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REVIEW

Assessing plastic debris in aquatic food webs: what we know and don't know about uptake and trophic transfer

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Abstract: Plastic pollution is now recognized as a global environmental issue that can affect the health of biota and ecosystems. Now that a growing number of species and taxa are known to ingest a diverse range of sizes and types of plastics and retain the plastics in their guts, there are increasing questions relating to the movement of plastics through food webs, and how biota may directly and indirectly ingest plastics. Here, we synthesize what is known from the published, peer-reviewed literature about plastic ingestion by animals and identify critical gaps in our knowledge. We systematically reviewed and examined the literature for studies that reported ingested plastics in marine and freshwater biota at a global scale. Our objective was to inform discussions and future studies regarding what we know about plastic ingestion and fate in food webs. We assessed what regions, ecosystems, and food webs have been studied to date and whether potential information may already be available to assess if trophic transfer of plastics may be occurring. We found 160 relevant publications through 2016. Most studies were concentrated in specific regions and in specific ecosystem types, with freshwater studies being the most limited. Moreover, most studies examined one species at a time with only a handful of regions with multiple taxa examined across multiple studies. Twenty-one percent of the regions have no published data on plastic ingestion to date. Although some studies have measured ingestion in multiple species across trophic levels, few have tested the hypothesis that plastics are transferred across trophic levels. Moreover, none have addressed questions related to biomagnification. While our review suggests that numerous papers have recorded the ingestion of plastics by biota across many trophic levels, habitats, and geographic regions, many questions regarding how or whether biota retain, bioaccumulate, biomagnify, and trophically transfer plastics still need to be addressed.

Key words: plastic pollution, bioaccumulation, biomagnification, retention, trophic transfer.

Résumé : La pollution plastique est maintenant reconnue comme un problème environnemental mondial qui peut influer sur la santé du biote et des écosystèmes. Maintenant que l'on sait qu'un nombre croissant d'espèces et de taxons ingèrent de plastiques d'une grande gamme de tailles et de divers types, et conservent les plastiques dans leurs intestins, il y a de plus en plus de questions liées au cheminement des plastiques dans les réseaux trophiques et à la façon dont le biote peut ingérer directement ou indirectement les plastiques. Nous résumons ici ce que nous savons selon la littérature publiée et évaluée par des pairs, et ce, au sujet de l'ingestion de plastique chez les animaux et nous déterminons les lacunes critiques dans nos connaissances. Nous avons systématiquement passé en revue et examiné la documentation afin d'obtenir les études qui ont rapporté des plastiques ingérés chez le biote marin et dulcicole à l'échelle mondiale. Notre objectif était d'éclairer les discussions et les études futures sur ce que nous savons sur l'ingestion de plastique et son devenir dans les réseaux trophiques. Nous avons évalué les régions, les écosystèmes et les réseaux trophiques qui ont été étudiés jusqu'à maintenant, à savoir si des renseignements potentiels étaient déjà disponibles pour évaluer si des transferts trophiques de matières plastiques pouvaient se produire. Nous avons trouvé 160 publications pertinentes jusqu'en 2016. La plupart des études étaient concentrées dans des régions spécifiques et dans des types d'écosystèmes spécifiques, les études sur l'eau douce étant les plus limitées. De plus, la plupart des études ont examiné une espèce à la fois, avec seulement quelques-unes portant sur des régions avec de multiples taxons examinés dans le cadre de multiples études. Vingt et un pour cent des régions n'ont pas encore publié de données sur l'ingestion de matières plastiques. Bien que certaines études aient mesuré l'ingestion chez plusieurs espèces à différents niveaux trophiques, peu ont vérifié l'hypothèse que les plastiques sont transférés d'un niveau trophique à l'autre. De plus, aucune n'a abordé des questions liées à la bioamplification. Bien que notre examen laisse entendre que de nombreuses études ont noté l'ingestion de matières plastiques par le biote à de nombreux niveaux trophiques, habitats et régions géographiques, de nombreuses questions doivent encore être abordées sur la façon dont le biote conserve, bioaccumule, bioamplifie et transfère les matières plastiques entre les niveaux trophiques. [Traduit par la Rédaction]

Mots-clés : pollution plastique, bioaccumulation, bioamplification, rétention, transfert trophique.

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Introduction

Plastic pollution is ubiquitous in the marine environment and is now recognized as a global environmental problem that also extends to freshwater (STAP 2011; Liappiatt et al. 2013; UNEP 2014). Plastic pollution in marine and freshwater ecosystems comes from a variety of land- and aquatic-based sources and includes a diverse mixture of shapes, sizes, polymers, and chemistries (GESAMP 2015). Plastic pollution can negatively affect diverse biota via several different mechanisms, including entanglement, smothering, and ingestion (Rochman et al. 2016). Here, we focus on the ingestion of plastic by wildlife.

Ingestion of plastic debris, large and small, has been demonstrated across food webs from zooplankton to large predatory fish and marine mammals (GESAMP 2015; Avio et al. 2017; Barrows et al. 2018). Studies examining ingestion by marine and freshwater species have increased rapidly over the last several decades since the phenomenon was first reported in the 1940s (Gudger 1949; Provencher et al. 2017). While many of the early reports of plastic ingestion were in surface-feeding species, the literature now includes reports of plastic ingestion from species that feed throughout the water column, including midwater zooplankton and fish (Tahir and Rochman 2014; Desforges et al. 2015; Bråte et al. 2016), as well several benthic species (Davidson and Dudas 2016; López-López et al. 2018). Today, ingested plastics have been reported in hundreds of species of wildlife, most of which are marine (Kühn et al. 2015).

There are a number of negative effects associated with ingestion of plastic pollution (Teuten et al. 2009; Rochman et al. 2016; Galloway et al. 2017). In the laboratory, ingestion of small plastics can alter gene expression (Rochman et al. 2014), cause inflammation of tissues (von Moos et al. 2012), and can reduce growth (Wright et al. 2013), reproductive success (Sussarellu et al. 2016), and survival (Cole et al. 2015). Ingested plastic can puncture the stomachs of animals (Brandão et al. 2011), which may lead to a number of other physiological problems. Plastic ingestion has also been correlated with reduced body weight or condition (Harper and Fowler 1987; Donnelly-Greenan et al. 2014; Lavers et al. 2014). Finally, ingested plastics can lead to blocked gastrointestinal tracts (Poli et al. 2015; Nelms et al. 2015), and have been reported as the cause of death in stranded wildlife (Jacobsen et al. 2010; Brandão et al. 2011).

A wide range of studies have synthesized what species of wildlife ingest plastics (Laist 1997; Kühn et al. 2015; Provencher et al. 2017). Still, few studies examined why or how plastic pollution is ingested by wildlife or the fate of plastic pollution within and across food webs. Several papers suggested that wildlife likely ingest plastics through direct consumption, and that they mistake it for prey items (Cadée 2002; Janinhoff et al. 2010; Schuyler et al. 2014). Others have suggested that some species ingest plastic because they are attracted to the scent of the biofilm that grows on the plastic (Savoca et al. 2016; Dell'Ariccia et al. 2017). Finally, some studies discussed trophic transfer, suggesting that plastic debris in the food web is a result of both direct and indirect ingestion and (or) inhalation (Hammer et al. 2016; Carbery et al. 2018; Nelms et al. 2018; Chae et al. 2018). Generally, these studies focussed on small, nano-, or micro-sized (<1 mm) pieces, as these are the size classes that are thought to most likely accumulate within or outside the gut and affect wildlife species (Provencher et al. 2017).

