Science of the Total Environment 892 (2023) 164563

Contents lists available at ScienceDirect

Science of the Total Environment

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

A multi-taxonomic, trait-based framework for assessing macroplastic vulnerability

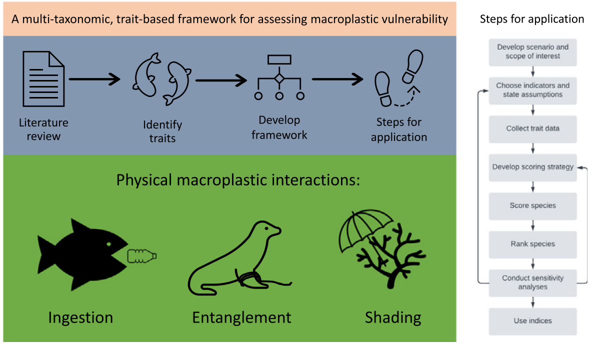
Erin L. Murphy [a,*], Cassidy Fredette-Roman [a], Chelsea M. Rochman [b], Leah R. Gerber [a,c], Beth Polidoro [a,c,d]

[a] *School of Life Sciences, Arizona State University, Tempe Campus, Life Sciences Center A Wing 451 E Tyler Mall, Room 209, Tempe, AZ 85281, United States of America*
[b] *Ecology & Evolutionary Biology, University of Toronto, 25 Wilcocks St, Earth Sciences, Room 3054, Toronto, ON M5S3B2, Canada*
[c] *Center for Biodiversity Outcomes, Arizona State University, Tempe Camus, Life Sciences Center A Wing 451 E Tyler Mall, Room 351, Tempe, AZ 85281, United States of America*
[d] *School of Mathematical and Natural Sciences, Arizona State University, West Campus PO Box 37100, Phoenix, AZ 85069-2352, United States of America*

HIGHLIGHTS

- Twenty-two life history traits were found to influence macroplastic vulnerability across taxa.
- Our framework can be applied to develop a relative ranking of species vulnerability to macroplastic.
- Trait-based vulnerability rankings can inform management and research priorities for macroplastic.
- Rankings should be based on specific scenarios and require sensitivity analyses and validation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jay Gan

Keywords:
Plastic pollution
Risk assessment
Vulnerability
Marine species
Biological traits

ABSTRACT

Individual interactions with plastic pollution have been documented in hundreds of marine species. However, the population and community level effects of these interactions remain poorly understood. Trait-based approaches provide a method for assessing the relative vulnerability of populations or communities to plastic pollution when empirical studies and data are limited. We conducted a literature review and identified 22 traits that influence likelihood of exposure, species sensitivity, and population resilience to the physical impacts of macroplastic. The resulting trait-based framework provides a process for assessing the relative vulnerability of marine biota to macroplastic ingestion and entanglement. Our framework can be applied to develop vulnerability indices for marine taxonomic groups that can inform targeted management efforts, identify priorities for long-term monitoring, and identify species for future quantitative risk assessments.

1. Introduction

Plastic is found in every marine ecosystem around the world, with interactions already documented in >1300 marine species (Santos et al., 2021). Interactions with macroplastic occur primarily through ingestion, entanglement, or shading, and have been linked to injury, illness, and mortality across marine taxa (Bucci et al., 2020). However, 90 % of studies evaluating these interactions have measured the effects at or below the organismal level (Bucci et al., 2020). Little is known about the consequences of macroplastic pollution for population, community, or ecosystem health (Koelmans et al., 2017). Still, studies that have evaluated the effects of macroplastic at higher levels of biological organization have documented cases of population decline and adverse ecological outcomes (Perez-Venegas et al., 2021, Lamb et al., 2018). Better understanding these effects is critical for informing and prioritizing future research, management, and policy (Koelmans et al., 2017). Therefore, general approaches for assessing risk from plastic pollution are urgently needed.

---

[*] Corresponding author.
E-mail address: elmurph1@asu.edu (E.L. Murphy).

http://dx.doi.org/10.1016/j.scitotenv.2023.164563
Received 30 January 2023; Received in revised form 28 May 2023; Accepted 28 May 2023

Progress has been made in developing concentration-based risk frameworks for microplastic ingestion (Mehinto et al., 2022). However, organisms can interact with macroplastics (defined here as >5 mm) through mechanisms beyond ingestion, and the likelihood and impacts of these interactions vary significantly based on the characteristics of the plastic debris and the organism interacting with it (Roman et al., 2019; Bucci et al., 2020). As a result, macroplastics require a distinct alternative set of risk assessment approaches.

Trait-based approaches (TBAs) offer a method to estimate the relative vulnerability of populations and communities to anthropogenic stressors by comparing biological, ecological, and physiological traits that influence organismal vulnerability (Van den Brink et al., 2011). This approach allows for inference to understudied species, across levels of biological organization, and to different geographies (Van den Brink et al., 2011). Over the last few decades, TBAs have been applied to a breadth of stressors (e.g., pesticides, metals, pharmaceuticals, and petrochemicals), and are increasingly used to inform regulatory frameworks for ecological risk assessments (Van den Brink et al., 2011; Polidoro et al., 2021; De Lange et al., 2009; Golden and Rattner, 2003). Early research on the applicability of TBAs for plastic pollution shows promise. Good et al. (2020) applied a TBA to evaluate the vulnerability of marine birds in the California Current Large Marine Ecosystem and found that pelagic species are at greater risk than coastal species. Similarly, Compa et al. (2019) analyzed data from 26 studies representing 84 species from six taxa to identify traits associated with exposure to plastic ingestion. Both studies are limited, however, in the traits they consider. To standardize the use of TBAs for plastic pollution, a comprehensive framework is needed to better estimate vulnerability for cross-taxa and cross-locale comparisons.

