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Microplastics and seafood: lower trophic organisms at highest risk of contamination

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Abstract

Microplastic debris is a prevalent global pollutant that poses a risk to marine organisms and ecological processes. It is also suspected to pose a risk to marine food security; however, these risks are currently poorly understood. In this review, we seek to understand the current knowledge pertaining to the contamination of commercially important fished and farmed marine organisms with microplastics, with the aim of answering the question "Does microplastic pollution pose a risk to marine food security?". A semi-systematic review of studies investigating the number of microplastics found in commercially important organisms of different trophic levels suggests that microplastics do not biomagnify, and that organisms at lower trophic levels are more likely to contaminated by microplastic pollution than apex predators. We address the factors that influence microplastic consumption and retention by organisms. This research has implications for food safety and highlights the risks of microplastics to fisheries and aquaculture, and identifies current knowledge gaps within this research field.

Keywords

Plastic; Food security; Aquaculture; Trophic transfer; Biomagnification

Highlights

- Microplastic contamination of commercially important marine and aquaculture species was assessed
- We provide evidence that microplastics do not biomagnify
- Microplastics are more prevalent in lower trophic organisms
- There is currently insufficient evidence to consider risks to human health

1. Introduction

Microplastics are a ubiquitous global contaminant, identified throughout the marine environment, including seawater, sediment and biota (Cole *et al.*, 2011; Law and Thompson, 2014). Microplastics describe tiny plastic particulates, although a coherent definition remains under debate, especially in terms of their size (Frias and Nash, 2019; Hartmann *et al.*, 2019). For the purposes of this review, we refer to microplastics and nanoplastics as synthetic solid particles or polymer matrices, with at least one dimension ranging 0.1 µm–1 mm. The literature describes microplastic shapes in a myriad of different ways, from spheres, beads and fragments, to films, filaments and fibres; for consistency, we here opt for using the terms “bead” (any spherical plastic), “fibre” (plastic threads such as those used in clothing), or “fragment” (irregularly shaped particulates). Microplastics can be further classified based on their origin: primary microplastics are manufactured in the micro size range, and include cosmetic microbeads, pre-production pellets and industrial scrubbers; secondary microplastics are formed by the breakdown of macroplastics within the environment (Andrady, 2017). Microplastic fibres have been identified as a particular concern for the environment, owing to their abundance and bioavailability, with research suggesting that microplastic fibres can contribute up to 91% of all plastics collected in global seawater samples (Barrows, Cathey and Petersen, 2018).

Plastic production has increased rapidly since its inception, with an estimated 8.3 billion metric tonnes of virgin plastic produced to date. Approximately 4.6 billion metric tonnes of this (55%) has been produced since 2000 (Geyer, Jambeck and Law, 2017). Microplastics enter the marine ecosystem through many different pathways, including riverine transport, sewage and wastewater effluent, direct release (e.g. from shipping and ports) and atmospheric deposition (Boucher and Friot, 2017). Plastics are incredibly durable,, and rather than undergoing a straightforward process of mineralization in the marine environment, plastics first degrade into smaller and smaller pieces, eventually forming micro- and nanoplastics (Andrady, 1998, 2011). Microplastic debris can travel vast distances via oceanic currents and winds, impinging on remote habitats including mid-oceanic islands and the polar ice caps (Barnes *et al.*, 2009; Peeken *et al.*, 2018). Sinks of microplastics include the ocean gyres, sediments, shorelines, polar sea ice, and biota, including animals destined for human consumption (Hardesty *et al.*, 2017; Peeken *et al.*, 2018). Whilst there are efforts to remove microplastics from the marine environment, it is widely accepted that once released, it is practically and economically infeasible to recapture marine microplastics for recycling or responsible disposal.

Microplastics pose a risk to marine life and ecological processes (Galloway, Cole and Lewis, 2017), and it has been suggested they may further impact on food security (Barboza *et al.*, 2018a), socio-economic wellbeing (Beaumont *et al.*, 2019) and human health (Galloway, 2015). The perceived risks, pathways, effects, and consequences arising from microplastic pollution on food security and ecosystem health in the marine environment are displayed in Fig. 1.

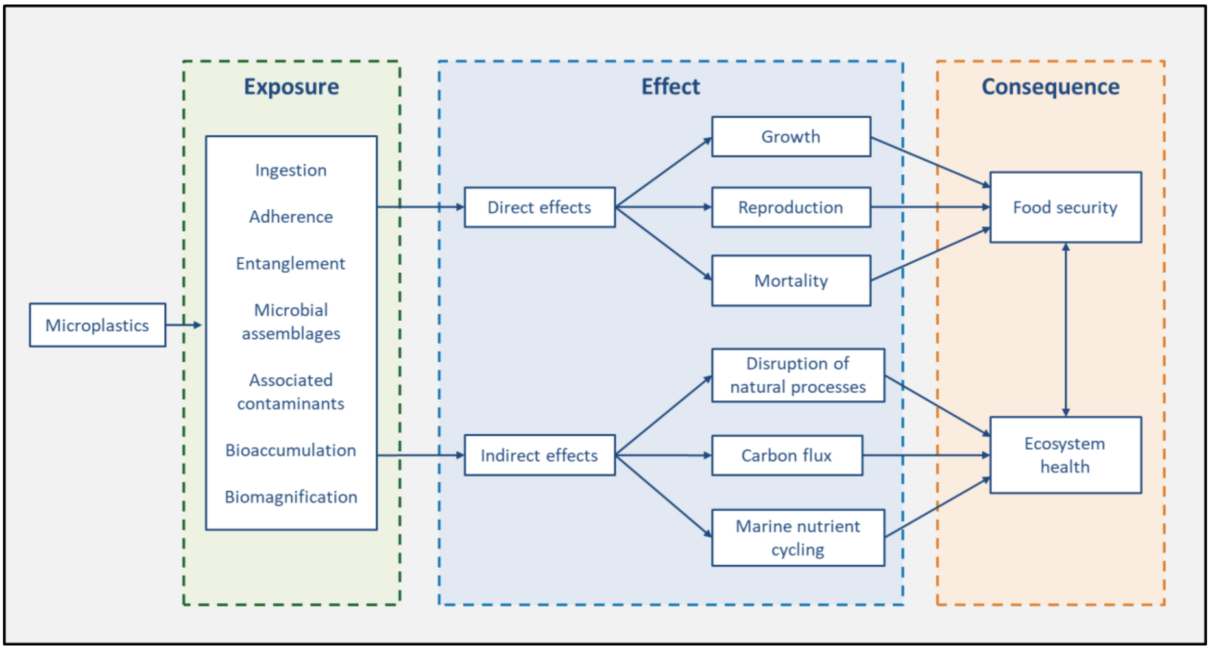

Fig. 1. Perceived impact pathways of microplastics on food security and ecosystem health.

1.1 Marine food security

Fisheries and aquaculture provide a critical proportion of the world's food supply, providing over 4.5 billion people with at least 15% of their average per capita intake of animal protein (Béné *et al.*, 2015), and production is predicted to grow in the future, from 171 million tonnes in 2016 to approximately 201 million tonnes in 2030, an increase of 17.5% (FAO, 2018). Global fish exports in 2017 were valued at 152 billion USD (FAO, 2018). Total capture from fisheries has remained fairly constant since the 1990s and is not expected to increase considerably, with growth instead expected from aquaculture, predominantly in Asia, which as a continent accounts for almost two thirds of global fish consumption

(Béné *et al.*, 2015). The FAO predicts that aquaculture production will reach 109 million tonnes in 2030 (FAO, 2018).

Food security is defined by the Food and Agriculture Organisation as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO *et al.*, 2017). Current identified risks to food security include climate variability due to both short-term events and climate change, eutrophication, ocean acidification, oxygen depletion, conflict, economic recession, pathogens, and pollution (Chakraborty and Newton, 2011; Wollenberg *et al.*, 2016). Larger plastic debris, particularly derelict fishing gear (i.e. abandoned or lost nets, lines, pots), has been shown to pose a substantial risk to food security. For example, in Chesapeake Bay the removal of 34,408 derelict fishing pots led to the harvest of an additional 13,504 metric tonnes in blue crab (*Callinectes sapidus*) valued at 21.3 million USD (Scheld, Bilkovic and Havens, 2016). However, whilst there has been considerable research into the effects of microplastics on marine organisms, evidence is lacking on the effect of microplastics on food security and food safety. We hypothesise that in marine ecosystems already affected by a multitude of environmental stressors, microplastics may represent a significant additional risk to food security.