Consumption via ingestion, inhalation, and trophic transfer has been demonstrated in fish and invertebrates in controlled laboratory settings (Cole and Galloway 2015; Welden and Cowie 2016). When we encounter retained plastics in the gut of animals, for most species we do not know how they were consumed. In addition to direct consumption of plastics, there is also the potential for indirect, or secondary, consumption of plastic pollution via prey that have ingested plastic debris (Nelms et al. 2018). Moreover, there are questions about retention, whether plastics are retained in the gut and eventually excreted or eliminated via feces or guano (Gil-Delgado et al. 2017; e.g., Provencher et al. 2018; Reynolds and Ryan 2018), or whether plastics accumulate over time in the gut or even outside the gut, in the tissues of organisms (Table 1). This pathway for how plastics enter organisms, and their fate inside organisms, is important to consider, especially for understanding how plastics move through food webs, whether they magnify up the food chain, and how this may facilitate plastic contamination in humans via seafood consumption.

Table 1. Definitions of terminology related to the fate of contaminants in food webs.

Bioaccumulation—Progressive increase in the amount of a substance in an organism or part of an organism that occurs because the rate of intake from all contributing sources and by all possible routes exceeds the organism's ability to eliminate the substance from its body.
Bioconcentration—Process leading to a higher concentration of a substance in an organism than in environmental media to which it is exposed.
Biomagnifcation—Sequence of processes by which higher concentrations of a substance are attained in organisms at higher trophic levels.
Trophic dilution—Decrease in contaminant concentration as trophic level increases; this results from a net balance of ingestion rate, uptake from food, internal transformation, and elimination processes favoring loss of contaminant that enters the organism via food.
Trophic transfer—Transfer of a substance from one trophic level to another.

Note: All definitions are from Nordberg et al. 2009.

The fate and transfer of plastic debris along food webs and its accumulation in upper trophic levels is likely influenced by several factors. First, trophic transfer and accumulation of debris will likely depend on food web characteristics such as the size relation of predators and prey. For example, zooplankton can accumulate plastics in their stomachs, but large baleen whales that consume large amounts of krill and other zooplankton are unlikely to accumulate large amounts of this size of plastics within their guts because of allometric effects of scale, and will likely excrete most of the plastics (Provencher et al. 2018). Second, the retention of plastics in some biota likely will depend on the physiology of the animal. For example, animals that have gastrointestinal tracts with narrow passageways (e.g., seabirds) may be more likely to accumulate plastics than predators that have more undifferentiated guts (e.g., fish). Third, the accumulation and fate of plastics in the organism will likely depend on the size of the plastic particle. Particles less than 150 μm in size are thought to be able to translocate outside the gut and into the blood and tissues of an organism (FAO 2018). While we can speculate on what factors might influence the trophic transfer and accumulation of plastics in food webs based on known patterns of other contaminants and prey items, there is currently no overview of what is known about how plastics move through the food web.

Although the trophic transfer of plastics is often discussed, there are very few papers to date that either investigate or document indirect ingestion (Furness 1985; Hammer et al. 2016; Nelms et al. 2018) and fate inside the body (Brennecke et al. 2015; Avio et al. 2017), and thus few papers actually demonstrate trophic transfer and (or) retention in nature. The goal of this paper was to determine and describe what we know about plastic ingestion, accumulation, and trophic transfer. We systematically reviewed and examined the literature for studies that reported ingested plastics in all available aquatic (i.e., marine and freshwater) biota at a global scale. Our objective was to inform discussions and future studies regarding our understanding about plastic ingestion and fate in food webs and its directionality (biomagnification vs. trophic dilution). We assessed what regions, ecosystems, and food webs have been studied to date and whether potential information may already be available to assess if trophic transfer of plastics may be occurring. Specifically, we aimed to better understand and inform how we can focus research efforts to address questions relevant to whether plastics transfer, bioaccumulate, or biomagnify in freshwater and marine food webs.

Methods

Literature search

To examine how plastic ingestion in biota has been assessed across trophic and geographic scales we conducted a literature review using the Web of Science platform and searching all databases. We used the search terms "marine debris", "plastic debris", and "microplastic" along with "ingestion" to search the database through the year 2016. Each article title and abstract was then reviewed to ensure relevance to the topic of ingestion of plastics by biota. Relevant papers were reviewed in more detail and the following data were extracted: the year of study, the number of species examined, the types of biota examined (i.e., pelagic invertebrates, benthic invertebrates, pelagic fish, demersal fish, benthic fish, marine mammals, aquatic birds, sea turtles), and whether trophic transfer of plastics was explicitly examined in the study (see Table S1 for compiled data)[1]. We also noted whether each article specifically mentioned trophic transfer of plastics by scanning the subset of articles for the words or phrases "trophic transfer", "bioaccumulation", "biomagnification", "indirect", "food web", or "food chain", and if we found those, we reviewed each article in detail to record if they looked for or found trophic transfer of plastic debris.

Our synthesis was limited to articles that were available in English and reported on free-living species (e.g., papers that reported on plastic ingestion exclusively in a laboratory setting were excluded). No terrestrial studies were included in this review as this was beyond the scope of our objectives. We were inclusive of multiple life stages of species to capture as much information available on aquatic species as possible. We did not limit studies reviewed by the types or size of plastics recorded and thus these are pooled together. Therefore, our review incorporates studies that include all the size categories found in the literature including microplastics (<5 mm), as well as many studies reporting larger plastic size classes (e.g., mesoplastics; 5–20 mm).

Regional patterns

To characterize the regional distribution of published studies on plastic ingestion, we classified each paper by a number of regional and habitat categories. First, we recorded the large marine ecosystem(s) (LME) reported for each study (NOAA 2018). The LME designation is a recognized way to understand interconnected marine regions at the global scale (NOAA 2018). This approach was conducive to sorting many studies without being confined or bounded to a specific set of coordinates (i.e., trawl collections or survey cruises). Since LMEs are only used for coastal regions, we additionally used the Major Fishing Areas (MFA) under the Food and Agriculture Organization (FAO) of the United Nations to classify regions if LME definitions did not apply (FAO 2018). LME and FAO MFA classifications (Table 2) were based on the geographic coordinates given in each paper based on stated sampling latitudes and longitudes. For freshwater environments a large-scale watershed assignment was given at the country level. While watersheds can be identified at a number of different scales, we simply identified the freshwater system reported on at this level of detail because the scale was similar to that of the LMEs and FAO MFAs and met the purposes of this large regional overview which was mainly targeted towards the marine environment.

Species and trophic levels examined for plastic ingestion

We categorized species in relevant papers by their trophic levels to examine what information was available for plastic ingestion across multiple trophic levels. We included the categories: filter-feeding invertebrates, detritivore-eating invertebrates, carnivorous invertebrates, herbivorous fish, planktivorous fish, benthic invertebrate-eating fish, piscivorous fish, herbivorous birds, planktivorous birds, benthic invertebrate-eating birds, piscivorous birds, bird-eating birds, mammal-eating birds, herbivorous marine mammals, planktivorous marine mammals, piscivorous marine mammals, marine mammal-eating marine mammals, herbivorous turtles, and omnivorous turtles. This information for marine mammals and turtle species was based on known feeding strategies as reported in the papers. For fish and birds, respectively, we used Fishbase.org (Froese and Pauly 2018) and Birdlife.org (Birdlife International 2018).