We present a trait-based framework that can be applied to estimate the relative vulnerability of marine species to the physical impacts of macroplastic pollution (>5 mm). Due to its comprehensive nature, this multi-taxonomic framework can be applied to develop vulnerability indices of species within or across taxonomic groups from local to global scales. Application of this framework can be used to identify vulnerable marine species and communities for targeted management efforts, long-term monitoring, and more in-depth risk assessments.

2. Methods

To develop this framework, we first identified all traits that have been associated with increased species vulnerability to the physical impacts of macroplastic pollution. We focused on the physical impacts of macroplastic across all taxa because we found the impacts of microplastics, nanoplastics, and associated chemicals differ from macroplastics and should be considered independently of macroplastics (Koelmans et al., 2017). We then categorized traits from our literature review into three dimensions of population risk assessment to inform vulnerability: likelihood of exposure, species sensitivity, and population resilience (Polidoro et al., 2021).

2.1. Literature review

We identified traits through a comprehensive review of the literature from 1898 to 2021. We began our review with the literature presented in Bucci et al. (2020) (through Nov. 2017), only reviewing studies that included plastics >5 mm in size. We then applied the same methods as those presented in Bucci et al. (2020) to search Scopus for literature from November 27th, 2017, to March 31st, 2021, using the terms “marine debris”, “plastic debris”, “macrodebris”, and “mesodebris.”

Each abstract was reviewed once to determine if the paper should be included. Papers were excluded if they did not evaluate the physical effects of plastic pollution, exclusively evaluated microplastics (plastics <5 mm), or did not present novel data (e.g., literature reviews, perspective pieces). For each paper included in the final review, we recorded the author, year of publication, taxonomic group and species evaluated, study location, exposure type (i.e., ingestion, entanglement, other), age of study individuals, information about the effect demonstrated, and any evidence of a relationship between a biological, physiological, or ecological trait and effect measured. We also collected information about the plastic material in the study (e.g., size, shape, polymer), and included a summary of the study.

Each effect measured was categorized by an effect type. If a study only evaluated frequency of plastic interactions, then the effect measured was designated as exposure. Other effect categories included, body condition (e.g., emaciation), injury (laceration, gut perforation), mortality, population decline, or assemblage shift. A new effect line was coded for each effect-species combination in a study (i.e., if a study evaluated injury and mortality rates for two species, then four distinct effects were coded in our review—injury data for species one, injury data for species two, mortality data for species one, mortality data for species two). Exposure, however, was not coded independently if other effects were measured. Species were coded together as “multiple” if studies (1) evaluated assemblages (typically invertebrates), (2) presented results for several species together, or (3) evaluated one effect type for >20 species. (See Supplementary Materials for literature review results).

2.2. Categorizing traits

Traits identified to be associated with vulnerability were aggregated into broad trait buckets. For instance, a study finding dipping and seizing increased ingestion rates and a study finding diving decreased plastic ingestions rates, would both exemplify “feeding and foraging behaviors” as a trait influencing vulnerability. Once all the traits identified in the literature review were characterized, we then categorized them into three dimensions of vulnerability—likelihood of exposure, species' sensitivity, and population resilience—informed by Polidoro et al. (2021). Categorization was informed by how the trait influenced vulnerability. Traits that increased the likelihood of a species having plastics in their proximity, were categorized as “likelihood of exposure”, traits that increased the likelihood of a species to interact with plastic and/or have negative outcomes from interactions were categorized as “species' sensitivity” and traits that influenced population recovery to interactions with plastic pollution were categorized as “population resilience”.

3. Results and discussion

3.1. Traits associated with likelihood of plastic exposure

We identified seven traits that influence a species' likelihood of exposure to macroplastics, which must be considered along with environmental macroplastic concentration: distribution, water column position, habitat, longevity, motility, longevity of the most sensitive pre-adult stage, and distribution of the most sensitive pre-adult stage (Table 1). Distribution, water column position, and habitat influence the likelihood that a species encounters macroplastic in their environment, as species present in areas with higher densities of macroplastic will have a higher likelihood of encounter. For instance, plastic accumulates near coasts and in gyres (Eriksen et al., 2014). If a species' range overlaps with accumulation zones it is more likely to encounter plastics in its environment than species who do not. Proximity to coasts, urban populations, and anthropogenic activities have all been associated with increased exposure to macroplastic (Thiel et al., 2018). Similarly, patterns of different plastic densities throughout the water column, such as increased density on the ocean surface and/or seafloor, can inform likelihood of exposure (Choy et al., 2019). Specifically, benthic species or species that live at the surface may encounter more plastics than species in the middle of the water column (Mouchi et al., 2019; Raum-Suryan et al., 2009). Habitat preference has a higher resolution effect on likelihood of exposure as some habitats are better depositional zones for plastics. For example, macroplastics are more likely to accumulate in rocky substrates or marine canyons than on reef slopes (Corcoran, 2015, Page et al., 2004).

Longevity and motility can also influence a species' likelihood of exposure to plastic pollution. Adults that are longer lived have more opportunity for repeated contact with marine plastic pollution over time. Some studies found species with larger foraging ranges may be at higher risk of plastic

Table 1

Likelihood of exposure component of the macroplastic vulnerability index framework, including traits, assumptions, and example indicators.

Likelihood of exposure							
Trait	Distribution	Water column position	Motility	Longevity	Habitat	Longevity of most sensitive pre-adult stage	Distribution of most sensitive pre-adult stage
Assumption	Species with more of their range overlapping with macroplastic accumulation areas have greater exposure	Species that spend more time where plastic accumulates in the water column have greater exposure	Exposure rates differ between sessile, small-range, and large-range species	Longer-lived adults have more repeated exposures	Certain habitats accumulate more plastics than others	Likelihood of exposure increases with the longevity of the most sensitive pre-adult stage	Likelihood of exposure increases due to pre-adult stage distribution or mobility
Example indicators	•Overlap with plastic accumulation zones •Proximity to human activity	•Zone (e.g., benthic) •Depth range	•Site fidelity •Mobility	•Lifespan	•Foraging habitat •Nest habitat	•Time in most sensitive pre-adult stage	•Overlap of pre-adults and plastic accumulation zones

exposure (Raum-Suryan et al., 2009). Alternatively, sessile, or nearly sessile species cannot escape plastic interactions, so they may be at higher risk of exposure in high accumulation areas. For instance, corals and sponges may be particularly vulnerable to entanglement (or smothering), since they are benthic organisms often found in coastal areas near urban zones (Mouchi et al., 2019). When applying the framework, the influence of motility on sensitivity may be bimodal and case study-dependent.

