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Towards a North Pacific Ocean long-term monitoring program for plastic pollution: A review and recommendations for plastic ingestion bioindicators☆

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ABSTRACT

Marine debris is now a ubiquitous component of the Anthropocene global ocean. Plastic ingestion by marine wildlife was first reported in the 1960s and since that time, roughly one thousand marine species have been reported to consume this debris. This study focuses on plastic ingestion by marine invertebrates and vertebrates in the North Pacific Ocean. Specifically, we reviewed the scientific literature to assess the scope of the problem, identified key bioindicator species, and proposed guidelines for future monitoring of plastic debris in North Pacific marine ecosystems. Our meta-analysis confirmed that the North Pacific is among the most polluted ocean regions globally; roughly half of all fish and seabird specimens and more than three-quarters of sea turtles and bivalve specimens examined in this region had consumed plastic. While there are not enough standardized data to assess if these ingestion rates are changing, sampling standardization and reporting of methods are improving over time. Using a rubric-evaluation approach, we evaluated 352 species for their potential to serve as bioindicators of the prevalence of plastic pollution in the North Pacific. This analysis revealed a suite of 12 bioindicator species candidates which sample a variety of ecosystem components and cover a wide range of plastic size classes. Thus, we contend that these bioindicator candidates provide a key foundation for developing a comprehensive plastic monitoring program in the region. To enhance the utility of these bioindicators, we developed a framework for standardized data collection to minimize methodological variability across different studies and to facilitate the assessment of temporal trends over space and time. Tracking plastic ingestion by these bioindicators will help to assess the effectiveness of mitigation actions in the region, a critical step to evaluate progress towards sustainability and improved ocean health in the 21st century.

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1. Introduction

Plastic production and disposal have increased exponentially over the past half-century (Borrelle et al., 2020). The ocean is the ultimate sink for much of the world's mismanaged plastic waste, with much of it originating from land-based sources as well as from fisheries and aquaculture (Morales-Caselles et al., 2021). Assessments of plastic ingestion conducted for many large marine organisms, such as seabirds, sea turtles, and predatory fishes, have revealed an increasing number of exposed species (Lynch, 2018; Savoca et al., 2021; Wilcox et al., 2015). The North Pacific (NP) has long been recognized as a global hotspot for marine plastic pollution (Moore et al., 2001; Shaw and Mapes, 1979), and researchers working in this region have documented anthropogenic debris ingestion by marine wildlife for decades (Boerger et al., 2010; Kenyon and Kridler, 1969; Lynch, 2018; Spear et al., 1995; Sun et al., 2017; Young et al., 2009).

Testing for the ecological and biological effects of plastic ingestion in the field is challenging due to multiple interacting stressors and the rarity of non-exposed control groups in nature. Even when necropsies have revealed evidence of impaction or ulcerative lesions in the stomach, it has been difficult to ascertain the degree of population-level impacts of this ingestion (Auman et al., 1997; Senko et al., 2020; Sievert and Sileo, 1993). Moreover, the potential sub-lethal impacts operating on short (e.g. growth and development) and long-time scales (e.g. fecundity and survivorship) are inherently difficult to measure in many wild species. Thus, there is a need for coordinated long-term monitoring programs to track plastic pollution in the marine environment, to assess potential effects on species and ecosystems, and to understand correlations between mitigation policies and plastic pollution trends in the environment.

The terms 'indicator' and 'monitor' have been used interchangeably in the plastic pollution literature for decades. The United Nations define environmental monitoring as "*a tool to assess environmental conditions and trends,* support *policy development and its implementation, and develop information for reporting to national policymakers, international forums and the public*" (https://unece.org/environmental-monitoring). Of particular relevance, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) has been providing guidelines for assessment and monitoring of plastic in marine environments since 2015 (GESAMP, 2015). More recently, GESAMP has outlined criteria for selecting bioindicator species, and suggested guidelines for developing monitoring programs (GESAMP, 2019).

Several types of environmental monitoring with distinct, yet complementary, goals can be used to track plastic pollution in the environment. *Baseline monitoring* aims to establish the current benchmark levels of pollution to allow for the tracking of future changes and offer insight for implementing policies. When baseline information is available, *trend monitoring* can reveal spatial and temporal patterns in pollution. Repeated sampling at set intervals and with robust sample sizes is critical for detecting trends in the data. Additional types of monitoring may be appropriate in specific contexts, including *source and surveillance monitoring, compliance monitoring, risk-based monitoring*, and *effects monitoring* (AMAP, 2021a). As part of the activities arising from the North Pacific Marine Science Organization (PICES) working group 42, on "Indicators of Marine Plastic Pollution" (https://meetings.pices.int/members/working-groups/wg42), this review focuses on plastic pollution ingested by marine organisms in the North Pacific. Specifically, we focus on recommending cost-effective baseline and trend monitoring that can inform future risk-based monitoring.

Indicators are used to improve our ability to monitor the environment, and can be biotic (e.g., individual species or community structure) or abiotic (e.g., water temperature, pH, oxygen concentration). To be most effective, indicator species need to be accessible for sampling and have a moderate exposure and loading of the pollutant of interest. Bioindicators offer logistical advantages because they sample the biotic (e.g., prey) and the abiotic (e.g., water properties) environment for researchers, sometimes in remote locations that are difficult and costly to access. Moreover, specimens are often sampled by population monitoring or conservation programs, which can be leveraged to reduce costs (McDonald-Madden et al., 2010).

The longest-running and most well-known monitoring program for plastic pollution in wildlife using a bioindicator species was established in 2002 under the Oslo and Paris Convention for the protection of the marine environment of the northeast Atlantic (OSPAR). OSPAR identified the northern fulmar (*Fulmarus glacialis*) as a relevant bioindicator for plastic pollution in the North Sea region (OSPAR Commission, 2010). Aside from establishing and promoting standardizing methods of collection, dissection, quantification, and reporting, possibly the most useful output of this program has been defining an Ecological Quality Objective (EcoQO) target level for plastic ingestion. The EcoQO threshold is defined as '*less than 10% of fulmars should have more than 0.1 g plastic particles in the stomach, calculated using 50–100 beach-washed fulmars from each of four to five areas of the North Sea over a period of at least five years*' (OSPAR, 2009). However, it should be noted that this threshold does not correlate to known harm, as is often the case for other pollutants. Nevertheless, the application of the EcoQO threshold in fulmars enables assessments of progress and highlights a goal to strive for. For example, recent work predicts that plastic pollution will decrease and fall below the EcoQO threshold by 2054 (van Franeker et al., 2021).

More recently, the Arctic Monitoring and Assessment Program (AMAP) has developed a litter and microplastics monitoring program that uses multiple environmental compartments in a holistic ecosystem monitoring approach (AMAP, 2021b). As in the North Sea, northern fulmars have been recommended for trend monitoring in the Arctic region. In the Mediterranean Sea, loggerhead sea turtles (*Caretta caretta*) have been proposed as trend and effect indicators for plastic pollution in the region (Matiddi et al., 2017; MSFD, 2013).

In the NP, the Intergovernmental Oceanographic Commission group for the Western Pacific has been conducting training workshops on distribution, source, fate, and impacts of marine microplastics in Asia and the Pacific since 2017 (https://ioc-westpac.org). However, official plastic pollution biomonitoring programs exist only in few regions in the NP (e.g., South Korea). The Ministry of Oceans and Fisheries in the Republic of Korea launched a national coastal monitoring program on microplastic pollution using bivales (*Mytilus edulis* and *Crassostrea gigas*) in 2020 based on a national research and development project (2015–2020) that established microplastic monitoring and assessment protocols and conducted the first nationwide assessment of microplastic pollution (Cho et al., 2021; Ministry of Oceans, 2021). Several additional species have been suggested as indicators of plastic pollution for the NP including the long-nosed lancetfish (*Alepisaurus ferox*) (Portner et al., 2017), and the northern fulmar (Avery-Gomm et al., 2012; Donnelly-Greenan et al., 2014), but no official programs are in place to date for these two species (Fig. 1). While many species have been studied for plastic ingestion over decades in the NP and elsewhere, and monitoring has been proposed, official programs are scarce.

Although there is historical information of plastic ingestion dating back half a century for Laysan and black-footed albatrosses (*Phoebastria immutabilis* and *P. nigripes*, respectively; Fig. 1), these data were not collected or reported in a standardized manner, involving the analysis of mummified chicks, boluses, and stomach contents (e.g., Gray et al., 2012; Kenyon and Kridler, 1969; Young et al., 2009). Only recently (since 2006–2010), have these albatross samples been analyzed using standardized approaches consistent across multiple seabird species (e.g., Nevins et al., 2018; Rapp et al., 2017). Monitoring using sea turtles in this region has also been strongly encouraged (Lynch, 2018), but no official programs have begun. Overall, the data from these seabird and fish species show that the magnitude of this problem in the NP has not improved in recent decades and may have worsened, which is consistent with models and observations in the region (Avery-Gomm et al., 2012; Clukey et al., 2017; Goldstein et al., 2012; Law et al., 2014; Lebreton et al., 2018; Savoca et al., 2021).