Ecosystem-level patterns

To examine what habitats and (or) ecosystem types have been examined for plastic ingestion and trophic transfer of plastics we categorized papers by where plastic ingestion had been examined (e.g., freshwater, estuary, coastal, coral, seamount, pelagic). These designations were based on the foraging attributes of the species examined in each study. We also noted whether there was information about the feeding strategies of the species examined. We used the categories of surface, pelagic, bathypelagic, benthopelagic, bathydemersal, and demersal feeders as defined by Cheung et al. (2007). For mammals and sea turtle species, this was based on known feeding strategies as reported in the papers. For fish and birds respectively, we used Fishbase.org (Froese and Pauly 2018) and Birdlife.org.

The data collected from the literature were then synthesized to identify patterns in relation to geographies, trophic levels, and aquatic regions. Specifically, we quantified how many studies were found in each LME and FAO at the global scale. We also quantified how many papers examined species across multiple trophic levels, and how many specifically looked at trophic transfer of plastics. We then examined how these papers clustered within marine and aquatic regions.

Results

Literature search

Our literature search returned 204 papers. Of these, 160 were included in this review. The remaining 44 were excluded because they were either laboratory studies, not ingestion studies (i.e., cases of entanglement), or did not occur in the aquatic environment (i.e., terrestrial species). All the papers reviewed reported plastic ingestion in at least one species, and some also reported the lack of plastic ingestion evidence in other species. All papers examined reported plastic ingestion for at least one species, although several reported zero plastic ingestion in some species examined. The papers reviewed were published between 1968 and 2016, with 70% of these papers published since 2011 (Fig. 1). Transfer of plastics between trophic levels was observed and reported in five (3%) papers, while an additional 17 papers (11%) acknowledged that trophic transfer may be possible but did not test it.

Regional patterns

Of the 80 total LMEs and FAO oceanic regions, that were considered within this study, we found papers reporting data from 63 of these plus an additional five watersheds (Fig. 2, Table 2). Most

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/er-2018-0079.

Table 2. List of large marine ecosystems (LMEs) and Fishing and Agriculture Organization (FAO) regions and the numbers of plastic ingestion reports found within each.

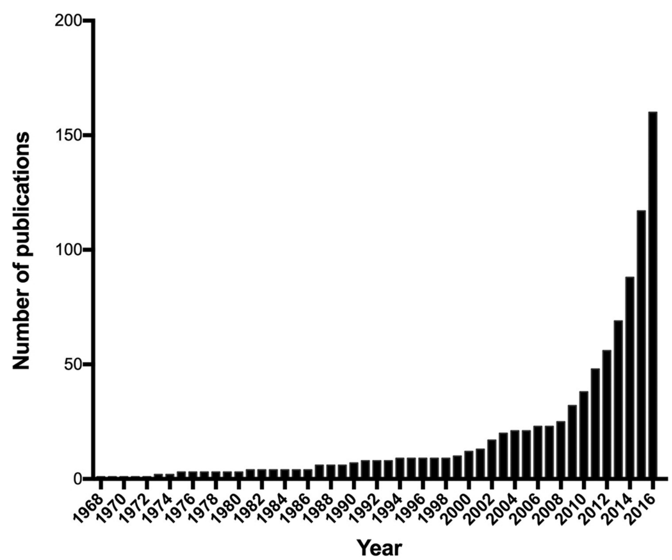
Region	Number of reports
LME	
Agulhas Current	4
Aleutian Islands	2
Antarctic	1
Arabian Sea	1
Baltic Sea	3
Barents Sea	1
Bay of Bengal	0
Beaufort Sea	0
Benguela Current	2
Black Sea	0
California Current	7
Canadian Eastern Arctic - W Greenland	5
Canadian High Arctic-North Greenland	4
Canary Current	4
Caribbean Sea	2
Celtic-Biscay Shelf	10
Central Arctic Ocean	0
East Bering Sea	1
East Brazil Shelf	13
East Central Australian Shelf	4
East China Sea	2
East Siberian Sea	0
Faroe Plateau	5
Greenland Sea	1
Guinea Current	1
Gulf of Alaska	5
Gulf of California	2
Gulf of Mexico	3
Gulf of Thailand	0
Hudson Bay Complex	2
Humboldt Current	0
Iberian Coast	4
Iceland Shelf and Sea	3
Indonesian Sea	1
Insular Pacific Hawaiian	8
Kara Sea	0
Kuroshio Current	2
Laptev Sea	0
Mediterranean	19
Northeast Australian Shelf-Great Barrier Reef	3
NE US Continental shelf	2
New Zealand Shelf	1
Newfoundland-Labrador Shelf	18
North Australia Shelf	0
North Sea	14
Northern Bering Chukchi Seas	0
Norwegian Sea	1
Oyashio Current	0
Pacific Central American	2
Patagonian Shelf	7
Red Sea	0
Scotian Shelf	9
SE Australian Shelf	3
SE US Continental shelf	3
Sea of Japan/East Sea	0
Sea of Okhotsk	0
Somali Coastal current	0
South Brazil Shelf	9
South China Sea	0
SW Australian Shelf	0
West Bering Sea	0
West Central Australian Shelf	1
Yellow Sea	1

Table 2 (*concluded*).

Region	Number of reports
FAO fishing regions	
Antarctic and S Indian Ocean 58	2
Antarctic Pacific 88	0
Arctic Sea 18	0
E Central Atlantic 34	0
E Central Pacific 77	3
E Indian Ocean 57	1
NE Atlantic 27	0
NE Pacific 67	3
NW Atlantic 21	0
NW Pacific 61	1
SE Atlantic 47	3
SE Pacific 87	0
SW Atlantic 41	1
SW Pacific 81	3
W Central Atlantic 31	0
W Central Pacific 71	2
W Indian Ocean 51	
Watersheds	
African Great lakes	1
Amazon Watershed	1
France Watershed	1
Great Lakes/St Lawrence River	1
Nova Scotia Watershed	1
Northwest Territories Lakes	1

Note: All of the LMEs and FAO fishing regions are listed, but only watersheds where ingested plastics were reported are shown.