For several species, distribution and longevity of the most sensitive pre-adult stage should also be considered, as adult and sub-adult life stages of many marine organisms occupy different ranges, habitats, and positions in the water column (Raum-Suryan et al., 2009). For instance, many juvenile fishes inhabit estuaries or coastal waters that are kilometers to hundreds of kilometers from adult habitats (Gillanders et al., 2003).

3.2. Traits associated with species sensitivity to macroplastic

Species sensitivity refers to traits that influence variation in individual rates of interaction with plastic and physiological responses to plastic ingestion, entanglement, or shading, such as injury, reduced body condition, and mortality. In this study, we identify nine traits influence species' sensitivity to plastic—body morphology, feeding and foraging behavior, prey preferences, non-foraging behaviors, egestion potential, respiration mode, behavior of pre-adult stages, relative physiological susceptibility of pre-adult stages, and reduced fitness due to other stressors (Table 2). Importantly, species sensitivity to ingestion, shading, and entanglement is also dependent on macroplastic type.

Body morphology influences both a species' likelihood of plastic ingestion or entanglement and the likelihood of reduced health or death from these interactions. Body size influences species sensitivity to ingestion, with smaller species generally being more sensitive (Compa et al., 2019). However, species must have large enough mouths to consume macroplastics (Roman et al., 2019). Morphology of the gastrointestinal (GI) tract, in particular—intake ratio, and GI tract width and length—affects likelihood of obstruction and perforation from ingested plastic, which increases risk of injury, starvation, and death (Wilcox et al., 2018).

Body morphology, such as size and shape, influences likelihood of entanglement (Kaplan Dau et al., 2009). For some taxa, smaller-bodied species are less likely to become entangled or experience tight entanglements (Nunes et al., 2018). However, in dolphins and whales, larger-bodied species may be more able to break free from entanglements, reducing their risk of drowning compared to smaller species (Thiel et al., 2018). Species with proportionally large heads may be less likely to get their heads entangled in plastics, such as hammerhead sharks (Sazima et al., 2002), while other species, with specific morphologies were more prone to injury and death, such as sawfish due to the thinness and fragility of their rostrum, or sea turtles due to shape of their flippers and how they protrude from their shells (Seitz and Poulakis, 2006; Lucchetti et al., 2017). Birds may have higher mortality rates from entanglement, because entanglements are more likely to hinder flight than swimming (Kaplan Dau et al., 2009). Finally, coral morphology influenced likelihood of shading and entanglement (Lamb et al., 2018). Overall, our review provided evidence that body morphology influences entanglement sensitivity for marine vertebrates and invertebrates and likelihood of ingestion for marine vertebrate taxa.

Feeding and foraging behaviors may also influence species sensitivity to plastic. For example, feeding behaviors can influence rates of both ingestion and entanglement (Page et al., 2004; Bond et al., 2013). Surface seizing and dipping birds are at higher risk of ingestion, while divers are at lower risk (Roman et al., 2019; Bond et al., 2013). Alternatively, diving species are more likely to drown from entanglement in marine debris than surface seizers (Thiel et al., 2018). Scavengers and opportunistic feeders experience more plastic ingestion and entanglement, due to increased interaction with vessels, ports, dumps, and fishing gear—common sources of macroplastic (Thiel et al., 2018; Basto et al., 2019). Finally, the strategies organisms use to sense their prey may influence their likelihood of ingestion, such as sight, sonar, or smell (López-López et al., 2018). For instance, the smell of

Table 2

Species sensitivity component of the macroplastic vulnerability index framework, including traits, assumptions, and example indicators.

Species sensitivity									
Trait	Body morphology	Feeding and foraging behaviors	Prey preferences	Non-foraging behaviors	Egestion potential	Respiration mode	Behavior of pre-adult stages	Relative physiological sensitivity of pre-adult stages	Reduced fitness from other stressors
Assumption	Certain morphologies are more sensitive to macroplastic	Certain feeding and foraging behaviors increase macroplastic sensitivity	Certain prey preferences increase macroplastic sensitivity	Some non-foraging behaviors increase macroplastic sensitivity	Species that can egest plastics are less sensitive to ingestion	Certain modes are more sensitive to entanglement	Differences in pre-adult and adult behavior alter interaction rates	The most sensitive life stage have the greatest influence on sensitivity	Species impacted by other stressors are more sensitive to macroplastic
Example indicators	•Stomach: mouth ratio •Gape size •Body shape •Body size	•Active vs. passive •Feeding strategy (e.g. diving, dabbling)	•Prey type (e.g., fish, cephalopod) •Prey specificity	•Curiosity •Aggression •Nesting	•Ability to regurgitate •Ability to pass debris	•Presence or absence of lungs or gills	•Altricial vs. precocial young •Foraging behaviors •Curiosity	•Relative sensitivity of pre-adult stage to adult	•Proportion of range with high temps, urbanization, or hypoxia

biofouled plastics attracted turtles through a similar mechanism as their food (Pfaller et al., 2020). Overall, the link between feeding and foraging behaviors and ingestion sensitivity were well-documented for marine vertebrates, with sea birds being the most well researched, but evidence for feeding and foraging behavior influencing entanglement sensitivity were also observed in marine vertebrates and invertebrates.