To support the development of a coordinated monitoring strategy for plastic debris in the NP, we undertook three main activities. First, we assessed the status and trends of plastic ingestion by NP marine organisms by creating a comprehensive inventory of all studies examining plastic in biota from the region, reviewed plastic ingestion trends in all major taxonomic groups – invertebrates, fish, seabirds, marine mammals and sea turtles – in the PICES region. Next, we developed a rubric to evaluate the potential use of species as bioindicators of plastic pollution levels and trends in the NP. Based on the outcome of the rubric scoring, we propose a suite of indicator species to monitor NP trends in plastic pollution. Finally, we propose a monitoring strategy for the selected bioindicators by identifying monitoring goals, proposing harmonized sampling methods with standardized reporting, and defining ingestion targets (i.e., our EcoQO threshold). Specifically, our findings and recommendations are geared towards research scientists and resource managers such that they can be easily translated to policymakers and extended to other regions worldwide. This will aid the global effort to further coordinate, harmonize, and focus the research efforts on this topic.

2. Methods

2.1. Global comparison of NP to other ocean basins

To compare plastic ingestion in NP biota with other ocean basins, we used data from the comprehensive review by Kühn and van Franeker (2020) for seabirds, sea turtles, marine mammals, fish and invertebrates. This allowed us to compare the NP to seven other large generalized oceanographic regions including the South Pacific, North Atlantic, South Atlantic, Arctic, Indian, and Southern Oceans and the Mediterranean Sea. We compared plastic ingestion metrics in five taxonomic groups (invertebrates, fish, seabirds, marine mammals and sea turtles) across the regions. To explore general trends, the data we present are limited to ocean basins where at least five studies have sampled taxa using standardized methods that met a series of filtering requirements, specific to each taxon.

For invertebrates this included studies that: 1) quantified fibers and controlled for fiber contamination (i.e., used a procedural blank), and 2) had a minimum debris size threshold of <5 mm. Of the invertebrates, only bivalves met the minimum number of studies to allow comparison

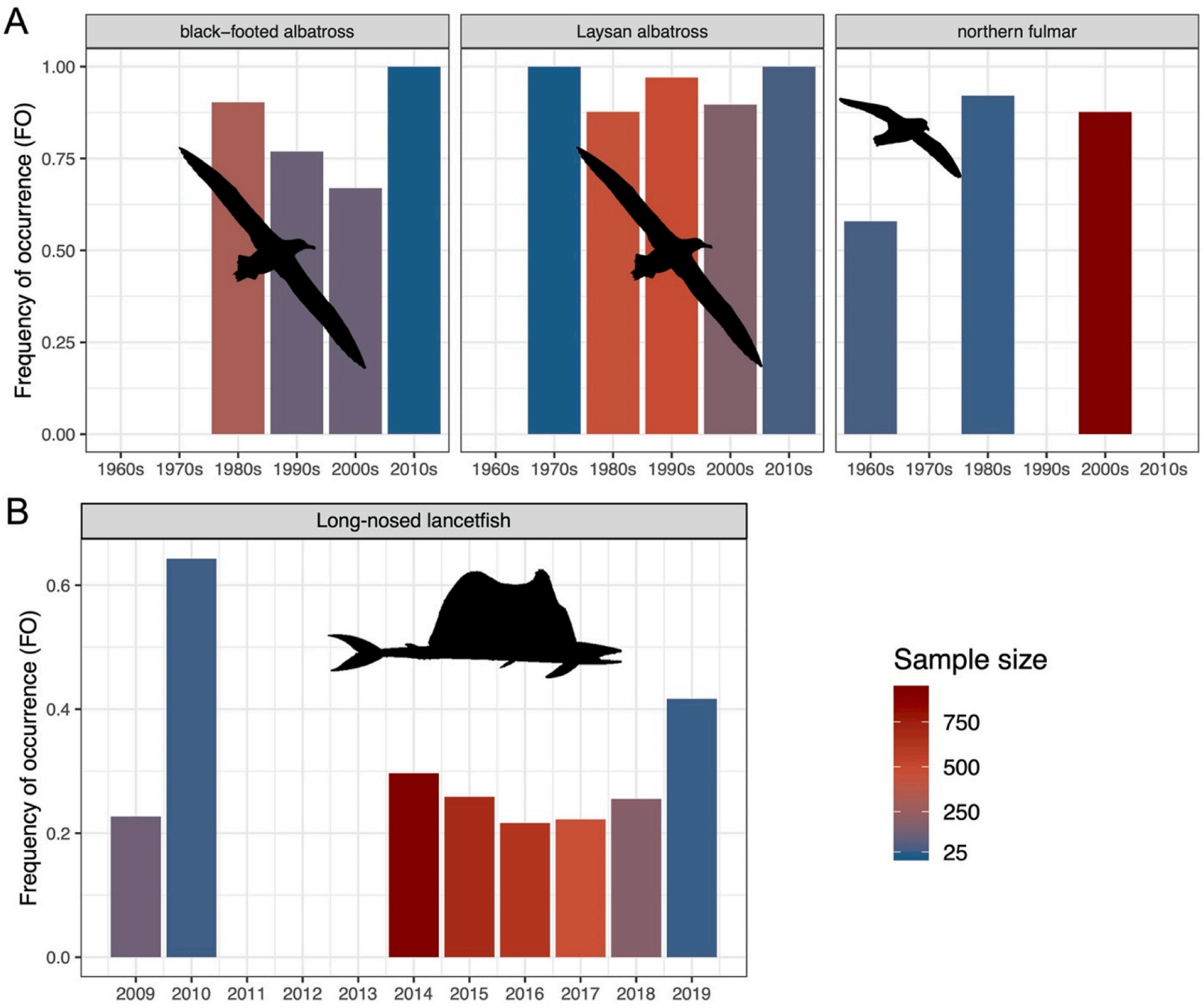

Fig. 1. Historic data on plastic ingestion by NP fauna.

A) Frequency of occurrence of plastic ingestion by decade in three seabirds in the NP; the black-footed albatross (*P. nigripes*), the Laysan albatross (*P. immutabilis*) and the northern fulmar (*F. glacialis*). Seabird data from (Auman et al., 1997; Avery-Gomm et al., 2012; Baltz and Morejohn, 1976; Blight and Burger, 1997; Conant, 1984; Cooper et al., 2004; Day, 1980; Donnelly-Greenan et al., 2014; Gray et al., 2012; Harrison et al., 1983; Kenyon and Kridler, 1969; Kinan and Cousins, 2000; Lavers and Bond, 2016; Nevins et al., 2005; Nilsen et al., 2014; Padula et al., 2020; Petit et al., 1981; Rapp et al., 2017; Robards et al., 1995; Sileo et al., 1990; Tanaka et al., 2019; Terepocki et al., 2017; Young et al., 2009). These data were not collected in a standardized manner.

B) Plastic ingestion by long-nosed lancetfish (*A. ferox*) in the NP from 2009 to 2019 collected and analyzed in a standardized manner. Lancetfish data from (Choy and Drazen, 2013; Portner et al., 2017) and Choy et al. *unpublished.*

across regions. Using these filters yielded three regions with at least five studies: North Pacific and North Atlantic Oceans, and the Mediterranean Sea. For fishes, this included studies that met three criteria: 1) analyzed the complete gastrointestinal tract (GIT), 2) had a minimum debris size threshold of <5 mm, and 3) quantified fibers and controlled for fiber contamination. Applying these filters to the data yielded four regions with large enough sample sizes ($n \geq 5$ studies per region): North Pacific, North Atlantic, and Indian Oceans, and the Mediterranean Sea. For seabirds, this included studies where dissection was the method of sampling, rather than analyzing regurgitations or castings (e.g., boluses and pellets). Applying this filter yielded six regions with large enough sample sizes for comparisons: North Pacific, South Pacific, North Atlantic, South Atlantic, Indian, and Southern Oceans. For marine mammals, no filters were used due to the largely opportunistic nature of these studies and the lack of common sampling methods. As a result, five regions had at least five marine mammal studies: North Pacific, South Pacific, North Atlantic, South Atlantic Oceans, and the Mediterranean Sea. For sea turtles, this included if the complete GIT was analyzed. Applying this filter yielded four regions with a large enough sample size for comparisons: North Pacific, North Atlantic, and South Atlantic Oceans, and the Mediterranean Sea. To assess the extent of plastic in the taxonomic groups of interest we used two metrics: 1) frequency of occurrence (% FO), defined as the number of individuals with ingested plastic debris divided by the total number of sampled specimens, and 2) the average number of plastic items ingested per individual across studies, including specimens with plastic present and absent (zero plastic pieces ingested), weighted by the sample size of each study.

2.2. *A regional review of plastic ingestion data in the NP*

To understand plastic ingestion patterns specific to the NP, we reviewed the data for the PICES region encompassing the temperate latitudes of the NP. According to the PICES Convention (https://meetings.pices.int/about/convention) Article II, the PICES region is:

> *"the temperate and sub-Arctic region [i.e., Bering Sea] of the North Pacific Ocean and its adjacent seas, especially northward from 30° North Latitude … Activities of the Organization, for scientific reasons, may extend farther southward in the North Pacific Ocean"*.

