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A macroplastic vulnerability index for marine mammals, seabirds, and sea turtles in Hawai‘i

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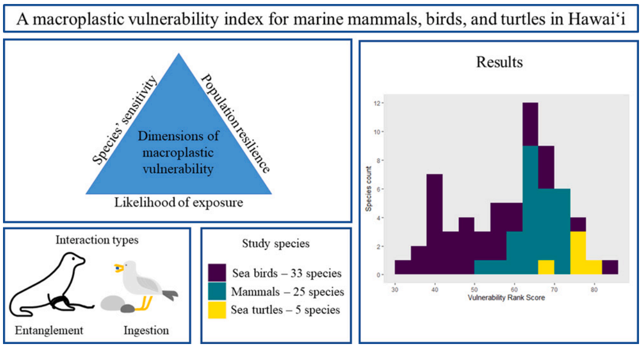
HIGHLIGHTS

- We present a macroplastic vulnerability index for Hawaiian marine megafauna.
- Turtles, baleen whales, long-lived birds, and the Hawaiian monk seal were most vulnerable.
- Ducks, waders, and noddies with large populations were among the least vulnerable.
- This highlights the management value of vulnerability indices for macroplastic.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic pollution is having devastating consequences for marine organisms across the planet. However, the population level effects of macroplastic pollution remain difficult and costly to quantify. As a result, there is a need for alternative approaches to evaluate species risk to plastic pollution and inform management needs. We apply a trait-based framework for macroplastic pollution to develop a relative vulnerability index—informed by three dimensions: likelihood of exposure, species' sensitivity, and population resilience—for marine mammals, seabirds, and sea turtles found in Hawai‘i. This index ranks 63 study species based on their population level vulnerability to macroplastic pollution, with the highest scoring species being the most vulnerable. Our results indicate that ducks, waders, and noddies with large populations were the least vulnerable to macroplastics, while the most vulnerable were the Hawaiian monk seal, sea turtles, baleen whales, and some albatross and petrel species. This index can inform species in need of population monitoring in Hawai'i, and direct other management priorities (e.g., locations for clean-ups or booms). More broadly, this work exemplifies the value of qualitative

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risk assessment approaches for better understanding the population level effects of macroplastic pollution and showcases how vulnerability indices can be used to inform management priorities.

1. Introduction

Plastic pollution is ubiquitous in our global oceans with increasing impacts on marine organisms (Bucci et al., 2020). To date, interactions with plastic pollution have been documented in >1300 marine species (Kühn and Van Franeker, 2020; Santos et al., 2021). These interactions are both physical and chemical and vary depending on plastic size (Thornton Hampton et al., 2022; Bucci et al., 2020). For macroplastics (>5 mm in diameter), physical interactions pose the greatest documented threat (Bucci et al., 2020). Understanding the impacts these interactions have at higher levels of biological organization is critical to addressing and mitigating the ecological consequences of macroplastics (Bucci et al., 2020; Koelmans et al., 2017). In this paper, we apply a traits-based approach to assess the vulnerability of Hawaiian marine species to macroplastic pollution and exemplify its potential for plastic pollution research and management more broadly.

Physical exposure to macroplastic occurs primarily via ingestion and entanglement, which have been observed across a wide range of taxa (Kühn and Van Franeker, 2020; Santos et al., 2021; Jepsen and de Bruyn, 2019; Lamb et al., 2018). Most research has been conducted on organismal exposure to macroplastics through these pathways, with research on effects—such as injury, illness, or mortality—focusing primarily on the sub-organismal and organismal level (Bucci et al., 2020). As a result, very little is known about the physical impacts of macroplastics at the population, assemblage, or ecosystem levels (Murphy et al., 2023).

Trait-based approaches allow for inference across levels of biological organization by using information on the ecological, physiological, and biological traits that influence organisms' vulnerability to a stressor to predict the relative vulnerability of understudied species (Koelmans et al., 2017). These methods are robust and can improve ecological risk assessments when data are limited by allowing for extrapolation between levels of biological organization and across spatial and temporal scales (Van den Brink et al., 2011). Such analyses generally involve the development of vulnerability indices that rank species' relative vulnerability to a stressor to understand a given stressor's population and assemblage level impacts. Such indices have already been implemented to inform research and management of several other anthropogenic stressors, including pesticides, metals, pharmaceuticals, lead shot, oil, and climate change (Polidoro et al., 2021; Foden et al., 2013; Chin et al., 2010; De Lange et al., 2009; Golden and Rattner, 2003).

The potential value of trait-based approaches for plastic pollution has been exemplified through a few studies, though their application has been limited in scope (Good et al., 2020; Compa et al., 2019). To facilitate more consistent and broader applications of trait-based approaches for plastic pollution, Murphy et al. (2023) present a multi-taxonomic approach for developing macroplastic vulnerability indices. Through a comprehensive literature review, Murphy et al. (2023) identify 22 traits that have been shown to influence species vulnerability to plastic pollution along three dimensions: likelihood of exposure, species' sensitivity, and population resilience. This work provides steps to apply the resulting framework to develop a vulnerability index for any marine species or geographic area.

Here, we apply the framework presented in Murphy et al. (2023) to develop a multi-taxonomic vulnerability index for marine mammals, seabirds, and sea turtles in the Hawai‘ian exclusive economic zone (EEZ). Hawai‘i presents a valuable case study given its high densities of marine plastic pollution, vulnerable marine species, and evidence of organismal interactions with macroplastic (Hawai‘i Department of Land and Natural Resources, 2022; NOAA Marine Debris Program, 2021). Our results provide insight into the Hawai‘ian species that are most and least vulnerable to macroplastic pollution. We then discuss the usefulness and limitations associated with the broad application of our method.

2. Methods

To develop our relative multi-taxonomic vulnerability index, we followed the steps outlined in Murphy et al. (2023) - (1) identify the scope of interest, (2) choose indicators and state assumptions, (3) collect trait data, (4) develop scoring strategy, (5) score and rank species, (6) conduct sensitivity analyses.

2.1. *Identify the scope of interest*

We focused on three taxa—marine mammals, seabirds, and sea turtles—found within the Hawaiian EEZ, which extends 200 nautical miles from the coast. Hawai‘i is biodiverse, with the highest proportion of endemism of any tropical marine ecosystem on Earth (Fautin et al., 2010). Most of the marine plastic pollution in Hawai‘i comes from external sources, which make clean-up and remediation important components of the local marine debris management plan (NOAA Marine Debris Program, 2021). Therefore, government officials, non-governmental organizations and other groups managing plastic pollution and conserving marine species in Hawai‘i would benefit from a relative vulnerability index to inform priorities and identify the best species to monitor for population decline.