In this review, we critically assess microplastics research with relevance to fishing and aquaculture, the health of commercially exploited organisms, and food security; to understand the current state of microplastics research and evaluate whether microplastics pose a risk to food security. Several marine pollutants are known to biomagnify, causing heightened risk to higher trophic organisms, however, very little research is available to show whether this may occur with microplastics, with current research giving opposing viewpoints (GESAMP, 2016; Akhbarizadeh, Moore and Keshavarzi, 2019; Hantoro *et al.*, 2019). We evaluate currently available data regarding microplastic content within organisms of different trophic levels to assess whether biomagnification is likely to be a risk with microplastic contamination. Current research gaps will also be discussed to highlight areas where unknown risks may threaten marine food security and human health.

2. Methods

2.1 Sourcing reference material

In order to investigate the prevalence of microplastics in commercially exploited marine organisms, including fish, shellfish, crustaceans and macroalgae, we undertook a semi-systematic review of the scientific literature, performed by using a specific set of search terms separated by Boolean operators

(Table 1), utilising the academic literature search engines *Web of Science*, *ScienceDirect*, *Pubmed* and *PLOS ONE*. This search method was supplemented by use of a snowballing method, where further literature was identified in the references of the articles reviewed to encompass the broadest set of literature. Only articles published up to the end of 2018 were included in the data analysis in this review. See Table 2 for a summary of the number of articles found from each search engine. These articles were considered for relevant information and subjected to a quality control step (see below); literature that passed this stage was utilised in this review.

Table 1. Search terms and Boolean operators used in the identification of scientific literature.

Search term	**Boolean operator**	**Search term**
Microplastic Microplastic pollution Marine microplastic	AND OR	Food security Food Marine Health Fish (including individual species searches) Effect Shellfish (including individual species searches) Bivalve (including individual species searches) Organism

Table 2. Relevant literature identified through searches of different academic literature search engines

Academic search engine	**Results retrieved**
Web of Science	955
ScienceDirect	1516
PubMed	668
PLOS ONE	46

2.2 Quality control

The primary literature from which data was extracted for analysis had been peer-reviewed prior to publication, providing a base level of quality assurance. We additionally conducted a quality assessment to verify that: (1) experimental replication was performed for statistical analysis; and (2) suitable controls were implemented in the study protocol (e.g. negative controls in toxicity testing, procedural blanks, and contamination controls in environmental analyses). If any of these quality control parameters was not met, the literature was not included in this review. After these steps, the identified literature was cross-referenced with available data showing organisms of global importance to aquaculture and fisheries. Following further narrowing of studies to select those that analysed organisms of commercial importance, 32 pieces of literature were selected to ascertain the data presented in this review.

2.3 Data analysis

In the literature data is typically presented as the number of microplastics per individual (MP/individual) for fish, or microplastics per gram (wet weight, w. w.) (MP/gram) for shellfish. For assessing whether microplastics biomagnify within lower trophic level organisms it was necessary to convert MP/individual values by ascertaining mean wet weights for individual species, drawn from primary and grey literature. MP/gram w. w. values were subsequently estimated by dividing average microplastics per organism by the average mass of that organism as reported in the literature (see Table S1 for further information).

3. Results

3.1 Risks to food security

3.1.1 Prevalence of microplastics in commercially exploited species

Microplastics can be ingested by a wide range of marine life, and the presence of microplastics in marine organisms destined for human consumption has been widely reported. Tables 3 and 4 below show the 10 most caught marine species and 10 most farmed aquaculture species in 2016 (FAO, 2018), alongside evidence of their capacity to ingest microplastic debris. 60% of the most farmed aquaculture species have been investigated for the presence of microplastics, and 80% of the most caught marine species have been investigated. The organisms that are not mentioned in any microplastic ingestion studies up to the end of 2018 represented a total of approximately 22.5 million tonnes of food in 2016.

Table 3. 10 most cultured aquaculture species in 2016 (data from FAO, 2018). NIF = no information found.

Common name	**Species name**	**Production (thousand tonnes, 2016)**	**Habitat**	**Feeding strategy**	**Microplastic ingestion reference**
Grass carp	*Ctenopharyngodon idellus*	6 068	Freshwater	Herbivorous	NIF

Silver carp	*Hypophthalmichthys molitrix*	5 301	Freshwater	Planktivorous	Jabeen *et al.*, 2017
Cupped oysters NEI	*Crassostrea spp.*	4 864	Estuarine	Filter feeder	Van Cauwenberghe and Janssen, 2014; Rochman *et al.*, 2015; Phuong *et al.*, 2018; Waite, Donnelly and Walters, 2018
Common carp	*Cyprinus carpio*	4 557	Freshwater	Omnivorous	Jabeen *et al.*, 2017
Japanese carpet shell	*Ruditapes philippinarum*	4 229	Seawater and estuarine	Filter feeder	Li *et al.*, 2015
Nile tilapia	*Oreochromis niloticus*	4 200	Freshwater	Omnivorous	Rochman *et al.*, 2015; Biginagwa *et al.*, 2016
Whiteleg shrimp	*Penaeus vannamei*	4 156	Seawater	Planktivorous (plus more: detritus, worms, bivalves and crustaceans)	NIF
Bighead carp	*Hypophthalmichthys nobilis*	3 527	Freshwater	Planktivorous	NIF
Crucian carps	*Carassius spp.*	3 006	Freshwater	Omnivorous	Jabeen *et al.*, 2017; Yuan *et al.*, 2019
Catla	*Catla catla*	2 961	Freshwater	Planktivorous	NIF

Table 4. 10 most caught marine species in 2016 (data from FAO, 2018). NIF = no information found.

Common name	**Species name**	**Production (thousand tonnes, 2016)**	**Habitat**	**Feeding strategy**	**Microplastic ingestion reference**
Alaska pollock	*Theragra chalcogramma*	3 476	Demersal	Fish and invertebrates	NIF
Peruvian anchovy	*Engraulis ringens*	3 192	Pelagic	Planktivorous	Ory *et al.*, 2018
Skipjack tuna	*Katsuwonus pelamis*	2 830	Pelagic	Fish, crustaceans, molluscs	Rochman *et al.*, 2015; Choy and Drazen, 2013; Markic *et al.*, 2018
Sardinellas NEI	*Sardinella spp.*	2 290	Pelagic	Planktivorous	NIF
Jack and horse mackerels NEI	*Trachurus spp.*	1 744	Pelagic/ demersal	Fish and plankton	Neves *et al.*, 2015; Foekema *et al.*, 2013; Lusher, McHugh and Thompson, 2013; Murphy *et al.*, 2017; Markic *et al.*, 2018; Güven *et al.*, 2017
Atlantic herring	*Clupea harengus*	1 640	Pelagic	Planktivorous	Ogonowski *et al.*, 2017; Foekema *et al.*, 2013; Rummel *et al.*, 2016; Hermsen *et al.*, 2017
Pacific chub mackerel	*Scomber japonicus*	1 599	Pelagic	Fish and plankton	Neves *et al.*, 2015; Rochman

					et al., 2015; Güven *et al.*, 2017; Ory *et al.*, 2018
Yellowfin tuna	*Thunnus albacares*	1 463	Pelagic	Fish, crustaceans, molluscs	Choy and Drazen, 2013; Markic *et al.*, 2018
Atlantic cod	*Gadus morhua*	1 329	Demersal	Fish and crustaceans	Foekema *et al.*, 2013; Bråte *et al.*, 2016; Liboiron *et al.*, 2016; Rummel *et al.*, 2016
Japanese anchovy	*Engraulis japonicus*	1 304	Pelagic	Planktivorous	Tanaka and Takada, 2016

3.1.2 Fish

Many species of edible demersal, pelagic and reef fish, sampled from across the globe, have been found to ingest microplastics (Bellas *et al.*, 2016; Rummel *et al.*, 2016; Bråte *et al.*, 2016; Lusher, McHugh and Thompson, 2013; Ory *et al.*, 2018; Tanaka and Takada, 2016; Rochman *et al.*, 2015; Neves *et al.*, 2015; Critchell and Hoogenboom, 2018). Of the seven most farmed aquaculture species which are fish (Table 3), all are freshwater species, and their feeding strategies are mostly planktivorous or omnivorous, with the exception of the grass carp which is herbivorous and feeds mostly on aquatic weeds. These fish may be likely to consume microplastics due to their prey being within a similar size range. However, microplastic ingestion investigations have only been performed on Common carp, Crucian carps, Nile tilapa and Silver carp, and no data is available for the other three species, even though they represent a combined 12.5 million tonnes of farmed fish (as of 2016). These studies gave a combined average amount of microplastics per organism of 2.5 ± 1.3 MP/individual (Common carp), 1.9 ± 1.0 MP/individual (Crucian carps), and 3.8 ± 2.0 MP/individual (Silver carp). Nile tilapia data was presented by the authors as the number of individuals which had consumed microplastics, which was an average of 16% (Rochman *et al.*, 2015; Biginagwa *et al.*, 2016). Where it is possible to view the morphology of plastic particles ingested, fibres are the most common microplastic shape seen and make up 57.6-86.5% of the plastic shapes observed.