For our purposes, we considered Hawai'i in the PICES region, particularly because plastic bioindicators (especially vertebrates) sampled in Hawai'i regularly forage in the PICES region. All papers in the comprehensive Kühn and van Franeker (2020) review of marine mammals, seabirds, sea turtles fish and invertebrates, as well as Lynch (2018) review of sea turtles, Savoca et al. (2021) for fish, and Li et al. (2019) for bivalves were included. A literature search was performed on Google Scholar using relevant search terms ('plastic' and 'ingestion' and 'North Pacific') to discover a small number of additional or more recent peer-reviewed studies and agency reports published from 1960 through the end of 2020. As this search method may bias results toward marine megafauna, we conducted additional searches using terms 'microplastic', 'ingestion', 'monitoring', 'fish', 'invertebrate', 'bivalve' and 'North Pacific' in an effort to uncover as many studies as possible. We chose 1960 as the start date because the first scientific observation of plastic ingestion by wildlife was reported in the late 1960s (Kenyon and Kridler, 1969). We retained publications that reported original plastic ingestion data (at minimum, plastic frequency of occurrence [FO] for each species sampled) and any referenced publications. Through these methods, we found 130 studies published from 1969 to 2020 for the NP region.

2.3. *Review of methods and QAQC approaches used by studies in the NP*

Within the NP ingestion data, we were interested in methods used to detect, chemically characterize, and quantify plastic ingestion by biota. To enable this, we recorded the methodologies used to isolate, quantify, and confirm plastic ingestion, to track how methods varied over time, between taxa (or both), and how different methods might affect the final data and could standardize summary data between studies. All criteria were simplified from the original data to binomial yes or no entries to enable visualization of trends (Savoca et al., 2021).

2.4. *Methodological details we recorded for each study included*

Chemical digestion was used in sample processing
Fibers and fiber controls (i.e., procedural blanks) were included in the analysis
Complete GITs were analyzed
The minimum size-detection threshold was reported
Polymer confirmation was conducted and by what method (e.g., FT-IR or Raman spectroscopy).

2.5. *Development and implementation of bioindicator rubric*

To evaluate each species' potential to serve as a bioindicator of plastic pollution in NP biota as objectively as possible, we used a combined flowchart and rubric approach to score each species to identify those best suited to monitor plastic ingestion trends. Our bioindicator rubric was adapted from Bray et al. (2019) and is closely aligned with GESAMP's criteria for selection of indicator species (GESAMP, 2019). First, we determined if the species is "accessible", as predictable availability is essential to a long-term monitoring program. We defined "accessible" as species that can be obtained in sufficient numbers to monitor trends. What constitutes "sufficient numbers" varies by taxa and was judged by authors that were taxa experts. For example, while 30 to 40 birds collected each year to monitor trends in a certain region would be sufficient for most seabird species (Provencher et al., 2015; van Franeker et al., 2021), larger sample sizes (50 individuals per location) are needed for fish, but this needs to be considered in the context of the research questions to be addressed. Marine mammals are not suggested as bioindicators of plastic ingestion due to the inability to obtain large sample sizes (>10 individuals of the same species) across multiple regions. We considered species to be accessible if they are commercially available, common bycatch species, regularly wash up on shores, annually hunted or harvested, or are common enough to be obtained with research permits. Next, we evaluated if the species had a large enough prior sample size for plastic studies (>10) and if plastic ingestion had been documented ($FO > 0$); if not then no further rubric evaluation was conducted for that species, if so then we completed the remainder rubric evaluation (Fig. 2, Table 1). The full rubric scored each species on seven categories, with a maximum of four points possible per category. The total score was out of 28 points with higher scores representing better indicator potential.

3. Results

Our review found that the NP contains biota that are among the most polluted globally, as measured by either plastic FO, or the number of items ingested per individual (Figs. 3 and 4, Table S1, Supplementary Dataset). However, there is a large spread in the data, both within and across species (Table S1), indicating substantial heterogeneity in plastic ingestion within the region. This high variability is expected when considering an area as large as the NP. In addition to having species with some of the highest levels of plastic ingestion globally (Li et al., 2015; Lynch, 2018; Rapp et al., 2017; Robards et al., 1995), the NP has higher average values than most regions. When considering plastic FO, the NP has either the highest or second-highest incidence of plastic ingestion for all five taxonomic groups considered (Fig. 3). Overall, 66% fish, 64% seabird, 100% sea turtle, and 100% bivalve species sampled in the NP contained plastic debris. In most cases, the number of plastic items recovered from organisms was low (<2 items per individual); however, numerous studies of sea turtles, marine mammals, and seabirds report

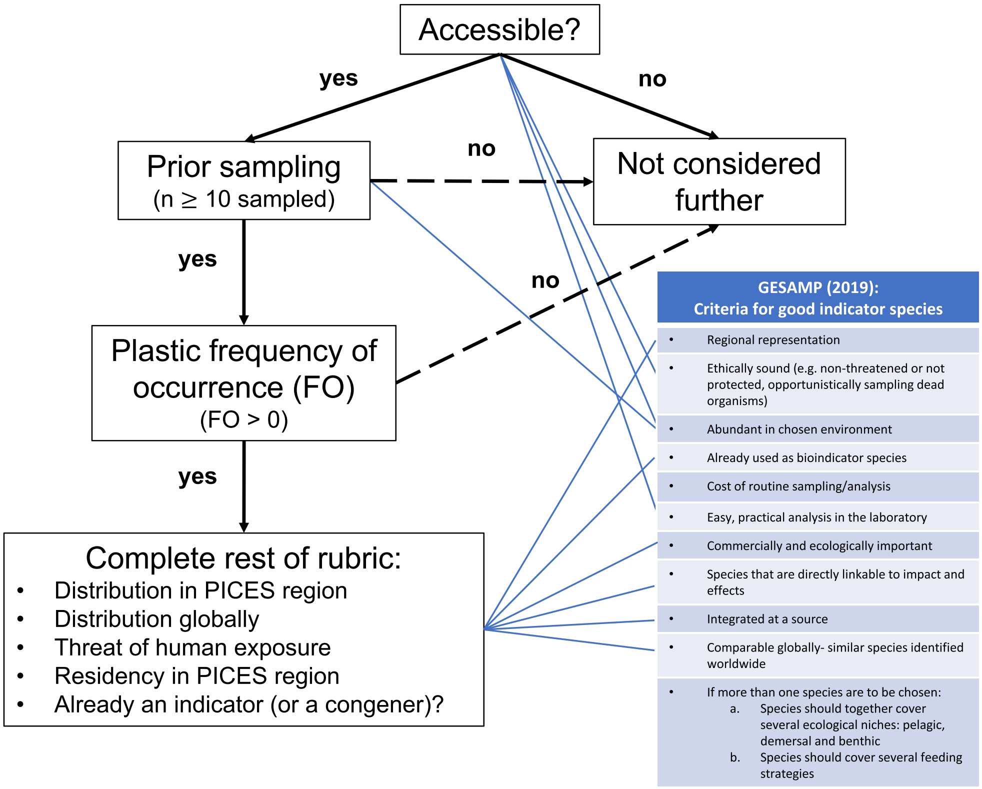

Fig. 2. Flowchart of the rubric evaluation process. This schematic depicts how species were evaluated through the rubric created for this study. The blue box connected to our rubic with lines demonstrates the close parallels between our rubric and one proposed by GESAMP 2019. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

higher abundances of ingested plastic items (>10 items per individual).

We attempted to look for trends in plastic ingestion over time in the NP, but there are not enough data to do so (Table 2, Figs. 1 and 5). For example, data for fishes were well represented across one decade with a significant increasing slope from 2010 to 2020 ($y = 0.045\times - 90.13$; F-$\text{value}_{1,220} = 6.12$; $p < 0.0001$; Fig. 5). However, this finding cannot be taken at face value, because the data across time were not collected in a standardized way. Through time, the studies looked for smaller and smaller plastic particles ($y = -0.053x + 106.79$; F-$\text{value}_{1,23} = -3.92$; $p < 0.001$; Fig. 5), increasing the chances of finding plastic ingestion in later dates. Furthermore, in the past five years, studies on plastic ingestion by marine biota from the western NP have outpaced those from the central and eastern NP (Savoca et al., 2021). These temporal and spatial biases in research across the basin further impede our ability to definitively identify temporal trends throughout the NP.

Reporting of methodological details has become more common through time by studies in the NP. In 2010, no studies reporting plastic ingestion in biota in the NP stated whether they chemically digested biotic material in their samples, analyzed their samples for fibers, or chemically confirmed polymer identification on putative plastic particles they isolated (e.g., via FTIR or Raman spectroscopy). By the end of the decade, reporting of these metrics was nearly universal. We find 2017 to be a shift point in methodological reporting; quality assurance metrics were reported and adhered to in the majority of studies published since 2017, but not prior (Fig. 6).

We considered 352 NP species using our bioindicator rubric, excluding marine mammals due to the logistical difficulties of consistently obtaining numerous samples annually of a single species in multiple locations (i.e., they are not “accessible”). Most species in our assessment were fish (n = 216) or seabirds (n = 80), with considerably fewer invertebrate species (n = 51). All five sea turtle species occurring in the NP had been studied for plastic ingestion and were assessed.

Table 1
Rubric for species evaluation as bioindicators. Note that if species had less than 10 individuals sampled or had no records of plastic ingestion in the NP they were not considered further.