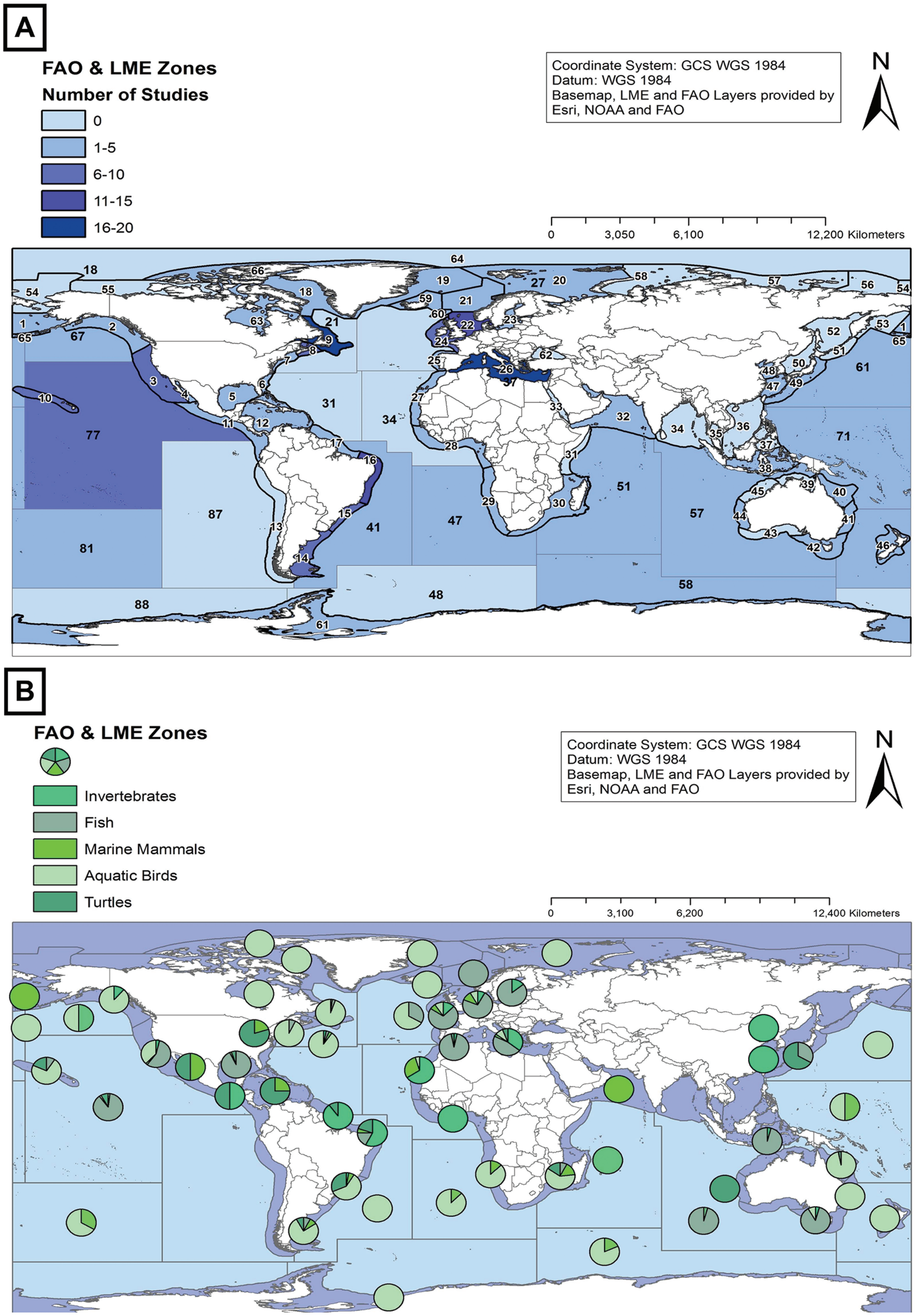
Fig. 1. Number of cumulative studies over time on plastics ingestion by biota.



papers reported values within a single LME, FAO, or watershed (average 1.4 regions), with 24% reporting from within more than one region (*n* = 38). Only five papers reported on five or more LME–FAO regions, but most of these were synthesis papers comparing large spatial patterns in plastic ingestion and all examining seabirds (Young et al. 2009; van Franeker et al. 2011; van Franeker and Law 2015).

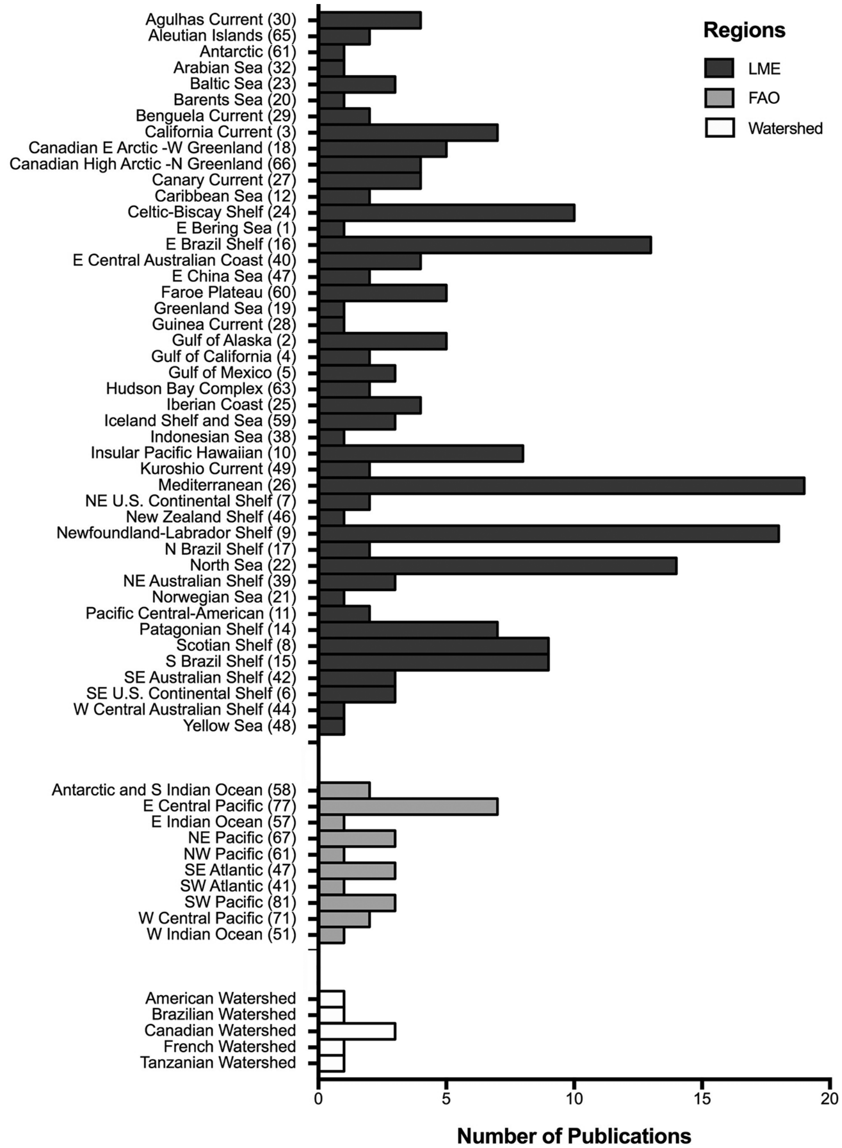
Several published studies were focused in specific regions, suggesting that research on plastics is more active in some parts of the world than others. The top regions for reports of ingested plastics by biota were the Mediterranean region (*n* = 19 studies), the Newfoundland–Labrador Shelf (*n* = 18), the North Sea (*n* = 14),

Fig. 2. (A) large marine ecosystem (LME) and Food and Agriculture Organization (FAO) fishing region maps with the number of studies conducted in each region denoted by color shading (numbers denote corresponding areas in Table 2). (B) LME (dark blue) and FAO major fishing areas (MFA) (dark blue) with the types of biota examined in each region.



the East Brazil Shelf (n = 13), and the Celtic–Biscay Shelf (n = 10; Fig. 3). It is notable that three of these regions are in Europe, including the North Sea where plastic ingestion work has been mandated via the North Sea Ministers over the last few decades (Provencher et al. 2017; van Franeker et al. 2011). These regions are also all LME regions. In the offshore FAO fishing regions, the highest concentrations of studies were in the Eastern Central Pacific, the North East Pacific, the South West Pacific, and the South East Atlantic, each with three reports. A total of 26 LME–FAO regions lacked any studies measuring plastic debris ingestion by biota. Overall 70% of the coastal LME regions were included in studies for plastic debris ingestion (44 out of 63 total), and 59% of

Fig. 3. Number of studies that report on ingested plastics within large marine ecosystems (LME), the United Nations Food and Agriculture Organization (FAO) offshore fishing regions and various freshwater watersheds.



the FAO regions included in studies for plastic debris ingestion (10 out of the 17 total).