We applied the trait-based approach to all marine mammals (25 species), seabirds (33 species), and sea turtles (5 species) present in Hawaiian waters, because the physical exposures of macroplastic pollution are well-documented in these taxa (Kühn and Van Franeker, 2020; Bucci et al., 2020). Additionally, these taxa have ecological, cultural, and economic importance globally (Tavares et al., 2019). Importantly, by including three taxonomically distinct groups, we exemplify the functionality of the framework for multi-taxonomic analyses. Finally, we chose to focus on the physical vulnerability of species to macroplastics due to ingestion and entanglement, as all three taxa are influenced by both types of interactions (Kühn and Van Franeker, 2020; Senko et al., 2020). Microplastics, nanoplastics, and the chemical impacts of macroplastic ingestion have all also been identified as threats to marine megafauna (Bucci et al., 2020); however, the mechanisms by which these effects occur are different and they should be evaluated independently (Koelmans et al., 2017; Murphy et al., 2023).

2.2. *Choose indicators, and state assumptions*

A first step in applying the framework is selecting relevant traits. We included 11 of the 22 traits presented in the Murphy et al. (2023) framework: two traits linked to likelihood of exposure to macroplastics, five traits linked to species' sensitivity to ingestion and/or entanglement, and four traits to overall population resilience (Table 1). Trait selection was based on data availability as well as their usefulness for distinguishing the study species. More details on trait selection are provided below.

The two traits included for likelihood of exposure were distribution and longevity. We used average density of surficial macroplastic pollution (from Eriksen et al., 2014) within the species' total range (IUCN, 2022) as an indicator for distribution (quantified using species range data and plastic distribution maps), based on the assumption that the higher the density of macroplastic in a species range (items per km^2) the more likely an individual is to encounter it (See supplementary materials for methods to quantify items per km^2). If a portion of a bird species range was terrestrial than marine plastic pollution in the terrestrial portion of its range was included as zero. Surficial plastic densities likely

Table 1

Traits, indicators, and scoring approach for each indicator. Crossed out traits are excluded from.

Dimension	Trait	Indicator	Scoring method
Likelihood of exposure	Distribution	Plastic density in species range	Quintiles (Low = 1 to High = 5)
	Longevity	Life span	Quintiles (Low = 1 to High = 5)
	~~Motility~~		
	~~Habitat~~		
	~~Water Column Position~~		
	~~Longevity of most sensitive pre-adult stage~~		
	~~Distribution of most sensitive pre-adult stage~~		
Species' sensitivity	Body morphology	Body mass	Quintiles (High = 1 to Low = 5)
	Feeding and foraging behaviors	Foraging behavior influence on ingestion rate	1 = pick and probe; pursuit diving; stealing food in flight; chase prey 2 = biter; plunge diving 3 = dabbling; swallower; deep dive 4 = fluttering on surface; dipping; grazer 5 = surface seizing; scavenging; filter feeding
	Prey preferences	Interaction risk based on prey type	1 = Specialist that does not eat prey resembling plastic, feed on waste, or feed on fisheries species 2 = Generalist that does not eat high risk prey 3 = Generalist that eats some high-risk prey 4 = Specializes on prey sometimes mistaken for plastic or feeds on fisheries species 5 = Specializes on prey commonly mistaken for plastic or fisheries species, or feeds on human waste
	Reduced fitness from other stressors	IUCN threat list	Score based on number and severity of threats. Each stressor had a severity score (1–8) and severity scores were summed for all stressors to give a total threat score.
	Egestion potential	Ability to regurgitate or use of gastroliths	1 = Regurgitate pellets frequently and regurgitate to young 2 = Regurgitate and limited pellet production observed; occasional pellet casting in young; may produce pellets based on species 3 = Capable of regurgitation or ingest gastroliths 4 = May regurgitate to young; may regurgitate based on species 5 = Does not regurgitate to offspring, no evidence of pellets; anatomical structure reduces regurgitation potential; no information
	~~Respiration mode~~		
	~~Relative physiological sensitivity of pre-adult stages~~		
	~~Behavior of pre-adult stages~~		
	~~Non-foraging behaviors~~		
Population resilience	Abundance	Population size	Quintiles (High = 1 to Low = 5)
	Specialization	Habitat number	Quintiles (High = 1 to Low = 5)
	Reproductive turnover rate	Generation length	Quintiles (Low = 1 to High = 5)
	Extinction risk	IUCN Red List status	1 = Least concern 2 = Near threatened 3 = Vulnerable 4 = Endangered 5 = Critically endangered
	~~Population Connectivity~~		
	~~Importance of most impacted life stage~~		

do not perfectly represent the exposure of species foraging deeper in the water column; however, global sub-surface plastic density models are not available. The expected life span was the chosen indicator for longevity, assuming longer-lived species have more opportunities for plastic interactions.

Motility, habitat, longevity of the most sensitive pre-adult stage, distribution of the most sensitive pre-adult stage, and water column position were excluded due to data availability. For example, some habitats have been linked with plastic capture and accumulation (e.g., mangroves), but research is not available on plastic accumulation rates or taxa use for all habitat types (Luo et al., 2021).

Species' sensitivity relates to the likelihood of an organism to interact (via ingestion or entanglement) with plastic in the environment and subsequent sub-lethal or lethal impacts of these interactions. The five traits included for species' sensitivity were body morphology, feeding and foraging behavior, prey preferences, egestion potential, and vulnerability to other stressors. Body mass was the indicator chosen for body morphology, assuming that species with higher body mass are less sensitive to drowning if entangled and are less sensitive to negative impacts from ingestion (Kaplan Dau et al., 2009; Thiel et al., 2018). Sensitivity associated with different foraging behaviors and prey preferences were informed by the literature (Roman et al., 2019a; Thiel et al., 2018; Bond et al., 2013). We used regurgitation potential as an indicator of egestion potential, as species that can regurgitate indigestible plastics more easily are less sensitive to ingestion (Basto et al., 2019). Finally, we used listed threats from each species assessment on the IUCN Red List of Threatened Species (www.iucnredlist.org) as an indicator for vulnerability to other stressors. Species experiencing significant impacts from other stressors are likely more sensitive to macroplastic pollution; therefore, we assumed species experiencing more IUCN red list designated threats are more likely to experience other stressors that compound plastic pollution (Drever et al., 2018; Lacombe et al., 2020). We excluded respiratory mode because all species selected have the same mode of respiration. Non-foraging behavior, pre-adult behavior and relative sensitivity of pre-adult stages were excluded due to data availability.

Four out of six traits were included to inform population resilience: abundance, habitant and feeding specialization, reproductive turnover rate, and risk of extinction. Population size was used as the indicator for abundance, as smaller populations are less resilient (Dulvy et al., 2003; Mace et al., 2008). We chose number of habitats as the indicator for habitat and feeding specialization, assuming species that are more specialized are less resilient (Ducatez et al., 2020). Generation length, defined as the average age of reproducing adults, was selected as the indicator for reproductive turnover rate, as species with longer generation lengths have populations that recover more slowly from disturbances (Dulvy et al., 2003). Finally, we used IUCN Red List status as an indicator of extinction risk. We excluded population connectivity, because it is difficult to identify the role of connectivity in improving population resilience for large ranged species with complex migration patterns (McManus et al., 2021; Compa et al., 2019). We excluded the relative importance of the most sensitive life stage due to limited knowledge of population structure and intra-life stage variation in species' sensitivity for most species.

