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

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6   **Microplastics and seafood: lower trophic organisms at highest risk of**

7   **contamination**

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17

18 **Abstract**

19 Microplastic debris is a prevalent global pollutant that poses a risk to marine organisms and ecological

20 processes. It is also suspected to pose a risk to marine food security; however, these risks are currently

21 poorly understood. In this review, we seek to understand the current knowledge pertaining to the

22 contamination of commercially important fished and farmed marine organisms with microplastics,

23 with the aim of answering the question "Does microplastic pollution pose a risk to marine food

24 security?". A semi-systematic review of studies investigating the number of microplastics found in

25 commercially important organisms of different trophic levels suggests that microplastics do not

26 biomagnify, and that   organisms at lower trophic levels are more likely to contaminated by

27 microplastic pollution than apex predators. We address the factors that influence microplastic

28 consumption and retention by organisms. This research has implications for food safety and highlights

29 the risks of microplastics to fisheries and aquaculture, and identifies current knowledge gaps within

30 this research field.

31

32 **Keywords**

33 Plastic; Food security; Aquaculture; Trophic transfer; Biomagnification

34

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

69   ocean gyres, sediments, shorelines, polar sea ice, and biota, including animals destined for human

70   consumption (Hardesty *et al.*, 2017; Peeken *et al.*, 2018). Whilst there are efforts to remove

71   microplastics from the marine environment, it is widely accepted that once released, it is practically

72   and economically infeasible to recapture marine microplastics for recycling or responsible disposal.

73

74   Microplastics pose a risk to marine life and ecological processes (Galloway, Cole and Lewis, 2017), and

75   it has been suggested they may further impact on food security (Barboza *et al.*, 2018a), socio-

76   economic wellbeing (Beaumont *et al.*, 2019) and human health (Galloway, 2015). The perceived risks,

77   pathways, effects, and consequences arising from microplastic pollution on food security and

78   ecosystem health in the marine environment are displayed in Fig. 1.

79
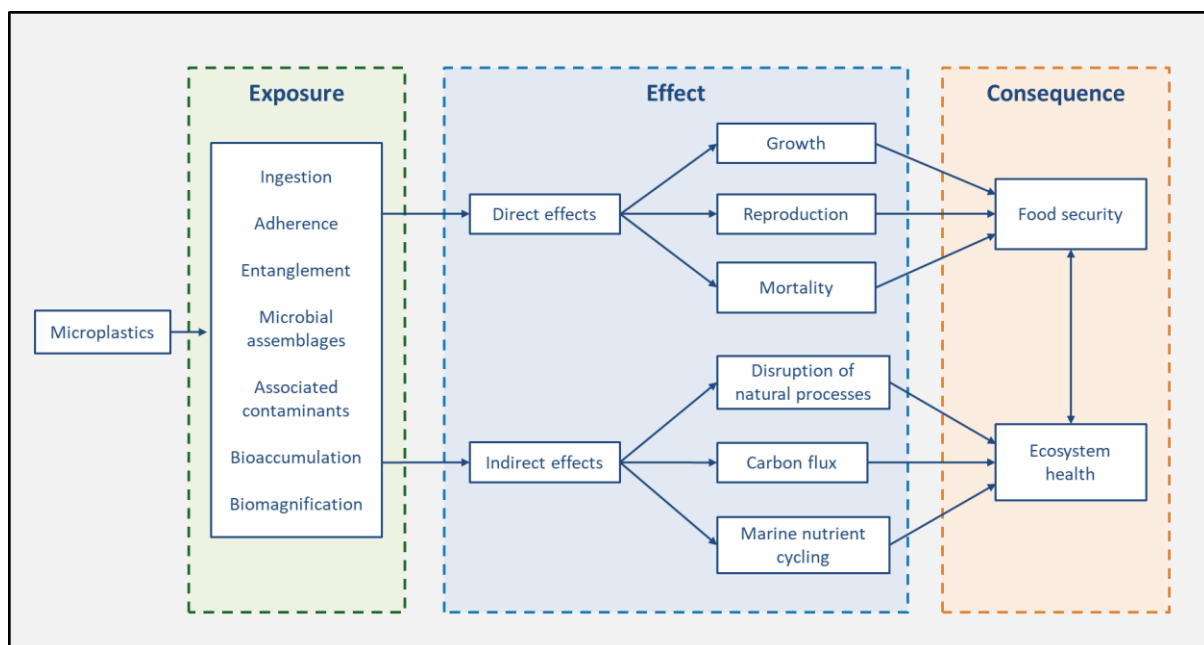
80

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

82

83   *1.1 Marine food security*

84   Fisheries and aquaculture provide a critical proportion of the world's food supply, providing over 4.5

85   billion people with at least 15% of their average per capita intake of animal protein (Béné *et al.*, 2015),