Category	Score	Description
Prior sampling conducted in the PICES Region	1	0 to 10 individuals sampled (not considered further)
	2	11 to 50 individuals sampled
	3	51 to 100 individuals sampled
	4	>100 individuals sampled
Plastic frequency of occurrence in the PICES region	1	0 (not further considered)
	2	0.01 to 0.24
	3	0.25 to 0.49
	4	≥0.5
Species distribution in PICES region	1	<24% coverage
	2	25–49% coverage
	3	50–74% coverage
	4	≥75% coverage
Species distribution globally	1	found only in PICES region, and no similar species found elsewhere
	2	only found in North Pacific, and few similar species found elsewhere
	3	only found in North Pacific, but many similar species found elsewhere
	4	globally distributed/cosmopolitan
Threat of human exposure	1	not eaten
	2	minor food source
	3	regularly consumed in parts (e.g. fish filets)
	4	regularly consumed whole (e.g. bivalves)
Residency in the PICES region	2	non-resident (migrant)
	4	resident
Is it (or a congener) an indicator (in PICES region or elsewhere)?	2	No
	4	Yes

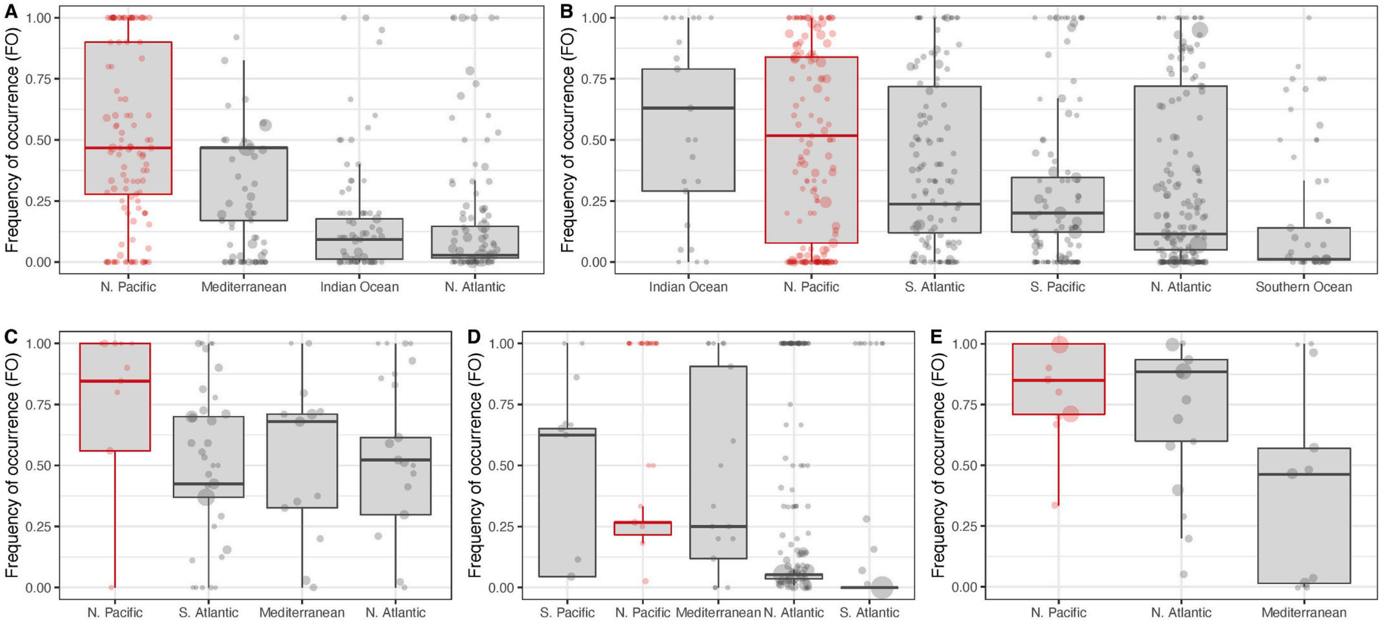

Fig. 3. Frequency of occurrence of plastic ingestion across taxa. Plastic ingestion by taxa between regions that had at least five studies of that taxonomic group in the region. A) fishes B) seabirds C) sea turtles D) marine mammals E) bivalves. Boxplots are ordered, from left to right, from highest to lowest regional median concentration. Each point represents a species within a study; the relative sizes of the points denote differences in sample sizes. The NP is highlighted with red-outlined boxplots, all other regions are in gray. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

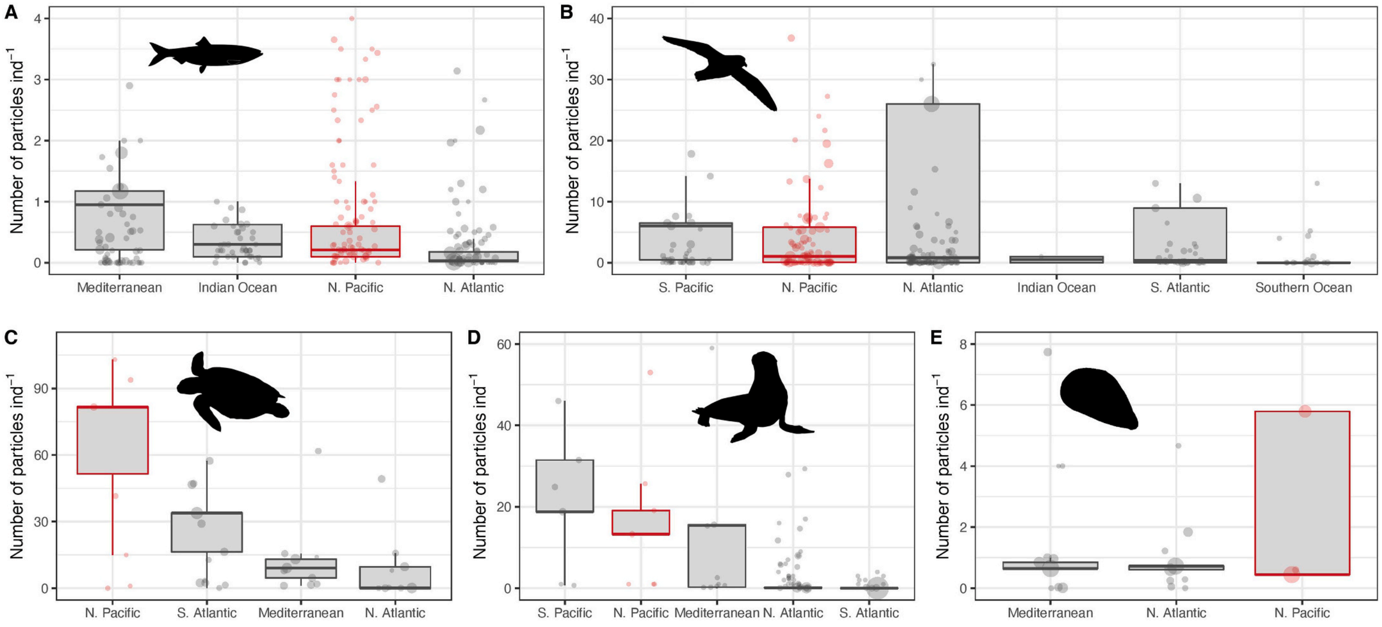

Fig. 4. Average number of plastic items per individual across taxa. Plastic ingestion by taxa between regions that had at least five studies of that taxonomic group in the region. A) fishes B) seabirds C) sea turtles D) marine mammals E) bivalves. Boxplots are ordered, from left to right, from highest to lowest regional median concentration. Each point represents a species within a study; the relative sizes of the points denote differences in sample sizes. The NP is highlighted with red-outlined boxplots, all other regions are in gray. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Species that were understudied in the NP (i.e., <10 individuals sampled), or showed no evidence of plastic ingestion (i.e., FO = 0) were not evaluated fully (Fig. 2). For the 178 species in NP marine ecosystems that were fully evaluated (87 fishes, 48 seabirds, 38 invertebrates, and five sea turtles), bioindicator scores ranged from 11/28 points (39% suitability) to 28/28 points (100%) (Fig. 7, Supplementary Data). The following species scored highest for each taxonomic group (Fig. 8): loggerhead sea turtle (25/28 points), northern fulmar (24/28 points), long-nosed lancetfish (24/28 points), and blue mussel (*Mytilus edulis*; 28/28 points).

4. Discussion

We found that plastic ingestion in biota from the NP is highly heterogeneous, with substantial variability within and across species, but that the region contains species that are among the most polluted

Table 2
Overview of data used in this paper to address global and regional comparisons.

SB = seabirds, F = fishes, I = invertebrates, MM = marine mammals, ST = sea turtles.

Analysis	Temporal (Spatial) Scope	# Species evaluated	Taxonomic groups considered	Metrics
Global comparison of plastic ingestion data	1969 to 2020 (Global)	1090	SB, F, I, MM, ST	frequency of occurrence, mean number of ingested items per individual
Bioindicator evaluation	1969 to 2020 (PICES region)	352	SB, F, I, ST	accessibility of samples, frequency of occurrence
Full bioindicator assessment	1969 to 2021 (PICES region)	178	SB, F, I, ST	bioindicator score
Quality assurance metrics	2010 to 2020 (PICES region)	289	SB, F, I, MM, ST	chemically digested, complete GIT analyzed, fibers analyzed, minimum size threshold, polymer confirmation
Trends	2010 to 2020 (PICES region)	193	F	frequency of occurrence, minimum size threshold

globally. Overall, sea turtles and bivalves are most likely to ingest debris with 80% plastic frequency of occurrence (FO) rates within the NP. Across the sampled individuals, the plastic ingestion on average varied from less than two items per individual ingested by invertebrates and fishes, to greater than ten items per individual reported in seabirds and sea turtles. While plastic ingestion by biota is on the rise globally (Savoca et al., 2021; Wilcox et al., 2015), there were not enough standardized data to draw temporal conclusions from the NP specifically. Importantly, even for some of the most commonly studied species in the region, the most recent data are from the early 2010s (e.g. northern fulmar, albatrosses) limiting analysis of long-term temporal trends.