2.3. Collect trait data

To collect species-specific trait data, we used a variety of databases and organizations, including the IUCN Red List, Birds of the World, Animal Diversity Web, National Oceanic and Atmospheric Administration, and Sea Turtle Conservancy (IUCN, 2022; Birds of the World, 2022; Myers et al., 2022; NOAA, 2022; Sea Turtle Conservancy, 2022). We then addressed data gaps using peer-reviewed literature. Macroplastic concentration maps were taken from Eriksen et al., 2014, because this includes publicly available data on surficial plastic distribution globally and has been used in other assessments of macroplastic risk (Høiberg et al., 2022).

For continuous, quantitative indicators—plastic density per km^2, longevity, mass, population, and average generation length—we used quantitative data whenever available and converted data provided to a mean value with a standard deviation (SD). When the data source provided a single value with high confidence (e.g., population size), we assumed this was the mean value for the species with no SD. When a single value was provided with a statement of uncertainty (e.g., approximate population size), we assumed the provided value was the mean, but included a 10 % standard deviation to be conservative. When a range was provided by a single data source or two sources provided conflicting values (e.g., population is 100,000 to 300,000), we assumed the range given had a 95 % confidence interval. In this instance, we used the average of the two values as the mean (e.g., 200,000), and assumed the range captured two SDs in each direction (e.g., SD is 50,000). If quantitative data were not available, we included qualitative information provided. For example, the population size of Pygmy Sperm Whale (*Kogia breviceps*) is unknown, but it is considered a rare species (IUCN, 2022). Therefore, general abundance was coded as "rare". If data were not available for a certain species, we assigned a best estimate based on data available for other species (e.g., we used American Coot mass for the Hawaiian Coot) and included an SD of 10 % (See supplementary materials for more detail).

For non-continuous or categorical indicators—feeding behavior, prey preferences, listed IUCN threats, regurgitation potential, IUCN Red List status, and habitat specialization—we collected all available information from the provided databases. For number of habitats and the number of IUCN threats each species was exposed to, we summed the number listed in the IUCN database (IUCN, 2022), and assumed no standard deviation (because no uncertainty was provided). For other traits, we recorded qualitative data (See supplementary materials for more detailed methods on indicator calculations and trait data).

2.4. Develop scoring metrics

All indicators were scored on a scale of one to five, with one representing the lowest possible contribution to vulnerability and five being the highest, to ensure all traits were equally weighted within a given vulnerability dimension (e.g., distribution and longevity had equal influence on likelihood of exposure scores). Table 1 provides a summary of the scoring metrics used for each indicator. For the continuous

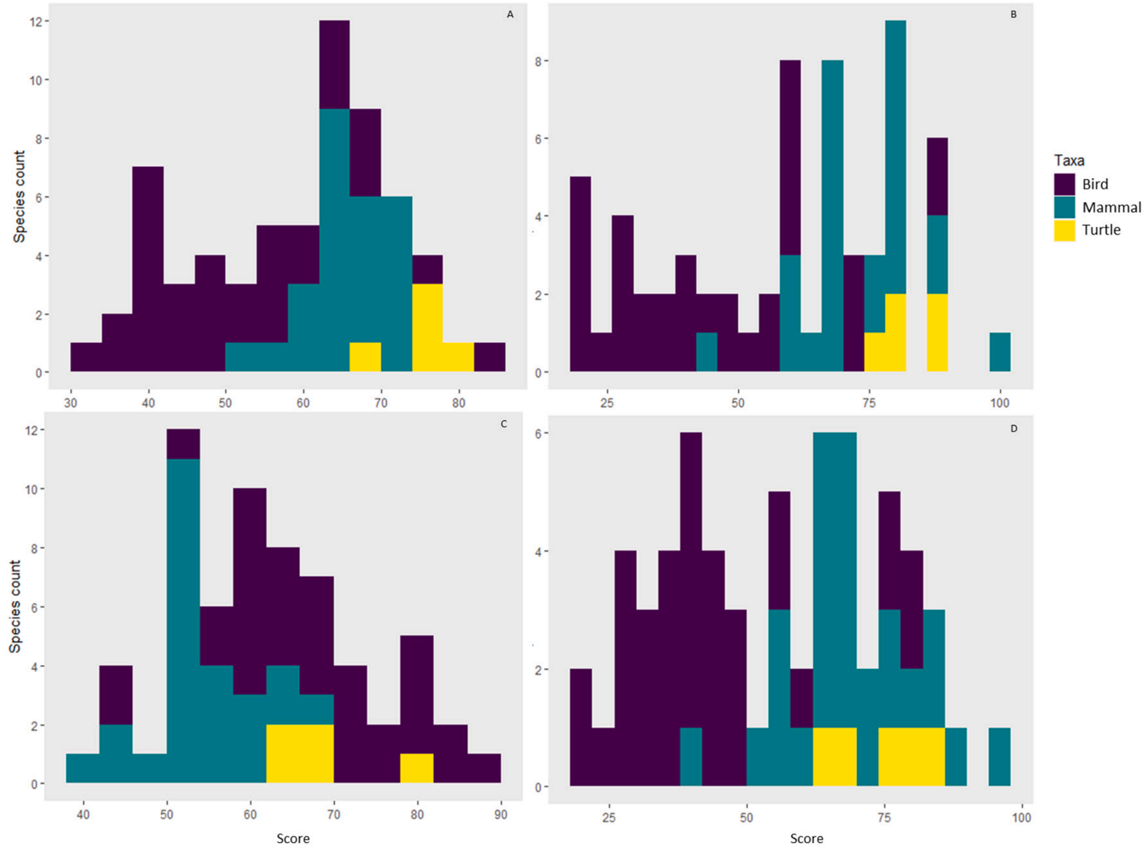

Fig. 1. (A) Distribution of total scores by taxa. (B) Distribution of exposure scores by taxa. (C) Distribution of sensitivity scores by taxa. (D) Distribution of resilience scores by taxa.

Table 2
Vulnerability index for Hawai'ian marine mammals, sea turtles, and seabirds, with total scores, and scores for each vulnerability dimension shown. Horizontal lines signify quintile cutoffs. Green signifies the lowest quintile species within a vulnerability dimension or total vulnerability. Yellow signifies the second lowest, orange the middle, red the second highest and dark red the highest.

