



9-30-2021

Prevalence of microplastics and anthropogenic debris within a deep-sea food web

Bonnie M. Hamilton
University of Toronto

Chelsea M. Rochman
University of Toronto

Timothy J. Hoellein
Loyola University Chicago

Bruce H. Robison
Monterey Bay Aquarium Research Institute

Kyle S. Van Houtan
Monterey Bay Aquarium

See next page for additional authors

Follow this and additional works at: https://ecommons.luc.edu/biology_facpubs

Recommended Citation

Hamilton, Bonnie M.; Rochman, Chelsea M.; Hoellein, Timothy J.; Robison, Bruce H.; Van Houtan, Kyle S.; and Choy, C. Anela. Prevalence of microplastics and anthropogenic debris within a deep-sea food web. *Marine Ecology Progress Series*, 675, : 23-33, 2021. Retrieved from Loyola eCommons, Biology: Faculty Publications and Other Works, <http://dx.doi.org/10.3354/meps13846>

This Article is brought to you for free and open access by the Faculty Publications and Other Works by Department at Loyola eCommons. It has been accepted for inclusion in Biology: Faculty Publications and Other Works by an authorized administrator of Loyola eCommons. For more information, please contact ecommons@luc.edu.



This work is licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/).

Authors

Bonnie M. Hamilton, Chelsea M. Rochman, Timothy J. Hoellein, Bruce H. Robison, Kyle S. Van Houtan, and C. Anela Choy



Prevalence of microplastics and anthropogenic debris within a deep-sea food web

Bonnie M. Hamilton¹, Chelsea M. Rochman¹, Timothy J. Hoellein²,
Bruce H. Robison³, Kyle S. Van Houtan^{4,5}, C. Anela Choy^{6,*}

¹University of Toronto, Department of Ecology and Evolutionary Biology, Toronto, Ontario M5S, Canada

²Loyola University Chicago, Department of Biology, Chicago, Illinois 60660, USA

³Monterey Bay Aquarium Research Institute, Moss Landing, California 95039, USA

⁴Monterey Bay Aquarium, Monterey, California 93940, USA

⁵Duke University, Nicholas School of the Environment, Durham, North Carolina 27708, USA

⁶Scripps Institution of Oceanography, University of California San Diego, La Jolla, California 92037, USA

ABSTRACT: Microplastic particles (<5 mm) are ubiquitous throughout global marine ecosystems, including the deep sea. Ingestion of microplastics and other anthropogenic microparticles is reported in diverse marine taxa across trophic levels. Trophic transfer, or the movement of microplastics across trophic levels, is reported in laboratory studies but not yet widely measured in marine food webs. The Monterey Bay submarine canyon ecosystem contains a well-studied, known deep-sea food web in which to examine the trophic fate of microplastics. We measured microplastic abundance across 17 genera spanning approximately 5 trophic levels and a diversity of feeding behaviors. Samples were collected using remotely operated vehicles and oblique midwater trawls, and gut contents of all individuals examined (n = 157) were analyzed for microplastic abundance and other anthropogenic particles greater than 100 µm using stereo microscopy. Microparticles were analyzed with Raman spectroscopy to confirm material type. Anthropogenic particles were found in all genera examined, across crustacean, fish, mollusk, and gelatinous organisms, in amounts ranging from 0 to 24 particles per individual. There was no significant relationship between microplastic amount and fish trophic level, suggesting that the trophic transfer of microparticles is not occurring. Body size was positively correlated with microplastic abundance across all taxa. The fish genus *Scomber* sp. drove this relationship, suggesting higher microplastic abundance in mobile individuals with broad horizontal distributions. Future work should examine physiological pathways for microplastic transport within organisms (e.g. excretion, accumulation on gills, internal translocation of particles) and between organisms within shared habitats to more fully understand the fate of microplastics within aquatic food webs.

KEY WORDS: Monterey Bay · Trophic ecology · Marine food web · Raman spectroscopy · Deep pelagic · Ingestion · Body size

1. INTRODUCTION

Large-scale plastic production was introduced to the global economy in the mid-20th century (Geyer et al. 2017). The durability, light weight, low cost, and convenience of the material accelerated the demand for plastic products to the present day. High rates of

production, combined with large-scale waste mismanagement, resulted in unprecedented amounts of environmental plastic pollution. Plastic pollution is globally pervasive, and ingestion is reported in over 300 animal species, mostly marine (Kühn et al. 2015, Markic et al. 2020), and observed in some of the world's most remote systems, including the Arctic

*Corresponding author: anela@ucsd.edu

(e.g. Lusher et al. 2015, Bergmann et al. 2017) and the deep sea (e.g. Chiba et al. 2018, Choy et al. 2019). This environmental ubiquity necessitates ecological and environmental understanding of how plastic pollution interacts with and affects diverse organisms across varying ecosystems.

As a material, plastic continuously degrades into smaller particles, which can increase in abundance over time in the environment (Eriksen et al. 2014). Microplastics (i.e. particles <5 mm) are physically and chemically heterogeneous, ranging in size, color, shape, and chemical constituents (Rochman et al. 2019). Microplastics have been documented globally in aquatic environments (freshwater and marine) and terrestrial ecosystems (Suaria et al. 2020). Compared to larger plastics, microplastic particles are readily transported within and between ecosystems by myriad physical and biological processes (Cozar et al. 2014, Eriksen et al. 2014), including long-range atmospheric transport (Dris et al. 2016, Zhang et al. 2019, Brahney et al. 2020) and deep-ocean circulation (Kane et al. 2020), and direct ingestion by animals or indirect ingestion via prey (Watts et al. 2016, Chagnon et al. 2018, Nelms et al. 2018).

Once ingested, microplastic particles can induce physiological damage and may also leach plastic-associated chemicals to an organism, ultimately persisting and cycling within food webs via trophic transfer (Worm et al. 2017). Alternatively, microplastics may pass directly through an organism's digestive system (Katija & Choy et al. 2017), with minimal or no physiological consequences (Foley et al. 2018). Microplastic ingestion is pervasive in organisms across trophic levels and feeding strategies, including filter-feeding zooplankton (Desforges et al. 2015, Brandon et al. 2020), mesopelagic fishes (Davison & Asch 2011, Choy et al. 2013, Wiczorek et al. 2018), sea turtles (Van Houtan et al. 2016, Wilcox et al. 2018), and marine mammals (Moore et al. 2020). Species actively feeding and moving throughout aquatic ecosystems can also transport microplastics, including those feeding at the surface, across the water column (midwater fishes and zooplankton; Choy & Drazen 2013, Desforges et al. 2014, Bråte et al. 2016), and down to the seafloor, including the deep sea (López-López et al. 2018, Choy et al. 2019). Currently, there is a lack of understanding about the fate and cycling of microplastics within complex and interconnected food webs and ecosystems. Differential rates of microplastic retention and/or excretion may impact and result in bioaccumulation, biomagnification, or trophic dilution (Provencher et al. 2019). Such investigations would benefit from a careful

examination in food webs with clearly defined trophic connections (Provencher et al. 2019).