As calls for methodological standardization and transparency have increased (Cowger et al., 2020; Provencher et al., 2020), so too have the reporting of these methods in the NP. We found that a variety of quality assurance metrics that were rarely discussed or undertaken as recently as a decade ago are now commonly reported and adhered to. These widespread improvements occurred swiftly and recently, between 2015 and 2020. Continuing standardization, harmonization, and clear reporting of field and laboratory methods are essential to draw robust conclusions spanning data across studies, species, and regions within and beyond the NP.

Our rubric evaluation showed a suite of species with the potential to serve as bioindicators of synthetic debris in the NP. Several of these species, such as the loggerhead turtle, northern fulmar and blue mussel, have been previously suggested as bioindicators in the NP and elsewhere (Avery-Gomm et al., 2012; Fossi et al., 2018; Li et al., 2019; van Franeker et al., 2011). Bivalves are commonly suggested as bioindicators for marine microplastics. The blue mussel and related species have been proposed as a global indicator of microplastic concentration in the water they filter (Beyer et al., 2017; Li et al., 2019). Whether or not bivalves, specifically blue mussels – or *Mytilus* species more generally – are useful bioindicators of microplastic and microfiber pollution is an active area of research (Bråte et al., 2018; Qu et al., 2018; Ward et al., 2019). Identifying baselines is a further concern of monitoring programs, such that progress towards goals can be assessed. Northern fulmar, Laysan, black-footed albatross, and long-nosed lancetfish were all highlighted by our rubric as potential bioindicators and have decades of historical, yet mostly non-standardized, plastic ingestion data from the NP to generate baseline estimates of pollution (Fig. 1).

It is important for monitoring programs to consider what aspects can be harmonized, and which aspects must be standardized to produce comparable results. For example, the collection of seabird carcasses can be harmonized using different techniques, as applicable to a region. While beached northern fulmars have been collected via shoreline surveys in most places in Europe and western North America (e.g., Coastal Observation and Seabird Survey Team; www.coasst.org), harvested

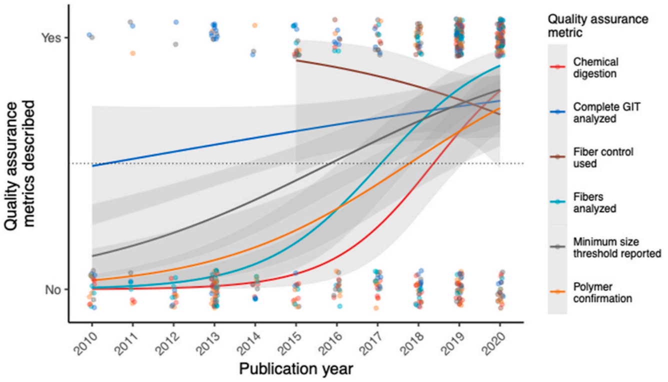

Fig. 6. Methodological reporting trends over time in the NP. Binomial plot illustrating the probability of a study reporting each of the four quality assurance metrics over time. Data presented includes all studies from all taxa in the North Pacific from 2010 to 2020. Each point represents a quality assurance metric within a study. Points were jittered (random noise added) to prevent overlap and facilitate visualization. The horizontal dotted line represents a 50% probability indicating that 2018 was the first year when the probability that each given study reported the quality assurance metrics exceeded 50%.

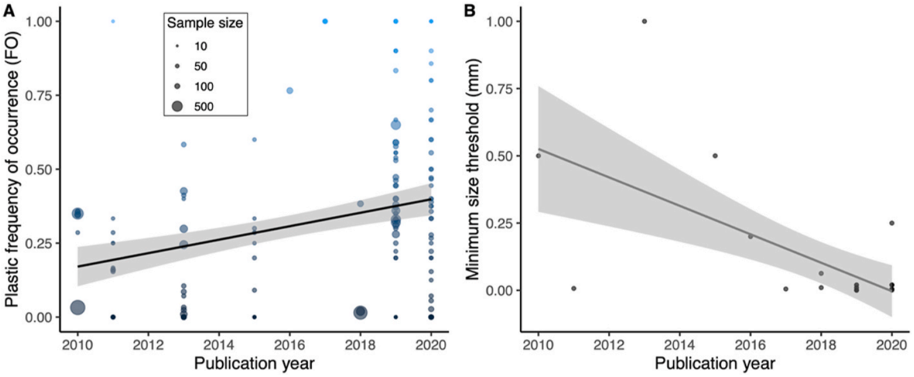

Fig. 5. Temporal trends of plastic ingestion by fishes in the NP are confounded by method and spatial biases. A) The black line shows an increasing plastic FO across all fishes sampled in the NP from 2010 to 2020. Each point represents the plastic FO of a species within a study; the size of the points indicate the sample sizes, and the color represents plastic FO. The regression accounts for varying samples sizes of each species within each study. B) The gray line indicates a trend for studies' reporting increasingly smaller minimum particle detection limits from 2010 to 2020. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

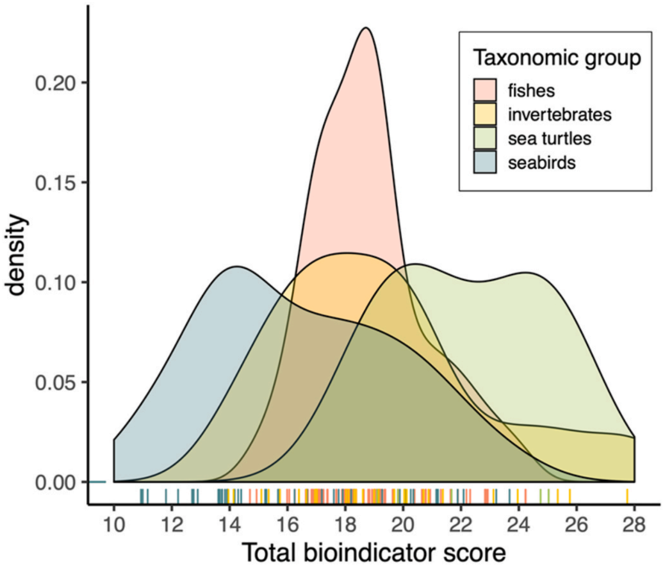

Fig. 7. Distribution of bioindicator scores by taxa. Scores of all species fully evaluated (n = 175) with our bioindicator rubric, with higher scores signifying greater bioindicator potential. The marks beneath the density plots represent the raw scores for each species within each taxonomic group.

fulmars are used for plastic ingestion studies in northern Canada, and fulmars incidentally caught in fisheries are used in both the North Atlantic and the NP. Applying harmonized collections and standardized reporting within the NP is critical not only to comparisons across the NP, a region that covers 20% of the global ocean, but also to ensure that data from the NP is comparable to other global regions.

4.1. Proposed monitoring guidelines

4.1.1. Invertebrates

While zooplankton species were evaluated with our rubric, only bivalves scored high enough to be considered as bioindicators for our purposes. Commonly studied bivalves in the NP include mussels, clams, oysters, scallops, and cockles. The bivalves can be categorized into epifaunal, which live on top of the substratum, and infaunal, those that live within the substratum. We recommend two invertebrate species as bioindicators for microplastics with mussels (e.g. *Mytilus* spp.) representing the epifaunal indicator and clams representing the infaunal indicator (e.g. *Venerupis philippinarum*). Oysters (*Crassostrea* spp.) can serve as another epifaunal indicator. It is important to note that bivalves can be selective feeders. For example, *M. edulis* can selectively ingest spheres and fibers of different size ranges (Ward et al., 2019). This potential for selectivity should be taken into consideration when using bivalves as indicators, and when interpreting the data from such studies.

Recommended frequency of collection is once every three months or bi-annually with a sample size of at least 20 individuals each time, (>30 individuals would be desirable in areas with high variability). As many invertebrates (including mussels and clams) ingest mainly plastic particles less than 1 mm, particular attention should be paid to preventing contamination during sample treatment (e.g. processing samples in a laminar flow hood). Creating composite samples of several individuals (e.g., three or five) into one sample for analysis can be a way to overcome low detection limitations and background contamination during sample processing. For the assessment of the environmental status of microplastic contamination, the specimens should be collected live from a local area and should not have gone through any depuration. If samples cannot be processed immediately, they should be frozen right away. Several techniques can be used to isolate microplastics from shellfish (Dimitrijevic et al., 2019; Ding et al., 2020). Although the need for sample processing standardization has been demonstrated (Provencher et al., 2020), currently no standardized procedures for bivalves at regional and global levels exist. But, at the national level, some countries established protocols for the assessment of microplastic pollution using marine bivalves. The Republic of Korea established the microplastic monitoring and assessment protocols using bivalves (KIOST, 2020), and is applying it to the national microplastic monitoring program. China is developing its national bivalve monitoring program with nation wide bivalve microplastic research data dating back to 2015 (Li et al., 2015). A Canadian technical report (Dimitrijevic et al., 2019) outlines recommended procedures for bivalves and other organisms. So far, there is still a need to establish international standardized methods for monitoring microplastics in bivalves.