Of the ten most caught species (Table 4), all are marine fish; the majority are pelagic species that consume mostly plankton and small fish, with three exceptions (pollock, tuna and cod). The microplastic content of these fish are much more studied than common aquaculture species, with 80% of the top ten most fished species included in at least one microplastic study. Collating all available literature on these organisms gives the following percentages of each species that were seen with microplastics in their gastrointestinal tract (GIT): 0.9% Peruvian anchovy; 9.4% Skipjack tuna; 24.5% Jack and Horse mackerels; 8.8% Atlantic herring; 23.3% Pacific chub mackerel; 23.4% Yellowfin tuna; 2.8% Atlantic cod, and 76.6% Japanese anchovy (Neves *et al.*, 2015; Foekema *et al.*, 2013; Lusher, McHugh and Thompson, 2013; Murphy *et al.*, 2017; Güven *et al.*, 2017; Ogonowski *et al.*, 2017; Rummel *et al.*, 2016; Hermsen *et al.*, 2017; Rochman *et al.*, 2015; Ory *et al.*, 2018; Choy and Drazen, 2013; Markic *et al.*, 2018; Bråte *et al.*, 2016; Liboiron *et al.*, 2016; Tanaka and Takada, 2016). Other species of commercial importance that have been included in several pieces of literature (plus percentages seen with microplastics in their GIT) include Scads (*Decapterus spp*, 46%.), European pilchards (*Sardina pilchardus*, 26%), Blue whiting (*Micromesistius poutassou*, 29.8%), and Atlantic mackerel (*Scomber scombrus*, 23.2%). As with aquacultured species, fibres are the most common microplastic shape seen, forming 30-87.6% of the plastic shapes observed. Unfortunately it is not possible to view in detail the most common size of microplastics observed in each species due to how the data is reported, however this information may not be reliable due to constraints in minimum observable size in the methodology used (e.g. choice of filters, sensitivity of analytical techniques, Lusher *et al.*, 2017). Notable by its absence in the literature is the Alaska Pollock (*Theragra chalcogramma*) and members of *Sardinella spp.*, neither of which were found to have been analysed to investigate microplastic ingestion in the literature. Both species are an extremely important food source, with more than 3.47 million tonnes of Pollock and 2.29 million tonnes *Sardinella spp.* fished in 2016.

3.1.3 Shellfish

Cupped oysters (*Crassostrea spp.*) and Japanese carpet shell (*Ruditapes philippinarum*) are among the most prevalently aquacultured shellfish species worldwide. Microplastic ingestion in shellfish is generally reported as the number of microplastics per gram of wet tissue. In Cupped oysters, the average result reported ranged from 0.18 to 3.84 microplastics gram^{-1} w. w., and in the Japanese carpet shell, the average reported result ranged from 0.9 to 2.5 microplastics gram^{-1} w. w.

By far the most studied shellfish are mussels of the family *Mytilidae*. 9 pieces of literature were identified that studied the amount of microplastics found in sea mussels in their natural environments, with ingestion ranges varying from 0.2-5.36 microplastics g^{-1} w. w. (Bråte et al., 2018; Catarino *et al.*, 2018; De Witte *et al.*, 2014; Li *et al.*, 2015, 2016; Phuong *et al.*, 2018; Qu *et al.*, 2018; Van Cauwenberghe and Janssen, 2014; Van Cauwenberghe *et al.*, 2015). Whilst ingestion values look different when analysing the number of microplastics ingested per individual, when normalised for soft tissue weight, the values for all three species overlap, seemingly showing that microplastic ingestion in shellfish is not species-specific. Though shellfish can show selective feeding, rejecting particles based on size or lack of organic material (Newell and Jordan, 1983; Defossez and Hawkins, 1997), they are found to ingest microplastics. Whilst these species all ingest similar amounts of microplastics, it is possible that they selectively ingest different size microplastics due to organism size, with for example oysters being able to ingest larger particles than mussels. Data from the analysis of mussels and oysters taken from the French Atlantic coast (Phuong *et al.*, 2018) suggests this, as both organisms ingested a majority of microplastics in the 50-100 µm size range, but mussels ingested a higher proportion of 20-50 µm particles than oysters (37% and 15 %, respectively), and oysters ingested a higher proportion of > 100 µm particles than mussels (32% and 11%, respectively).

3.1.4 Crustaceans

Crustaceans form a very large and diverse group of organisms including many that are important for worldwide food security, such as crabs, lobsters, crayfish and prawns. Many edible species of crustaceans have been shown to ingest microplastics (Devriese *et al.*, 2015; Welden and Cowie, 2016a; Abbasi *et al.*, 2018). Organisms such as copepods and krill are also critically important as a food for organisms which are consumed by humans, and have been reported to ingest microplastics (Botterell *et al.*, 2019).No studies have been performed to investigate microplastic ingestion in the Whiteleg shrimp, one of the top ten most farmed aquatic species with 4.2M tonnes farmed in 2016 (Table 3), however, investigations have taken place with other commercially important species. Brown shrimp, *Crangon crangon,* a commercially important crustacean fished in the eastern Atlantic and Mediterranean Sea, were found with an average of 0.68 ± 0.55 microplastics $gram^{-1}$ w. w. and 63% of the 165 shrimp analysed containing microplastics (Devriese *et al.*, 2015). Green tiger prawn, *Penaeus semisulcatus*, an organism of commercial important in East Africa and Asia, was found to have ingested an average of 7.8 particles per individual (1.5 particles $gram^{-1}$, n=12) in the Musa estuary, Persian Gulf (Abbasi *et al.*, 2018). Nylon fibres were observed in the stomachs of 5.93% *Plesionika narval* (narwhal shrimp), an important fishery in the Aegean Sea, although it is hypothesised by the authors that these fibres may result from the fishing method (Bordbar *et al.*, 2018). Other commercially important species that have been observed to contain microplastics include *Eriocheir sinensis* (Wójcik-Fudalewska, Normant-Saremba and Anastácio, 2016),*Carcinus maenas* (Watts *et al.*, 2014, 2015), and *Nephrops norvegicus* (Murray and Cowie, 2011; Welden and Cowie, 2016b).

3.1.5 Macroalgae

Seaweeds have been consumed as a traditional food around the globe; however, consumption of seaweed has been increasing in recent years with much of this increase from farming of seaweed rather than from harvesting wild crops. Statistics from the Food and Agriculture Organisation of the United Nations state that aquatic plant production grew from 13.5 million tonnes to over 30 million tonnes from 1995 to 2016, with 96.5% of the 31.2 million tonnes produced in 2016 from aquaculture (FAO, 2018). Seaweeds for consumption are generally classified into three groups: red algae (Rhodophyta) such as Dulse and Nori, brown algae (Phaeophyceae) such as kelp and green algae (an informal group containing Chlorophyta, Charophyta, Mesostigmatophyceae, Chlorokybophyceae and Spirotaenia) such as sea lettuce. *Fucus vesiculosus* is a common seaweed in the British Isles and Atlantic coastlines, in the class of brown algae, and is often comsumed as a health supplement. Recent studies have shown the ability for 20 µm polystyrene microparticles to sorb to *F. vesiculosus* (Sundbæk *et al.*, 2018). Trophic transfer via this macroalgae has also been observed; Gutow *et al.* (2016) demonstrated the ability for the common periwinkle *Littorina littorea* to ingest microplastics via *Fucus vesiculosus*. Algal pieces were exposed to polystyrene microbeads (10 µm), fragments (1-100 µm), and polyacrylic fibres (90 to 2200 µm), followed by a washing step. Feeding assays with the three types of microplastic-contaminated algal pieces showed that *Littorina* littorea did not show a feeding preference between contaminated and non-contaminated algal pieces, and microplastics were found in the stomach content, gut and faecal pellets, with 89% of *L.* littorea faecal pellets containing microplastics.