Monterey Bay, within the California Current system, is a well-studied deep submarine canyon ecosystem, with relatively well-known physical and biological dynamics (e.g. Carter et al. 2005, Robison et al. 2010, Choy et al. 2017, Martini & Haddock 2017). Deep-sea ecosystems are likely to be a vast, permanent sink for microplastics (Woodall et al. 2014), but the distributions of microplastics within deep-sea food webs are largely unknown. The Monterey Bay submarine canyon is an ideal food web for examining the fate of microplastics across trophic levels since vertical microplastic distributions and overarching food web interactions are known (Choy et al. 2017, 2019). We evaluated the abundance of microplastics and other anthropogenic microparticles (e.g. non-plastic particles of human origin or manipulation; hereinafter referred to as microparticles) in the digestive tracts of organisms (17 taxonomic groups of fishes, crustaceans, mollusks, and gelatinous animals) spanning approximately 5 trophic positions from the Monterey Bay deep-pelagic ecosystem. Organisms were collected from depths spanning epipelagic and mesopelagic waters, which are infrequently sampled and quantified for microplastic abundance and food web uptake despite comprising the volumetrically largest habitats on earth. Our primary objective was to examine ingestion patterns relative to trophic position and body size to identify the ecological drivers of microplastic movement(s) within a marine food web.

2. MATERIALS AND METHODS

2.1. Sample collection

All animals were collected from the greater Monterey Bay ecosystem during routine research cruises spanning the years 2015 to 2017. The majority of samples (~60%, 11 of 17 taxonomic groups; see Table 1) were collected near Midwater 1, a time-series site (36.7°N, 122.05°W; 1600 m deep) maintained by the Monterey Bay Aquarium Research Institute (MBARI; see Robison et al. 2017). Whole animal collections were made using samplers deployed on the remotely operated vehicle (ROV) 'Doc Ricketts' (200–4000 m operating depth range) and the ROV 'Ventana' (50–1850 m operating depth range). Additional animals were collected by oblique midwater trawling using a 3 m Tucker Trawl deployed to depths ranging from the surface to ~750 m.

Table 1. Animals examined for microparticle analysis. Mass (wet weight) and length measurements were taken prior to dissection. ROV: remotely operated vehicle; NR: not recorded

Taxonomic group	Animal type	Common name	Sampling method	No. of ind.	Mass range (g)	Length range (cm)
<i>Magallana gigas</i>	Mollusk	Pacific oyster	Local market	12	16.88–36.45	4.80–10.10
<i>Pyrosoma atlanticum</i>	Gelatinous	Sea pickle	Trawling	10	1.83–15.78	9.90–10.20
<i>Pleuroncodes planipes</i>	Crustacean	Pelagic red crab	Fishers	10	6.44–11.96	5.00–7.00
<i>Euphausia</i> sp.	Crustacean	Krill	Trawling	5	0.63–2.59	1.76–2.06
<i>Periphylla periphylla</i>	Gelatinous	Red helmet jellyfish	Trawling	7	0.11–5.54	0.35–1.75
<i>Sergestes similis</i>	Crustacean	Pacific sergestid	Trawling	28	0.10–0.58	0.70–2.20
<i>Pandalus platyceros</i>	Crustacean	California spot prawn	Local market	6	65.22–94.29	20.23–21.59
<i>Gnathophausia ingens</i>	Crustacean	Giant red mysid	Trawling	10	1.64–10.59	5.00–10.50
<i>Nanomia bijuga</i>	Gelatinous	Agalmid siphonophore	ROV	10	0.05–0.27	NR
<i>Doryteuthis opalescens</i>	Mollusk	California market squid	Local market	8	45.86–78.50	28.57–33.02
<i>Engraulis mordax</i>	Fish	Californian anchovy	Fishers and local market	10	11.72–23.57	11.70–15.20
<i>Cyclothone</i> sp.	Fish	Bristlemouth	Trawling	4	0.88–1.22	5.30
<i>Scomber japonicus</i>	Fish	Chub mackerel	Fishers	14	19.75–213.3	18.10–29.50
<i>Stenobranchius leucopsarus</i>	Fish	Northern lampfish	Trawling	9	1.61–4.35	5.20–7.75
<i>Bathylagus pacificus</i>	Fish	Deep-sea smelt	ROV	5	12.15–54.25	14.60–16.51
<i>Chauliodus macouni</i>	Fish	Pacific viperfish	Trawling	3	7.31–37.60	2.86–19.05
<i>Merluccius productus</i>	Fish	Pacific hake	ROV	5	40.37–48.58	19.10–20.60

At sea, using clean techniques (nitrile gloves and solvent-cleaned surfaces and collection tools), animals were identified with taxonomic keys and expertise, and individual body lengths were measured to the nearest millimeter. Whole organism samples were wrapped in combusted aluminum foil packets and kept frozen at -80°C until transport to the lab for particle analysis.

Highly mobile species were purchased and/or obtained whole from seafood wholesalers and local anglers based in Moss Landing, California, USA (~40% of samples, 6 of 17 taxonomic groups; see Table 1). Fishing locations were confirmed to be from within the Monterey Bay and were made across the same years (2015–2017) as the ROV and trawl-collected samples. All samples were wrapped in combusted aluminum foil and kept frozen at -80°C in the laboratory until microplastic processing and analysis.

2.2. Sample processing

Sample dissection and alkaline digestions were adapted from Foekema et al. (2013) and Rochman et al. (2015). Individual samples were removed from the freezer approximately 30 min prior to dissection to allow thawing, while remaining covered. In the laboratory, we weighed (wet mass) and measured the length of each individual organism (Table 1).

Digestion procedures were adjusted relative to the size of the organism. Smaller individuals less than ~2 cm body length, where the digestive tract could

not be properly extracted, were digested whole. For the majority of organisms larger than 2 cm, gastrointestinal (GI) tracts were dissected and the GI contents processed without the remainder of the carcass. Once the entire GI tract was removed, we carefully massaged the gut contents out of the digestive tract and into a clean, labeled 100 ml specimen vial (VWR specimen containers, polypropylene with polyethylene cap). Extracted gut contents or entire organisms were placed in a 3:1 liquid:organism ratio of a 20% potassium hydroxide solution in reverse-osmosis (RO) water for a 14 d digestion period to break down organic matter while leaving microplastics intact (Munno et al. 2018). When a visible lipid layer remained in the sample jar at 14 d, we transferred the contents to a 4% Alcojet detergent solution for an additional 24 h (Crichton et al. 2017). Samples were then sieved using a stainless steel 100 μm mesh sieve and transferred to a clean glass petri dish for microplastic sorting and quantification. Separate clean glass petri dishes were lined with clear plastic sheet (transparency paper) and strips of double-sided tape. We visually sorted and enumerated suspected microplastics and other anthropogenic particles using stereo microscopy (Stereo-microscope, AmScope), sorting particles by color and shape (i.e. fiber, bead, fragment) (Hidalgo-Ruz et al. 2012, MERI 2017) and placing each particle on the double-sided tape lined petri-dish. Each particle extracted from the sample was numbered. Individual particles were photographed with an IDS μEye camera (IDS) and measured using ImageJ software.