86   and production is predicted to grow in the future, from 171 million tonnes in 2016 to approximately

87   201 million tonnes in 2030, an increase of 17.5% (FAO, 2018). Global fish exports in 2017 were valued

88   at 152 billion USD (FAO, 2018). Total capture from fisheries has remained fairly constant since the

89   1990s and is not expected to increase considerably, with growth instead expected from aquaculture,

90   predominantly in Asia, which as a continent accounts for almost two thirds of global fish consumption

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

92   (FAO, 2018).

93

94   Food security is defined by the Food and Agriculture Organisation as "a situation that exists when all

95   people, at all times, have physical, social and economic access to sufficient, safe and nutritious food

96   that meets their dietary needs and food preferences for an active and healthy life" (FAO *et al.*, 2017).

97   Current identified risks to food security include climate variability due to both short-term events and

98   climate change, eutrophication, ocean acidification, oxygen depletion, conflict, economic recession,

99   pathogens, and pollution (Chakraborty and Newton, 2011; Wollenberg *et al.*, 2016). Larger plastic

100 debris, particularly derelict fishing gear (i.e. abandoned or lost nets, lines, pots), has been shown to

101 pose a substantial risk to food security. For example, in Chesapeake Bay the removal of 34,408 derelict

102 fishing pots led to the harvest of an additional 13,504 metric tonnes in blue crab (*Callinectes sapidus*)

103 valued at 21.3 million USD (Scheld, Bilkovic and Havens, 2016). However, whilst there has been

104 considerable research into the effects of microplastics on marine organisms, evidence is lacking on

105 the effect of microplastics on food security and food safety. We hypothesise that in marine ecosystems

106 already affected by a multitude of environmental stressors, microplastics may represent a significant

107 additional risk to food security.

108

109 In this review, we critically assess microplastics research with relevance to fishing and aquaculture,

110 the health of commercially exploited organisms, and food security; to understand the current state of

111 microplastics research and evaluate whether microplastics pose a risk to food security. Several marine

112 pollutants are known to biomagnify, causing heightened risk to higher trophic organisms, however,

113 very little research is available to show whether this may occur with microplastics, with current

114 research giving opposing viewpoints (GESAMP, 2016; Akhbarizadeh, Moore and Keshavarzi, 2019;

115 Hantoro *et al.*, 2019). We evaluate currently available data regarding microplastic content within

116 organisms of different trophic levels to assess whether biomagnification is likely to be a risk with

117 microplastic contamination. Current research gaps will also be discussed to highlight areas where

118 unknown risks may threaten marine food security and human health.

119

120 **2. Methods**

121 **2.1 Sourcing reference material**

122 In order to investigate the prevalence of microplastics in commercially exploited marine organisms,

123 including fish, shellfish, crustaceans and macroalgae, we undertook a semi-systematic review of the

124 scientific literature, performed by using a specific set of search terms separated by Boolean operators

125   (Table 1), utilising the academic literature search engines *Web of Science*, *ScienceDirect*, *Pubmed* and

126   *PLOS ONE*. This search method was supplemented by use of a snowballing method, where further

127   literature was identified in the references of the articles reviewed to encompass the broadest set of

128   literature. Only articles published up to the end of 2018 were included in the data analysis in this

129   review. See Table 2 for a summary of the number of articles found from each search engine. These

130   articles were considered for relevant information and subjected to a quality control step (see below);

131   literature that passed this stage was utilised in this review.