Prey preferences also influence species sensitivity. Generalists may be more likely to consume plastics than specialists (Francis et al., 2020). Predators are also more likely to consume plastics if common plastics resemble their prey; for instance, soft, white plastics resemble jellyfish and squid (Poli et al., 2015).Carnivores can also be exposed through secondary ingestion(Romeo et al., 2015), while herbivores can consume plastics entangling plants (Guterres-Pazin, 2012). Prey preferences can also increase the likelihood of detrimental outcomes, as certain plastics are more likely to cause impaction and perforation in the GI tract (Roman et al., 2019). Prey preferences can increase entanglement sensitivity, as certain prey types are more likely to be near entangling items, such as fishing gear. Fish-eaters, detritivores, or scavengers are more likely to seek out active and ghost fishing nets, which are common entanglers for marine vertebrates and invertebrates (e.g., crab) (Good et al., 2010). This can lead to disproportionally high mortality rates because fishing nets are more likely to cause death from entanglement than consumer plastics (Costa et al., 2020). In summary, prey preference was closely linked to several components of macroplastic sensitivity for many taxa, increasing likelihood of ingestion and effects from ingestion for marine mammals, birds, turtles, and fish; and increasing likelihood of entanglement for all marine vertebrate orders, and many marine invertebrates.

Non-feeding behaviors also influence species sensitivity to plastic. Curiosity and aggression have both been linked with higher rates of plastic ingestion and entanglement in marine mammals (Raum-Suryan et al., 2009). These behaviors can be sex-linked in certain species, with research indicating that males may be more vulnerable in pinnipeds (Kaplan Dau et al., 2009). Nesting behaviors have been shown to influence species sensitivity as well (Townsend and Barker, 2014). Some bird species preferentially select plastics for nest building, increasing their own sensitivity to entanglement as well as their offspring(Townsend and Barker, 2014). The link between non-foraging behaviors and plastic ingestion and entanglement were only documented in marine mammals and birds, with a focus on specific behaviors, but it is possible non-foraging behaviors influence sensitivity for other species as well.

Egestion potential influences a species' sensitivity to the physical impacts of plastic ingestion. Lower plastic accumulation rates have been observed in species that can regurgitate or easily pass consumed plastics, such as gulls (Basto et al., 2019), compared with species that cannot easily egest plastic once it is consumed, such as storm petrels and sea turtles (Wilcox et al., 2018; Nam et al., 2021).

Mode of respiration influences sensitivity to entanglement. Air breathing species are more vulnerable to entanglement than non-air breathing species due to risk of drowning (Thiel et al., 2018; Kaplan Dau et al., 2009). Fishes may be injured or hindered but are less likely to die quickly from entanglement than marine mammals, birds, or turtles (Nunes et al., 2018).

Both the behavior and relative physiological susceptibility of pre-adult stages are also important, as the behavior and morphology of pre-adults vary from adults for many species. In several species, the inexperience of young animals has been associated with higher ingestion and entanglement rates than for adults (Page et al., 2004; Costa et al., 2020). Juveniles may be more likely to mistake plastics for food items (Ryan et al., 2016). Additionally, young pinnipeds are often more playful than adults and as a result may have higher entanglement rates (Raum-Suryan et al., 2009). The physiological susceptibility of the most-sensitive pre-adult stage—which is based on physiological differences between the most sensitive juvenile state and adults of the species—can be complex. In species where the juvenile is likely to be more susceptible than the adult, the species overall sensitivity will be greater than in species where the juvenile stage is less susceptible than adults (McIntosh et al., 2015). For instance, turtle hatchlings are more susceptible to entanglement than adults when they try to reach the sea, because they are less able to break free from entanglements and are highly vulnerable to predation at this stage (Triessnig et al., 2012). In some species, juvenile birds are at higher risk from ingestion and entanglement than adults, because of regurgitative feeding and increased time spent in nests, respectively (Raum-Suryan et al., 2009). In other taxa, if juveniles are too small to consume macroplastics or become entangled, as is the case for many fishes and invertebrates, adults will be the most sensitive life-stage (Nunes et al., 2018). Overall, intraspecies variation in entanglement and ingestion sensitivity across life stages was documented in both marine vertebrates and invertebrates, but the direction of sensitivity was species dependent.

Finally, marine organisms are not exposed to macroplastic pollution in isolation from other environmental stressors. Reduced fitness due to other stressors has been associated with increased interactions with macroplastic as well as more severe consequences of these interactions (Drever et al., 2018; Lacombe et al., 2020). Climate change and other stressors can reduce food availability, driving animals to broaden their diet and consume more plastics. For example, a mortality event of Red Phalaropes was linked to reduced upwelling—an important food source—due to unseasonably warm ocean temperatures. All carcasses were severely underweight and 100 % contained plastics (Drever et al., 2018). In odontocetes, parental loss and central nervous system disease were also both identified as risk factors for plastic ingestion (Lacombe et al., 2020). Environmental stressors, such as pollution, climate change, and increased human activity, can increase the likelihood of disease or mother-calf separation due to death of the mother (Fair and Becker, 2000). Overall, many studies identified relationships between macroplastic sensitivity and exposure to other stressors, including disease, climate change, nutrient pollution, vessel strikes. These relationships were documented primarily in marine vertebrates, but also mentioned for marine plants and corals (Lamb et al., 2018; Suyadi and Manullang, 2020).

3.3. Traits associated with population resilience

Six traits influence a species' resilience to population decline due to individual mortalities or reduced fitness from exposure to plastic interactions—abundance, population connectivity, reproductive turnover, behavioral specialization, sensitivity of most important life stage, and risk of extinction (Table 3). Four of these traits (abundance, population connectivity, reproductive turnover, and feeding or habitat specialization) were also employed by Polidoro et al. (2021).

Small populations are more vulnerable to local extinctions due to death or reduced fitness of individuals, than large populations (Dulvy et al., 2003). Population connectivity similarly influences the resilience of local populations. If a vulnerable population has high connectivity with resilient populations, then immigration can reduce local extinction risk and increase resilience, but if connectivity to resilient populations is low then local extinction risk increases (Jones et al., 2007). Importantly, connectivity to maladaptive populations may reduce population resilience (McManus et al., 2021).