3.2 Factors influencing microplastic consumption

3.2.1 Feeding strategy

Broadly speaking, there are two main ways for marine organisms to ingest microplastics: direct ingestion from the natural environment; or indirect ingestion, including trophic transfer from prey and consumption of contaminated aquaculture feedstock. Furthermore, there is some indication that microplastics can be taken up via the gills (Watts *et al.*, 2014). Dietary strategy may be a defining characteristic influencing microplastic ingestion in fish, with planktivores more likely to consume microplastics direct from the natural environment, while piscivores (e.g. tuna) would be expected to consume microplastics mainly through trophic transfer via prey or accidental ingestion while feeding.

Direct ingestion of microplastics is often a consequence of feeding strategy. Indiscriminate feeders show no selection in the matter that they ingest, ingesting prey in proportion to their availability in the environment, whilst discriminate feeders select based on preferential feeding factors (colour, size etc.). Filter feeders such as some bivalves can be considered as indiscriminate feeders as they feed by filtering water through their gills, capturing particulate matter such as plankton and microalgae. This is generally in a non-selective manner; however some of the filtered matter can be rejected. This has been shown recently by Ward *et al.* (2019), who demonstrated that the bivalves *Crassostrea virginica* and *Mytilus edulis* selectively ingested microplastics preferentially, based on the physical characteristics of the plastic. In this way, microplastics are ingested if they resemble the properties of the organic matter these organisms feed on, such as in size and shape. Discriminate feeders may directly ingest microplastics either when they resemble prey items, or incidentally whilst feeding, e.g. in contaminated feedstock; this feeding strategy is generally utilised by higher trophic-level organisms. Discriminate feeders such as fish may therefore ingest microplastics that resemble their prey. Amberstripe scad (Decapterus muroadsi) appear to ingest blue microplastics preferentially as they resemble their copepod prey in both colour and size (Ory *et al.*, 2017). Evidence of selective feeding on the blue copepods *Pontella sinica* and *Sapphirina spp.* was seen, as was selectivity for blue microplastics.

Indirect ingestion, or "trophic transfer" occurs when organisms consume prey that have already consumed microplastics. Trophic transfer from blue mussels *Mytilus edulis* to the shore crab *Carcinus maenas* has been observed in laboratory conditions (Farrell and Nelson, 2013; Watts *et al.*, 2014). Farrell and Nelson (2013) fed 0.5 µm fluorescent polystyrene microspheres to *M. edulis*, with *C. maenas* subsequently being fed one mussel per crab. Microspheres were subsequently detected in the stomach, hepatopancreas, ovary, gills and haemolymph of the crabs. Results from Nelms *et al.* (2018) suggest the ability for microplastics to be ingested by grey seals (Halichoerus grypus) through trophic transfer from Atlantic mackerel (Scomber scombrus). Detritivores may also be prone to indirectly consuming microplastics present in faeces of contaminated organisms; for example coprophagous copepods can ingest microplastics present in other copepods' egests (Cole *et al.*, 2016). Feedstock contaminated with microplastics may be a risk to aquaculture, as fishmeal is a commonly used fish feed manufactured from whole fish, therefore any microplastics within the fish may pass into the processed fishmeal (Karbalaei *et al.*, 2019).

3.2.2 Trophic level

The percentage of planktivorous and piscivorous fish populations contaminated with microplastics might suggest that trophic level and feeding strategy alone are not indicative of microplastic ingestion, however, this may be due to a difference in how microplastics data are usually presented (See Table 5). For example, Markic *et al.* (2018), saw no significant difference in their study on plastic ingestion rate in 23 species of fish in the South pacific based on their trophic level, with the only significant difference in ingestion rates seen between benthic predators and omnivores. However, while similar proportions of the total population of marine organisms with different dietary strategies contained microplastics, the number of microplastics per gram of tissue may be very different. For example, data presented in this review shows a similar percentage of *S. japonicus* (23.3%) and *T. albacares* (23.4%) contained microplastics, but the average weight of *T. albacares* caught by Markic *et al.* (2018) is 5228.7 g, whereas the average caught weight for *S. japonicus* by Güven *et al.* (2017) was 28.86 g. Using these weights, the average amount of plastic particles per gram (wet weight) for S*comber japonicus* from Güven *et al.* (2017) is estimated as 0.33 particles gram^{-1} and the maximum number of microplastics found per gram in *Thunnus albacares* from Markic *et al.* (2018) is estimated at 5.9x10^{-4} particles gram^{-1}, a 1000-fold difference.

In order to investigate this further, 11 commercially exploited taxa, including bivalves, crustaceans and fish, were selected for analysis from a variety of trophic levels. Taxa were selected that had either a wide range of literature available for analysis (e.g. *Mytilus spp.*, *Scomber japonicus*), or were at a trophic level not covered by other data (e.g. *Thunnus* albacares, *Katsuwonus* pelamis). The data was normalized to give the number of microplastics ingested per gram wet weight of these organisms. Table 5 lists the fish, crustaceans and bivalves in which the number of microplastics per gram wet weight of tissue has been calculated.

Table 5. Number of microplastics per gram wet weight marine organisms.

Species	**Common name**	**Family**	**Diet**	**Microplastics per gram wet weight**	**Raw data references**
Katsuwonus pelamis	Skipjack tuna	Fish	Largely piscivorous	0.000249	Markic *et al.,* 2018

Thunnus albacares	Yellowfin tuna	Fish	Largely piscivorous	0.00059	Markic *et al.*, 2018
Clupea harengus	Atlantic herring	Fish	Planktivorous	0.01	Foekema *et al.*, 2013
Engraulis ringens	Peruvian anchovy	Fish	Planktivorous	0.057	Ory *et al.*, 2018
Trachurus spp.	Jack and horse mackerels NEI	Fish	Planktivorous	0.000126-0.14	Foekema *et al.*, 2013; Neves *et al.*, 2015; Güven *et al.*, 2017; Markic *et al.*, 2018
Scomber japonicus	Pacific chub mackerel	Fish	Planktivorous	0.0025-0.33	Neves *et al.*, 2015; Güven *et al.*, 2017; Ory *et al.*, 2018
Crangon crangon	Brown shrimp	Crustacean	Planktivorous/ herbivorous	0.13-1.23	Devriese *et al.*, 2015
Penaeus semisulcatus	Green tiger prawn	Crustacean	Planktivorous/ herbivorous	1.5	Abbasi *et al.*, 2018
Ruditapes philippinarium	Japanese carpet shell	Shellfish	Filter feeder	0.9-2.52	Li *et al.*, 2015; Davidson and Dudas, 2016
Crassostrea spp.	Cupped oysters	Shellfish	Filter feeder	0.18-3.84	Foekema *et al.*, 2013; Van Cauwenberghe and Janssen, 2014; Phuong *et al.*, 2018; Waite, Donnelly and Walters, 2018
Mytilus spp.	Sea mussels	Shellfish	Filter feeder	0.2-5.36	De Witte *et al.*, 2014; Van Cauwenberghe and Janssen, 2014; Li *et al.*, 2015,

					2016; Van Cauwenberghe *et al.*, 2015; Bråte *et al.*, 2018; Catarino *et al.*, 2018; Phuong *et al.*, 2018; Qu *et al.*, 2018

There is up to four magnitudes of difference between microplastics per gram present in shellfish compared to higher trophic level fish. The data presented above therefore suggests that trophic level and feeding strategy may play a key role in the level of microplastic contamination within marine organisms; though similar percentages of the total population of organisms at different trophic levels contain microplastics within their body tissues, lower trophic level organisms have a higher proportion of microplastic comparatively with body weight, which may be more indicative of risks from microplastics. Fig. 2 displays a comparison of microplastics per gram wet weight of the organisms in Table 5 with the amount of mercury in tissues of similar organisms reported by Plessi, Bertelli and Monzani (2001; *Mytilus spp.*) and the FDA (FDA, 2017; all other species). Mercury is well known to biomagnify, and values are inversely proportional with the microplastic data presented here, which shows a decrease in microplastic concentration with increasing trophic level. Based on this data, we conclude that unlike other contaminants such as organochlorines (Borgå, Gabrielsen and Skaare, 2001) or mercury (Lavoie *et al.*, 2013), microplastics do not biomagnify. This is likely because the evidence currently suggests that microplastics do not, in most cases, translocate from the digestive system into tissues or circulatory fluid, therefore it is a more transitory contaminant with a limited residence time within organisms.