132

133   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

134

135   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

136

2.2 Quality control

138   The primary literature from which data was extracted for analysis had been peer-reviewed prior to

139   publication, providing a base level of quality assurance. We additionally conducted a quality

140   assessment to verify that: (1) experimental replication was performed for statistical analysis; and (2)

141   suitable controls were implemented in the study protocol (e.g. negative controls in toxicity testing,

142   procedural blanks, and contamination controls in environmental analyses). If any of these quality

143   control parameters was not met, the literature was not included in this review. After these steps, the

144   identified literature was cross-referenced with available data showing organisms of global importance

145   to aquaculture and fisheries. Following further narrowing of studies to select those that analysed

146   organisms of commercial importance, 32 pieces of literature were selected to ascertain the data

147   presented in this review.

148

149   **2.3 Data analysis**

150   In the literature data is typically presented as the number of microplastics per individual

151   (MP/individual) for fish, or microplastics per gram (wet weight, w. w.) (MP/gram) for shellfish. For

152   assessing whether microplastics biomagnify within lower trophic level organisms it was necessary to

153   convert MP/individual values by ascertaining mean wet weights for individual species, drawn from

154   primary and grey literature. MP/gram w. w. values were subsequently estimated by dividing average

155   microplastics per organism by the average mass of that organism as reported in the literature (see

156   Table S1 for further information).

157

158   **3. Results**

159

160   **3.1 Risks to food security**

161

162   ***3.1.1 Prevalence of microplastics in commercially exploited species***

163   Microplastics can be ingested by a wide range of marine life, and the presence of microplastics in

164   marine organisms destined for human consumption has been widely reported. Tables 3 and 4 below

165   show the 10 most caught marine species and 10 most farmed aquaculture species in 2016 (FAO, 2018),

166   alongside evidence of their capacity to ingest microplastic debris. 60% of the most farmed aquaculture

167   species have been investigated for the presence of microplastics, and 80% of the most caught marine

168   species have been investigated. The organisms that are not mentioned in any microplastic ingestion

169   studies up to the end of 2018 represented a total of approximately 22.5 million tonnes of food in 2016.

170

171   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

172

173

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

175

3.1.2 Fish

176 Many species of edible demersal, pelagic and reef fish, sampled from across the globe, have been

177 found to ingest microplastics (Bellas *et al.*, 2016; Rummel *et al.*, 2016; Bråte *et al.*, 2016; Lusher,

178 McHugh and Thompson, 2013; Ory *et al.*, 2018; Tanaka and Takada, 2016; Rochman *et al.*, 2015; Neves

179 *et al.*, 2015; Critchell and Hoogenboom, 2018). Of the seven most farmed aquaculture species which

180 are fish (Table 3), all are freshwater species, and their feeding strategies are mostly planktivorous or

181 omnivorous, with the exception of the grass carp which is herbivorous and feeds mostly on aquatic

182 weeds. These fish may be likely to consume microplastics due to their prey being within a similar size

183 range. However, microplastic ingestion investigations have only been performed on Common carp,

184 Crucian carps, Nile tilapa and Silver carp, and no data is available for the other three species, even

185 though they represent a combined 12.5 million tonnes of farmed fish (as of 2016). These studies gave

186 a combined average amount of microplastics per organism of 2.5 ± 1.3 MP/individual (Common carp),

187 1.9 ± 1.0 MP/individual (Crucian carps), and 3.8 ± 2.0 MP/individual (Silver carp). Nile tilapia data was

188 presented by the authors as the number of individuals which had consumed microplastics, which was

189 an average of 16% (Rochman *et al.*, 2015; Biginagwa *et al.*, 2016). Where it is possible to view the

190 morphology of plastic particles ingested, fibres are the most common microplastic shape seen and

191 make up 57.6-86.5% of the plastic shapes observed.

194   Of the ten most caught species (Table 4), all are marine fish; the majority are pelagic species that

195   consume mostly plankton and small fish, with three exceptions (pollock, tuna and cod). The

196   microplastic content of these fish are much more studied than common aquaculture species, with 80%

197   of the top ten most fished species included in at least one microplastic study. Collating all available

198   literature on these organisms gives the following percentages of each species that were seen with

199   microplastics in their gastrointestinal tract (GIT): 0.9% Peruvian anchovy; 9.4% Skipjack tuna; 24.5%