Microplastic abundances in bivalves vary greatly by region. If the goal of the monitoring program is to maintain or reduce currently observed microplastic ingestion levels, a starting threshold could be to not exceed the current level of plastic ingestion in of the region of study. If studies in the area indicate a positive correlation between microplastic abundance in the water and within bivalves then bivalve microplastic abundance may be used as a proxy for environmental levels (i.e. in the water). Target thresholds should be tailored to meet the objectives of each monitoring program.

4.2. Fishes

Our rubric assessment highlighted several fish species that can serve as plastic ingestion bioindicators. Common dolphinfish (*Coryphaena hippurus*) scored high despite low levels of plastic ingestion (FO = 0.04 of 50 individuals in the NP, Table 3). However, because they are commercially fished, sampling programs could work with fisheries to monitor the epipelagic regions of the central NP known to be high in plastic debris. The digestive tracts offer no financial value to fisheries, so each animal could be used for two purposes, muscle for human consumption and GIT for monitoring research. Dolphinfish monitoring programs would likely focus on mesoplastics and not microplastics and fibers. Complementary to dolphinfish, anchovy (*Engraulis* spp.) would be good candidates to monitor nearshore epipelagic food webs because they are commercially fished, often consumed whole (and therefore of interest to human consumption questions), and are a key prey item for many predatory species in the exceptionally productive eastern and western boundary ecosystems of the NP (Glaser, 2010; Szoboszlai et al., 2015; Tanaka and Takada, 2016). In addition, anchovy can be used to monitor a smaller size class of plastics (i.e., microplastics and fibers) compared to other fish species identified by our rubric (Chavarry et al., 2022).

Our top fish species to continue monitoring for plastic debris is the long-nosed lancetfish. Lancetfish are globally distributed, are regularly caught as bycatch and would otherwise be discarded, and have already been suggested as bioindicators of plastic debris in mesopelagic food webs in the eastern North Atlantic (Gago et al., 2020). Within the NP, a monitoring program has been initiated (see Fig. 1B) and we strongly encourage the continuation of that program (Choy et al. *in prep*), particularly to monitor larger size classes (>5 mm) of plastic debris ingestion in deeper, mesopelagic habitats of the NP. Microfibers are also not considered in this lancetfish monitoring program.

Longline fishery observers from the National Oceanic and Atmospheric Administration's (NOAA) Pacific Islands Regional Office regularly sample lancetfish stomachs (only the stomachs are examined) from the Hawai'i-based US longline fishery. Observers are provided with sampling materials (bags, labels) and are asked to dissect lancetfish stomachs from a set number of fish caught in specific longline sets (up to two fish per longline set). Sample sizes are variable depending on access but generally, monthly collections occur and average approximately 20–25 stomachs per fishing trip. Observers measure fish length and denote sampling information related to time and a very general location (non-confidential locations that represent 5° × 5° cells). Specific fishing locations can only be released in accordance with NOAA's

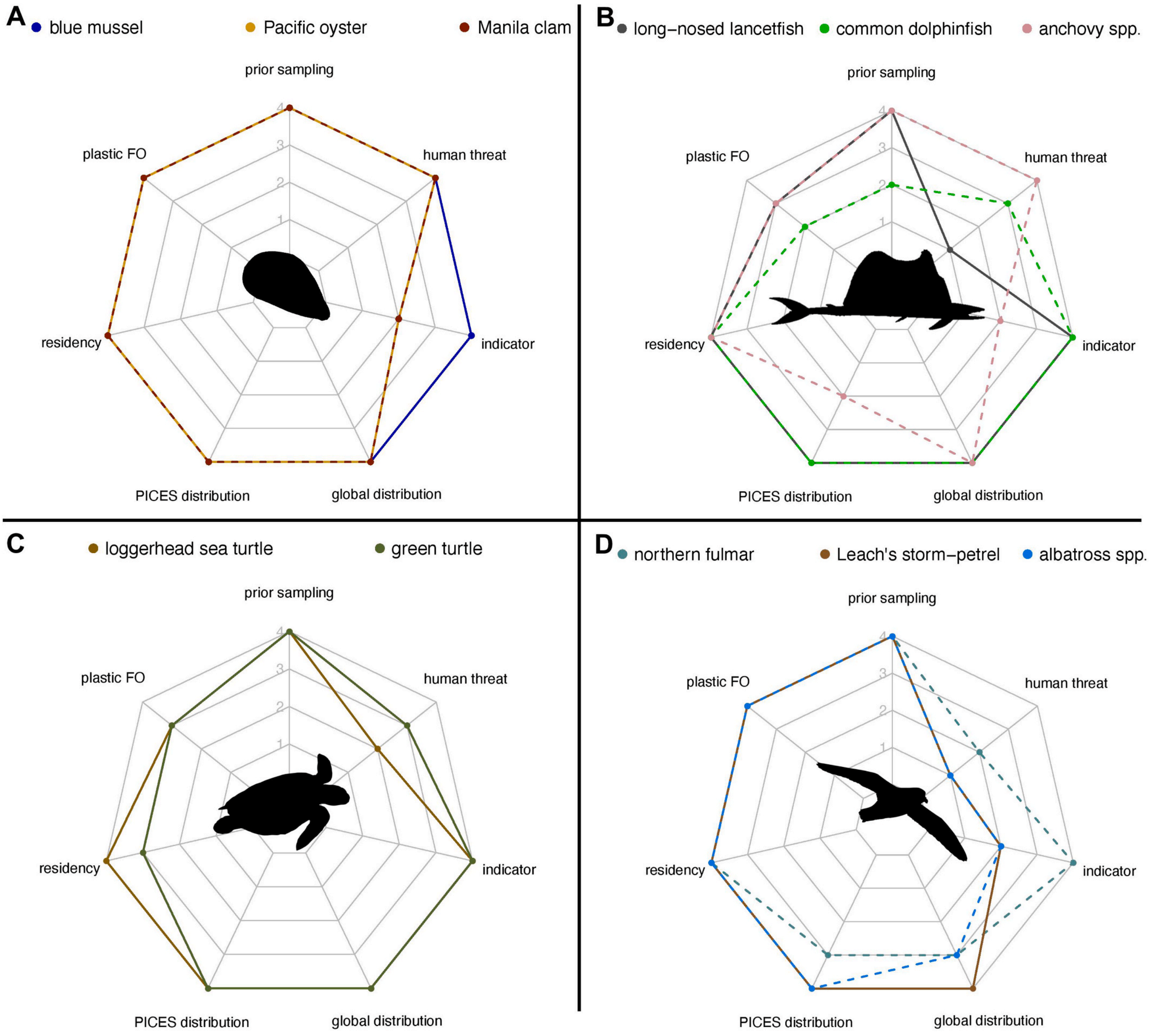

Fig. 8. Bioindicator rubric for top-scoring species by taxa. The top 12 scoring species by taxa, with the top selection as a bioindicator for each taxa as a silhouette in the center of each plot. A) invertebrates, blue mussel (*M. edulis*), Pacific oyster (*C. gigas*) and Manila clam (*V. phillipinarum*) (note overlapping lines, indicating identical scores, for *C. gigas* and *V. phillipinarum*). B) fishes, long-nosed lancetfish (*A. ferox*), common dolphinfish (*C. hippurus*), and anchovy (*Engraulis* spp.). C) sea turtles, loggerhead sea turtle (*C. caretta*) and green sea turtle (*C. mydas*). D) seabirds, northern fulmar (*F. glacialis*), Leach's storm-petrel (*O. leucorhoa*), and Laysan and black-footed albatross (*Phoebastria* spp.). Some species, such as northern fulmar, have already been proposed as bioindicators of plastic ingestion in the NP and elsewhere, while other species such as common dolphinfish, have not. The blue mussel is the only species that received a score of 28 points (100%). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

confidentiality restrictions to protect data. In the lab, stomachs are defrosted and analyzed visually for diet contents, and plastic items are hand picked, categorized, counted, weighed, lengthed and saved for later analysis, as described in (Choy and Drazen, 2013; Choy et al., 2013; Portner et al., 2017). As the Hawai'i-based longline fleet operates over large areas of the central NP Ocean (see sampling maps in above references), these monitoring efforts have the potential to capture plastic ingestion over sufficiently large time and space scales that are otherwise very challenging.

These top scoring species cover meso- and epipelagic realms in tropical and temperate regions of the NP. Numerous species and regions within the NP are understudied including species in the Gulf of Alaska, Bering Sea, and Sea of Okhotsk. In addition, abyssal and benthic food webs are not covered by any of our highlighted species. These understudied fish species are in need of improved coverage as are high latitude regions in the NP, which are home to some of the most productive marine ecosystems on Earth as well as abundant commercial fisheries.