Species and trophic levels examined for plastic ingestion

Of the 160 papers reviewed, 87 (54%) examined species across multiple trophic levels (e.g., planktivorous fish and piscivorous fish), but only 48 (30%) were studies that examined more than one species. This counter-intuitive result of more reports across trophic levels than multiple species is because many studies reported on species that fall into multiple trophic levels (e.g., herring gulls (*Larus argentatus*) are generalists that eat fish, as well as other birds, invertebrates, and scavenge waste). One paper reported as many as six trophic levels (Avery-Gomm et al. 2013), with birds being the dominant taxa in this and other multi-trophic level papers. One study reported plastic ingestion in 61 species (Roman et al. 2016), and 18 papers (11%) reported ingestion for 10 or more species with both fish ($n = 9$) and birds ($n = 7$) being reported the most in these reports. Several of these papers reported plastic ingestion in groups of species that were not sampled with plastic trophic studies in mind. For example, there are a number of papers that reported plastic ingestion via opportunistic sampling of seabirds (Avery-Gomm et al. 2013; Codina-García et al. 2013; English et al. 2015; Holland et al. 2016). While this type of reporting of plastic ingestion is important for understanding what species are vulnerable (Provencher et al. 2017), this type of sampling is not conducive to examining questions related to trophic transfer because the time and locations of sampling can be disparate, and the species may not be directly connected in a food web.

Ten papers specifically expressed intentions in reviewing or reporting ingested plastics within biota at different trophic levels, but only three papers specifically tested the hypothesis that plastics were trophically transmitted (Table 3). Two of the three tested trophic transfer in bird species (Furtado et al. 2016; Hammer et al. 2016) and the other in invertebrates (Remy et al. 2015).

Notably, several papers were based on studies that collected multiple species, representing multiple trophic levels in a systematic sampling effort in time and space that could have been used to explore trophic transfer. These were missed opportunities, as the projects did not test for trophic transfer of plastic debris. For example, Davison and Asch (2011) examined >24 fish species from three trophic levels during a sampling effort that was standardized

Table 3. List of studies that examined and tested for the trophic transfer of anthropogenic debris in wildlife.

Study	How measured?	Taxa	Prey species	Predator species	Trophic transfer determined?
Furtado et al. 2016	Counted prey and plastics in the pellet and correlated the two	Bird	White-faced storm-petrels (*Pelagodroma marina*)	Yellow-legged gulls	Yes
Hammer et al. 2016	Counted prey and plastics in the pellet and correlated the two	Bird	Northern fulmars (*Fulmarus glacialis*); other seabirds, fish and hare	Great skua (*Stercorarius skua*)	Yes
Remy et al. 2015	Counted plastics in different species at different trophic levels and compared	Crustacean	*Palaemon xiphias*	Other invertebrates	No

Note: Only three studies of the 160 reviewed explicitly examined whether plastics were transferred between prey and predators. All are field studies.

within a single region in the East Central Pacific. Anastasopoulou et al. (2013) also looked at plastic ingestion in fish species from three trophic levels during a standardized sampling effort of deep-water fishes. Similarly, Rochman et al. (2015) examined fish and invertebrates collected from similar locations and did not consider trophic transfer questions. These studies could have been used to not only measure contamination, but also address questions related to trophic transfer, bioaccumulation, and biomagnification.

Ecosystem-level patterns

It is noteworthy that only six (4%) of the studies included in our review measured and reported plastic ingestion in freshwater biota. These six studies came from very different regions. One paper was from a Tanzanian watershed (Biginagwa et al. 2016), one from a Brazilian watershed (Guterres-Pazin 2012), one from a French watershed (Sanchez et al. 2014), and three from North American watersheds (English et al. 2015; Phillips and Bonner 2015; Holland et al. 2016). We did not find any watershed-level reports or multiple papers on single watersheds, which demonstrates that our current understanding of the fate and contamination of plastic pollution in freshwater food webs is very limited.

Not surprisingly, about 85% of the papers reported plastics in either coastal or offshore marine ecosystems (41% and 45%, respectively; Fig. 4), as these were the regions where the issue of plastic pollution ingestion was first noted and continues to command the most attention (Rochman 2018). However, we note that there is limited information about plastic ingestion in specialized habitats like coral reefs and deep sea environments, despite that these areas are known sinks for various plastics (e.g., Woodall et al. 2014).

In our review, the highest number of studies examined birds (n = 80) (Fig. 5A). Of the bathymetric depth ranges of the birds (three categories in total), surface feeders were the dominant category examined (67%) followed by pelagic feeders (29%). Studies investigating plastic ingestion in birds often examined groups of species (>3 species) that feed at various different depth ranges (see Table S1 for further details[1]; Avery-Gomm et al. 2013; Codina-García et al. 2013; Gilbert et al. 2016). By contrast to the limited bathymetric feeding ranges examined for birds, studies of plastic ingestion in fish collected species from six different depth ranges (Fig. 5B). Although benthopelagic and demersal species were sampled evenly (33% and 35%, respectively), fish from other ranges such as the surface, pelagic, and intertidal lacked such representation in terms of study numbers (<5%).

The second most studied taxonomic group were sea turtles (n = 51 studies; Fig. 5C). The majority of species examined were either pelagic (63%) or surface (30%) in depth range, whereas species from deeper habitats were less sampled (<10%). Only four depth ranges were examined among turtle studies, as sea turtles are relatively limited to shallow waters. Notably, studies focused on certain species (i.e., including but not limited to: loggerheads (*Caretta caretta*), leatherbacks (*Dermochelys coriacea*), and green sea turtles (*Chelonia mydas*)) that were sampled because of stranding events or bycatch (e.g., Stamper et al. 2009; Tomás et al. 2002).

Despite the high diversity of invertebrates globally, only 35 (22%) of the 160 papers focused on these organisms (Fig. 5D). The majority of these studies (74%) examined more than one species, but they generally did not examine species from more than two bathymetric depth ranges. Several of the studies focused efforts on sampling specific habitats and regions, and thus bathymetric ranges were similar among the species sampled within a study (Remy et al. 2015; Lima et al. 2015; Gusmão et al. 2016). The majority of habitats examined for invertebrates were pelagic (51%) followed by intertidal (17%). Similar to the trends identified in fish, depth ranges were examined and sampled unevenly; <10% examined species from surface, bathypelagic, bathydemersal, and demersal depths.

Lastly, marine mammals had the fewest number of studies (n = 34) but had the greatest number of depth ranges (n = 6; Fig. 5E). This difference in depth ranges could be attributed to the diversity of species sampled such as manatees, whales, dolphins, and seals. Similar to sea turtles, the majority of the studies examined single species that were opportunistically sampled by stranding events (Lusher et al. 2015; Fossi et al. 2016; Garrigue et al. 2016). This type of sampling bias has also shown true in seabirds as well, which is a relatively better studied group than most (Provencher et al. 2017).