200   Jack and Horse mackerels; 8.8% Atlantic herring; 23.3% Pacific chub mackerel; 23.4% Yellowfin tuna;

201   2.8% Atlantic cod, and 76.6% Japanese anchovy (Neves *et al.*, 2015; Foekema *et al.*, 2013; Lusher,

202   McHugh and Thompson, 2013; Murphy *et al.*, 2017; Güven *et al.*, 2017; Ogonowski *et al.*, 2017;

203   Rummel *et al.*, 2016; Hermsen *et al.*, 2017; Rochman *et al.*, 2015; Ory *et al.*, 2018; Choy and Drazen,

204   2013; Markic *et al.*, 2018; Bråte *et al.*, 2016; Liboiron *et al.*, 2016; Tanaka and Takada, 2016). Other

205   species of commercial importance that have been included in several pieces of literature (plus

206   percentages seen with microplastics in their GIT) include Scads (*Decapterus spp*, 46%.), European

207   pilchards (*Sardina pilchardus*, 26%), Blue whiting (*Micromesistius poutassou*, 29.8%), and Atlantic

208   mackerel (*Scomber scombrus*, 23.2%). As with aquacultured species, fibres are the most common

209   microplastic shape seen, forming 30-87.6% of the plastic shapes observed. Unfortunately it is not

210   possible to view in detail the most common size of microplastics observed in each species due to how

211   the data is reported, however this information may not be reliable due to constraints in minimum

212   observable size in the methodology used (e.g. choice of filters, sensitivity of analytical techniques,

213   Lusher *et al.*, 2017). Notable by its absence in the literature is the Alaska Pollock (*Theragra*

214   *chalcogramma*) and members of *Sardinella spp.*, neither of which were found to have been analysed

215   to investigate microplastic ingestion in the literature. Both species are an extremely important food

216   source, with more than 3.47 million tonnes of Pollock and 2.29 million tonnes *Sardinella spp.* fished in

217   2016.

218

219   *3.1.3 Shellfish*

220   Cupped oysters (*Crassostrea spp.*) and Japanese carpet shell (*Ruditapes philippinarum*) are among the

221   most prevalently aquacultured shellfish species worldwide. Microplastic ingestion in shellfish is

222   generally reported as the number of microplastics per gram of wet tissue. In Cupped oysters, the

223   average result reported ranged from 0.18 to 3.84 microplastics gram^{-1} w. w., and in the Japanese

224   carpet shell, the average reported result ranged from 0.9 to 2.5 microplastics gram^{-1} w. w.

225

226 By far the most studied shellfish are mussels of the family *Mytilidae*. 9 pieces of literature were

227 identified that studied the amount of microplastics found in sea mussels in their natural environments,

228 with ingestion ranges varying from 0.2-5.36 microplastics g^{-1} w. w. (Bråte et al., 2018; Catarino *et al.*,

229 2018; De Witte *et al.*, 2014; Li *et al.*, 2015, 2016; Phuong *et al.*, 2018; Qu *et al.*, 2018; Van

230 Cauwenberghe and Janssen, 2014; Van Cauwenberghe *et al.*, 2015). Whilst ingestion values look

231 different when analysing the number of microplastics ingested per individual, when normalised for

232 soft tissue weight, the values for all three species overlap, seemingly showing that microplastic

233 ingestion in shellfish is not species-specific. Though shellfish can show selective feeding, rejecting

234 particles based on size or lack of organic material (Newell and Jordan, 1983; Defossez and Hawkins,

235 1997), they are found to ingest microplastics. Whilst these species all ingest similar amounts of

236 microplastics, it is possible that they selectively ingest different size microplastics due to organism

237 size, with for example oysters being able to ingest larger particles than mussels. Data from the analysis

238 of mussels and oysters taken from the French Atlantic coast (Phuong *et al.*, 2018) suggests this, as

239 both organisms ingested a majority of microplastics in the 50-100 μm size range, but mussels ingested

240 a higher proportion of 20-50 μm particles than oysters (37% and 15 %, respectively), and oysters

241 ingested a higher proportion of > 100 μm particles than mussels (32% and 11%, respectively).