Species	Vulnerability Group	Vulnerability Rank	Exposure	Species sensitivity	Population resilience	Taxa
Sanderling (*C. Alba*)	Low	33	20	44	35	Bird
American Wigeon (*M. americana*)		35.2	26.1	59.6	20	Bird
Eurasian Moorhen (*G. chloropus*)		36.8	20	70.4	20	Bird
Ruddy Turnstone (*A. interpres*)		38.1	23.4	63.9	27	Bird
Northern Shoveler (*S. clypeata*)		39.2	20	67.6	30	Bird
Wandering Tattler (*T. incana*)		39.7	20	44	55	Bird
Black-crowned Night Heron (*N. nycticorax)*		39.9	26.3	62.5	31.1	Bird
Pacific Golden Plover (*P. fulva*)		40	26.2	58.8	35	Bird
White-tailed Tropicbird (*P. lepturus*)		40	30.1	60	30	Bird
Grey-backed Tern (*O. lunatus*)		40.5	30.3	60	31.3	Bird
Blue Gray Noddy (*A. ceruleus*)		43.5	21	74.5	35	Bird
Black Noddy (*A. minutus*)		43.7	29.1	72	30	Bird
Brown Noddy (*A. stolidus*)		45.4	39.8	66.1	30.5	Bird
Red-tailed Tropicbird (*P. rubricauda*)	Medium-Low	47.1	44.3	52	45	Bird
Masked Booby (*S. dactylatra*)		48.5	41.6	64	40	Bird
Red Footed Booby (S. *sula*)		49	50.9	56.2	40	Bird
Christmas Shearwater (*P. nativitatis*)		49.6	34.9	64	50	Bird
Sooty Tern (*O. fuscatus*)		51.3	60.1	68.8	25	Bird
Fraser's Dolphin (*L. hosei*)		51.4	45.2	56	53.2	Mammal
White Tern (*G. alba*)		52.2	35.9	80	40.8	Bird
Brown Booby (*S. leucogaster*)		54.3	58	60.1	45	Bird
Great Frigate Bird (F. *minor*)		55	60	60	45	Bird
Spinner Dolphin (*S. longirostris*)		55.3	70	56	40	Mammal
Bonin Petrel (*P. hypoleuca*)		56	72.1	56	40	Bird
Wedge-tailed Shearwater (*A. pacifica*)		56.7	55	80	35	Bird
Band-rumped Storm Petrel (*H. castro*)		58.6	49.7	76	50	Bird
Bulwer's Petrel (*B. bulwerii*)	Medium	59.1	49.4	88	40	Bird
Pygmy Sperm Whale (*K. breviceps*)		60.3	60	56	65	Mammal
Pygmy Killer Whale (*F. attenuata*)		60.5	60	52.4	69.3	Mammal
Risso's Dolphin (*G. griseus*)		60.6	64.9	60	56.8	Mammal
Pantropical Spotted Dolphin (*S. attenuata*)		62.1	80	51.2	55	Mammal

Common Minke Whale (*B. acutorostrata*)		62.3	70	52	65	Mammal
Newell's Shearwater (*P. newelli*)		62.5	39.6	68	79.9	Bird
Melon-headed Whale (*P. electra*)		62.8	66.5	52	70	Mammal
Tropical Bottlenose Whale (*I. pacificus*)		63.9	61.4	56	74.3	Mammal
Hawaiian Coot (*F. alai*)		64.0	60	71.9	60	Bird
Humpback Whale (*M. novaeangliae*)		64	70	52	70	Mammal
Striped Dolphin (*S. coeruleoalba*)		64.5	98.4	40	55	Mammal
Rough-toothed Dolphin (*S. bredanensis*)	Medium-High	64.8	78.6	50.6	65	Mammal
Short-finned Pilot Whale (*G. macrorhynchus*)		65.1	86.9	48.3	60	Mammal
Laysan Duck (*A. laysanensis*)		65.3	60	60.9	75	Bird
Dwarf Sperm Whale (*K. sima*)		65.8	69.8	64.1	63.7	Mammal
False Killer Whale (*P. crassidens*)		66	77.6	45.3	75	Mammal
Tristram's Storm Petrel (*H. tristrami*)		66.3	60	84	55	Bird
Cuvier's Beaked Whale (*Z. cavirostris*)		66.8	70	60	70.4	Mammal
Sperm Whale (*P. macrocephalus*)		67.3	80	52	70	Mammal
Laysan Albatross (*P. immutabils*)		68.6	88.9	72	45	Bird
Black-footed Albatross (*P. nigripes*)		68.9	72.8	84	50	Bird
Olive Ridley (*L. olivacea*)		69	77.9	64	65	Turtle
Blainville's Beaked Whale (M. *densirostris*)		69.5	80	64	64.4	Mammal
Orca (*O. orca*)		69.8	77.4	52	80.1	Mammal
Bryde's Whale (*B. edeni*)	High	70.4	89.3	52	70	Mammal
North Pacific Right Whale (E. *japonica)*		70.7	70	52	90	Mammal
Sei Whale (*B. borealis*)		71.7	70	60	85	Mammal
Fin Whale (*B. physalus*)		72.3	80	52	85	Mammal
Hawaiian Monk Seal (*N. Schauinslandi*)		72.6	79.8	68	70	Mammal
Blue Whale (*B. musculus*)		73	80	44	95	Mammal
Green Turtle (*C. mydas*)		74.7	80	68.8	75.4	Turtle
Hawaiian Petrel (P. *sandwichensis*)		75	70.1	80	75	Bird
Loggerhead (C. *caretta*)		76.1	90	68.2	70	Turtle
Hawksbill (*E. imbricata*)		77.4	88.4	63.9	80	Turtle
Leatherback (*D. coriacea*)		81.4	80	80	84.3	Turtle
Short-tailed Albatross (*P. albatrus*)		82.9	88.7	80	80	Bird

quantitative traits, we calculated quintiles to identify the cut-off points for scores. For unknown population sizes with qualitative descriptors, "rare" species were scored a five, "fairly common" species were scored a two and "unknown" species were scored a three, all with a SD of one for the score. For categorical data, we developed scores based on the stated assumptions and the Murphy et al. (2023) literature review. For example, each IUCN Red List status corresponded to a number from one to five with least concern species receiving a score of one and critically endangered species receiving a score of five. For unknown categorical data a score of three was used with an SD of 1 for the score (See supplementary materials for more detailed information on scoring).

Regurgitation potential, feeding and foraging behavior, and prey preference score categories were informed by the literature (Good et al., 2020; Roman et al., 2022; Andrades et al., 2019; Ryan, 2019; Schuyler et al., 2014). Importantly, both the traits of species and the traits of the plastic influence the likelihood of ingestion and entanglement. For example, surface seizing birds eat more hard fragments on the surface, while turtles consume more films. This is because plastic traits influence their occurrence in the water column and how similarly they resemble prey items (Ryan, 2019; Schuyler et al., 2014).

2.5. Score and rank species

Each species received a score for every trait based on the scoring system developed (Table 1). Trait-specific scores were then put into Eq. (1) to calculate a final relative vulnerability score for every species.

$$\text{Vulnerability score} = ((\Sigma T_{1-2})/2 + (\Sigma T_{3-7})/5 + (\Sigma T_{8-11})/4)/3^{*}\ 20 \qquad (1)$$

T_1 and T_2 represent the two likelihood of exposure traits—distribution and longevity—T_3 to T_7 represent the five species' sensitivity traits and T_8 to T_{11} represent the four population resilience traits. Therefore, the equation weighs each dimension of vulnerability—likelihood of exposure, species' sensitivity, and population resilience—equally by finding a mean score out of five for each dimension. Without strong evidence from the literature for increased weighting of certain traits, we chose equal weighting for traits within each dimension and for each dimension in the final score. These three scores are then averaged and multiplied by 20 so each species has a possible total vulnerability score between 20 and 100. This was done to make index interpretation easier but did not influence results as rankings are relative. We then identified quintiles for the total vulnerability score and each species was placed into one of five vulnerability groups: low vulnerability (20–45.44), low-medium vulnerability (45.44–58.58), medium vulnerability (58.58–64.52), medium-high vulnerability (64.52–69.88), or high vulnerability (69.88–100).