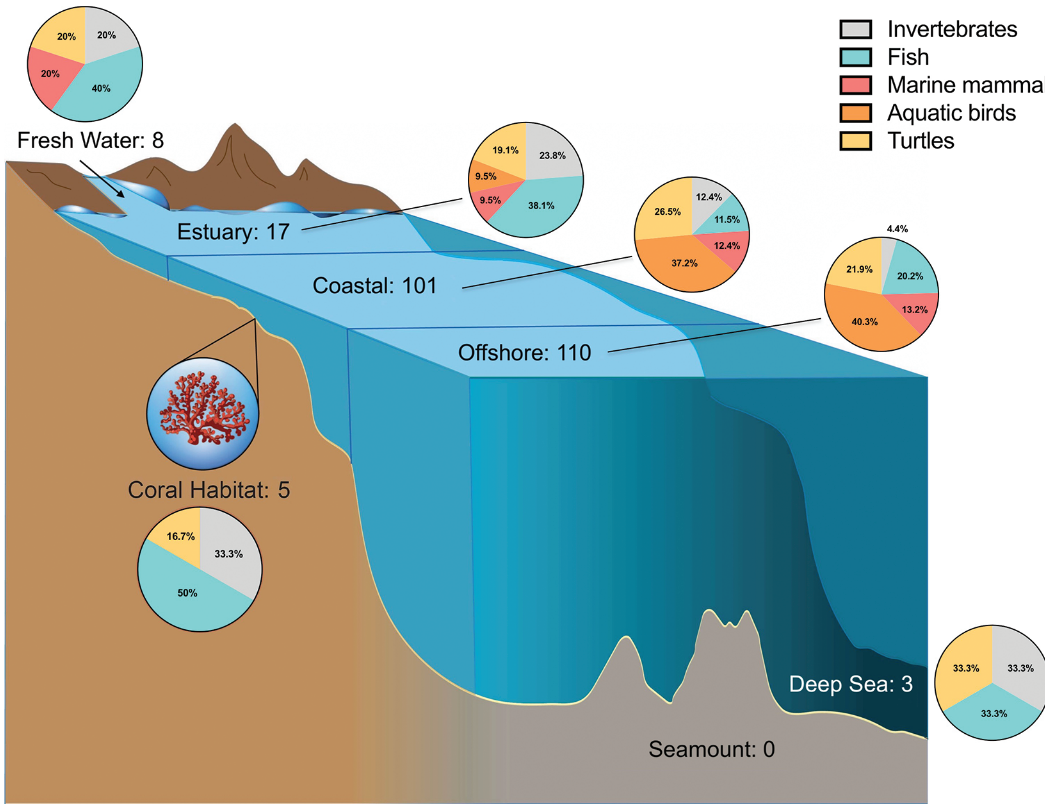
Discussion

Overall, while the contamination and fate of plastics in food webs is a pressing environmental concern for scientists and the public (Gall and Thompson 2015; Borrelle et al. 2017; Worm et al. 2017), we found that most studies examined contamination, and very few asked questions about fate. Specifically, very few studies discussed the trophic transfer of plastics, and most importantly very few have tested the hypothesis that it occurs. Our review suggests that numerous papers have recorded the ingestion of plastics by biota across many trophic levels, habitats, and geographic regions, but questions regarding whether or how biota excrete, bioacumulate, biomagnify, and trophically transfer plastics still need to be addressed.

Regional patterns

Our results suggest that there are nine regions, all LMEs, where plastic ingestion is already relatively well documented (i.e., many discrete studies and species examined), and these areas are suitable for investigation of detailed trophic interactions in plastic ingestion. These regions include the California Current, the Canary Current, the Celtic–Biscay Shelf, the East Brazil Shelf, the East Central Australian Shelf, the Faroe Plateau, the Mediterranean, the Newfoundland–Labrador Shelf, and the North Sea (Fig. 2). Since there is already a body of knowledge in these regions on plastic ingestion by aquatic biota, future studies should endeavor to include sampling and analytical approaches that address questions relating to the fate of plastics in food webs. This

Fig. 4. Habitat types where plastic ingestion by biota (invertebrates, fish, marine mammals, aquatic birds, and turtles) have been reported and the number of studies.



could include approaching plastic studies using trophic interaction methods as in Hammer et al. (2016) and Remy et al. (2015) or targeting species that have trophic connections during plastics studies (e.g., Furtado et al. 2016).

There has been much less work on plastic ingestion in the offshore regions (FAO fishing regions) with the most reported FAO regions being the East Central Pacific, the North East Pacific, the South East Atlantic and the South West Pacific (Fig. 2). While it is well established that coastal and nearshore environments have high loads of plastic debris (Barnes et al. 2009), environmental research is increasingly showing that offshore and deep water habitats may be sinks for plastic debris accumulation (Cozar et al. 2014; Taylor et al. 2016). Despite the fact that the deep-sea covers more than 60% of the globe and can foster high levels of biodiversity (Gage and Tyler 1991), the study of plastic ingestion in deep-sea ecosystems was not well represented in the available literature. The sheer size of these offshore areas implies that we lack knowledge about the fate of plastic debris at a global scale, and with presumably simpler food chains (Gage and Tyler 1991) these regions may prove fertile research opportunities to study the occurrence and effects of trophic transfer of plastic debris (e.g., Taylor et al. 2016). Given that the major accumulation zones of plastics in the marine environment are offshore regions, our findings suggest that we know very little about how many offshore species may be affected in these high concentration zones (Law et al. 2010).