242

243 ### *3.1.4 Crustaceans*

244 Crustaceans form a very large and diverse group of organisms including many that are important for

245 worldwide food security, such as crabs, lobsters, crayfish and prawns. Many edible species of

246 crustaceans have been shown to ingest microplastics (Devriese *et al.*, 2015; Welden and Cowie, 2016a;

247 Abbasi *et al.*, 2018). Organisms such as copepods and krill are also critically important as a food for

248 organisms which are consumed by humans, and have been reported to ingest microplastics (Botterell

249 *et al.*, 2019).No studies have been performed to investigate microplastic ingestion in the Whiteleg

250 shrimp, one of the top ten most farmed aquatic species with 4.2M tonnes farmed in 2016 (Table 3),

251 however, investigations have taken place with other commercially important species. Brown shrimp,

252 *Crangon crangon,* a commercially important crustacean fished in the eastern Atlantic and

253 Mediterranean Sea, were found with an average of 0.68 ± 0.55 microplastics $gram^{-1}$ w. w. and 63% of

254 the 165 shrimp analysed containing microplastics (Devriese *et al.*, 2015). Green tiger prawn, *Penaeus*

255 *semisulcatus*, an organism of commercial important in East Africa and Asia, was found to have ingested

256 an average of 7.8 particles per individual (1.5 particles $gram^{-1}$, n=12) in the Musa estuary, Persian Gulf

257 (Abbasi *et al.*, 2018). Nylon fibres were observed in the stomachs of 5.93% *Plesionika narval* (narwhal

258 shrimp), an important fishery in the Aegean Sea, although it is hypothesised by the authors that these

259 fibres may result from the fishing method (Bordbar *et al.*, 2018). Other commercially important

260 species that have been observed to contain microplastics include *Eriocheir sinensis* (Wójcik-
261 Fudalewska, Normant-Saremba and Anastácio, 2016),*Carcinus maenas* (Watts *et al.*, 2014, 2015), and
262 *Nephrops norvegicus* (Murray and Cowie, 2011; Welden and Cowie, 2016b).

263

264 ### 3.1.5 Macroalgae

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

284

285 **3.2 Factors influencing microplastic consumption**

286

287 ### 3.2.1 Feeding strategy

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

293   microplastics direct from the natural environment, while piscivores (e.g. tuna) would be expected to

294   consume microplastics mainly through trophic transfer via prey or accidental ingestion while feeding.

295

296   Direct ingestion of microplastics is often a consequence of feeding strategy. Indiscriminate feeders

297   show no selection in the matter that they ingest, ingesting prey in proportion to their availability in

298   the environment, whilst discriminate feeders select based on preferential feeding factors (colour, size

299   etc.). Filter feeders such as some bivalves can be considered as indiscriminate feeders as they feed by

300   filtering water through their gills, capturing particulate matter such as plankton and microalgae. This

301   is generally in a non-selective manner; however some of the filtered matter can be rejected. This has

302   been shown recently by Ward *et al.* (2019), who demonstrated that the bivalves *Crassostrea virginica*

303   and *Mytilus edulis* selectively ingested microplastics preferentially, based on the physical

304   characteristics of the plastic. In this way, microplastics are ingested if they resemble the properties of

305   the organic matter these organisms feed on, such as in size and shape. Discriminate feeders may

306   directly ingest microplastics either when they resemble prey items, or incidentally whilst feeding, e.g.

307   in contaminated feedstock; this feeding strategy is generally utilised by higher trophic-level organisms.

308   Discriminate feeders such as fish may therefore ingest microplastics that resemble their prey.

309   Amberstripe scad (Decapterus muroadsi) appear to ingest blue microplastics preferentially as they

310   resemble their copepod prey in both colour and size (Ory *et al.*, 2017). Evidence of selective feeding

311   on the blue copepods *Pontella sinica* and *Sapphirina spp.* was seen, as was selectivity for blue

312   microplastics.

313

314   Indirect ingestion, or "trophic transfer" occurs when organisms consume prey that have already

315   consumed microplastics. Trophic transfer from blue mussels *Mytilus edulis* to the shore crab *Carcinus*

316   *maenas* has been observed in laboratory conditions (Farrell and Nelson, 2013; Watts *et al.*, 2014).