2.3. Chemical characterization

A subsample of suspected microplastics and other anthropogenic particles from each sample were analyzed using Raman spectroscopy with an Xplora Plus (Horiba Scientific) equipped with LabSpec6 software to determine material type. The spectra generated were compared to spectra in reference libraries from BioRad and inhouse libraries (Munno et al. 2020) with spectral peaks corresponding to known functional groups. This approach allows for identification of each particle to a specific material type. Raman spectroscopy of microparticles is labor intensive, and we utilized a subsampling method to analyze ~10% of the total particles via Raman spectroscopy spanning all colors, categories, and species (Huntington et al. 2020). In each sample, we chemically identified ~10% of the particles in each unique color/shape combination (e.g. blue fiber, red fragment). Particle counts were rounded up to whole numbers for subsampling purposes. In this manner, if a species had ingested one particle of a specific color/shape combination, the particle was included for Raman analysis.

In total, 18% (n = 122) of all suspected particles were analyzed via Raman spectroscopy. Of these, 81% were confirmed as anthropogenic (which includes microplastics), validating our ability to distinguish anthropogenic particles from natural particles under a dissecting microscope. Chemical identities were categorized by plastic type. In cases where the base polymer could not be identified, we categorized particles as anthropogenic cellulosic, natural particles, anthropogenic unknown, and unknowns. Dyed particles with a 'cotton' or 'cellulose' identity (e.g. blue cotton) were combined and classified as 'anthropogenic cellulosic'. 'Natural' particles include natural substances such as minerals. Conservatively, this category also includes white or clear particles with no dye match but a cellulosic or cotton match. Individual particles that were dyed (e.g. blue fiber), and produced a noisy spectrum, were classified as 'anthropogenic unknown'. When spectra could not be matched with anything in the library, particles were classified as 'unknown'.

2.4. Accounting for contamination

Quality control and clean techniques were employed while processing samples in the laboratory. To prevent procedural contamination, all laboratory technicians wore white cotton lab coats during dissection and quantification. Additionally, a sheet of

100 µm mesh was attached to the RO water faucet to decrease procedural contamination; by doing so, the microparticle concentration decreased from 7 to 2 particles per 300 ml. All sample cups and glassware were rinsed in triplicate using laboratory RO water. Potassium hydroxide solution was mixed in a fume hood and then covered with clean foil. All glassware was kept covered as much as possible during quantification and analysis. For every 10 samples, a laboratory blank with 30 ml of potassium hydroxide solution was included. Laboratory blanks (n = 15; 15 ml) were analyzed for microparticles using the same procedure described for animal tissues. The number of suspected microplastic particles found in laboratory blanks for each set of digestions were subtracted by color/shape from each sample within each corresponding digestion set. As a result of the 100 µm mesh added to the RO faucet, only 1 microparticle was identified across all blanks, which was subsequently subtracted out of the corresponding digestion set.

2.5. Statistical analyses

Microparticle data from all individuals (n = 157) were included in the statistical analysis, including those individuals without suspected anthropogenic microparticles found in their gut. A simple linear regression was used to determine the relationship between the number of anthropogenic microparticles per individual and body size. Individual regressions were done for both body mass and length. Regressions were completed for all taxa combined and each species individually. We used linear regression to determine the relationship between quantities of microparticles per individual within a specific taxon as well as trophic level for fish species only. Fish trophic position was derived from FishBase (Froese & Pauly 2019). All analyses were conducted in R (version 3.6.1).

3. RESULTS AND DISCUSSION

3.1. Microparticle ingestion was ubiquitous across taxa

Microplastics and other suspected anthropogenic microparticles (referred to as microparticles hereafter) were found in 96.4% of all samples, confirming that microparticles are widely ingested by organisms from diverse habitats, including the deep sea (Bergmann et al. 2017, Choy et al. 2019, Courtene-Jones

et al. 2019, Martinelli et al. 2020). A total of 680 ingested microparticles were characterized from 157 individual organisms spanning 17 genera which encompass a diversity of phyla including fishes (7 genera), crustaceans (5 genera), cephalopods (1 genus), mollusks (1 genus) and gelatinous zooplankton (3 genera). The average (\pm SD) number of microparticles found per individual organism across all genera was 4.2 (\pm 1.7) (range = 0–24 particles per individual), with fishes containing the highest number of identified microparticles on average (4.9 ± 2.4).

Of the total microparticles quantified, 84.7% were fibers, 14.4% were fragments, and 0.1% were beads (Fig. 1b). Fragments and fibers were found in all taxa spanning crustaceans, fishes, mollusks, and gelatinous zooplankton, whereas spherical beads were only found in fishes, gelatinous zooplankton, and mollusks. Of the fibers found, 72% were blue, which is consistent with the literature spanning a variety of ecosystems (Morgana et al. 2018, Nelms et al. 2018). Fibers are the predominant form of microplastics found in marine systems elsewhere (Desforges et al. 2014, Courtene-Jones et al. 2017, Martinelli et al.

2020); thus, the high count of microfibers across samples aligns with previous studies.

We examine patterns in microparticle size according to taxonomic group, feeding strategy and feeding location. Overall, we found that ingested microparticle size was unrelated to taxonomic group, with high variability both within and between groups (Fig. S1 in the Supplement; www.int-res.com/articles/suppl/m675p023_supp.pdf). The most common microparticle size range across taxonomic groups was 100–500 μ m (Fig. S1). We expected to see ingested particle size increase with animal size for higher trophic-level species, while decreasing in zooplanktivorous organisms that are directly ingesting microparticles. Our data do not support these predictions, as the size of ingested microparticles varied distinctly between taxonomic groups. Since we observed no discernable trends in increasing microparticle size with organism trophic level, our data suggest that trophic transfer occurs broadly. Finally, when organisms feed directly from a specific habitat (e.g. the seafloor, surface waters, midwaters), we would expect particle sizes to align with particle characteristics that have been observed in

that habitat. While our data did not allow us to assess this pattern, Choy et al. (2019) reported similar environmental microplastic sizes and material types ingested by filter-feeding zooplankton species from Monterey Bay.