When calculating species final scores, we used bootstrapping in our analyses to account for uncertainty in trait data. For each species' trait value, we generated 1000 random values, assuming a normal distribution around the recorded mean and SD. This assessment included 63 species, ultimately producing 63,000 total estimates for a single trait for all species. We then used these values to develop the quintile cut offs for all continuous, quantitative traits (i.e., quintile cut-offs were based on 63,000 generated values based on SD within data, instead of based on mean values alone). We applied the quintile cutoff points to all 1000 trait estimates for each species to generate 1000 scores for a given trait. Finally, we used Eq. (1) to calculate 1000 final vulnerability scores for each species. From these 1000, we calculated the mean vulnerability score and identified the standard error (two SD) for each species score. All analyses in Rstudio Version 2022.02.2 + 485 "Prairie Trillium" Release (See supplementary materials for detailed description of methods and R script).

It is important to note that a high standard error for trait data did not always lead to a high error in score. This is because if the range provided all fell within one quintile, then the score for a given trait would still always be the same. For example, a population range could be 10,000,000 to 15,000,000, but even the lowest population size in this range is still high enough to produce a score of one for population size.

2.6. Sensitivity analyses

To ensure that all the traits included in our analysis were important in determining species scores, we conducted sensitivity analyses. We first calculated the Pearson's correlation between raw trait data and tested for significant correlation. We then recalculated vulnerability scores, removing traits that were correlated with another trait in the same vulnerability dimension (e.g., removed generation length due to correlation with population abundance). We evaluated trait redundancy

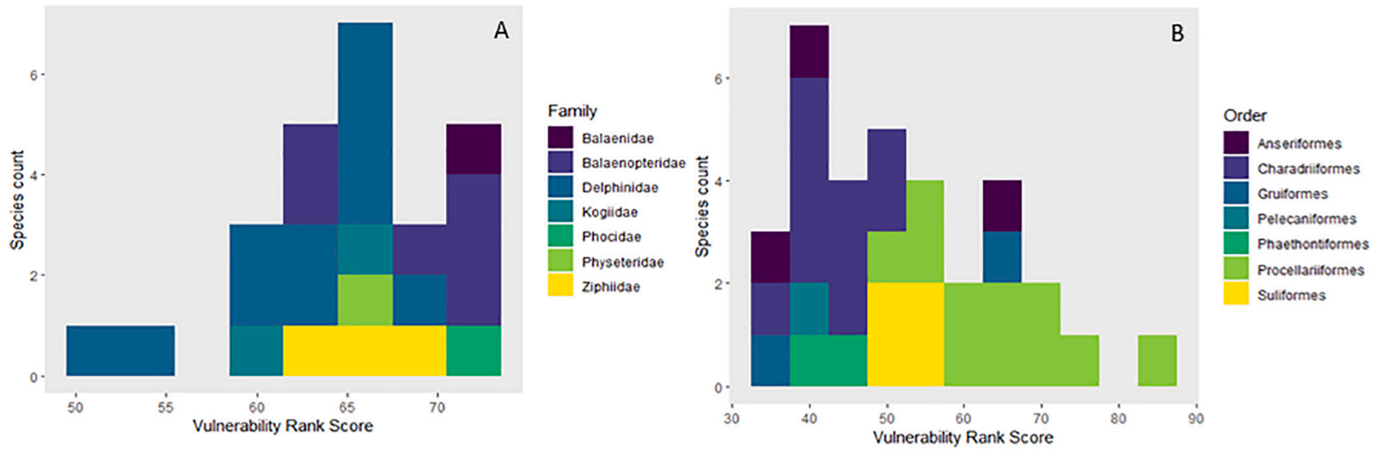

Fig. 2. (A) Distribution of total scores for birds by order. (B) Distribution of final scores for mammals by family.

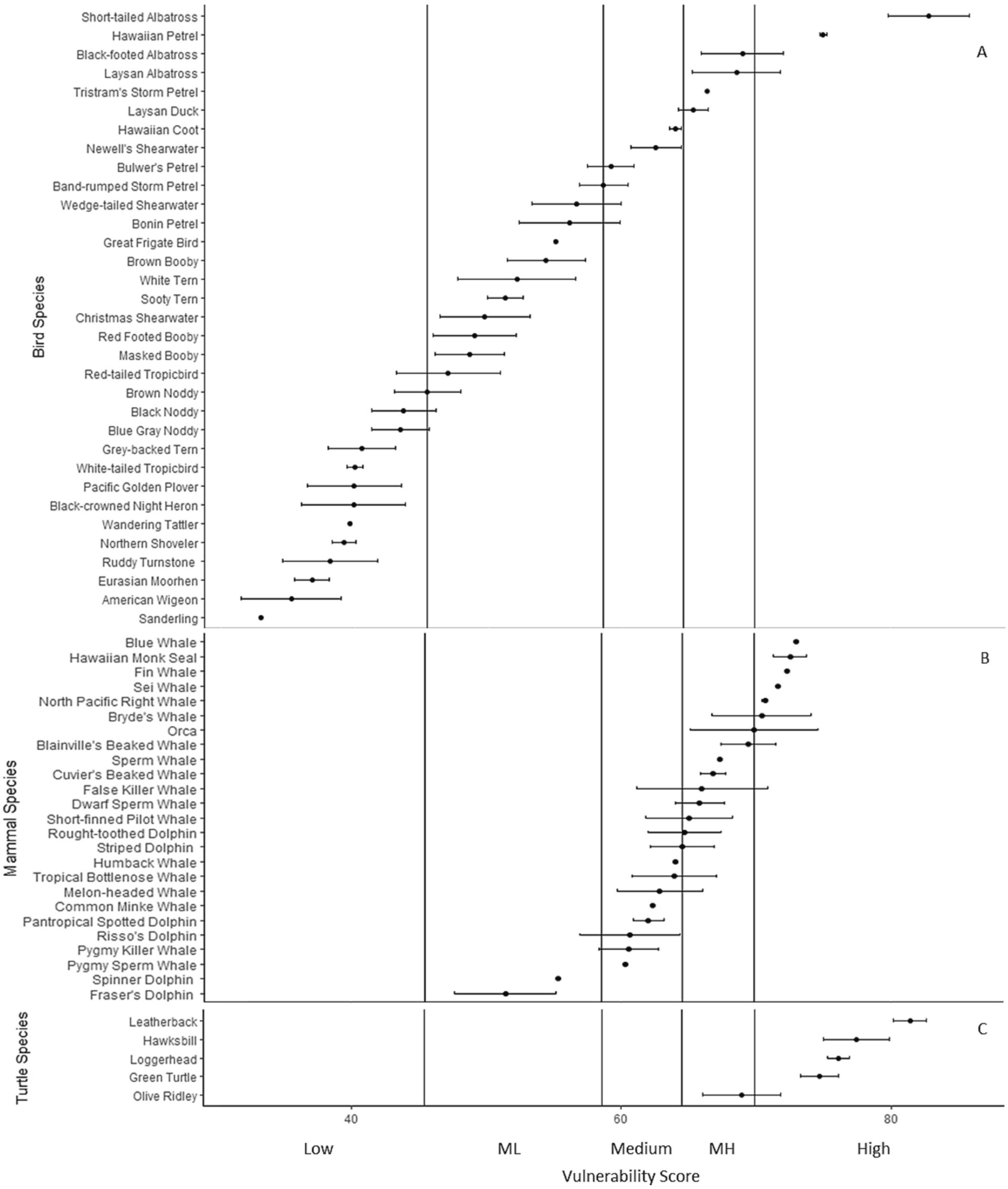

Fig. 3. Confidence intervals for each species vulnerability score; (A) confidence intervals for seabird scores, (B) scores for marine mammals, (C) scores for sea turtles.