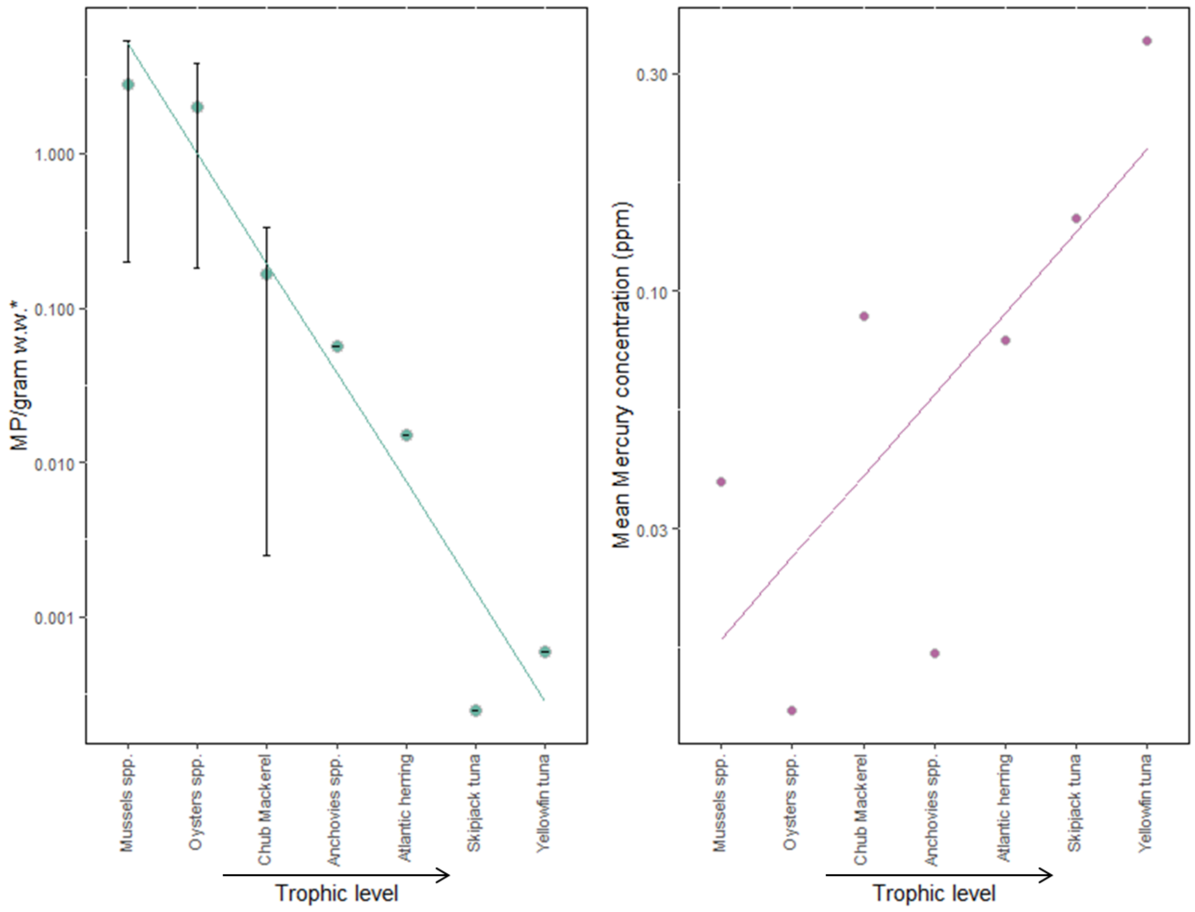

Fig. 2. A comparison of the number of microplastics (MP) per gram wet weight of organisms of different trophic levels to the amount of Mercury (ppm) reported in the tissues of similar organisms as listed by the FDA (FDA, 2017) and Plessi, Bertelli and Monzani (2001). Trophic level shows general increase with direction of arrow. Line of best fit added to show trend in data. *Value is average value of ranges shown in Table 5 and Table S1, with error bars displaying the range of the results.

3.2.3 Environmental concentrations

It is possible that another variable such as habitat may have a pronounced effect on the amount of microplastic ingestion. Markic *et al.* (2018) saw a significant difference in the vertical habitat of a species and their plastic ingestion rates. Although they did not see a significant difference with respect to horizontal distribution (Neritic/Neritic-oceanic/Oceanic), it may be expected that for example fish caught in an oceanic gyre or other area of high microplastic load may have a higher incidence of ingestion than those caught in other areas. In fact, this is observed in the study in question; significantly higher ingestion of microplastic debris was observed in a sampling area within the South Pacific 'garbage patch' than in fish from other locations. This was seen with for example *Thunnus albacares*, where ingestion was seen in 70% of individuals within the garbage patch, and 24% and 15% at two locations outside of this area. In juvenile fish, there was an increased incidence of microplastic ingestion and increasing concentrations of microplastic in seawater with proximity to the coast, with higher encounter rates where microplastic concentrations exceeded those of fish larvae (Steer *et al.*, 2017).

Environmental concentrations may be a particularly important variable for microplastic ingestion in crustaceans and molluscs (Li *et al.*, 2019). As bivalves are filter feeders, any differences in microplastic ingestion are likely due to microplastic distribution in their habitat. Li *et al.* (2016) investigated microplastic abundance in mussels in 22 sites along the coast of China, and significant differences in microplastic ingestion were seen at different sites. Wild mussels contained on average 2.7 items/g (4.6 items/individual) and farmed mussels contained on average 1.6 items/g (3.3 items/individual). In heavily contaminated areas, mussels contained an average of 3.3 items/g (5.3 items/individual), whereas in less contaminated areas, microplastic abundance in mussels was significantly lower (1.6 items/g or 3.3 items/individual). Gut content of individuals of the crustacean *Nephrops norvegicus* collected from three sites in North and West Scotland had significantly different microplastic ingestion; 84.1%, 43% and 28.7% of *N. norvegicus* individuals ingested microplastic in the Clyde Sea Area, North Minch and North Sea, respectively (Welden and Cowie, 2016a), suggesting crustaceans may also ingest microplastics relative to environmental availability.

3.3 Risks of microplastics to marine organisms

3.3.1 Retention in the digestive system (gut blockages)

Following ingestion, microplastics may be rejected by the organism through pseudofaeces or post-ingestion rejection, egested through faeces, transferred across the GIT epithelium, or be retained in the GIT. Microplastic retention in the digestive system may adversely affect organism health through physical perforation of the gut or by giving the organism a feeling of false satiety, decreasing feeding activity and nutrient intake.

Shore crabs fed with 10 µm polystyrene microspheres had plastic detected in the foregut 5 days after exposure to microplastic-containing mussels (Watts *et al.*, 2014). In this feeding experiment, crabs were fed with mussels that had been exposed to microplastics and subsequently sampled over a 21-day period, and n=6 crabs were analysed for microplastics in the foregut at each time point post-ingestion. Polystyrene microspheres were detected in all six crabs after 24hrs; decreasing to 50-66% of the crabs from days 2-5. Microplastics were then not detected in the crab faecal pellets after 7 and 22 days post-exposure (but were on day 14).

Blue mussels (*Mytilus edulis*) were shown to ingest 9% of all available microplastic fibres (approx. 450 µm length) in an ingestion study where microplastic fibres were ingested alongside the microalgae *Rhodomonas salina* (Woods *et al.*, 2018). Mussel filtration rate decreased when exposed to microplastic fibres in addition to *R. salina*, and though most fibres (71%) were rejected as pseudofaeces, 9% were ingested, and < 1% were excreted in faeces. Microplastics were identified in the gills, digestive gland and other soft tissues at all time points over a 72 hr exposure period. In another experimental study, 2 of 31 Palm Ruff (*Seriolella violacea*) fish were shown to retain microplastics after a 49-day exposure period (Ory *et al*., 2018). The transitory nature of microplastics within the digestive system of organisms may explain why microplastics do not appear to biomagnify. If microplastics pass through the GIT of organisms and are not retained within the GIT or tissues, it is much less likely that organisms at higher trophic levels will ingest significant amounts of microplastics through a carnivorous diet.

Research by Welden and Cowie (2016) suggests whilst Norway lobster (*Nephrops norvegicus*) are seen to retain microplastics within their foregut for extended periods of time, the main route by which they are removed is by ecdysis, whereby the individual moults and sheds its gut lining. This gut lining was found to contain microplastics which were removed from the individual during moulting.

3.3.2 Growth rate, reproduction or function affected?

Any changes to growth rate, reproduction, mortality or behaviour due to external factors may significantly alter population dynamics. In the case of commercially important organisms, this may significantly affect the efficiency and profitability of fishing and aquaculture. Lower growth rates may mean that fewer organisms can be harvested in a season, or lower reproduction rates may cause population decreases in following seasons, both of which would have a negative effect on food security. A similar concept is discussed by Galloway, Cole and Lewis (2017), who propose that, though chronic exposure to microplastic is not usually lethal, it is associated with reductions in energy, growth, fecundity and reproductive output. These individual and population-level effects can as a consequence cause ecosystem level effects, such as community shifts and changes to ecosystem function, which would result in risks to food security.