Chemical categorization from the subsample of extracted microparticles revealed a range of material types (Fig. 2). Of the 122 microparticles analyzed by Raman spectroscopy, 81% were anthropogenic, 33% of which were confirmed microplastics, 26% matched a synthetic dye, 11% were deemed anthropogenic unknown, and 12% were anthropogenic cellulosic. Confirmed microplastics include polypropylene (7%), polyurethane (4%), polyethylene (4%), polyester (4%), and polyamide (4%). The following polymer types comprised less than 2% of the total number of particles analyzed: acrylonitrile butadiene, polycarbonate, polystyrene, polyterepene, polyvinyl acetate, polyvinyl chloride, and polyvinyl naphthalene. To simplify data visualization and highlight the more commonly identified material types, these polymers were combined and categorized as 'other plas-

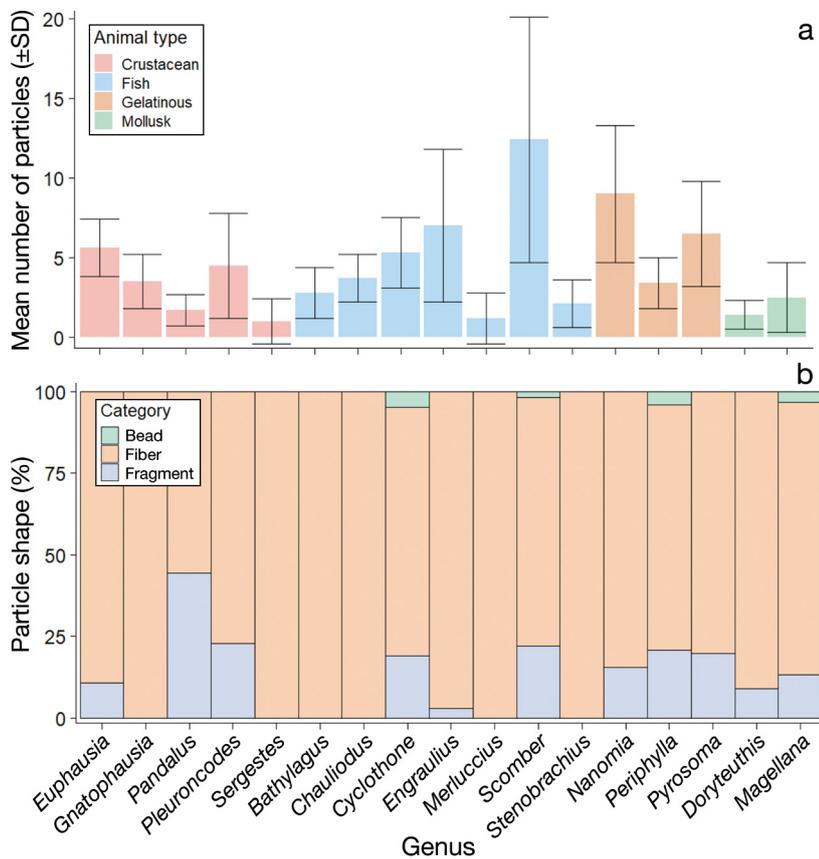


Fig. 1. (a) Mean (\pm SD) number of suspected anthropogenic microparticles per individual, according to taxonomic group. (b) Relative proportion of suspected anthropogenic microparticle morphologies found by genus

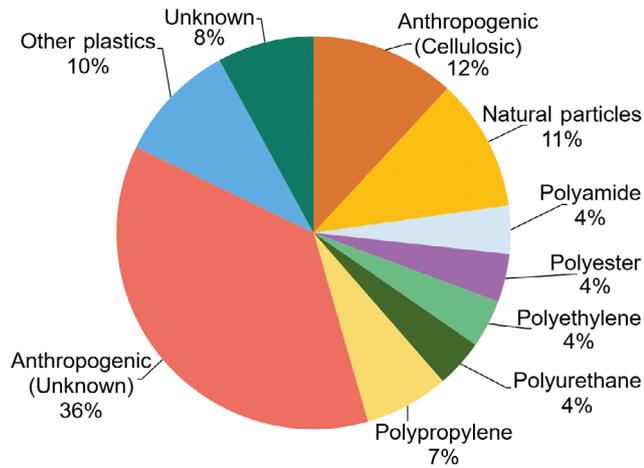


Fig. 2. Chemical identities of subsampled particles (N = 122) across all taxa. Polymer types comprising 2% or less of the total identified polymers across all taxa were grouped together and categorized as 'other plastics'

tics' (10%). The remaining 19% of microparticles were chemically identified as natural (11%) and unknown (8%).

Our combination of identified material types was similar to those identified in marine organisms from other ecosystems. For example, polyester is a commonly identified material type in deep-sea organisms (Carreras-Colom et al. 2018, Choy et al. 2019). Courtene-Jones et al. (2019) evaluated microplastics in deep-sea benthic invertebrates across 4 decades, and polyester was found throughout their sample time series (Courtene-Jones et al. 2019). It is worth noting that 48% of particles that could not be verified as microplastic were classified as anthropogenic, which includes anthropogenic cellulosic, identified synthetic dyes, and unknown origins with clear anthropogenic manipulations (i.e. dyed particles with noisy spectra due to high fluorescence). Athey et al. (2020) show that the microfibers from denim (often blue in coloration) are pervasive in samples ranging from the Canadian Arctic to the Great Lakes. Additionally, Jamieson et al. (2019) evaluated microplastics in amphipods from the Mariana Trench and reported 40% of microplastics as semi-synthetic cellulose fibers, which is higher than what we observed in our study (12%). Based on the purported high abundance of anthropogenic cellulosic microparticles in the environment, it is important to consider this alongside identified plastic material types.

3.2. Microparticles and trophic position

To assess anthropogenic microparticle fate in the food web, we explored the relationship between the trophic positions of fishes (retrieved from FishBase; Froese & Pauly 2019) and the amount of microparticles assessed per individual. We examined the extent of microparticle ingestion for fishes across distinct trophic positions to assess evidence of trophic transfer in the food web. A positive correlation would suggest that trophic transfer may be occurring in this food web and that biomagnification may occur at higher trophic levels. We completed the analysis for microplastic abundance and trophic position for fishes only, as the data available for the trophic positions of invertebrate taxa were insufficient. We found no relationship between microparticle abundance and estimated trophic position ($p > 0.05$; Fig. 3), suggesting that microplastic abundance does not increase with increasing trophic position (Farrell & Nelson 2013, Setälä et al. 2014, Watts et al. 2016, Nelms et al. 2018).