based on the number of species that changed final vulnerability ranking with trait removal. Ultimately, no traits were redundant, and all 11 traits were included in the final analysis. To identify the sensitivity of results to trait data quality, we recalculated vulnerability scores by increasing all SD values of zero to 1.25 and 2.5 (2.5 % SE and 5 % SE). We then identified how confidence in trait data values influenced confidence in the final vulnerability groups (Results in supplementary materials).

3. Results

Fig. 1 shows the final vulnerability scores and scores for each dimension of vulnerability, by taxonomic group. On a scale from 20 to 100, final scores ranged from 33 to 83, indicating a wide range of vulnerability. Based on quintiles of final relative vulnerability scores, thirteen species were categorized as low vulnerability, 13 as low-medium, 12 as medium, 13 as medium-high, and 13 as high (Table 2). Generally, differences in vulnerability can be seen by taxonomic group (Figs. 1 and 2). All 13 low vulnerability species are birds, primarily ducks (Anatidae), and waders (Rallidae, Scolopacidae, Charadriidae, and Ardeidae). This group also includes three noddies (Laridae), the white-tailed tropic bird (*Phaethon lepturus)* and the gray-backed tern *(Onychoprion lunatus)*. Species in the lowest vulnerability group typically had scores for exposure and population resilience in the lowest quintile; however, species varied in their sensitivity, with the Blue-gray Noddy (*Anous ceruleus)* falling into the highest quintile for its sensitivity scores due to its prey preferences, feeding behaviors and regurgitation potential (Table 2).

Medium-low species were also mostly birds but covered a wider range of families (Sulidae, Laridae, Fregatidae, Procellariidae) and included two mammals, the Fraser's dolphin (*Lagenodelphis hosei*) and Spinner dolphin (*Stenella longirostris*). Two birds—Bulwer's Petrel (*Bulweria bulwerii*) and Newell's Shearwater (*Puffinus newelli*)—and ten mammals were ranked medium vulnerability (Fig. 2). The mammals were mostly Delphinidae (dolphins, six species), but there were also Kogiidae (Dwarf and Pygmy Sperm Whales), Balaenopteridae (baleen whales), and Ziphiidae (beaked whales) species. Seven mammals, five seabirds, and one sea turtle, Olive Ridley (*Lepidochelys olivacea)* had medium-high vulnerability. The mammals in this category represented four families (Delphinidae, Kogiidae, Ziphiidae, and Physeteridae), as did the birds, which included storm petrels, rails, ducks, and albatrosses (Hydrobatidae, Rallidae, Anatidae, and Diomedeidae). Finally, all three taxa were represented in the high vulnerability group, including four out of five sea turtles (*Caretta caretta, Chelonia mydas, Dermochelys coriacea, and Eretmochelys imbricata)*, two seabirds—Short-tailed Albatross (*Phoebastria albatrus*) and Hawaiian Petrel (*Pterodroma sandwichensis*)—and six mammals—Hawaiian Monk Seal (*Neomonachus schauinslandi*), North Pacific Right Whale (*Eubalaena japonica*), and four Balaenopteridae.

3.1. Confidence in vulnerability groups

Fig. 3 shows confidence in final species scores and vulnerability categories based on uncertainty in the trait data collected. Confidence intervals are shown for each taxon—birds, mammals, and turtles—in 3a, 3b, and 3c, respectively. For 22 of the 33 bird species, the species confidence interval fell within the assigned vulnerability group, showing that despite uncertainty in some species data (i.e., ranges provided for possible mass, population, or longevity of a species), there can be confidence in the final vulnerability group. The 11 species that had confidence intervals spanning multiple vulnerability groups had means close to the category bounds and comparatively large standard errors. No birds spanned three vulnerability categories.

Of the 25 mammals, roughly half (12) had confidence intervals that spanned multiple vulnerability groups, and one mammal spanned three categories. Importantly, confidence in the rankings for the five most vulnerable mammal species was high. There was more uncertainty for mammals in the medium and medium-high categories. Unlike with birds, this was more driven by high uncertainty in trait data than by mean vulnerability scores lying close to the category cut-offs. Additionally, the score ranges for medium and medium high species were smaller. Nonetheless, it is important to note that for some of these species, confidence in the given vulnerability ranking is still high as >90 % of the standard error bar was contained in a single vulnerability group.

Confidence in the turtle species vulnerability groups was high, with all four high vulnerability species' standard errors contained within that category. Only the Olive Ridley vulnerability score range crosses two categories: medium-high and high.

3.2. Correlation between traits

Fig. 4 shows the magnitude and direction of correlations between traits. *P*-values are given for indicators with statistically significant correlations. ($p < 0.05$). Habitat number was most correlated with other traits, having weak negative correlations with IUCN Red List category, longevity, distribution, generation length, and mass; habitat number had a weak, positive correlation with population size (note correlation with habitat specialization is the inverse direction of correlation with habitat number). Generation length had a significant, but weak, negative correlation with population, and had stronger, positive correlations with IUCN status, distribution, and longevity. Population had significant, negative correlations with egestion potential, IUCN status, and longevity. Mass had a significant, and strong, positive correlation with longevity, and a significant, strong correlation with prey preferences. Finally, IUCN status had a significant, positive, correlation with longevity.