Several articles have shown reduction of growth rates and reproductive function (Cole *et al.*, 2015; Sussarellu *et al.*, 2016), and behavioural changes (Cole *et al.*, 2015; Sussarellu *et al.*, 2016; Ribeiro *et al.*, 2017; Woods *et al.*, 2018) in marine organisms as a result of exposure to microplastics. Significant effects from microplastic exposure were observed in laboratory exposure studies with the Pacific oyster (*Crassostrea gigas*) (Sussarellu *et al.*, 2016). Significantly higher algal consumption was observed for oysters exposed to microplastics, possibly in an attempt for the oyster to compensate for lower nutrient intake. Significant reproductive effects were observed; exposed female oysters had fewer, smaller oocytes and a reduction in D-larval yield; exposed male oysters had lower sperm velocity. *C. gigas* larval growth was significantly slower, with a reduction in mean size of 18.6% at 17 days post-fertilization and a 6-day lag time to metamorphosis.

Behavioural changes are observed in clams; 20 µm polystyrene microplastics also induced effects on antioxidant capacity, DNA damage, neurotoxicity and oxidative damage in *Scrobicularia plana* (Ribeiro *et al.*, 2017), and reduced clearance rate in *Atactodea striata* (Xu *et al.*, 2017). Behaviour may also be affected in the presence of nanoplastics. For example, Wegner *et al* (2012) observed no pseudofaeces production in *Mytilus edulis* exposed to microalgae alone, but found heightened pseudofaeces production in *Mytilus edulis* exposed to microalgae (*Pavlova lutheri*) and 30 nm polystyrene, along with a decrease in filtering activity.

3.3.3 Risk of disease

Once in the marine environment, microplastics are quickly colonised by a variety of organisms termed the plastisphere (Zettler, Mincer and Amaral-Zettler, 2013). The plastisphere is a risk to the marine environment, aquaculture and food security as it has the potential to support pathogenic microorganisms, and allow them to become more bioavailable to the organisms consuming microplastics. Recent research has identified hazardous microorganisms present on microplastics, along with microorganisms usually found in sewage and gut-associated pathogens (Oberbeckmann, Löder and Labrenz, 2015). The microbial biofilms discussed here affect the physical characteristics of the plastic, including size and buoyancy, which could in turn affect the vertical distribution of microplastics within the water column, transporting microplastics to the benthos (Kaiser, Kowalski and Waniek, 2017; Kooi *et al.*, 2017). This, in addition to the horizontal transport of microplastics via ocean currents and wind therefore means that microplastics have the capacity to transport microorganisms to new environments over vast distances, suggesting the potential for microplastics to act as a vector for the transfer of invasive pathogens to new environments.

High concentrations of microplastic debris in the North pacific subtropical gyre have resulted in an increase in the pelagic insect *Halobates sericeus* and in *H. sericeus* egg densities (Goldstein, Rosenberg and Cheng, 2012). Jiang *et al.* (2018) profiled bacterial communities attached to microplastic samples taken from intertidal locations around the Yangtze estuary in China, and found a wide range of bacterial taxa, including some that are associated with human and animal pathogens: *Vibrio* (0.4% of taxonomic abundance, found at Xiangshan bay); *Leptolyngbya* (1.6% abundance, found at Chongming island), and *Pseudomonas spp.* (<0.01% abundance, all plastics).

Harmful pathogens travelling large distances could have severe implications for food security. One potential example of this would be the colonisation of marine plastics by HAB (harmful algal bloom) species. When floating plastic debris collected along the North-west Mediterranean were analysed, several potentially harmful dinoflagellates were identified, including *Ostreopsis spp, Coolia spp* and *Alexandrium taylori* (Masó *et al.*, 2003), all of which can cause HABs. *Alexandrium spp.* can cause paralytic shellfish poisoning (PSP), which is hazardous to both marine organisms and humans. *Alexandrium catanella* has caused significant economic losses to the salmon industry in Chile, for example in 2009 when a large bloom was associated with a loss of over $10 million to the Chilean Salmon industry (Mardones *et al.*, 2015). *Alexandrium taylori* has also been shown to produce paralytic shellfish toxins and has recently been identified for the first time in Malaysian waters (Lim *et al.*, 2005). Invasive HAB species, potentially transported by microplastics, could therefore be incredibly damaging to global fishery and aquaculture industries.

Marine plastic debris collected from multiple locations in the North Atlantic was analysed and bacterial assemblage sequenced to characterize the plastisphere community (Zettler, Mincer and Amaral-Zettler, 2013). In this diverse community, the bacteria genus *Vibrio* and dinoflagellate genus *Alexandrium* were identified. Both of these genii contain species that are pathogenic to both humans and animals. Several strains of *Vibrio spp.* including potentially pathogenic *Vibrio parahaemolyticus* were also detected on microplastics and in seawater from the North and Baltic sea by Kirstein *et al*. (2016). Microplastics samples from a transect taken along the Slovenian coast of the North Adriatic Sea were subjected to DNA extraction, amplification and phylogenetic analysis, and the bacterial pathogen *Aeromonas salmonicida* was identified on the particles (Viršek *et al.*, 2017). This species is pathogenic to several commercially important species, such as salmonids.

3.3.4 Chemical additives and adhered contaminants

Microplastics contain chemicals added during plastic manufacture to enhance certain properties, and have also been shown to adsorb and concentrate contaminants from the environment such as PCBs, PAHs, and metals (Teuten *et al.*, 2007; Brennecke *et al.*, 2016). Many of these contaminants can be toxic to marine organisms. Several researchers have therefore investigated whether microplastics can act as a vector for contaminant transfer to marine organisms, and whether this is a significant pathway compared to other methods of contaminant ingestion.

3.3.4a Chemical additives

Chemical additives in plastics enhance the different properties that make plastics so useful; some act as fire retardants, while others may act as stabilisers, foaming agents or strength enhancers. When plastic pollution occurs, these additives slowly leach from plastics into their surrounding media, for example seawater. This has led to concerns that they may enter biological systems and affect the health of exposed organisms, however, there is also a growing set of evidence that the overall exposure of organisms to these chemicals from plastics is negligible compared to other sources.

The potential for leaching of nonylphenol (NP) and bisphenol A (BPA) in the GIT of *Arenicola marina* (lugworm) and *Gadus morhua* (Atlantic cod), and a comparison of exposure to these two substances by microplastics alone and total environmental exposure, was investigated utilising a biodynamic model by Koelmans, Besseling and Foekema (2014). They suggest that for cod, ingestion of microplastic is highly unlikely to lead to negative effects from NP and BPA and is negligible compared to uptake from water and prey. For lugworms, though ingestion of microplastic was hypothesised to be a substantial exposure pathway in certain conditions, the low concentrations of NP and BPA involved would not cause a risk to the lugworm.

3.3.4b Adhered contaminants

In addition to leaching chemical additives, plastic particles can sorb contaminants from the environment, giving a possible route for the concentration of these chemicals, potentially increasing their toxicity if they are released into a marine organism. Teuten *et al.*, (2007) investigated the uptake and release of the hydrophobic organic contaminant phenanthrene by three virgin plastic polymers: polyethylene, polypropylene, and polyvinyl chloride. All three sorbed phenanthrene with varying efficiency, however all three plastics greatly exceeded the sorption of phenanthrene onto two natural sediments.

Ašmonaitė *et al.* (2018) investigated the effect of ingestion of large (100-400 µm) polystyrene microplastics (PS-MPs) on the rainbow trout (*Oncorhynchus mykiss*). Trout were exposed to virgin microplastics as well as microplastics exposed to either sewage effluent or environmental water in a harbour. All three sets of PS-MPs contained chemical contaminants including PAHs, plasticizers and surfactants, however, a wider variety of compounds were detected after exposure to sewage and harbour water, confirming the ability for PS-MPs to sorb contaminants from the aquatic environment. Rainbow trout were experimentally exposed to these microplastics following a dietary-exposure protocol, however no significant changes in hepatic biomarker responses were observed, suggesting that PS-MPs did not induce adverse hepatic stress in rainbow trout; however, Ašmonaitė *et al.* (2018) theorize that this may be due to the size of the PS-MPs used, as oxidative stress effects have been observed for smaller polystyrene particles (Jeong *et al.*, 2016; Lei *et al.*, 2018). Ašmonaitė, Sundh, *et al.* (2018) also show that PS-MPs did not affect intestinal health in the same species.