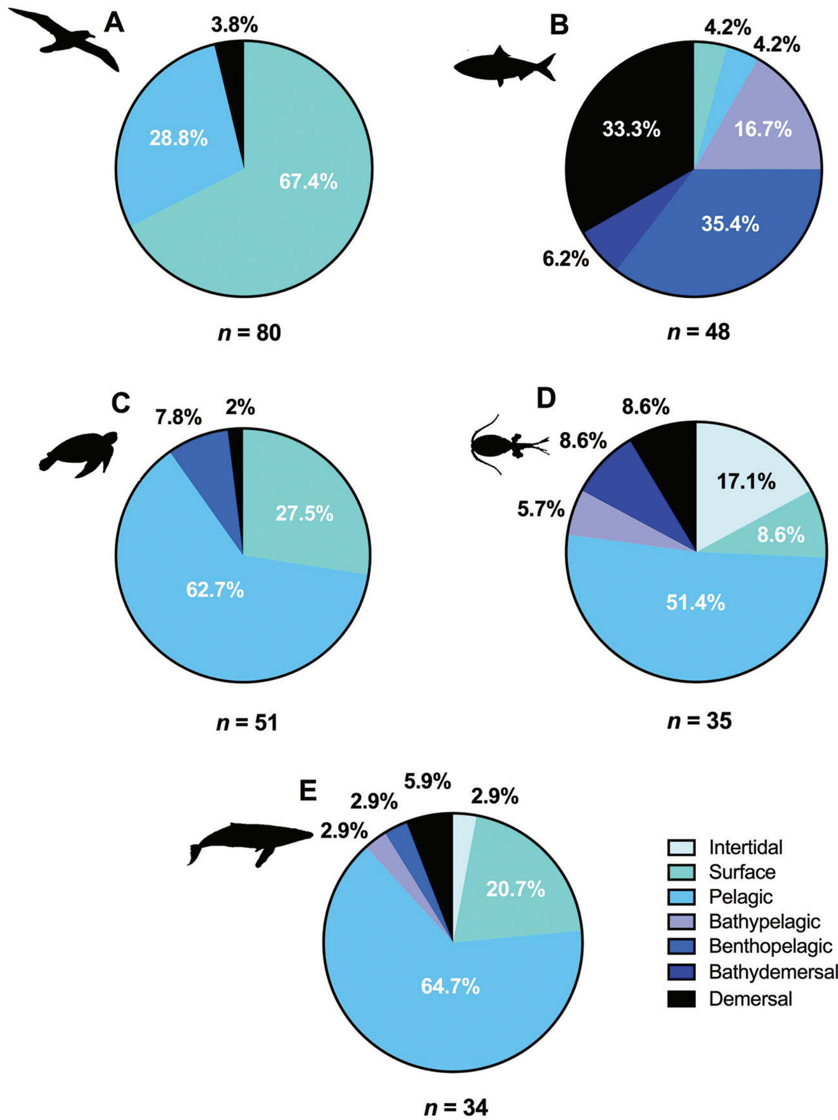
Our results also highlight that a number of LMEs and FAO fishing regions lack any research on plastic ingestion by biota. Key regions in this group include: Bay of Bengal, Beaufort Sea, Black Sea, Central Arctic Ocean, East Siberian Sea, Gulf of Thailand, Humboldt Current, Kara Sea, Laptev Sea, North Australia Shelf, Northern Bering-Chukchi Sea, Oyashio Current, Red Sea, Sea of Japan–East Sea, Sea of Okhotsk, Somali Coastal Current, South China Sea, and West Bering Sea (Fig. 2). Many of these are remote locations (e.g., Central Arctic Ocean, Kara Sea, Laptev Sea), but a number of these regions include LMEs that are heavily impacted by people and thus plastic pollution (e.g., Red Sea, Gulf of Thailand, South China Sea). While targeting these regions may not necessarily appear a direct route to exploring questions relating to trophic transfer, developing projects where people are deeply connected to the marine environment through coastal living may offer unique research opportunities to explore questions related to the trophic transfer of plastics via community-based monitoring programs (e.g., McKinley et al. 2017).

The movement of plastics through aquatic food webs

Trophic transfer of microplastics, or an animal indirectly ingesting microplastics via its prey, has been demonstrated in the laboratory (Farrell and Nelson 2013; Setälä et al. 2014), but our review suggests that few studies have looked for and (or) observed trophic transfer in the field (Furtado et al. 2016; Hammer et al. 2016). Nonetheless, even if trophic transfer does occur, we still do not know whether transferred plastic particles are excreted at higher trophic levels, or whether they bioconcentrate, bioaccumulate, and biomagnify (Fig. 6). For microplastics to do this, the particles have to accumulate in the tissues like they do for chemical pollutants such as methylmercury (Whitney and Cristol 2017). Although there is evidence that microplastics can transfer from the gut into the bloodstream (Browne et al. 2008), organs (Collard et al. 2017), and brain (Ding et al. 2018), the extent to which this occurs and the particle size range that might be involved remain poorly understood.

Most of the studies in our review reported on the ingestion of plastics and some on retention in the stomach. In the literature this is often referred to as accumulated plastics (e.g., Poon et al. 2017), but in the framework of ecotoxicology, plastics that are ingested and stay in the stomach are simply retained. Because micro- and nano- sized plastics can translocate outside the gut,

Fig. 5. Number of studies that report plastic ingestion by biota from different bathymetric depth ranges, including, (A) aquatic birds, (B) fish, (C) turtles, (D) invertebrates, and (E) marine mammals.



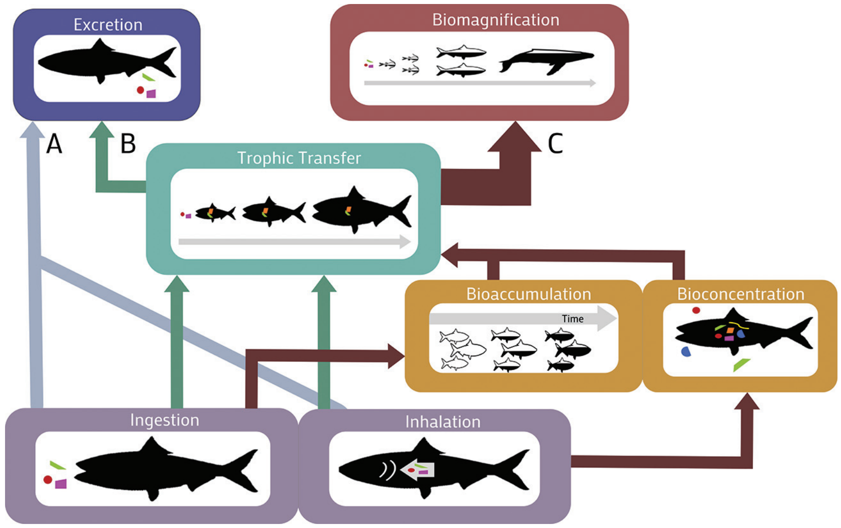
there is evidence they may actually bioaccumulate within biota (Browne et al. 2008; Collard et al. 2017). If they bioaccumulate, then there are some relevant questions regarding their fate that we should be testing. We should aim to understand whether microplastics can bioconcentrate in animals from the water (i.e., the process by which a contaminant in an aquatic organism exceeds that in water as a result of exposure to a waterborne contaminant) because there is evidence that plastics can be taken up by animals via other mechanisms than ingestion, such as via the gills (Watts et al. 2016). In direct relation to food webs, if microplastics bioaccumulate we should investigate whether they also biomagnify (i.e., an increase in the concentration of a contaminant in the tissues of organisms at successively higher levels in a food chain) in organisms like other chemicals, such as polychlorinated biphenyls. Whether plastic debris bio- concentrates, accumulates, or magnifies likely depends on many factors, including the size of the particle, the size of the animal, and feeding behavior. Understanding the fate of plastic pollution in food webs, and particularly the mechanism(s) by which it moves into and through species, would increase our understanding and ability to answer questions about ecological effects.

Types of ecosystems and habitats examined to date

Much of our knowledge of the occurrence and threats of plastic debris and wildlife comes from work in the marine environment, and particularly nearshore and coastal regions. These were the first areas that extensive research was conducted, and the first where scientists noticed wildlife being entangled or consuming plastics (Laist 1997; Derraik 2002). One challenge with this work is that many of the studies have focused on highly mobile species like seabirds, marine mammals, and sea turtles (Provencher et al. 2017). As a consequence, the possibility of examining trophic transfer of plastics is challenging because it is difficult to link locations of plastic ingestion with diet and the capture location (Young et al. 2009). Although there has been some focused research on plastic accumulation in specific marine habitats (e.g., deep sea (Woodall et al. 2014), estuaries (Browne et al. 2010; Possatto et al. 2011), coral reefs (Donohue et al. 2001)), the possibility of trophic transfer in these areas has received little attention.