To test for redundancy, vulnerability scores were recalculated removing correlated traits in the same dimension. Therefore, we removed prey and mass from the sensitivity traits and each population resilience trait. Removal of each trait changed the ranking of eight (removing mass or prey from sensitivity score) to 28 species (removing population from resilience score), which confirmed the lack of trait

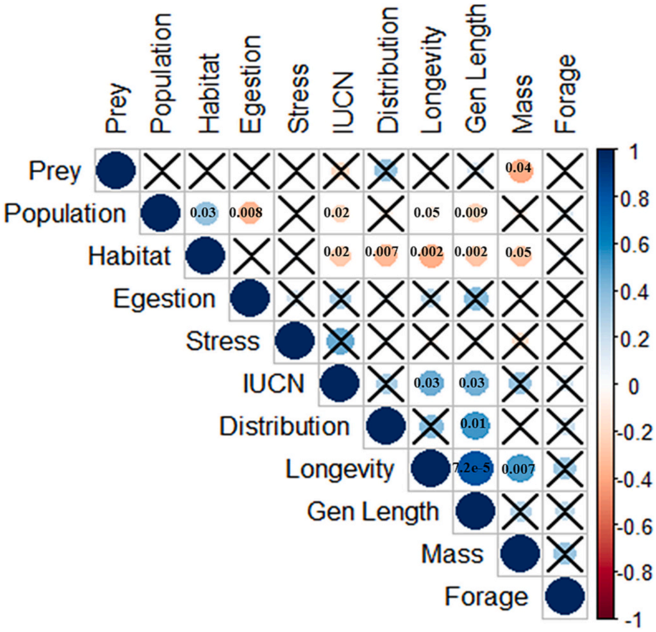

Fig. 4. Correlation coefficients between traits. Blue indicates positive correlations. Red indicates negative correlations. Larger circles indicator greater magnitudes of correlations. *P*-values are provided where correlation is significant and an "X" over the circle indicates the correlation is not statistically significant.

redundancy, despite some correlations. As a result, all 11 original traits were used to inform the final ranking (See supplementary materials for more detail).

4. Discussion

Sublethal and lethal effects of plastic ingestion and entanglement in marine megafauna are well-documented. However, linking these individual effects with population level outcomes remains difficult, due to the life history of these species and the ubiquity and heterogeneity of marine plastic pollution. The vulnerability index we present uses species' traits to provide insight into the Hawai'ian marine megafauna populations that are most vulnerable to macroplastic pollution. The four sea turtle species categorized as having high vulnerability, Green Turtles, Hawksbills, Loggerheads, and Leatherbacks are all known to be highly sensitive to both ingestion and entanglement throughout their life cycle (Tagliolatto et al., 2020; Gündoğdu et al., 2019; Thiel et al., 2018; Aguilera et al., 2018; Triessnig et al., 2012). This observed sensitivity coupled with slow reproductive turnover, long-life expectancy, and high plastic density within these species' ranges (IUCN, 2022) make high vulnerability rankings expected. The Olive Ridley was found to have lower vulnerability than the other turtles, because of their preference for benthic invertebrates, which are less frequently mistaken for plastics (Bjorndal et al., 1994; Abreo et al., 2019; NOAA, 2022). However, they are still long-lived and sensitive to entanglement during fishery interactions (Yaghmour, 2020).

Broadly, marine mammals were less vulnerable than sea turtles and more vulnerable than seabirds. Oceanic dolphins generally had the lowest vulnerability, followed by beaked whales, and then baleen whales, with the one pinniped species in the highest vulnerability group. Although it is difficult to study population level effects of macroplastic pollution on marine mammal species, these results are generally supported in the literature (Thiel et al., 2018; Im et al., 2020; Alexiadou et al., 2019; Puig-Lozano et al., 2018). There is extensive evidence that the Hawaiian Monk Seal is sensitive to macroplastic pollution through ingestion and entanglement (Henderson, 2001; Donohue and Foley, 2007). This species has a small population and, like other pinnipeds, is vulnerable to fisheries-based plastics due to their foraging behavior, curiosity, and prey preferences for fishes, cephalopods, and crustaceans (Hofmeyr et al., 2006; IUCN, 2022). Similarly, research indicating the Atlantic Right Whale is highly sensitive to entanglement, supports the categorization of the Pacific Right Whale as highly vulnerable (Moore and Van der Hoop, 2012). There are a few unexpected results for mammals. For example, the categorization of Pygmy Sperm Whales as medium, and dwarf sperm whale as medium-high is unexpected, as these two species are very similar (McAlpine, 2018). The primary difference between these species scores were driven by differences in listed IUCN threats, and the standard errors around their scores were high, giving lower confidence in their final categories. For poorly studied species, such as the Pygmy and Dwarf Sperm Whales, even though their rankings are more moderate, more research is needed to better understand their potential risk.

Overall, birds were identified as the least vulnerable taxa to macroplastic pollution, but they had the largest range in vulnerability rank. Generally, ducks and shorebirds had the lowest vulnerability; followed by noddies, terns and boobies; and shearwaters, petrels and albatross were the most vulnerable groups. This is supported by the relatively low rates of plastic ingestion documented in ducks, noddies, and terns, compared with albatrosses, petrels, and shearwaters (Fry et al., 1987; Sileo et al., 1990; Rapp et al., 2017). The large variability in vulnerability rank is supported by the heterogeneity in trait data seen across seabird species, as they had the largest variability in environmental plastic density, life expectancy, generation length, and population size.

A recent study showed that although shorebirds have not been a focus of plastic pollution research, limited data indicates they do ingest plastics (Flemming et al., 2022). Our results support this, as we saw relatively high species' sensitivity scores for shorebirds; however, our results also suggest that lower exposure rates and higher population resilience may reduce vulnerability at the population level.

The categorization of the petrels and albatrosses in the medium-high and high vulnerability groups also makes sense given the high ingestion rates documented for nocturnal petrels and albatrosses (Sileo et al., 1990; Rapp et al., 2017). This also aligns with the results from a trait-based assessment conducted for seabirds in the California Current (Good et al., 2020). Although research on the Short-tailed Albatross is limited, Donnelly-Greenan et al. (2018) found high rates of plastic ingestion in chicks and adults were likely to cause damage to the gastrointestinal tract. This species' assignment to the high vulnerability group also makes sense considering their long-life expectancy and small population (IUCN, 2022).

Overall, the relatively low ranks of some well-studied seabird species signal the value of this vulnerability index, by showing that high documented rates of plastic interaction does not necessarily equate to high relative vulnerability at the population level (Fry et al., 1987). For instance, Wedge-tailed Shearwaters (*A. pacifica*) and Newell's Shearwater (*P. newelli*) have high documented rates of ingestion in the literature (Kain et al., 2016; Fry et al., 1987) but were characterized as having medium-low and medium vulnerability in our assessment, respectively. Both species received high species' sensitivity scores, supporting the accuracy of this dimension in capturing the traits driving sensitivity. However, their large populations, fast reproductive turnover, and low risks of extinction make them less vulnerable at the population level. Alternatively, some species that ranked higher, such as the Pygmy and Dwarf Sperm Whales, have had few documented cases of plastic interaction; this reflects their small populations and life histories that make them difficult to study more than a low vulnerability to plastic pollution (McAlpine, 2018). Similarly, the medium-high ranking of the Laysan Duck was expected due to little evidence of species' sensitivity (ingestion or entanglement of individuals) in the literature. However, their extremely low population resilience increases their vulnerability, and their small population makes plastic interactions more difficult to study.

To our knowledge, this is the first effort to integrate uncertainty into a relative trait-based vulnerability index. Typically, studies provide a mid-range score (e.g., 3/5) for unknown data, or provide a best estimated score (Woodyard et al., 2022; Chin et al., 2010; Foden et al., 2013). Our results indicate that the ranking system can handle some uncertainty and provide precise vulnerability rankings for the species of interest. However, at an individual species level, there was less confidence in species' vulnerability rankings if there was a lot of uncertainty in their trait data. This had a bigger impact on vulnerability rankings for species in the low-medium to medium-high categories than on those in the low or high categories. For example, the Pygmy and Dwarf Sperm Whales are closely related, understudied species that we may expect to have similar vulnerability. They received different vulnerability rankings, but both have large error bars, and their possible score ranges overlap substantially. Therefore, for species with a lot of trait data missing or with broad estimates, specific vulnerability estimates may be inaccurate.