There is conflicting evidence in the literature as to whether microparticles accumulate in organisms and subsequently magnify within a food web. Our findings do not offer evidence to support trophic transfer, accumulation, and magnification, but we cannot say definitively whether trophic transfer occurs in the Monterey Bay submarine canyon pelagic food web. Other studies have inferred accumulation and magnification of microplastics from field-collected animals (D'Souza et al. 2020) or from laboratory feeding trials (Farrell & Nelson 2013, Setälä et al. 2014, Nelms et al. 2018). There is also evidence to suggest

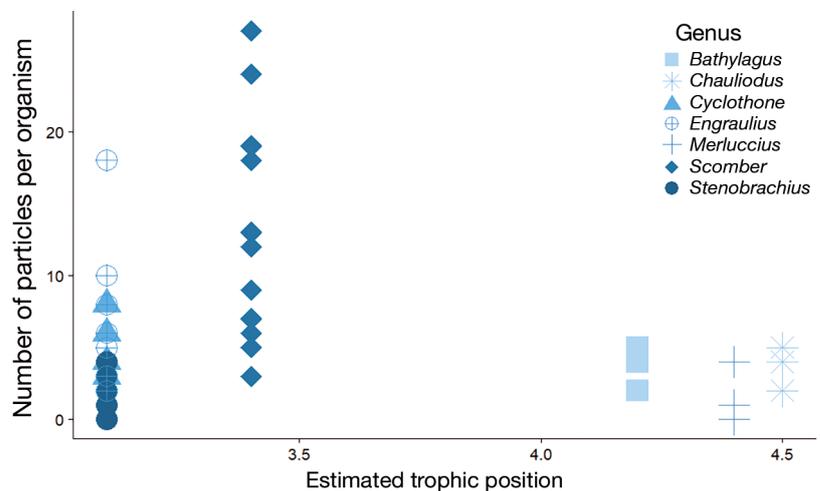


Fig. 3. Non-significant relationship between the number of microparticles per organism and estimated trophic position (estimated from FishBase; Froese & Pauly 2019) in fish genera sampled

that microparticles can translocate out of the gut and into the muscle tissues of fish (Zitouni et al. 2020). Particle size, polymer type, and species may influence translocation of particles and warrants further investigation. Furthermore, the physical and biological mechanisms need to be further evaluated to have a clear understanding of the fate of microparticles within a food web, and within individuals.

While trophic transfer of microplastics through known predator–prey feeding relationships and/or feeding modalities was not a primary objective of this study, there was a lack of notable findings for known predators and their prey in this study. For example, pyrosomes (mean 4.5 particles, $n = 10$) are holoplanktonic grazers that employ a filter-feeding strategy with high clearance rates and could thus come into contact with microplastics in the same size range as their natural food. Additionally, the mesopelagic fish taxa examined in this study span a wide range of trophic guilds ranging from zooplanktivores (e.g. *Stenobranchius leucopsaurus*, *Cyclothone* sp.) to carnivores (*Chauliodus* sp., *Merluccius productus*) and potential gelatinivores (e.g. *Bathylagus* sp.). However, no strong differences were found between these fish taxa and the average number of microplastic particles ingested. Instead, more mobile and shallow-dwelling fishes such as *Engraulis* and *Scomber* had the highest average number of microplastic particles (7 and 12.4, respectively), suggesting that ecological factors other than feeding relationships and feeding style were likely to influence microplastic burdens.

3.3. Microparticle abundance and body size

To assess variability in microparticle ingestion by taxonomic group, we examined the relationship between the total number of microparticles ingested and organism body size (length and weight). We observed no relationship between microparticle ingestion and body length across taxonomic groups ($p > 0.05$; $r^2 = 0.009$; Fig. S2). On the contrary, we did observe a positive and significant correlation between ingested microparticles and body mass across all taxonomic groups ($p < 0.0001$; $r^2 = 0.21$; Fig. 4), although the amount of variation explained was modest and unevenly distributed across taxonomic groups.

To better understand this trend, we ran linear regression analysis for body length and weight and the number of microparticles ingested across all fish and crustacean taxa grouped together, and each species individually. A positive relationship would suggest that microparticle ingestion and body size are relevant factors to these taxonomic groupings. There was a positive, significant relationship between microparticle abundance and both body length ($p < 0.0001$; $r^2 = 0.3$) and body mass ($p < 0.0001$; $r^2 = 0.4$) across all fishes and crustaceans (Fig. 5a,b). We then tested each species individually and found the relationship was only significant in *Scomber* sp. for body length ($p < 0.01$; $r^2 = 0.5$; Table S1). *Scomber* sp. ($p < 0.001$; $r^2 = 0.5$) and *Pleuroncodes planipes* ($p < 0.05$; $r^2 = 0.4$) both demonstrated a significant relationship between microparticle ingestion and body mass (Table S2). If *Scomber* sp. is removed from each regression analysis, these significant trends are no longer present (Fig. 5c,d), suggesting that *Scomber* drives the observed relationship.

We attribute the positive relationship between microplastics and body size in *Scomber* to the larger number of individuals analyzed and its unique life history. More individuals of *Scomber* sp. were sampled than most other genera ($n = 14$), while also spanning a larger gradient in overall body size. *S. japonicus* (chub mackerel) is a fast-swimming, coastal–pelagic species with a wide distribution along warm and temperate waters of the Indo-Pacific (Scoles et al. 1998, Infante et al. 2007, Catanese et al. 2010). Chub mackerel are known to migrate along the California Current Ecosystem ranging from British Columbia, Canada, to Baja California, Mexico

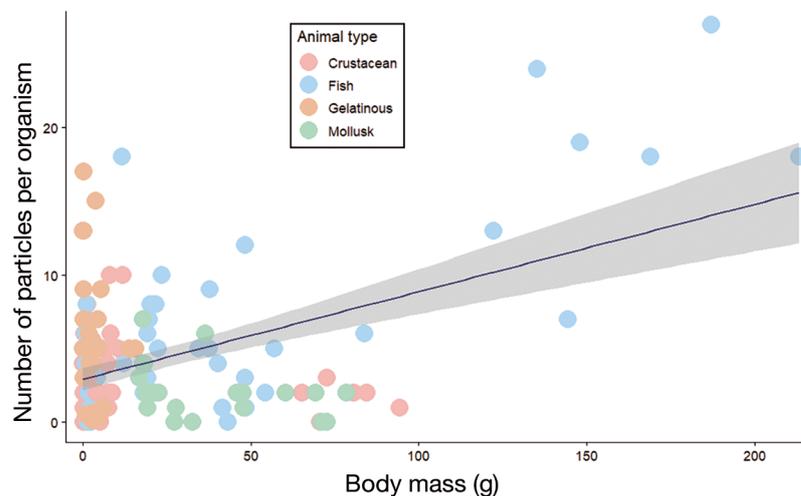


Fig. 4. A positive, significant relationship was observed between body mass and the number of microparticles identified per organism according to taxonomic group ($p = 4.732 \times 10^{-10}$, $r^2 = 0.2182$; grey shading indicates 95 %CI)