317   Farrell and Nelson (2013) fed 0.5 µm fluorescent polystyrene microspheres to *M. edulis*, with *C.*

318   *maenas* subsequently being fed one mussel per crab. Microspheres were subsequently detected in

319   the stomach, hepatopancreas, ovary, gills and haemolymph of the crabs. Results from Nelms *et al.*

320   (2018) suggest the ability for microplastics to be ingested by grey seals (Halichoerus grypus) through

321   trophic transfer from Atlantic mackerel (Scomber scombrus). Detritivores may also be prone to

322   indirectly consuming microplastics present in faeces of contaminated organisms; for example

323   coprophagous copepods can ingest microplastics present in other copepods' egests (Cole *et al.*, 2016).

324   Feedstock contaminated with microplastics may be a risk to aquaculture, as fishmeal is a commonly

325   used fish feed manufactured from whole fish, therefore any microplastics within the fish may pass

326   into the processed fishmeal (Karbalaei *et al.*, 2019).

327

328

329

330   ***3.2.2 Trophic level***

331   The percentage of planktivorous and piscivorous fish populations contaminated with microplastics

332   might suggest that trophic level and feeding strategy alone are not indicative of microplastic ingestion,

333   however, this may be due to a difference in how microplastics data are usually presented (See Table

334   5). For example, Markic *et al.* (2018), saw no significant difference in their study on plastic ingestion

335   rate in 23 species of fish in the South pacific based on their trophic level, with the only significant

336   difference in ingestion rates seen between benthic predators and omnivores. However, while similar

337   proportions of the total population of marine organisms with different dietary strategies contained

338   microplastics, the number of microplastics per gram of tissue may be very different. For example, data

339   presented in this review shows a similar percentage of *S. japonicus* (23.3%) and *T. albacares* (23.4%)

340   contained microplastics, but the average weight of *T. albacares* caught by Markic *et al.* (2018) is 5228.7

341   g, whereas the average caught weight for *S. japonicus* by Güven *et al.* (2017) was 28.86 g. Using these

342   weights, the average amount of plastic particles per gram (wet weight) for S*comber japonicus* from

343   Güven *et al.* (2017) is estimated as 0.33 particles gram^{-1} and the maximum number of microplastics

344   found per gram in *Thunnus albacares* from Markic *et al.* (2018) is estimated at 5.9×10^{-4} particles gram^{-1}

345   ^{1}, a 1000-fold difference.

346

347   In order to investigate this further, 11 commercially exploited taxa, including bivalves, crustaceans

348   and fish, were selected for analysis from a variety of trophic levels. Taxa were selected that had either

349   a wide range of literature available for analysis (e.g. *Mytilus spp.*, *Scomber japonicus*), or were at a

350   trophic level not covered by other data (e.g. *Thunnus* albacares, *Katsuwonus* pelamis). The data was

351   normalized to give the number of microplastics ingested per gram wet weight of these organisms.

352   Table 5 lists the fish, crustaceans and bivalves in which the number of microplastics per gram wet

353   weight of tissue has been calculated.

354

355   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

356

357

358   There is up to four magnitudes of difference between microplastics per gram present in shellfish

359   compared to higher trophic level fish. The data presented above therefore suggests that trophic level

360   and feeding strategy may play a key role in the level of microplastic contamination within marine

361   organisms; though similar percentages of the total population of organisms at different trophic levels

362   contain microplastics within their body tissues, lower trophic level organisms have a higher proportion

363   of microplastic comparatively with body weight, which may be more indicative of risks from

364   microplastics. Fig. 2 displays a comparison of microplastics per gram wet weight of the organisms in

365   Table 5 with the amount of mercury in tissues of similar organisms reported by Plessi, Bertelli and

366   Monzani (2001; *Mytilus spp.*) and the FDA (FDA, 2017; all other species). Mercury is well known to

367   biomagnify, and values are inversely proportional with the microplastic data presented here, which

368   shows a decrease in microplastic concentration with increasing trophic level. Based on this data, we

369   conclude that unlike other contaminants such as organochlorines (Borgå, Gabrielsen and Skaare,

370   2001) or mercury (Lavoie *et al.*, 2013), microplastics do not biomagnify. This is likely because the

371   evidence currently suggests that microplastics do not, in most cases, translocate from the digestive

372   system into tissues or circulatory fluid, therefore it is a more transitory contaminant with a limited

373   residence time within organisms.