The vulnerability index and ratings presented here can be used to prioritize species and geographic areas for improved management, monitoring, and plastic mitigation efforts in the Hawaii EEZ. Clean-up efforts can focus on marine regions, beaches, and nesting areas more frequently used by these species. Additionally, depending on the species, different upstream management efforts may provide more benefit. For instance, the most vulnerable mammals are disproportionately impacted by fisheries-based plastics (Puig-Lozano et al., 2018; Thiel et al., 2018; Boland and Donohue, 2003). Therefore, focusing on fisheries interactions—derelict gear removal, fishing for debris programs, or regulations on gear types—may provide greater outcomes for these species. Alternatively, addressing plastics, such as plastic bags, that are more often mistaken for food may provide greater benefits for species, such as albatrosses and green turtles, that feed on squid and other prey that resemble soft plastics (Poli et al., 2015; IUCN, 2022). Finally, long-term monitoring and population studies should focus on the species identified in the high and medium-high categories, as these face the greatest risk of plastic-driven population decline. These species will also provide a good indicator for overall ecosystem impacts of plastic pollution.

There is additional value in considering the quintile score of species for each dimension of vulnerability. For instance, if a species has a low likelihood of exposure but is highly sensitive with a vulnerable population, then it may be important to monitor for changes in likelihood of exposure. Changes in plastic use, marine activities, or ocean currents could rapidly alter plastic density within species ranges, and subsequently likelihood of exposure. Alternatively, looking at species sensitivity may highlight cases where species that are less vulnerable are getting more attention due to high individual interaction rates, but a species with lower observed interactions may be more vulnerable because of a less resilient population.

In the theory and practice of conservation, species recovery efforts are typically focused on single species versus broader threat mitigation (Clark and Harvey, 2002). Given the ubiquitous nature of plastic pollution in our oceans, focusing on the threat itself using trait-based approaches offers a promising strategy for designing effective mitigation strategies. Our work represents an important first step in this direction. In particular, the development of this vulnerability index exemplifies the potential of trait-based approaches for identifying populations at risk of macroplastic pollution. Although this index focuses on Hawai‘i, many of the species evaluated have social and ecological importance across the globe. Further, the methods applied here could be expanded for global analyses, or to include more taxonomic groups. Such indices could be used to identify understudied species, explore community and ecosystem level effects, and choose the species best suited for long-term monitoring.

These indices could be used to inform species management and plastic mitigation efforts. At the local scale, managers and decision-makers could apply this framework to understand the impact of plastics on local ecosystem health and direct local priorities, such as populations to monitor or areas for implementing targeted clean-up efforts. At a global scale, this framework could be implemented to identify species requiring international cooperation. In both cases, this could inform policy priorities for ecological outcomes, such as regions and plastics to target for mitigation. Finally, further research into trait-based approaches for macroplastic pollution could lead to their implementation for more advanced ecological risk assessments. Beyond being used to infer risk across levels of biological organization, trait-based approaches can be used to extrapolate impacts across varying doses of a pollutant or developmental stages of a species (Van den Brink et al., 2011).

There are important limitations to trait-based approaches that must be acknowledged with their implementation. The first limitation is data availability. One reason little is known about the consequences of macroplastic pollution on marine biodiversity, particularly marine mammals and sea turtles, at higher levels of biological organization is that these species are difficult to study at the population level (Bucci et al., 2020; Murphy et al., 2023). As a result, trait data are often limited in accuracy and precision. The three scenarios for standard error that we explored all demonstrated that confidence in vulnerability indices are closely tied to confidence in trait data.

Even when trait data are available, there is still uncertainty associated with the scoring of some traits. For example, plastic density within a species' range is the most important indicator of exposure. However, global plastic distribution maps are limited to surficial densities (Eriksen et al., 2014), and species range maps are coarse and assume equal distribution throughout the range. Some localized studies have used more precise species distribution maps (Good et al., 2020; Compa et al., 2019), but this resolution is not widely achievable at the global scale. Higher resolution data on plastic and species distribution could improve these predictions. Still, trait-based approaches will always be limited by the quality of their assumptions, so all assumptions should be clearly stated and considered when interpreting index outputs. When high-quality trait data are lacking, coarser vulnerability groups can be developed to build greater confidence in vulnerability ratings (i.e., split species into three categories: low, medium, and high, instead of five). These provide less resolution, but still identify the most vulnerable species.

There are also limitations specific to multi-taxonomic indices. There is causal data in the literature about how different feeding and foraging behaviors among birds affect ingestion rates, but it is more difficult to compare sensitivity associated with feeding and foraging behaviors across taxa (Caldwell et al., 2020; Roman et al., 2019b). This creates risks of inaccurate clumping of taxa and these challenges increase when trying to compare more distantly related taxa.

To improve the value of trait-based approaches for macroplastic pollution, four areas of future research are needed. First, more research on the life history of marine species is needed to improve the quality of trait data. This would increase the accuracy of trait-based approaches for macroplastic pollution and other stressors affecting marine biodiversity. Second, additional research is needed on the relationship between species' traits and plastic pollution vulnerability and on trait-based approach methodology more broadly to improve methods for weighting traits and scoring species. The current approach weights all traits equally within a vulnerability dimension (i.e., likelihood of exposure, species' sensitivity, or population resilience); however, some traits may have more influence on vulnerability than others and results could be more accurate if not all traits were weighted equally. Third, strategic, placed-based population, species, and community level research on the physical impacts of macroplastic pollution are needed to validate vulnerability indices on the ground. Validating indices would allow for these approaches to be applied more broadly with greater confidence in the traits included and accuracy of outcomes. Finally, more research is needed to integrate trait-based approaches into ecological and other risk assessments and increase their value for policy development and decision making. Already, efforts are underway to improve modelling methods and increase standardization of trait-based approaches across sectors (Zakharova et al., 2019), and increase the availability of more accurate and precise trait data (IUCN, 2022; Martini et al., 2021).

Marine macroplastic pollution has significant consequences for marine biodiversity. Given that little is known about the impacts of macroplastic pollution at population, species, or community levels, trait-based approaches provide a salient method for inference across biological organization. Here, we present the first multi-taxonomic index for vulnerability to marine macroplastic pollution ingestion and entanglement. This work provides insight into the most vulnerable marine megafauna in Hawai‘i, showcases the value of the framework put forth by Murphy et al. (2023) and exemplifies the potential for trait-based approaches in research and managing marine plastic pollution more broadly.

CRediT authorship contribution statement

Erin L. Murphy: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Project administration. **Leah R. Gerber:** Validation, Writing – review & editing. **Chelsea M. Rochman:** Validation, Writing – review & editing. **Beth Polidoro:** Conceptualization, Validation, Supervision, Writing – review & editing.

Declaration of competing interest

No authors have any interests to declare.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168247.

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