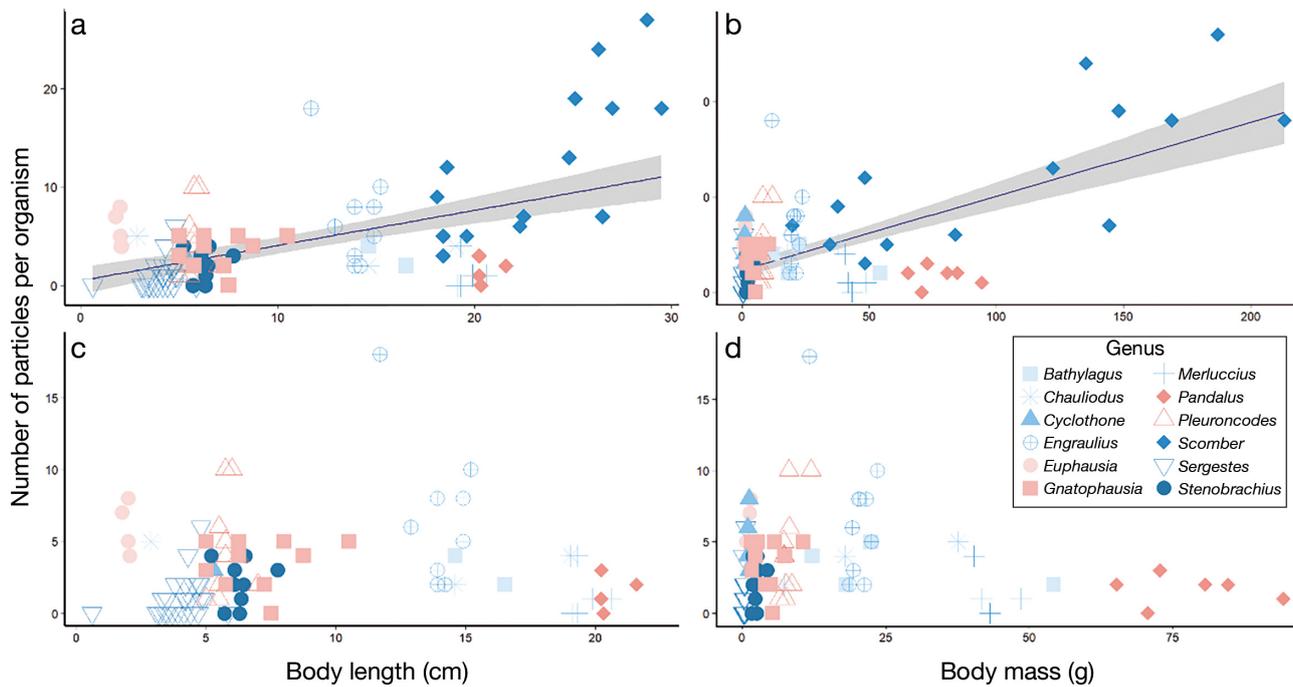


Fig. 5. (a) Significant relationship between body length and the number of microparticles ($p = 3.0367 \times 10^{-9}$, $r^2 = 0.2926$; grey shading indicates 95%CI) identified in crustacean (red) and fish (blue) genera. (b) Significant relationship between body mass and the number of microparticles ($p = 5.594 \times 10^{-15}$, $r^2 = 0.4355$) identified in crustacean and fish genera. (c) Non-significant relationship between body length and the number of microparticles ($p = 0.3603$, $r^2 = 0.0057$) identified in crustacean and fish genera with the omission of *Scomber* sp. (d) Non-significant relationship between body mass and the number of microparticles ($p = 0.8672$, $r^2 = 0.0003$) identified in crustacean and fish genera with the omission of *Scomber* sp.

(Schaefer 1980). Based on their wide distribution, coastal migrations, and diurnal feeding behaviors (Collette & Nauen 1983), chub mackerel swim across waters draining multiple densely populated metropolitan areas along the west coast of North America, which may result in higher exposure to anthropogenic microparticles. Pereira et al. (2020) report a range of 1–4 microparticles in *S. colias*, while Herrera et al. (2019) found 1–9 microparticles in *S. colias*, both ranges lower than our finding of 3–27 microparticles in *S. japonicus* (Table S3). *S. colias* is the Atlantic Ocean species, which is genetically and ecologically different than its Indo-Pacific relative (Catanese et al. 2010), so differences could be attributed to ecology, region, or other factors. However, high plastic loading in *Scomber* could have implications for predatory pelagic fishes, seabirds, and marine mammals that consume *Scomber* (e.g. *Stenobrachius leucopsaurus*; Duffy et al. 2017).

This general trend for increasing body size and microplastic ingestion is not yet well examined in the literature, but large-scale meta-analyses suggest that body length accounts for much of the variance in the length of plastic particles that animals ingest (Jåms et al. 2020). Similar to our study, McNeish et al. (2018)

report a similar relationship in fish species from the Great Lakes, while also stating that a single species drove the overall trend between body size and microparticle ingestion. While it is likely that multiple, interacting ecological factors drive plastic ingestion in the wild, future work should move beyond the simple linear models we use to examine ingestion trends within a limited dataset.

4. CONCLUSIONS AND FUTURE WORK

We determined that microplastics and other anthropogenic particles are ubiquitous within a well-defined deep-pelagic marine food web, in congruence with studies that document microplastic ingestion across a wide variety of taxa and trophic levels elsewhere. The abundance of particles ingested were unrelated to taxonomic groups and trophic position of fish species, suggesting that trophic transfer may not be occurring. Moreover, particle ingestion amounts did not increase with increasing trophic position in fish species, suggesting that microparticle accumulation and magnification do not occur within the gut. Instead, we saw a positive correlation between body

length and microparticle abundance, as well as between body mass and microparticle abundance, suggesting that body size can predict the number of microparticles that can be found within the gut of an aquatic organism. However, this trend varies across genera and was principally driven by 2 taxa (*Scomber* sp. and *Pleuroncodes planipes*), suggesting that large size gradients are necessary to quantify the strength of this relationship, which may also be driven by life history characteristics (e.g. behavior, migration). Evaluating gut content is not an exhaustive means for determining the biological fate of microplastics in organisms and food webs. Further evaluation of the tissue would help us better understand other physiological pathways (i.e. bioaccumulation, biomagnification, and biodilution), to bolster our understanding of how these anthropogenic particles move through organisms and accompanying food webs. Strengthening our knowledge of the biological fate of microplastics will lead to a more comprehensive understanding of ecological effects at different levels of biological organization.

Acknowledgements. This research was supported by the David and Lucile Packard Foundation and through contributions to the Monterey Bay Aquarium. We thank the pilots of ROV 'Ventana' and ROV 'Doc Ricketts', and the crews of R/Vs 'Rachel Carson' and 'Western Flyer'. C.A.C. was supported by the L'Oréal USA Fellowship for Women in Science. We thank John Kelly of Loyola University Chicago for the use of his laboratory to process these samples. Real Good Fish was very helpful in assisting with commercial samples from Monterey Bay. We thank Jared Figurski for his assistance in collecting samples and Joe Biggs for his assistance in photographing particles.