Reproductive turnover likely influences a population's resilience to plastic pollution. Generally, slower reproductive turnover (i.e., K strategists) is associated with a higher sensitivity to stressors than species with high reproductive turnover (Dulvy et al., 2003). Reproductive turnover can be measured as generation time, number of offspring, reproductive age, and population turnover rate (Polidoro et al., 2021; Mace et al., 2008). Though population studies are limited, one found plastic ingestion in albatrosses likely led to population decline because they are long-lived species with slow reproductive turnover (Roman et al., 2021). Entanglement also caused population decline of South American fur seals, another species with a slow reproductive turnover (Perez-Venegas et al., 2021). Finally, less specialized species are generally more resilient to local and regional stressors, as they can adapt their behaviors, habitats, and feeding preferences more readily than species that are highly specialized (Ducatez et al., 2020).

Table 3
Population resilience component of the macroplastic vulnerability index framework, including traits, assumptions, and example indicators.

Population resilience						
Trait	Abundance	Population connectivity	Reproductive turnover rate	Feeding or habitat specialization	Importance of most impacted life stage	Species extinction risk
Assumption	Populations with fewer individuals are less resilient	Populations with little or no connectivity to populations outside high-risk zones are less resilient	Species with lower turnover rates recover more slowly	Species with high specialization in habitat and/or dietary choice are less resilient	Species where the most sensitive life-stage is of high importance for population maintenance are less resilient	Species with higher risk of extinction are less resilient
Example indicators	•Population size	•Connectivity with populations in or outside of high impact areas	•Offspring per year •Generation length •Recruitment rate	•Number of habitat preferences •Number of food preferences	•Population importance of the most sensitive life-stage	• IUCN status

Available data suggest high intraspecies variation in vulnerability to plastic pollution among life stages. For instance, juveniles are often more vulnerable to entanglement than adults (Page et al., 2004; Kaplan Dau et al., 2009; Costa et al., 2020). Additionally, certain life stages are more important for population maintenance than others (Gerber and Heppell, 2004), and this is often species dependent (e.g., adult males, immature females, new borns, juveniles). Therefore, if the most important life stage is also the most sensitive to plastic pollution than population resilience will be disproportionately low. For example, even small amounts of entanglement of adult female South American fur seals had large population effects, because of the population level importance of breeding females and the subsequent decrease in offspring, the colony produced (Perez-Venegas et al., 2021). Finally, species populations that are already at risk of extinction are less resilient to new stressors. In such cases, plastic pollution can directly influence extinction risk for threatened and endangered species (Good et al., 2010). For example, entanglement-induced injury and death from marine debris in the Hawaiian Islands has hindered recovery efforts for the endangered Hawaiian Monk Seal (*Monachus schauinslandi*) (Boland and Donohue, 2003).

3.4. Framework application

The resulting framework includes a comprehensive list of biological, physiological, and ecological traits identified in our literature review that influence the vulnerability of marine species to macroplastic. Users can apply this framework, following the eight steps described below, to develop vulnerability indices that estimate the relative vulnerability of marine species to macroplastic (Fig. 1). These indices can then be used to identify populations or ecosystems for long-term monitoring or to inform policy and management priorities.

Identify scenario of interest—The scenario should be informed by the management or research objectives of the implementer. This should include the species of interest (e.g., marine mammals, species of economic importance), the region of focus (e.g., local, global), the types of plastic pollution (e.g., fishing nets), and possibly a focus on particular interaction types. Plastics represent a category of various pollutants that interact with the environment and species differently. For example, if the goal of the manager is to prioritize marine regions for marine debris removal and long-term monitoring in the Northwest Hawaiian Islands (NWHI), the scope may be local—the NWHI—include all species native to this region, and focus on fisheries-based marine debris, as this is the primary plastic pollutant in this isolated group of uninhabited islands. Fishing-related plastics can have different positions in the water column or create a higher likelihood of mortality from entanglement than consumer plastics. Moreover, geographical context is critical for understanding possible confounding effects from other local anthropogenic stressors. For example, both coral bleaching events and plastic pollution can increase risk of coral disease (Lamb et al., 2018). Therefore, a clearly defined scenario that considers the context for which the vulnerability index is being developed is important.

Choose indicators & state assumptions— Our literature review included all taxa, so not every trait in our framework will be relevant for every scenario. For instance, though respiratory mode affects vulnerability, a within taxa analysis of mammals would not include respiratory mode as it is it would not inform relative vulnerability. Indicators for each included trait should also be scenario-specific and informed by both the traits that are most important for distinguishing the vulnerability of the study species and data availability. For example, an evaluation focused on seabirds

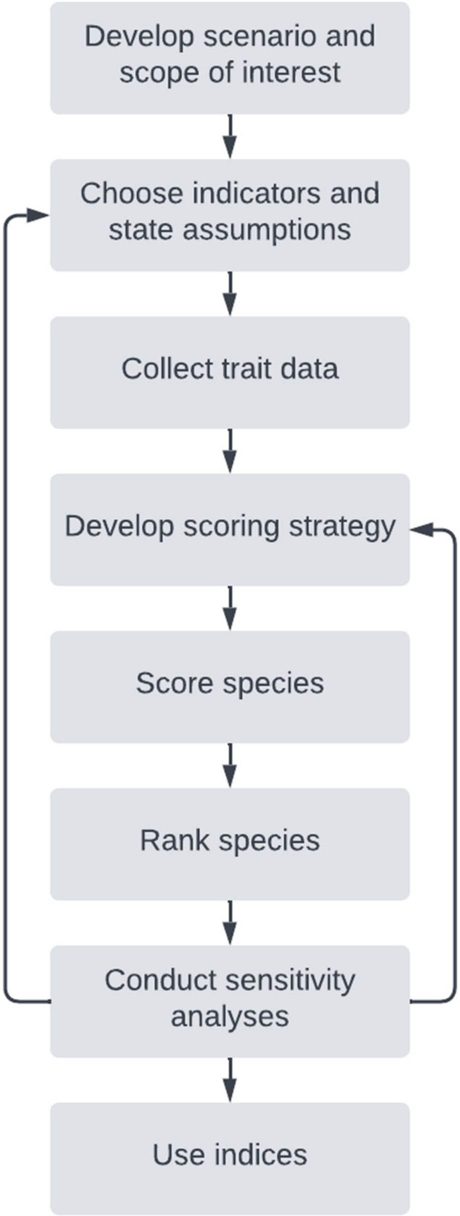


Fig. 1. Eight-step process for applying the framework to develop a vulnerability index