4.3. *Sea turtles*

Sea turtles generally scored high on the bioindicator rubric, with green and loggerhead sea turtles tied as the leaders (25/28 points). These two species' high scores are due to their broad tropical to temperate foraging distributions globally and across the PICES region, their residency in the PICES region, their prior use as bioindicators (Fossi et al., 2018; Keller, 2013), and their high FO of plastic ingestion in

Table 3
Details on top scoring bioindicator species.

Taxa (total number of species assessed)	Scientific name	Common name	Habitat	Prior sample size[a]	Plastic FO[a]	Median number of particles per individual [a]	Distribution	Threat of human exposure	Already an indicator?[α]	Total rubric score
invertebrates (51)	*Mytilus edulis*[b]	blue mussel	benthic-neritic	632	0.98	2.5	global	consumed whole	Yes	**28**
	Crassostrea gigas[b]	Pacific oyster	benthic-neritic	804	0.64	2.6	global	consumed whole	No	**26**
	Venerupis philippinarum[b]	Manila clam	benthic-neritic	503	0.95	2.1	global	consumed whole	No	**26**
fish (216)	*Alepisaurus ferox*	long-nosed lancetfish	mesopelagic	1563	0.30	1.0	global	not typically consumed	Yes	**24**
	Coryphaena hippurus	common dolphinfish	epipelagic	50	0.04	1.0	global	consumed in parts	No	**23**
	Engraulis spp.[c] [b]	anchovy species[c]	epipelagic-neritic	354	0.41	0.6	global	consumed whole	No	**23**
sea turtles (5)	*Caretta caretta*	loggerhead sea turtle	Epipelagic to benthic-neritic	168	0.25	17.1	global	not typically consumed	Yes	**25**
	Chelonia mydas	green turtle	Epipelagic to benthic-neritic	148	0.41	11.6	global	not typically consumed	Yes	**25**
seabirds (80)	*Fulmarus glacialis*	northern fulmar	epipelagic	850	0.81	7.4	Northern Hemisphere only	not typically consumed	Yes	**24**
	Oceanodroma leucorhoa	Leach's storm petrel	epipelagic	376	0.14	3.0	Northern Hemisphere only	not typically consumed	No	**23**
	Phoebastria immutabilis	Laysan albatross	epipelagic	1092	0.82	14.9	North Pacific only	not typically consumed	Yes	**22**
	Phoebastria nigripes	black-footed albatross	epipelagic	423	0.72	5.3	North Pacific only	not typically consumed	Yes	**22**

αIndicator here specifically refers to a formal indicator program at the regional, national or international level.

[a] In the PICES region; FO = frequency of occurrence of ingested plastic.

[b] Studied for microplastics and fibers.

[c] *Engraulis japonicus* and *E. mordax* combined.

the PICES region (0.25–0.41 overall). An additional advantage not captured in the rubric is their long gut residence time. Ingesta is held in the GIT of sea turtles for two to three weeks (González-Paredes et al., 2021), offering a sampling of plastics over a longer time than other organisms with gut residence time of minutes to hours. If only one species must be named, we recommend the green turtle in the NP. Green turtles occur across the tropical and subtropical NP including more coastal areas and marginal seas than loggerhead turtles. Green turtles have many distinct population segments in the Pacific Ocean that could offer more spatial resolution than the single population of NP loggerheads (Wallace et al., 2010). Green turtles can be sampled as pelagic fisheries bycatch and are more abundant as stranded specimens in California, Hawai'i, and Asia than loggerheads, and they eat the most plastic among all turtles in the pelagic realm (Clukey et al., 2017; Lynch, 2018; Moon et al., 2022). Moreover, long-term monitoring of plastic ingestion by sea turtles in Japan and South Korea has also begun (Fukuoka et al., 2016; Moon et al., 2022).

Sea turtle samples can be collected year-round from stranding or fisheries bycatch monitoring programs, but both sampling strategies are biased and may produce drastically different results. Stranded turtles typically represent a nearshore older life stage than fisheries bycatch. For example, in Hawai'i, the pelagic longline fishery captures younger juvenile, pelagic-phase, epipelagic omnivorous green turtles, while stranded green turtles are older juveniles to adults that have already switched to a benthic herbivorous diet. This ontogenetic shift in diet results in drastic differences in plastic ingestion, in which younger pelagic turtles eat much greater quantities than older neritic turtles (Lynch, 2018; Nelms et al., 2016; Schuyler et al., 2016). Bycatch is biased towards healthy, foraging turtles, whereas strandings include a combination of turtles bycaught in fisheries and injured or ill turtles that may have reduced foraging before death. In other words, these two sources of specimens bias the plastic ingestion quantities in opposite directions: strandings overestimate and bycatch underestimates. Thus, we recommend a target of at least 20 individuals per species per sampling method per year, if possible.

Sea turtles that are bycatch in the Hawaiian longline fishery offer an existing, long-term program through a collaboration of NOAA Longline Observer Program, NOAA Pacific Islands Fisheries Science Center, U.S. Geological Survey and the National Institute of Standards and Technology Biorepository project called BEMAST (Clukey et al., 2017; Keller et al., 2014). We highly recommend the continuation of this project that began annual standardized collections for plastic ingestion and paired internal tissues in 2012.

Necropsies should include thorough external and internal examinations for incidental or associated pathology from plastic ingestion and body size measurements including body mass and straight carapace length. Laboratory methods should examine the entire GIT for particles at least >1 mm in size, document the location in the GIT the plastic was found, categorize plastic type, size, polymer identity, photograph, and count and weigh all plastic pieces. We strongly recommend that studies always include non-detects (turtles that did not ingest plastic) and present quantities in multiple units of at least plastic pieces per turtle, but ideally plastic mass per turtle and plastic mass per kg of turtle to allow readily standardized comparison (Lynch, 2018). Quantifying plastic particles < 1 mm is not required for monitoring plastic ingestion in sea turtles, but can be incorporated into the laboratory methods when the liquid ingesta can be captured and processed in a clean air environment. These methods have been described in detail elsewhere (Clukey et al., 2017; Jung et al., 2018; Lynch, 2018).

Target reduction goals are set by policymakers ideally based on sound, replicated scientific data that prevents further harm to the environment and appeals to society. Sound environmental risk assessments require an understanding of both the exposure (e.g. quantities or concentrations of a hazard in the environment often from a monitoring program) and the dose-response relationship between the hazard concentration and adverse effects. For perceived urgent and precautionary reasons, OSPAR created a target reduction goal for northern fulmars that is based mostly on arbitrary numbers, rather than evidence of harm. No reduction goal has been presented for sea turtles. In order to create one, ideally science would inform the policymakers how much plastic can a turtle ingest before it injures or kills it (no-effect concentrations). However, this quantitative dose-response threshold is unknown (Senko et al., 2020). Wilcox et al. (2018) reported a 50% probability of mortality caused by ingesting only 14 pieces of plastic in coastal, stranded, necropsied sea turtles (green turtles accounting for 65% and loggerhead turtles 12% of 246 total individuals sampled) in Australia, although these reults are debated because it did not indicate the plastic debris sizes or shapes, nor pathological evidence of a causal effect. The quantities of plastic ingested by offshore pelagic-stage green turtles in the NP (average of 94 pieces/turtle; Clukey et al., 2017) exceed the proposed LD50 threshold by 6.7-fold (Wilcox et al., 2018). These NP green turtles, bycatch in longline fisheries, ingest this large quantity (in other preferred units, 1.74 g of plastic per kilogram of turtle mass) without signs of GIT pathology or dietary dilution (Clukey et al., 2017). Furthermore, the population of green turtles in the Northwestern Hawaiian Islands has been increasing since 1978 (Balazs and Chaloupka, 2004), despite the large plastic ingestion in young stages of this species and the increase in plastic production and disposal at sea during this time. Regardless of the constraint in quantifying threshold levels, it is undeniable that ingestion of a single plastic item and entanglement by large plastic debris, such as ghost fishing gear, can kill sea turtles (Chaloupka et al., 2008). Given the uncertainty in the lethality threshold for sea turtles globally, policymakers today, if needing to set a reduction target for sea turtle plastic ingestion for proactive measures in a timely manner, would have to resort to precedent arbitrary values and/or science that is limited to one coastal region. An approach is detailed in the Supporting Information document that uses a combination of OSPAR's precedent and Wilcox et al. (2018) controversial yet conservative threshold. Precautionary quantitative target goals are calculated and provided in the Supplementary Information for two life stages of loggerhead and green sea turtles in units recommended by Lynch (2018). Alternatively, quantitative reduction goals that lump all plastic types, shapes and sizes together (as suggested here) may be less effective in preventing harm to sea turtles than targeted preventative strategies for specific, more lethal plastic types like thin films and fishing gear (Roman et al. 2020). Both strategies should be considered and compared.