LITERATURE CITED

- Athey SN, Albotra SD, Gordon CA, Monteleone B and others (2020) Trophic transfer of microplastics in an estuarine food chain and the effects of a sorbed legacy pollutant. *Limnol Oceanogr Lett* 5:154–162
- Bergmann M, Wirzberger V, Krumpfen T, Lorenz C, Primpke S, Tekman MB, Gerdtz G (2017) High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN Observatory. *Environ Sci Technol* 51: 11000–11010
- Brahney J, Hallerud M, Heim E, Hahnenberger M, Sukumaran S (2020) Plastic rain in protected areas of the United States. *Science* 368:1257–1260
- Brandon JA, Freibott A, Sala LM (2020) Patterns of suspended and salp-ingested microplastic debris in the North Pacific investigated with epifluorescence microscopy. *Limnol Oceanogr Lett* 5:46–53
- Bråte ILN, Eidsvoll DP, Steindal CC, Thomas KV (2016) Plastic ingestion by Atlantic cod (*Gadus morhua*) from the Norwegian coast. *Mar Pollut Bull* 112:105–110
- Carreras-Colom E, Constenla M, Soler-Membrives A, Cartes JE, Baeza M, Padrós F, Carrassón M (2018) Spatial occurrence and effects of microplastic ingestion on the deep-water shrimp *Aristeus antennatus*. *Mar Pollut Bull* 133:44–52
- Carter GS, Gregg MC, Lien RC (2005) Internal waves, solitary-like waves, and mixing on the Monterey Bay shelf. *Cont Shelf Res* 25:1499–1520
- Catanese G, Machado M, Infante C (2010) Evolutionary relatedness of mackerels of the genus *Scomber* based on complete mitochondrial genomes: strong support to the recognition of Atlantic *Scomber colias* and Pacific *Scomber japonicus* as distinct species. *Gene* 452:35–43
- Chagnon C, Thiel M, Antunes J, Ferreira JL, Sobral P, Ory NC (2018) Plastic ingestion and trophic transfer between Easter Island flying fish (*Cheilopogon rapanouiensis*) and yellowfin tuna (*Thunnus albacares*) from Rapa Nui (Easter Island). *Environ Pollut* 243:127–133
- Chiba S, Saito H, Fletcher R, Yogi T and others (2018) Human footprint in the abyss: 30-year records of deep-sea plastic debris. *Mar Policy* 96:204–212
- Choy CA, Drazen JC (2013) Plastic for dinner? Observations of frequent debris ingestion by pelagic predatory fishes from the central North Pacific. *Mar Ecol Prog Ser* 485:155–163
- Choy CA, Portner E, Iwane M, Drazen JC (2013) Diets of five important predatory mesopelagic fishes of the central North Pacific. *Mar Ecol Prog Ser* 492:169–184
- Choy CA, Haddock SHD, Robison BH (2017) Deep pelagic food web structure as revealed by *in situ* feeding observations. *Proc Biol Sci* 284:20172116
- Choy CA, Robison BH, Gagne TO, Erwin B and others (2019) The vertical distribution and biological transport of marine microplastics across the epipelagic and mesopelagic water column. *Sci Rep* 9:7843
- Collette BB, Nauen CE (1983) *Scombrids of the world, Vol. 2. An annotated and illustrated catalogue of tunas, mackerels, bonitos and related species known to date.* FAO species catalogue. Food and Agriculture Organization of the United Nations, Rome
- Courtene-Jones W, Quinn B, Gary SF, Mogg AOM, Narayanaswamy BE (2017) Microplastic pollution identified in deep-sea water and ingested by benthic invertebrates in the Rockall Trough, North Atlantic Ocean. *Environ Pollut* 231:271–280
- Courtene-Jones W, Quinn B, Ewins C, Gary SF, Narayanaswamy BE (2019) Consistent microplastic ingestion by deep-sea invertebrates over the last four decades (1976–2015), a study from the north east Atlantic. *Environ Pollut* 244:503–512
- Cózar A, Echevarria F, Gonzalez-Gordillo JI, Irigoien X and others (2014) Plastic debris in the open ocean. *Proc Natl Acad Sci USA* 111:10239–10244
- Crichton EM, Noël M, Gies EA, Ross PS (2017) A novel, density-independent and FTIR-compatible approach for the rapid extraction of microplastics from aquatic sediments. *Anal Methods* 9:1419–1428
- D'Souza JM, Windsor FM, Santillo D, Ormerod SJ (2020) Food web transfer of plastics to an apex riverine predator. *Glob Chang Biol* 26:3846–3857
- Davison P, Asch RG (2011) Plastic ingestion by mesopelagic fishes in the North Pacific Subtropical Gyre. *Mar Ecol Prog Ser* 432:173–180
- Desforges JPW, Galbraith M, Dangerfield N, Ross PS (2014) Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. *Mar Pollut Bull* 79: 94–99