A review and reinterpretation of the available literature by Koelmans *et al.* (2016) and a modelling study by Bakir *et al.* (2016), both investigating the relative importance of microplastics as a pathway for the transfer of adhered contaminants from microplastics to biota, suggest that this is not a significant route for exposure to adhered contaminants when compared to bioaccumulation from natural prey and water.

3.3.4c Metals

Heavy metal pollution within the marine environment is increasingly becoming a serious threat to ecosystems (Naser, 2013) and may therefore become a risk to food security in the near future. Brennecke *et al.* (2016) examined the adsorption of two heavy metals, copper and zinc, leached from antifouling paint, to virgin polystyrene beads and aged polyvinylchloride fragments in seawater. Both heavy metals adsorbed onto the two microplastic types, with concentrations of Cu and Zn increasing significantly on PVC and PS over the 14-day experiment. Significantly greater adsorption of Cu onto PVC fragments was observed, with the authors theorizing this was due to the higher surface area and polarity of PVC.

The effect of exposure to microplastic (0.26 and 0.69 mg/L), mercury (0.010 and 0.016 mg/L) and mixtures of the two substances (same concentrations) on the gills and liver of juvenile European bass (*Dicentrarchus labrax*) over a 96-hour period showed that, while both alone caused oxidative stress in the gills and liver, the concentration of mercury in both gills and liver was significantly higher in the presence of microplastics than their absence (Barboza *et al.*, 2018b). This result is therefore indicative of a synergistic effect of microplastics on the accumulation of mercury within fish tissue. Heavy metals are proven environmental contaminants, and their interaction with microplastic debris therefore has potential to significantly alter the toxicity of microplastics within the marine environment.

3.3.5 Transfer across biological membranes

Microplastic ingestion may not be indicative of negative effects, as microplastics may be egested again quickly either by post-ingestion rejection or through faeces. However, if microplastics or nanoplastics are able to transfer into the tissues or circulatory system, by for example transfer across the gut lining or gill structures, this may lead to greater accumulation and negative effects as the organism may not be able to remove them. Transfer to tissues, organs and the circulatory system has been seen in laboratory studies in crabs (Farrell and Nelson, 2013; Watts *et al.*, 2014; Brennecke *et al.*, 2015), bivalves (Browne *et al.*, 2008; Von Moos, Burkhardt-Holm and Köhler, 2012; Al-Sid-Cheikh *et al.*, 2018) and fish (Avio, Gorbi and Regoli, 2015; Lu *et al.*, 2016).

Uptake of microplastics into the tissues of the blue mussel *Mytilus edulis* can cause changes on the cellular and tissue level (Von Moos, Burkhardt-Holm and Köhler, 2012). *M. edulis* were exposed to High-density polyethylene (HDPE) with irregularly shaped particles from >0-80 µm in size at a concentration of 2.5 g/L for up to 96 hours. Microplastic particles were found on the gills and in the digestive system, lysosomal system, connective tissue and digestive gland. Effects of microplastic exposure included granulocytoma formation after 3 hrs, and lysosomal membrane destabilization after 6 hrs; both effects are associated with the toxicological response of organisms to pollutants (Moore, 1985; Moore *et al.*, 2008).

Zebrafish *Danio rerio* exposed to polystyrene microplastic beads (5, and 20 µm) at 20 mg/L for up to 7 days showed microplastic accumulation in the fish gills and gut (5 and 20 µm particles), and in the liver by 5 µm particles only (Lu *et al.*, 2016). Toxicity testing, exposing *D. rerio* to 5 and 70 µm particles at 20, 200 and 2000 µg/L for 3 weeks showed that at 2000 µg/L both particle sizes caused inflammation and lipid accumulation in the liver. Particle size did not cause any observable histopathological differences in fish tissues.

Smaller plastic particles are more likely to transfer across biological membranes than particles at the larger end of the micro-scale, for example through the villi or M-cells of the peyer's patches within the intestine (Galloway, 2015). However, biologically-facilitated fragmentation of microplastics to nanometre-sized fragments has been reported to occur through microplastic ingestion by Antarctic krill (*Euphausia superba*, Dawson *et al.*, 2018). Here, 31.5 µm polyethylene beads (average size, ±7.6 standard deviation, S.D) were ingested by krill, and microplastic fragments identified in krill tissues and faecal pellets were decreased by an average of 78% (7.1 µm ± 6.2 S.D) and 81% (6.0 µm ± 5.0 S.D). This is the first time that fragmentation of microplastics to nanoplastics has been reported in planktonic crustaceans, and could be indicative of a mechanism for microplastic translocation to tissues in crustaceans where initially they may have been too large.

4. Discussion

4.1 What does the data show?

All of the commercially important organisms studied here, where data was available, were shown to contain microplastics. The population of animals shown to ingest microplastics varied widely by species, and when normalized for weight, the number of microplastics ingested per gram wet weight decreased with increasing trophic level. We conclude that commercially important organisms towards the base of the food chain (bivalves, crustaceans and small planktivorous fishes) are more likely to be contaminated with higher concentrations of microplastics, potentially posing a greater risk to their health and having implications for perceived or actual food safety.

The number of journal articles on the topic of microplastics has increased significantly over recent years: a search for ‘microplastics’ in Web of Science shows 473 papers published in 2018, up from 71 published in 2014. However, there are still gaps in our knowledge, particularly pertaining to commercially important organisms. It is critically important that more targeted research is done to assess the risk of microplastics to commercially important seafood species; several species, such as Alaska pollock, Grass carp and Whiteleg shrimp have had no research published on their ingestion of microplastics within the natural environment. As similar species have shown microplastic ingestion we can surmise that they will most likely be ingesting plastics, but we have no idea of the scale of this or effects on these populations. As these three organisms had a combined production of 13.7 million tonnes of food in 2016, this is a huge gap in this research field and potentially an important risk to consider for worldwide food security.

The data presented in Fig. 2 and Table 5 suggests that microplastics do not biomagnify. Comparing microplastic concentrations within the GIT of different marine organisms to Hg concentrations within similar organisms (Fig. 2), normalizing by organism weight, shows contrasting trendlines; Hg presence in organism tissues (ppm) biomagnifies with increasing trophic level whereas the number of microplastics g^{-1} w. w. decreases with increasing trophic level. Whilst the data presented here suggests that microplastics within marine organisms do not biomagnify, this may not be the case for nanoplastics. These particles are small enough to possibly pass through the gut lining and into the tissues of organisms (Al-Sid-Cheikh *et al.*, 2018), therefore they may be more likely to bioaccumulate in animal tissues and may potentially biomagnify through the food chain (although there is no data as of yet to support this hypothesis).

4.2 What factors influence microplastic consumption?

Feeding strategy and environmental prevalence are primary drivers for microplastic consumption. Generally, lower trophic level organisms appear to ingest more microplastics due to feeding strategy, as observed by our biomagnification data (Fig. 2 and Table 5). However, there can be huge variations, for example although they occupy the same ecological niche, 76.6% Japanese anchovy were found with microplastics within their GIT (Tanaka and Takada, 2016), but only 0.9% Peruvian anchovy (Ory *et al.*, 2018). This is most likely due to the location where the fish were caught and the sample digestion methodology utilised. The Japanese anchovy were caught in Tokyo bay, which is in extremely close proximity to a very large level of anthropomorphic activity, with a drainage basin population of 29 million people, whereas the Peruvian anchovy were caught in further offshore locations in proximity to smaller population centres, therefore less microplastic pollution may be expected. Tanaka and Takada (2016) also removed and digested the entire GIT, whereas Ory *et al*. (2018) instead removed and digested only the gut contents; such differences in methodology may lead to differing identification efficacies. These differences, in sampling site and methodology, may have resulted in the large difference in the number of anchovy caught containing microplastics, and care should always be taken when comparing ingestion studies to identify any sampling bias such as identified here.

Though trophic transfer does not appear to be an important factor in microplastic consumption, it is possible that organisms at aquaculture facilities may be exposed to dietary microplastic through contaminated fishmeal. In 2014, 15.8 million tonnes of fish were reduced to fishmeal (Green, 2016), for use as a feedstock in the agriculture sector. Miles and Chapman (2006) estimate that in 2010, 56% of fishmeal was used in the aquaculture sector, 20% in pig feed and 12% in chicken feed. This therefore represents a novel way for microplastics to be introduced into human food, with potential risks to many different agriculture industries. Fishmeal is advertised as a nutritious and protein-rich feedstock (Miles and Chapman, 2006), therefore microplastic contamination through the processing of contaminated organisms or contamination during fishmeal processing may affect this nutritional value and have knock-on effects on global agriculture.