should include a non-foraging behavior indicator related to nesting habits, while curiosity or aggression would be more appropriate indicators of non-foraging behaviors influencing marine mammal sensitivity. While choosing the best indicators, it is also important to clearly state the associated assumptions (e.g., longer life expectancy increases likelihood of exposure). These assumptions will depend on the target species. For instance, decreasing size may reduce sensitivity to entanglement in fishes if they are too small to become entrapped in marine plastics. Alternatively, increased size may reduce sensitivity to entanglement in marine mammals by making it easier for them to break free from entanglements. If the target species were only mammals, then the assumption may be that increasing size will decrease sensitivity, if the target species are only fish, the assumption may be decreasing size will decrease sensitivity and if both are included the of size on sensitivity may be bimodal.

Collect trait data—The next step is to compile available biological and ecological trait data. Sources outside of peer-reviewed, academic literature, such as the IUCN database, are important sources as well.

Develop scoring strategy—Scoring of metrics requires consideration of how to distinguish species of interest for each indicator. For instance, an assumption may be that long-lived species have higher exposure than a short-lived species. Longevity scores could be classified in categories between 1 and 5, where five represents the longest average life expectancies, with set cut offs or thresholds between each integer score. It is important to consider how data gaps will be scored (e.g., De Lange et al., 2009; Golden and Rattner, 2003). Unknown traits are often given a score of 3 following a precautionary approach (Woodyard et al., 2022).

Score, rank and categorize species—Based on available trait data, each species should be scored using the indicators and scoring metrics in place, with equal weight being put on each vulnerability dimension—likelihood of exposure, species' sensitivity, and population resilience—in the final score. The species of interest can be ranked in order from most to least sensitive by their scores. It is important to note that the difference in scores cannot be used to quantify differences in vulnerability (i.e., a score of 90 vs 45 does not mean one species is 2× more vulnerable). Instead, it provides information on the relative sensitivity of two species (i.e., which is more vulnerable). It is good practice to categorize final scores into categories of vulnerability rather than focusing on absolute scores. For example, species with scores in the top quartile might be classified as having high vulnerability, while species with scores in the bottom quartile are classified as having low vulnerability.

Conduct sensitivity analyses—After the first round of scoring, ranking and categorization is complete, it is important to validate rankings and conduct sensitivity analyses to ensure 1) indicators meaningfully contribute to the rankings, and 2) the scoring strategy properly weights traits. This can be done by removing or changing indicators, reranking species and validating rankings using species with more data in the literature or expert elicitation. If an indicator does not contribute to the ranking—due to significant data gaps (e.g., little is known about habitat use by species of interest) or negligible variation in the indicator among species (e.g., respiration mode would be the same for all marine mammals)—it should be removed, species should be rescored, and the new ranking should be validated. This should also be done if two traits representing the same vulnerability dimension have statistically significant correlation. Finally, if relative rankings still do not reflect existing data (e.g., a species with high documented rates of entanglement ranks low in species sensitivity), and the literature suggests certain traits have greater importance, then weighting of specific traits may be used to improve ranking accuracy. Other studies have done this by giving certain traits a multiplier that increase their relative importance to other traits in the final scoring (Golden and Rattner, 2003).

Use indices—After the final ranking is determined, the index can be used to inform future research and decision-making. For instance, communities and marine regions of high vulnerability can be mapped and identified based on species' distributions (e.g., Foden et al., 2013; Compa et al., 2019). This can inform regions to prioritize for mitigation efforts or long-term monitoring.

4. Concluding remarks and future directions

Marine plastic pollution is ubiquitous in ocean ecosystems around the world. Despite evidence that hundreds of marine species have been impacted by macroplastics, little is known about the impact of macroplastic at the population, community, or ecosystem level. Managers and policymakers need risk assessment frameworks to inform and prioritize conservation action. Our comprehensive trait-based framework aims to help researchers and decisionmakers use existing data to evaluate the relative vulnerability of populations and communities to marine macroplastics, within or across taxa, and at any spatial scale of analysis.

The impacts of plastic pollution on populations, species, and communities are confounded by other anthropogenic stressors facing marine wildlife; however, our review indicated limited research has been done to understand how other stressors influence macroplastic vulnerability. Our framework can be used to identify vulnerable populations, species, and ecosystems that should receive targeted management and mitigation efforts, as well as long-term monitoring of population and community health. This long-term monitoring could provide case study locations for researching the influence of multiple stressors as well as insight into the efficacy of mitigation efforts.

TBAs are a timely and effective tool to inform regulatory frameworks for ecological risk assessments on macroplastics. The negative consequences of macroplastic pollution are evident, yet the lack of ecologically informed limits for plastic pollution make regulatory management difficult. Implementation of TBAs for marine species in ecological risk assessment frameworks can facilitate identification of data gaps and effective regulatory action.

CRediT authorship contribution statement

Erin Murphy: conceptualization, methodology, formal analysis, investigation, writing (original draft, revisions, and editing), and project administration. Cassidy Fredette-Roman: investigation and writing (revisions and editing). Chelsea Rochman: validation and writing (revisions and editing). Leah Gerber: validation and writing (revisions and editing). Beth Polidoro: conceptualization, validation, supervision, and writing (revisions and editing).