4.4. Seabirds

While 80 NP seabird species have been documented ingesting plastic, our rubric highlighted four species with high bioindicator potential (Fig. 8, Table 3). Among these, the northern fulmar, a surface-feeding procellarid with a circumpolar distribution, had the highest score as an indicator of plastic pollution trends in the NP. We recommend that a plastic pollution monitoring program should be established using the stomach contents (proventriculus and gizzard) of the northern fulmar to evaluate spatiotemporal trends in the relative abundance and composition of small-sized (1 mm–10 mm) surface plastic pollution in the NP. This includes the implementation of the Canadian Environmental Sustainability Indicators program using northern fulmars as biomonitors for plastic pollution in Canada's Pacific region, as recently proposed (Canada, 2020). Doing so will facilitate regional comparisons across the temperate and subpolar regions, and will provide comparisons with the Arctic, North Atlantic, and the North Sea, where the species is already being used as an indicator of plastic pollution in the longest-running and most well-known monitoring program, as previously discussed (Baak et al., 2021; Canada, 2020; van Franeker et al., 2011). Programs established in the NP should adopt the official methodologies for this species (OSPAR, 2015; van Franeker, 2004). As discussed above, fulmars are accessible via shoreline surveys, as bycatch, and, if needed, are common enough to be collected via scientific collection permit or from hunters.

In addition to the northern fulmar, the NP albatrosses (Laysan and black-footed), also scored high in the assessment rubric and may serve as additional trend indicators for the NP because they venture farther south, spanning from subtropical to subpolar latitudes, and ingest a larger size range of marine debris than the northern fulmar. Moreover, these species provide two advantages for mechanistic studies of plastic sources and distribution. First, the ability to track the foraging trips of these birds allows researchers to study regional plastic pollution trends by comparing colonies with different at-sea distributions. Second, the retention and regurgitation of indigestible items as a bolus provide a non-destructive sample of the plastic ingested by chicks, allowing for the rapid assessment of plastic ingestion throughout the breeding season (Young et al., 2009). Of the two albatross species, the Laysan is the species with the largest population size and the wider at-sea distribution, venturing into the Bering Sea (Hunt et al., 2000), and is thus recommended as a second trend indicator to compare different areas within the PICES region. Necropsies of North Pacific albatrosses taken by longline fisheries in Alaska and Hawai'i are being used to develop a long-term standardized metric of plastic ingestion in these species, through a collaboration of NOAA's National Seabird Program, NOAA Longline Observer Program, and Oikonos – Ecosystem Knowledge (Donnelly-Greenan et al., 2018; Nevins et al., 2018).

Despite its high indicator score, Leach's storm-petrel was not deemed a convenient indicator due to the inability to reliably obtain large sample sizes from fisheries bycatch, beach-cast programs, or fallout during the fledging period. While specimens were collected at-sea in large numbers historically (1980s–1990s) (Spear et al., 1995), future studies would need to use non-destructive sampling methods (e.g., bolus or fecal analysis) in breeding colonies (Bond and Lavers, 2013). Thus, while this species was not selected as a trend indicator, opportunistic sampling of storm-petrels (e.g., mass-beaching events) could provide information for regional source and surveillance monitoring (Krug et al., 2021). The selection of additional surveillance indicators could be driven by the desire to monitor and track plastic pollution within specific food webs, by integrating with studies of seabird prey (e.g., forage fish and invertebrates). Such studies could expand to consider smaller fractions of plastic pollution (i.e. < 1 mm) and fibers and to involve diving species in addition to the two surface-feeding trend indicators recommended here (northern fulmar and Laysan albatross).

To provide a comprehensive assessment across the NP, and to facilitate regional comparisons, samples must be collected across multiple regions (e.g., 14 oceanographic domains within PICES region defined by Hunt et al. (2000)). Past studies have obtained specimens from fisheries bycatch, beach-cast programs, opportunistic die-offs, and harvesting. While longline fisheries could provide the bulk of samples from oceanic regions (e.g., North Pacific Transition Zone, Gulf of Alaska/Eastern Bering Sea Shelf), beach-cast programs could provide the bulk of samples from coastal regions (e.g., North and South California Current). Considering that variation in specimen sources and availability (i.e., the total number of specimens, seasonal variability, sex and age-class composition), a monitoring program will need to account for these biological factors by documenting the appropriate meta-data, including the location, date, source, age-class, and sex of the specimens as recommended following established monitoring procedures (Provencher et al., 2017, 2019; van Franeker et al., 2011).

We recommend that a minimum of 40 seabird specimens should be sampled, per bioindicator species and PICES region yearly, recognizing that these oceanic species may not be available in all regions (e.g., East China Sea). The value of 40 is recommended as a starting point due to a previous power analysis, and should be revisted regularly as new data becomes available (van Franeker and Meijboom, 2002). Due to the variability in ingested plastic loads in different age classes, the age of birds should be considered when analysing the data (Lavers and Bond, 2016; van Franeker and Meijboom, 2002). We also advocate the use of the quality assurance metrics discussed above in seabird studies, by: (1) analyzing both stomach chambers (proventriculus and gizzard), (2) the reporting of the minimum size threshold, and (3) the confirmation of ingested polymers via FTIR or Raman spectroscopy or similar method.

In the absence of species-specific biologically relevant targets, we strongly recommend a target goal that is clearly specified. For the sake of global comparability, we recommend using the North Sea EcoQO for northern fulmars in the NP region. Although the 0.1 g threshold may be arbitrary in terms of harm, it has been shown, that this threshold can be reached in clean regions (e.g. Arctic Canada; van Franeker et al., 2021). For the other focal seabirds, like the large-bodied black-footed and Laysan albatrosses, a comparable target could be scaled to account for the differences in the body mass of the selected indicators (e.g., Lavers and Bond, 2016). Moreover, to account for individual variability in body mass, the loads of ingested plastic can further be expressed as the percent of the body mass of the specimen (g plastic ingested/g of body mass), with these ratios ranging from <1% in albatross chicks to 10% in albatross chicks (Rapp et al., 2017).

5. Conclusions

The international community has recognized the mounting global threat of plastic pollution (Borrelle et al., 2017; Macleod et al., 2021). The UN Sustainable Development Goals have set the target of reducing plastic pollution – and other forms of marine debris – by 2025 (UN General Assembly, 2015). To achieve this ambitious goal, and ensure that mitigation actions enacted are having the desired outcomes, a reporting structure, such as those proposed by GESAMP (2019), is needed to measure progress towards these goals. Here, we build on the GESAMP framework by developing and using a rubric that highlights several bioindicator species of plastic pollution in the NP from a wide range of ecosystem constituents: bivalves, fish, sea turtles, and seabirds to best serve as bioindicators of plastic pollution in the NP (Table 1). We suggest using these species as the focus of official long-term monitoring programs and developing explicit targets for each indicator in the North Pacific (e.g., the Northern Fulmar's EcoQ Objective in the North Sea).

When selecting species to highlight (Table 3), we considered several factors in addition to their high bioindicator score. We wanted to choose species to monitor a variety of ecosystems across the NP. For example, our highlighted fish species include one oceanic-epipelagic species (mahi-mahi or dolphinfish, *C. hippurus*), one oceanic-mesopelagic species (lancetfish, *A. ferox*), and a genus of neritic-epipelagic species (anchovies, *Engraulis* spp). When coupled with neritic-benthic bivalve indicators, this approach provides robust coverage within the NP. We also wanted to include species that allowed regional comparisons across the NP and facilitated comparisons with other ocean basins for larger marine litter. For example, our highlighted sea turtle and seabird species include widely-distributed NP albatrosses (*P. immutabilis* and *P. nigripes*), a boreal species (northern fulmar, *F. glacialis*) found in multiple basins (North Atlantic, North Pacific and the Arctic) and a cosmopolitan sea turtle (green sea turtle, *C. mydas*) found throughout the world's tropical and subtropical waters. Moreover, these species monitor different size classes of plastic, including mesoplastics (>5 mm), large microplastics (1 mm–5 mm), and small microplastics and fibers (<1 mm). Identification and measurement of relatively large plastics (>5 mm) can be done by visible observation combined with density separation. Training is required, but this process can be done quickly and at low cost. However, identification and quantification of microplastics is more difficult and requires chemical digestion and validaton, typically via FTIR or Raman spectroscopy, which are expensive and time-consuming. For these smaller plastics commonly recovered from fish and invertebrates, trained analytical staff are necessary. These factors need to be considered and may limit the scope and scale of long-term monitoring programs.

Because this paper evaluates potential bioindicators for plastic pollution in the NP, it necessarily focuses on the species where plastic ingestion data were available. Nevertheless, we recognize that plastic ingestion has not been fully investigated in many species and components of the food webs of the NP. Additionally, we do not attempt to cover effects monitoring here. Thus, future work should aim to conduct a food web based gap analysis to consider what biota have yet to be studied in the context of plastic pollution, and further work on what the potential impacts on biota may be.

With the development and analysis of an extensive dataset with larger temporal and spatial coverage across the NP, we will be able to transition from baseline and trend monitoring to risk-based and effects monitoring. Only with long-term, standardized datasets can we achieve the multifaceted goal of monitoring plastic pollution trends, while simultaneously identifying the effects of plastic ingestion on wildlife. These dual goals are critical, as we move forward towards a sustainable future of improved human and ocean health.

Code availability

Code to reproduce the figures and analyses in this paper are available at: https://github.com/mssavoca/PICES_Biota_plastic_ingestion; all data and code are available on Github.

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Certain commercial equipment, instruments, or materials are identified in this paper to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Credit author statement

Matthew S. Savoca: Writing- Original draft preparation, Visualization, Formal analysis, Data curation All authors: Conceptualization, Methodology, Validation, Writing- Reviewing and Editing.

Declaration of competing interest

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

Data availability

Data and code available on Github at: https://github.com/mssavoca/PICES_Biota_plastic_ingestion

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.119861.

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