4.3 What are the issues with current studies?

Problems with laboratory analysis of microplastics remain, with several papers likely underestimating the amount of microplastics found in organic material due to worries about contamination and the use of filters with pore sizes too large to catch smaller microplastics. Microplastic fibres are commonly removed from analysis due to concerns about contamination (Rochman *et al.*, 2015; Rummel *et al.*, 2016; Ory *et al.*, 2018). Fibres are one of the most common types of microplastic debris worldwide (Lusher *et al.*, 2014; Barrows, Cathey and Petersen, 2018), therefore it is critical that research should utilise methodology to reduce contamination (laminar flow cabinets, non-synthetic laboratory consumables and clothing etc.), to allow for more robust and realistic analyses of environmental microplastic concentrations, as concentrations are very likely to be under-represented without the inclusion of microplastic fibres in results. Smaller microplastics are often missed from analysis due to equipment constraints, both in collection and analysis. Foekema *et al.*, (2013) and Rummel *et al*. (2016) only analysed particles larger than 0.2 and 0.5 mm respectively, due to the diameter of the sieve mesh used. Both Güven *et al.* (2017) and Foekema *et al.* (2013) investigated microplastic in the GIT of *Trachurus spp.;* Güven *et al.* filtered digested *Trachurus mediterraneus* stomach and intestine content through a 26 µm mesh, with the resulting percentage of *Trachurus* shown to ingest microplastics as 68% of the population; Foekema *et al.* filtered digested *Trachurus trachurus* samples through a 0.2 mm seive and found microplastics in 1% of the population. Güven *et al.* also included microplastic fibres in their results, while Foekema *et al.* did not. Mean microplastic size identified by Güven *et al.* was 656.18 µm ± 803.31 SD, median particle size observed by Foekema *et al*. was 800 µm. Extrapolation of observed environmental concentrations of microplastics compared to their size shows that as mesh size or bead diameter decreases, the number of microplastics found per litre seawater increases by several orders of magnitude (Lenz, Enders and Nielsen, 2016). This shows a clear bias of microplastics identified due to methodology, and without standardization it is very difficult to accurately compare microplastic studies in a rigorous manner.

Methodological differences are also clear in the preparation of samples for microplastic analysis. When preparing fish digestive tracts for microplastic analysis, some researchers inspect the entire GIT, while others opt to inspect only the stomach contents. Both of these methods involve manually inspecting GIT contents for microplastics once scraped from their respective lining, while another method more commonly in use in newer studies is to digest the entire GIT, filtering this solution to remove most of the organic matter and make microplastics more visible and easier to quantify. Common solvents used to digest the organic material are H_2O_2, KOH, HNO_3 and $HClO_4$ (Foekema *et al.*, 2013; Li *et al.*, 2015, 2016; Van Cauwenberghe *et al.*, 2015; Davidson and Dudas, 2016; Jabeen *et al.*, 2017; Phuong *et al.*, 2018; Qu *et al.*, 2018; Waite, Donnelly and Walters, 2018), with combinations of these solvents sometimes used to increase digestion efficacy (De Witte *et al.*, 2014; Devriese *et al.*, 2015). Some of these treatments have been shown to have a destructive effect on microplastic particles (Cole *et al.*, 2014; Lusher *et al.*, 2017) therefore care should be taken to ensure microplastics are not damaged or eliminated due to the digestion protocol utilised. One option is to use digestive enzymes; for example Cole *et al*. (2014) and Courtene-Jones *et al.* (2017) have utilised enzymatic digestion with proteinase K and trypsin, respectively, with no observed impacts on microplastics. However, the methods utilized to effectively measure microplastics whilst avoiding microplastic alteration or destruction must be balanced against the cost, speed and effort required.

4.4 What are the risks of microplastics to fisheries and aquaculture?

Measuring the cost of microplastic pollution to ecosystem services, such as food provisioning through fisheries and aquaculture, is very challenging, and research into this is still in its infancy. Measuring the economic cost of marine litter is complex due to the wide range of impacts on the environment, social and economic sectors (Newman *et al.*, 2015), and it can be expected to be even more challenging to look at the cost of only microplastics as a proportion of this. The close relationship between ecosystem services and the marine environment means that adverse environmental effects from microplastic pollution will have impacts on food provisioning, which could add risk to global food security. Research has been done to attempt to put a cost to large marine debris. A survey of Scottish fish vessels reported that 86% of vessels reported reduced catch and 95% reported snagging on their nets on seafloor debris, with an estimated cost of €11.7-13 million per year; the equivalent of 5% of the total revenue of affected fisheries (Mouat, Lozano and Bateson, 2010). Estimated values such as this are not available to look at the cost of microplastic pollution, however the risks of microplastics identified in this review may all add a cost to fisheries and aquaculture that we cannot currently quantify. Microplastics carrying pathogenic microbes or invasive species may decimate native populations of commercially important organisms such as shellfish and crustaceans. Increasing concentrations of microplastic within the marine environment may put a stress on the energetic burden of marine organisms if organisms have to spend more energy to consume nutritionally valuable food this will decrease the energy available for growth and reproduction, and could decrease mean population size and reproductive output. This would mean that commercially exploited organisms could take longer to reach a harvestable size, leading to decreased profits in the fisheries and aquaculture sector, and smaller organism size would lower the nutritional value of seafood.

Currently, there is no evidence that significant amounts of microplastics can translocate to the tissues of fish from e.g. the digestive tract or gills, and as most fish are consumed gutted or as processed pieces (e.g. fillets), there is little evidence that larger fish will transfer microplastics to humans through diet. However, in the case of smaller fish such as anchovies, as well as shellfish and edible seaweeds, where the whole organism is often consumed, there is a greater risk of humans consuming microplastics, with implications for food safety and food security. Studies have suggested that European consumers may consume 11,000 microplastics per year (Van Cauwenberghe and Janssen, 2014) or 4620 microplastics per year (Catarino *et al.*, 2018) through seafood. Although it has been a concern that microplastics may leach additives or adsorbed chemical contaminants into humans upon ingestion, the estimated chemical exposure to humans of persistent organic pollutants and plastic additives following consumption of seafood is expected to be negligible, at <0.1% of total dietary exposure (FAO, 2017). Although risks from seafood ingestion are not currently clear, it is possible that studies such as these will affect the perception of consumers, leading to a change in consumer habits and diet, before robust studies can be performed to give a clear picture of the effects of plastic pollution (Koelmans *et al.*, 2017) on food safety and food security. The results of a survey by the German Environment Agency found that 62% of the population studied felt that they were strongly (39%) or moderately (23%) contaminated by plastic particles in food and drinking water (SAPEA, 2019); microplastics research that is reported whilst failing to address human health and food security concerns may heavily alter public perceptions in similar ways. This may cause a lowering of seafood value and reduced profits in the seafood and aquaculture sector, potentially impacting public health in areas which rely heavily on seafood diets. In addition to researching the prevalence and effect of microplastics that are ingested by organisms in the marine environment, significant numbers of microplastics may be added to seafood during processing stages and packaging; such concerns should be researched through analysing microplastic content throughout the production process, to eliminate any potential areas of contamination that may occur.

Microplastics are present in commonly consumed aquatic species sourced from both aquaculture and the marine environment. Processing steps may remove some microplastics, e.g. by removing the GIT of fish, or washing shellfish and molluscs, however microplastics have been identified in processed aquatic biota that is being sold for consumption (Karami *et al.*, 2017, 2018). The effect pathways of microplastics on the health of commercially important marine organisms, and possible risks to human health from consuming these organisms, must therefore be researched more thoroughly, to evaluate the potential effect of microplastic pollution to food security.

5. Conclusion

This review examined the presence of microplastics within commercially important marine organisms, and the risks they may have on organism health. All commercially important organisms analysed in this review were shown to contain microplastics. Investigation of microplastic concentrations at different trophic levels suggests that microplastics do not biomagnify, and organisms at lower trophic levels are at greater risk of microplastic contamination. While organisms higher up the food chain may not contain as many microplastics per gram body weight, risks are still present from contaminant transfer and chronic effects, potentially including increased feeding pressure as a result of the higher risk to lower trophic level organisms. This review highlights that some marine organisms that are important to global food security are omitted from current microplastics research, and that microplastics are a risk to the health of marine organisms worldwide. As fisheries and aquaculture are critical for global food security, this has implications for food security and food safety. Microplastics present an added risk to an already stressed environment, and further research on the effects of microplastic pollution is required to be able to perform comprehensive risk assessments on the effect of microplastics on food security.

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