/10.1016/j.marpolbul.2022.114497.

Votier, S.C., Archibald, K., Morgan, G., Morgan, L., 2011. The use of plastic debris as nesting material by a colonial seabird and associated entanglement mortality. Mar. Pollut. Bull. 62, 168–172. https://doi.org/10.1016/j.marpolbul.2010.11.009.

Walker WA, Coe JM. Survey of marine debris ingestion by odontocete cetaceans. Proceedings of the second international conference on marine debris. 154. Citeseer, 1989, pp. 2–7.

Walther, B.A., Bergmann, M., 2022. Plastic pollution of four understudied marine ecosystems: a review of mangroves, seagrass meadows, the Arctic Ocean and the deep seafloor. Emerging Topics in Life Sciences 6, 371–387. https://doi.org/10.1042/etls20220017.

Waluda, C.M., Staniland, I.J., 2013. Entanglement of Antarctic fur seals at Bird Island. South Georgia. Marine Pollution Bulletin 74, 244–252. https://doi.org/10.1016/j.marpolbul.2013.06.050.

Waycott, M., Duarte, C.M., Carruthers, T.J., Orth, R.J., Dennison, W.C., Olyarnik, S., et al., 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc. Natl. Acad. Sci. U. S. A. 106, 12377–12381. https://doi.org/10.1073/pnas.0905620106.

Wehle, D., Coleman, F.C., 1983. Plastics at sea. Nat. Hist. 92, 20–26.

Wells, R.S., Allen, J.B., Hofmann, S., Bassos-Hull, K., Fauquier, D.A., Barros, N.B., et al., 2008. Consequences of injuries on survival and reproduction of common bottlenose dolphins (*Tursiops truncatus*) along the west coast of Florida. Mar. Mamm. Sci. 24, 774–794. https://doi.org/10.1111/j.1748-7692.2008.00212.x.

Wilcox, C., Hardesty, B., Sharples, R., Griffin, D., Lawson, T., Gunn, R., 2013. Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia. Conserv. Lett. 6, 247–254. https://doi.org/10.1111/conl.12001.

Wilcox, C., Van Sebille, E., Hardesty, B.D., 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc. Natl. Acad. Sci. 112, 11899–11904. https://doi.org/10.1073/pnas.150210811.

Wilcox, C., Puckridge, M., Schuyler, Q.A., Townsend, K., Hardesty, B.D., 2018. A quantitative analysis linking sea turtle mortality and plastic debris ingestion. Sci. Rep. 8, 1–11. https://doi.org/10.1038/s41598-018-30038-z.

Wilcox, C., Hardesty, B.D., Law, K.L., 2020. Abundance of floating plastic particles is increasing in the Western North Atlantic Ocean. Environ. Sci. Technol. 54, 790–796. https://doi.org/10.1021/acs.est.9b04812.

Wills, E., 2018. Whale dies after swallowing 80 plastic bags in Thailand. The Evening Standard. https://www.standard.co.uk/news/world/whale-dies-after-swallowing-80-plastic-bags-in-thailand-a3853931.html.

Wirsing, A.J., Kiszka, J.J., Allen, A.C., Heithaus, M.R., 2022. Ecological roles and importance of sea cows (order: Sirenia): a review and prospectus. Mar. Ecol. Prog. Ser. 689, 191–215.

Yao, W., Di, D., Wang, Z., Liao, Z., Huang, H., Mei, K., et al., 2019. Micro- and macroplastic accumulation in a newly formed Spartina alterniflora colonized estuarine saltmarsh in Southeast China. Mar. Pollut. Bull. 149, 110636 https://doi.org/10.1016/j.marpolbul.2019.110636.

Yick, J.L., Travers, T., 2022. The ingestion of large plastics by recreationally caught southern bluefin tuna Thunnus maccoyii off southern Australia. Mar. Pollut. Bull. 175, 113332 https://doi.org/10.1016/j.marpolbul.2022.113332.

Yool, A., Fasham, M.J.R., 2001. An examination of the “continental shelf pump” in an open ocean general circulation model. Global Biogeochem. Cycles 15, 831–844. https://doi.org/10.1029/2000GB001359.

Young, L.C., Vanderlip, C., Duffy, D.C., Afanasyev, V., Shaffer, S.A., 2009. Bringing home the trash: do Colony-based differences in foraging distribution Lead to increased plastic ingestion in Laysan albatrosses? PloS One 4, e7623. https://doi.org/10.1371/journal.pone.0007623.