374

375

376

377
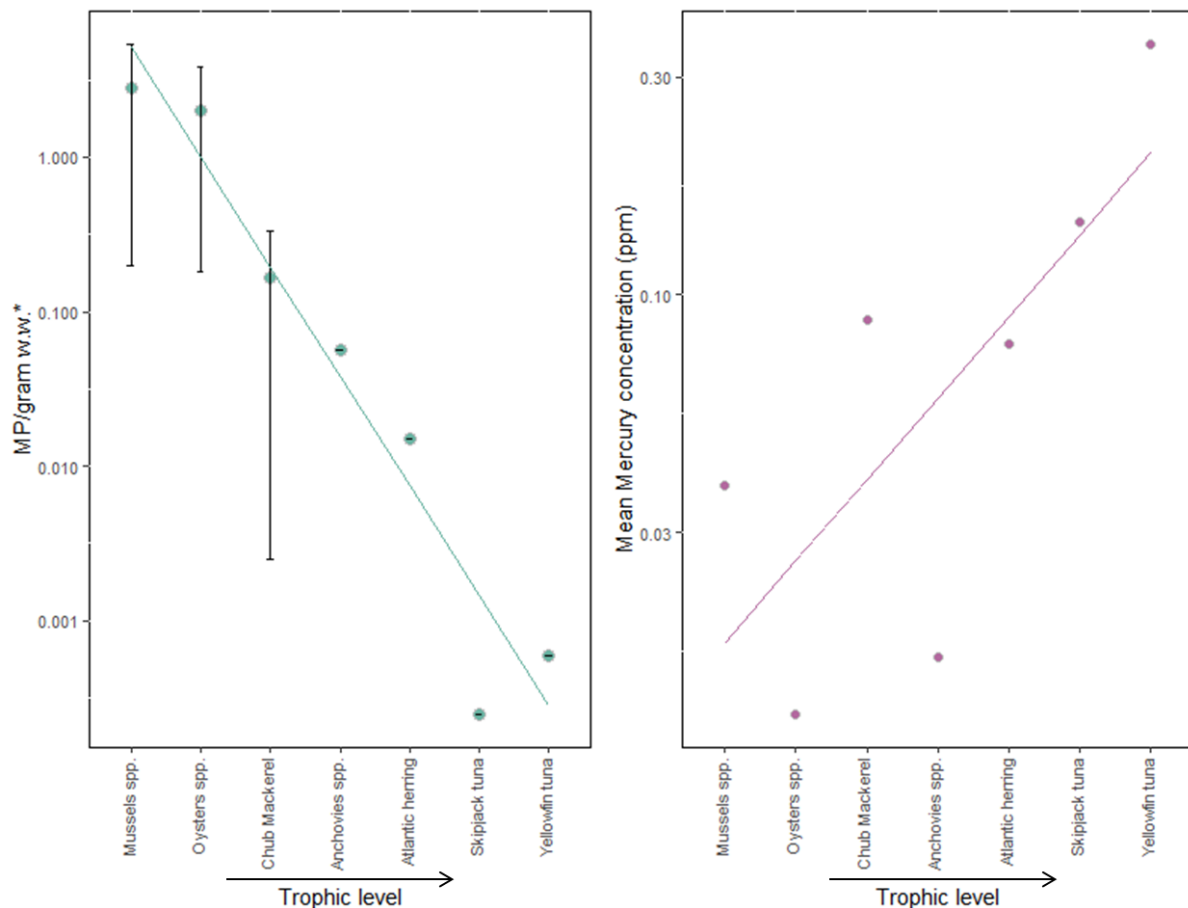
Fig. 2. A comparison of the number of microplastics (MP) per gram wet weight of organisms of different trophic levels to the amount of Mercury (ppm) reported in the tissues of similar organisms as listed by the FDA (FDA, 2017) and Plessi, Bertelli and Monzani (2001). Trophic level shows general increase 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

397 higher encounter rates where microplastic concentrations exceeded those of fish larvae (Steer *et al.*,

398 2017).