- Desforges JPW, Galbraith M, Ross PS (2015) Ingestion of microplastics by zooplankton in the northeast Pacific Ocean. *Arch Environ Contam Toxicol* 69:320–330
- Dris R, Gasperi J, Saad M, Mirande C, Tassin B (2016) Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? *Mar Pollut Bull* 104:290–293
- Duffy LM, Kuhnert PM, Pethybridge HR, Young JW and others (2017) Global trophic ecology of yellowfin, bigeye, and albacore tunas: understanding predation on micronekton communities at ocean-basin scales. *Deep Sea Res II* 140:55–73
- Eriksen M, Lebreton LCM, Carson HS, Thiel M and others (2014) Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLOS ONE* 9:e111913
- Farrell P, Nelson K (2013) Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.). *Environ Pollut* 177:1–3
- Foekema EM, De Gruijter C, Mergia MT, Van Franeker JA, Murk AJ, Koelmans AA (2013) Plastic in North Sea fish. *Environ Sci Technol* 47:8818–8824
- Foley CJ, Feiner ZS, Malinich TD, Höök TO (2018) A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. *Sci Total Environ* 631–632: 550–559
- Froese F, Pauly D (2019) FishBase. www.fishbase.org (accessed 1 July 2019)
- Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. *Sci Adv* 3:e1700782
- Herrera A, Štindlová A, Martínez I, Rapp J and others (2019) Microplastic ingestion by Atlantic chub mackerel (*Scomber colias*) in the Canary Islands coast. *Mar Pollut Bull* 139:127–135
- Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environ Sci Technol* 46:3060–3075
- Huntington A, Corcoran PL, Jantunen L, Thaysen C, Bernstein S, Stern GA, Rochman CM (2020) A first assessment of microplastics and other anthropogenic particles in Hudson Bay and the surrounding eastern Canadian Arctic waters of Nunavut. *Facets* 5:432–454
- Infante C, Blanco E, Zuasti E, Crespo A, Machado M (2007) Phylogenetic differentiation Atlantic *Scomber colias* and Pacific *Scomber japonicus* based on nuclear DNA sequences. *Genetica* 130:1–8
- Jamieson AJ, Brooks LSR, Reid WDK, Pierny SB, Narayanaswamy BE, Linley TD (2019) Microplastics and synthetic particles ingested by deep-sea amphipods in six of the deepest marine ecosystems on Earth. *R Soc Open Sci* 6:180667
- Jåms IB, Windsor FM, Poudevigne-Durance T, Ormerod SJ, Durance I (2020) Estimating the size distribution of plastics ingested by animals. *Nat Commun* 11:1594
- Kane IA, Clare MA, Miramontes E, Wogelius R, Rothwell JJ, Garreau P, Pohl F (2020) Seafloor microplastic hotspots controlled by deep-sea circulation. *Science* 368:1140–1145
- Katija K, Choy CA, Sherlock RE, Sherman AD, Robison BH (2017) From the surface to the seafloor: how giant larvae transport microplastics into the deep sea. *Sci Adv* 3:e1700715
- Kühn S, Bravo Rebolledo EL, van Franeker JA (2015) Deleterious effects of litter on marine life. In: Bergmann M, Gutow L, Klages M (eds) *Marine anthropogenic litter*. Springer International Publishing, Cham, p 75–116
- López-López L, Preciado I, González-Irusta JM, Arroyo NL, Muñoz I, Punzón A, Serrano A (2018) Incidental ingestion of meso- and macro-plastic debris by benthic and demersal fish. *Food Webs* 14:1–4
- Lusher AL, Tirelli V, O'Connor I, Officer R (2015) Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. *Sci Rep* 5:14947
- Marine & Environmental Research Institute (2017) Guide to microplastic identification. Marine & Environmental Research Institute – Center for Environmental Studies, Blue Hill, ME
- Markic A, Gaertner JC, Gaertner-Mazouni N, Koelmans AA (2020) Plastic ingestion by marine fish in the wild. *Crit Rev Environ Sci Technol* 50:657–697
- Martinelli JC, Phan S, Luscombe CK, Padilla-Gamiño JL (2020) Low incidence of microplastic contaminants in Pacific oysters (*Crassostrea gigas* Thunberg) from the Salish Sea, USA. *Sci Total Environ* 715:136826
- Martini S, Haddock SHD (2017) Quantification of bioluminescence from the surface to the deep sea demonstrates its predominance as an ecological trait. *Sci Rep* 7:45750
- McNeish RE, Kim LH, Barrett HA, Mason SA, Kelly JJ, Hoellein TJ (2018) Microplastic in riverine fish is connected to species traits. *Sci Rep* 8:11639
- Moore RC, Loseto L, Noel M, Etemadifar A and others (2020) Microplastics in beluga whales (*Delphinapterus leucas*) from the eastern Beaufort Sea. *Mar Pollut Bull* 150:110723
- Morgana S, Ghigliotti L, Estévez-Calvar N, Stifanese R and others (2018) Microplastics in the Arctic: a case study with sub-surface water and fish samples off northeast Greenland. *Environ Pollut* 242:1078–1086
- Munno K, Helm PA, Jackson DA, Rochman C, Sims A (2018) Impacts of temperature and selected chemical digestion methods on microplastic particles. *Environ Toxicol Chem* 37:91–98
- Munno K, De Frond H, O'Donnell B, Rochman CM (2020) Increasing the accessibility for characterizing microplastics: introducing new application-based and spectral libraries of plastic particles (SLoPP and SLoPP-E). *Anal Chem* 92:2443–2451
- Nelms SE, Galloway TS, Godley BJ, Jarvis DS, Lindeque PK (2018) Investigating microplastic trophic transfer in marine top predators. *Environ Pollut* 238:999–1007
- Pereira JM, Rodríguez Y, Blasco-Monleon S, Porter A, Lewis C, Pham CK (2020) Microplastic in the stomachs of open-ocean and deep-sea fishes of the north-east Atlantic. *Environ Pollut* 265:115060
- Provencher JF, Ammendolia J, Rochman CM, Mallory ML (2019) Assessing plastic debris in aquatic food webs: what we know and don't know about uptake and trophic transfer. *Environ Rev* 27:304–317
- Robison BH, Sherlock RE, Reisenbichler KR (2010) The bathypelagic community of Monterey Canyon. *Deep Sea Res II* 57:1551–1556
- Robison B, Reisenbichler K, Sherlock R (2017) The coevolution of midwater research and ROV technology at MBARI. *Oceanography (Wash DC)* 30:26–37
- Rochman CM, Tahir A, Williams SL, Baxa DV and others (2015) Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Sci Rep* 5:14340
- Rochman CM, Brookson C, Bikker J, Djuric N and others (2019) Rethinking microplastics as a diverse contaminant suite. *Environ Toxicol Chem* 38:703–711

- Schaefer KM (1980) Synopsis of biological data on the chub mackerel, *Scomber japonicus* Houttuyn, 1782, in the Pacific Ocean. Spec Rep Inter-Am Trop Tuna Comm 2: 395–446
- Scoles DR, Collette BB, Graves JE (1998) Global phylogeography of mackerels of the genus *Scomber*. Fish Bull 96: 823–841
- ✦ Setälä O, Fleming-Lehtinen V, Lehtiniemi M (2014) Ingestion and transfer of microplastics in the planktonic food web. Environ Pollut 185:77–83
- ✦ Suaria G, Achtypi A, Perold V, Lee JR and others (2020) Microfibers in oceanic surface waters: a global characterization. Sci Adv 6:eaay8493
- ✦ Van Houtan KS, Francke DL, Alessi S, Jones TT and others (2016) The developmental biogeography of hawksbill sea turtles in the North Pacific. Ecol Evol 6: 2378–2389
- ✦ Watts AJR, Urbina MA, Goodhead R, Moger J, Lewis C, Galloy TS (2016) Effect of microplastic on the gills of the shore crab *Carcinus maenas*. Environ Sci Technol 50: 5364–5369
- ✦ Wieczorek AM, Morrison L, Croot PL, Allcock AL and others (2018) Frequency of microplastics in mesopelagic fishes from the northwest Atlantic. Front Mar Sci 5:1–9
- ✦ Wilcox C, Puckridge M, Schuyler QA, Townsend K, Hardisty BD (2018) A quantitative analysis linking sea turtle mortality and plastic debris ingestion. Sci Rep 8:12536
- ✦ Woodall LC, Sanchez-Vidal A, Canals M, Paterson GLJ and others (2014) The deep sea is a major sink for microplastic debris. R Soc Open Sci 1:140317
- ✦ Worm B, Lotze HK, Jubinville I, Wilcox C, Jambeck J (2017) Plastic as a persistent marine pollutant. Annu Rev Environ Resour 42:1–26
- ✦ Zhang Y, Gao T, Kang S, Sillanpää M (2019) Importance of atmospheric transport for microplastics deposited in remote areas. Environ Pollut 254:112953
- ✦ Zitouni N, Bousserhine N, Belbekhouche S, Missawi O, Alphonse V, Boughatass I, Banni M (2020) First report on the presence of small microplastics ($\leq 3 \mu\text{m}$) in tissue of the commercial fish *Serranus scriba* (Linnaeus, 1758) from Tunisian coasts and associated cellular alterations. Environ Pollut 263:114576

Editorial responsibility: Stephen Wing,
Dunedin, New Zealand
Reviewed by: D. Amon, B. Allan

Submitted: December 20, 2020

Accepted: July 29, 2021

Proofs received from author(s): September 28, 2021