Data availability

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

Declaration of competing interest

No authors have any interests to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164563.

References

Basto, M.N., Nicastro, K.R., Tavares, A.I., McQuaid, C.D., Casero, M., Azevedo, F., Zardi, G.I., 2019. Plastic ingestion in aquatic birds in Portugal. Mar. Pollut. Bull. 138, 19–24.

Boland, R.C., Donohue, M.J., 2003. Marine debris accumulation in the nearshore marine habitat of the endangered Hawaiian monk seal, Monachus schauinslandi 1999–2001. Mar. Pollut. Bull. 46, 1385–1394.

Bond, A.L., Provencher, J.F., Elliot, R.D., et al., 2013. Ingestion of plastic marine debris by common and thick-billed Murres in the northwestern Atlantic from 1985 to 2012. Mar. Pollut. Bull. 77, 192–195.

Bucci, K., Tulio, M., Rochman, C.M., 2020. What is known and unknown about the effects of plastic pollution: a meta-analysis and systematic review. Ecol. Appl. 30.

Choy, C.A., Robison, B.H., Gagne, T.O., et al., 2019. The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. Sci Rep-UK 9, 7843.

Compa, M., Alomar, C., Wilcox, C., et al., 2019. Risk assessment of plastic pollution on marine diversity in the Mediterranean Sea. Sci. Total Environ. 678, 188–196.

Corcoran, P.L., 2015. Benthic plastic debris in marine and fresh water environments. Environ. Sci. P I 17 (8), 1363–1369.

Costa, R.A., Sá, S., Pereira, A.T., et al., 2020. Prevalence of entanglements of seabirds in marine debris in the central Portuguese coast. Mar. Pollut. Bull. 161, 111746.

De Lange, H.J., Lahr, J., Van der Pol, J.J.C., et al., 2009. Ecological vulnerability in wildlife: an expert judgment and multicriteria analysis tool using ecological traits to assess relative impact of pollutants. Environ. Toxicol. Chem. 28, 2233–2240.

Drever, M.C., Provencher, J.F., O'hara, P.D., et al., 2018. Are ocean conditions and plastic debris resulting in a 'double whammy' for marine birds? Mar. Pollut. Bull. 133, 684–692.

Ducatez, S., Sol, D., Sayol, F., et al., 2020. Behavioural plasticity is associated with reduced extinction risk in birds. Nat. Ecol. Evol. 4, 788–793.

Dulvy, N.K., Sadovy, Y., Reynolds, J.D., et al., 2003. Extinction vulnerability in marine populations. Fish Fish. 4, 25–64.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., 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.

Fair, P.A., Becker, P.R., 2000. Review of stress in marine mammals. J. Aquat. Ecos. Str. R. 7 (4), 335–354.

Foden, W.B., Butchart, S.H., Stuart, S.N., Vié, J.C., Akçakaya, H.R., Angulo, A., ... Mace, G.M., 2013. Identifying the world's most climate change vulnerable species: a systematic trait-based assessment of all birds, amphibians and corals. PloS One 8 (6), e65427.

Francis, A., Kumar Prusty, A., Azeez, P.A., 2020. Ingestion of unusual items by wetland birds in urban landscapes. Curr. Sci. 118, 977–983.

Gerber, L.R., Heppell, S.S., 2004. The use of demographic sensitivity analysis in marine species conservation planning. Biol. Conserv. 120 (1), 121–128.

Gillanders, B.M., Able, K.W., Brown, J.A., et al., 2003. Evidence of connectivity between juvenile and adult habitats for mobile marine fauna: an important component of nurseries. Mar. Ecol. Prog. Ser. 247, 281–295.

Golden, N.H., Rattner, B.A., 2003. Ranking terrestrial vertebrate species for utility in biomonitoring and vulnerability to environmental contaminants. Rev. Environ. Contam. T 67–136.

Good, T.P., June, J.A., Etnier, M.A., et al., 2010. Derelict fishing nets in Puget Sound and the Northwest Straits: patterns and threats to marine fauna. Mar. Pollut. Bull. 60, 39–50.

Good, T.P., Samhouri, J.F., Feist, B.E., et al., 2020. Plastics in the Pacific: assessing risk from ocean debris for marine birds in the California current large marine ecosystem. Biol. Conserv. 250, 108743.

Guterres-Pazin, M., 2012. Short note: ingestion of invertebrates, seeds, and plastic by the Amazonian manatee (Trichechus inunguis) (Mammalia, Sirenia). Aquat. Mamm. 38, 322–324.

Jones, G.P., Srinivasan, M., Almany, G.R., et al., 2007. Population connectivity and conservation of marine biodiversity. Oceanography 20, 100–111.

Kaplan Dau, B., Gilardi, K.V.K., Gulland, F.M., et al., 2009. Fishing gear-related injury in California marine wildlife. J. Wildl. Dis. 45, 355–362.

Koelmans, A.A., Besseling, E., Foekema, E., et al., 2017. Risks of plastic debris: unravelling fact, opinion, perception, and belief. Environ. Sci. Technol. 51, 11513–11519.

Lacombe, A., Pintado, E., O'Byrne, A., et al., 2020. Ingestion of foreign materials by odontocetes along the Catalan coast: causes and consequences. Dis. Aquat. Org. 142, 23–31.

Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., ... Harvell, C.D., 2018. Plastic waste associated with disease on coral reefs. Science 359 (6374), 460–462 Chicago.

López-López, L., Preciado, I., González-Irusta, J.M., et al., 2018. Incidental ingestion of meso- and macro-plastic debris by benthic and demersal fish. Food Webs 14, 1–4.

Lucchetti, A., Vasapollo, C., Virgili, M., 2017. Sea turtles bycatch in the Adriatic Sea set net fisheries and possible hot-spot identification. Aquat. Conserv. Mar. Freshwat. Ecosyst. 27 (6), 1176–1185.

Mace, G.M., Collar, N.J., Gaston, K.J., et al., 2008. Quantification of extinction risk: IUCN's system for classifying threatened species. Conserv. Biol. 22, 1424–1442.