While most of the literature that we reviewed focused on the marine environment, there were also recent reports of plastic ingestion in freshwater environments from five freshwater re-

Fig. 6. (A) The pathways by which microplastics may transport into organisms individually and (B and C) via trophic transfer. The width of the arrows is relative to the amount of the microplastics at each level. The image shows how microplastics may be (A) taken up into the gut and excreted or (B) taken up into the gut, retained and transferred to a predator, followed by excretion or may be taken up beyond the gut, into the blood or tissues, via bioconcentration or bioaccumulation and subsequently transferred up a food chain, potentially leading to biomagnification, as is seen with persistent organic contaminants.



gions. These papers focused either on a group within a specific location (Phillips and Bonner 2015; e.g., Biginagwa et al. 2016), or a single type of biota from across a broad set of locations (e.g., English et al. 2015; Holland et al. 2016). This suggests that currently there is limited information on trophic transfer of plastics within freshwater food webs. Given that freshwater environments are vulnerable to plastic pollution, especially in highly populated areas (Lechner et al. 2014; Driedger et al. 2015; Vermaire et al. 2017), we need an increased understanding of how freshwater species ingest plastics.

Recommendations and predictions

Modelling exercises have shown that the threat of plastic pollution is likely increasing (Jambeck et al. 2015; Geyer et al. 2017) and that high proportions of biota will ingest plastics by 2050 (seabirds; Wilcox et al. 2015). Still there remains a large gap in our understanding of how plastics move through food webs, and how trophic interactions mediate the fate of plastics between prey and predators. Although there is an immense amount of research being undertaken on plastic debris distribution, ingestion, and effects on biota (Woodall et al. 2014; Browne et al. 2015; Li et al. 2016; Geyer et al. 2017), our review shows that there remains relatively little work on trophic transfer of plastics in food chains (note that this gap is beginning to be filled; in the time between submission and acceptance of this manuscript, we found 4 new studies examining trophic transfer; Chagnon et al. 2018, Hipfner et al. 2018, Lambert and Wagner 2018.; Naji et al. 2018). Based on our study and recent reviews that serve as companions and background for our work (Worm et al. 2017; Bonanno and Orlando-Bonaca 2018), we provide the following recommendations on how as a research community we can focus our research efforts to better understand the fate of plastics in aquatic food webs:

1. Focal regions

   In focal regions where the ingestion of plastics by biota is already well documented, we should move beyond simply reporting plastic ingestion by species (i.e., surveillance–monitoring work) and aim to address questions that broaden our understanding of fate and trophic transfer. For example, plastic ingestion studies that take place in the most-studied LMEs should endeavor to include trophic interaction aspects to any studies that include multiple species from multiple trophic levels (e.g., dietary biomarker work) to fully maximize our knowledge about plastic ingestion.

2. Focal food webs

   (a) Well-defined food webs

   To appropriately address trophic transfer questions in relation to plastics and biota, purposely designed sampling efforts and experimental designs are needed. A large number of the studies examined in this review could only be attributed to the broad categories of coastal or pelagic habitats. This inherently constrains comparisons among trophic levels between papers, even when the studies occur in the region. Well-defined food webs, such as those found in lakes and inland seas may provide critical areas for targeted research questions about trophic transfer to be addressed.

   (b) Trophic transfer of plastics in closed natural systems or aquaculture

   There are an increasing number of studies examining plastics in aquaculture species due to the potential for effects on humans (Van Cauwenberghe and Janssen 2014; Rochman et al. 2015; Cole and Galloway 2015; Davidson and Dudas 2016). Aquaculture, or other systems that mimic wild settings in a controlled manner, may provide an ideal system to examine questions of trophic transfer given that they are often in relatively well-known and confined regions. Specifically, in aquaculture operations where multiple species are harvested, research questions regarding trophic transfer of plastics may be quite useful in determining how to minimize plastic contamination in different species.

3. Focal ecosystems

   Future studies interested in trophic transfer of plastics should target ecosystems that contain relatively confined sets of trophic levels. While seabirds are very useful indicators of plastics because they sample large areas, they are also a challenge to incorporate into trophic transfer studies given that their prey can come from hundreds of square kilometres that can be exceedingly challenging to study (e.g., Tranquilla et al. 2013). There are studies of trophic transfer in seabirds (e.g., Hammer et al. 2016), but these are limited to species that feed in a relatively defined region during the breeding season.

Freshwater ecosystems or alternately deep ocean areas are both bounded regions that may serve as good model systems to examine trophic transfer of plastics. For example, the Mediterranean has well-defined boundaries and known inputs; therefore, targeted studies in this region may be very beneficial in improving our understanding of the fate of plastics in food webs.

We believe that with the research suggestions outlined above, we can develop a much better understanding of how plastic debris moves through food webs. This may help us understand how species' vulnerability varies depending on diet and habitat, and ultimately where we should prioritize environmental recovery actions to achieve the greatest conservation returns. Based on our review, we make the following predictions for the relationship between plastic debris and trophic transfer in aquatic food webs:

1. The incidence of trophic transfer of plastics will likely mirror the availability of plastics in the environment and, therefore, is likely to be found differentially across regions.
2. The incidence of trophic transfer of plastics will be highest in food webs that contain species that feed at the same depths that plastics accumulate in the environment (i.e., the surface and the benthos).
3. Trophic transfer and retention of plastics is likely to occur for many small species, but may be limited for top predators in some food webs based on the size of the predators and the size of the dominant plastics in the environment (trophic dilution). Therefore, if biomagnification occurs, we may see different patterns than with chemical contaminants in the same system. If plastic pollution "behaves" similarly to persistent organic pollutants we would expect to see higher levels in higher trophic levels, but because of the physical nature of plastics, trophic dilution may also occur.
4. The trophic transfer of plastics in freshwater ecosystems will closely reflect trophic transfer of plastic pollution in marine ecosystems. Nevertheless, the transport and fate of ingested plastics in freshwater biota should be considered in future research as little research has been done to corroborate the parallel processes in these different ecosystems.

Conclusions

In general, there is no doubt that plastic contaminates a diverse set of species and in diverse regions and ecosystems around the world. Still, we know very little about the fate of this plastic contamination through food webs and the processes that affect where contamination is found. We also know very little about the effects of plastics on biota. Further research is needed to understand the retention of plastics in animals and whether bioconcentration, bioaccumulation, and biomagnification occur. Encouragingly, there appears to be increasing recognition of the possibility of trophic transfer (i.e., Nelms et al. 2018; Hipfner et al. 2018), although to date few papers have explicitly tested for it.

With plastics increasingly being considered among other environmental contaminants (e.g., metals, pesticides, nanomaterials), policy-makers are grappling with how to classify this emerging contaminant. The physical nature of plastics makes them unique when compared to chemical contaminants, as does the diverse mixture of chemicals associated with one particle. Still, there are arguably many similarities between plastics and chemical contaminants, and some are even suggesting reclassifying them as persistent organic pollutants (Worm et al. 2017). First, both chemicals and plastics can be persistent and subject to long-range transport on ocean and air currents (Kirk et al. 2012; van Sebille et al. 2015). Second, while the mechanisms are quite different, both chemicals and plastics can either be excreted or accumulated within an organism (Browne et al. 2008; Rigét et al. 2011; Braune et al. 2015). Third, because plastics can be translocated outside the gut, it is worth testing whether they bioaccumulate and biomagnify in tissues like some chemicals (Mattsson et al. 2017; Ding et al. 2018). To help determine how to characterize plastic debris and whether they should indeed be considered as a persistent organic pollutant, we need to better understand the fate of plastics and their associated contaminants in freshwater and marine food webs.

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