McIntosh, R.R., Kirkwood, R., Sutherland, D.R., et al., 2015. Drivers and annual estimates of marine wildlife entanglement rates: a long-term case study with Australian fur seals. Mar. Pollut. Bull. 101, 716–725.

McManus, L.C., Forrest, D.L., Tekwa, E.W., et al., 2021. Evolution and connectivity influence the persistence and recovery of coral reefs under climate change in the Caribbean, Southwest Pacific, and coral triangle. Glob. Change Bio 27 (18), 4307–4321.

Mehinto, A.C., Coffin, S., Koelmans, A.A., Brander, S.M., Wagner, M., Thornton Hampton, ... Rochman, C.M., 2022. Risk-based management framework for microplastics in aquatic ecosystems. Microplastics Nanoplastics 2 (1), 1–10.

Mouchi, V., Chapron, L., Peru, E., et al., 2019. Long-term aquaria study suggests species-specific responses of two cold-water corals to macro-and microplastics exposure. Environ. Pollut. 253, 322–329.

Nam, K.B., Kim, M., Hong, M.J., et al., 2021. Plastic debris ingestion by seabirds on the Korean peninsula. Mar. Pollut. Bull. 166, 112240.

Nunes, J.A.C.C., Sampaio, C.L.S., Barros, F., et al., 2018. Plastic debris collars: an underreported stressor in tropical reef fishes. Mar. Pollut. Bull. 129, 802–805.

Page, B., McKenzie, J., McIntosh, R., Baylis, A., Morrissey, A., Calvert, N., ... Goldsworthy, S.D., 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 (1–2), 33–42.

Perez-Venegas, D.J., Valenzuela-Sánchez, A., Montalva, F., et al., 2021. Towards understanding the effects of oceanic plastic pollution on population growth for a south American fur seal (Arctocephalus australis australis) colony in Chile. Environ. Pollut. 279, 116881.

Pfaller, J.B., Goforth, K.M., Gil, M.A., Savoca, M.S., Lohmann, K.J., 2020. Odors from marine plastic debris elicit foraging behavior in sea turtles. Curr. Biol. 30 (5), R213–R214.

Poli, C., Mesquita, D.O., Saska, C., et al., 2015. Plastic ingestion by sea turtles in Paraíba State, Northeast Brazil. Iheringia. Sér Zool 105, 265–270.

Polidoro, B., Matson, C.W., Ottinger, M.A., et al., 2021. A multi-taxonomic framework for assessing relative petrochemical vulnerability of marine biodiversity in the Gulf of Mexico. Sci. Total Environ. 763, 142986.

Raum-Suryan, K.L., Jemison, L.A., Pitcher, K.W., 2009. Entanglement of Steller Sea lions (Eumetopias jubatus) in marine debris: identifying causes and finding solutions. Mar. Pollut. Bull. 58, 1487–1495.

Roman, L., Hardesty, B.D., Hindell, M.A., et al., 2019. A quantitative analysis linking seabird mortality and marine debris ingestion. Sci Rep-UK 9, 3202.

Roman, L., Butche, R.G., Stewart, D., et al., 2021. Plastic ingestion is an underestimated cause of death for southern hemisphere albatrosses. Conserv. Lett. 14 (3), e12785.

Romeo, T., Peitro, B., Pedà, C., et al., 2015. First evidence of presence of plastic debris in stomach of large pelagic fish in the Mediterranean Sea. Mar. Pollut. Bull. 95, 358–361.

Ryan, P.G., Cole, G., Spiby, K., et al., 2016. Impacts of plastic ingestion on post-hatchling loggerhead turtles off South Africa. Mar. Pollut. Bull. 107, 155–160.

Santos, R.G., Machovsky-Capuska, G.E., Andrades, R., 2021. Plastic ingestion as an evolutionary trap: toward a holistic understanding. Science 373 (6550), 56–60.

Sazima, I., Gadig, O.B., Namora, R.C., Motta, F.S., 2002. Plastic debris collars on juvenile carcharhinid sharks (*Rhizoprionodon lalandii*) in southwest Atlantic. Mar. Pollut. Bull. 44 (10), 1149–1151.

Seitz, J.C., Poulakis, G.R., 2006. Anthropogenic effects on the smalltooth sawfish (Pristis pectinata) in the United States. Mar. Pollut. Bull. 52 (11), 1533–1540.

Suyadi, Manullang, C.Y., 2020. Distribution of plastic debris pollution and it is implications on mangrove vegetation. Mar. Pollut. Bull. 160, 111642.

Thiel, M., Luna-Jorquera, G., Álvarez-Varas, R., et al., 2018. Impacts of marine plastic pollution from continental coasts to subtropical gyres—fish, seabirds, and other vertebrates in the SE Pacific. Front. Mar. Sci. 5, 238.

Townsend, A.K., Barker, C.M., 2014. Plastic and the Nest entanglement of urban and agricultural crows. PLoS One 9, e88006.

Triessnig, P., Roetzer, A., Stachowitsch, M., 2012. Beach condition and marine debris: new hurdles for sea turtle hatchling survival. Chelonian Conserv Biol 11, 68–77.

Van den Brink, P.J., Alexander, A.C., Desrosiers, M., et al., 2011. Traits-based approaches in bioassessment and ecological risk assessment: strengths, weaknesses, opportunities and threats. Integr. Environ. Asses. 7, 198–208.

Wilcox, C., Puckridge, M., Schuyler, Q.A., et al., 2018. A quantitative analysis linking sea turtle mortality and plastic debris ingestion. Sci Rep-UK 8, 12536.

Woodyard, M., Polidoro, B.A., Matson, C.W., McManamay, R.A., Saul, S., Carpenter, K.E., ... Strongin, K., 2022. A comprehensive petrochemical vulnerability index for marine fishes in the Gulf of Mexico. Sci. Total Environ. 820, 152892.