399

400 Environmental concentrations may be a particularly important variable for microplastic ingestion in

401 crustaceans and molluscs (Li *et al.*, 2019). As bivalves are filter feeders, any differences in microplastic

402 ingestion are likely due to microplastic distribution in their habitat. Li *et al.* (2016) investigated

403 microplastic abundance in mussels in 22 sites along the coast of China, and significant differences in

404 microplastic ingestion were seen at different sites. Wild mussels contained on average 2.7 items/g

405 (4.6 items/individual) and farmed mussels contained on average 1.6 items/g (3.3 items/individual). In

406 heavily contaminated areas, mussels contained an average of 3.3 items/g (5.3 items/individual),

407 whereas in less contaminated areas, microplastic abundance in mussels was significantly lower (1.6

408 items/g or 3.3 items/individual). Gut content of individuals of the crustacean *Nephrops norvegicus*

409 collected from three sites in North and West Scotland had significantly different microplastic

410 ingestion; 84.1%, 43% and 28.7% of *N. norvegicus* individuals ingested microplastic in the Clyde Sea

411 Area, North Minch and North Sea, respectively (Welden and Cowie, 2016a), suggesting crustaceans

412 may also ingest microplastics relative to environmental availability.

413

414 **3.3 Risks of microplastics to marine organisms**

415

416 *3.3.1 Retention in the digestive system (gut blockages)*

417 Following ingestion, microplastics may be rejected by the organism through pseudofaeces or post-

418 ingestion rejection, egested through faeces, transferred across the GIT epithelium, or be retained in

419 the GIT. Microplastic retention in the digestive system may adversely affect organism health through

420 physical perforation of the gut or by giving the organism a feeling of false satiety, decreasing feeding

421 activity and nutrient intake.

422

423 Shore crabs fed with 10 µm polystyrene microspheres had plastic detected in the foregut 5 days after

424 exposure to microplastic-containing mussels (Watts *et al.*, 2014). In this feeding experiment, crabs

425 were fed with mussels that had been exposed to microplastics and subsequently sampled over a 21-

426 day period, and n=6 crabs were analysed for microplastics in the foregut at each time point post-

427 ingestion. Polystyrene microspheres were detected in all six crabs after 24hrs; decreasing to 50-66%

428 of the crabs from days 2-5. Microplastics were then not detected in the crab faecal pellets after 7 and

429 22 days post-exposure (but were on day 14).

430

431   Blue mussels (*Mytilus edulis*) were shown to ingest 9% of all available microplastic fibres (approx. 450

432   µm length) in an ingestion study where microplastic fibres were ingested alongside the microalgae

433   *Rhodomonas salina* (Woods *et al.*, 2018). Mussel filtration rate decreased when exposed to

434   microplastic fibres in addition to *R. salina*, and though most fibres (71%) were rejected as

435   pseudofaeces, 9% were ingested, and < 1% were excreted in faeces. Microplastics were identified in

436   the gills, digestive gland and other soft tissues at all time points over a 72 hr exposure period. In

437   another experimental study, 2 of 31 Palm Ruff (*Seriolella violacea*) fish were shown to retain

438   microplastics after a 49-day exposure period (Ory *et al*., 2018). The transitory nature of microplastics

439   within the digestive system of organisms may explain why microplastics do not appear to biomagnify.

440   If microplastics pass through the GIT of organisms and are not retained within the GIT or tissues, it is

441   much less likely that organisms at higher trophic levels will ingest significant amounts of microplastics

442   through a carnivorous diet.

443

444   Research by Welden and Cowie (2016) suggests whilst Norway lobster (*Nephrops norvegicus*) are seen

445   to retain microplastics within their foregut for extended periods of time, the main route by which they

446   are removed is by ecdysis, whereby the individual moults and sheds its gut lining. This gut lining was

447   found to contain microplastics which were removed from the individual during moulting.

448

449   ***3.3.2 Growth rate, reproduction or function affected?***

450   Any changes to growth rate, reproduction, mortality or behaviour due to external factors may

451   significantly alter population dynamics. In the case of commercially important organisms, this may

452   significantly affect the efficiency and profitability of fishing and aquaculture. Lower growth rates may

453   mean that fewer organisms can be harvested in a season, or lower reproduction rates may cause

454   population decreases in following seasons, both of which would have a negative effect on food

455   security. A similar concept is discussed by Galloway, Cole and Lewis (2017), who propose that, though

456   chronic exposure to microplastic is not usually lethal, it is associated with reductions in energy,

457   growth, fecundity and reproductive output. These individual and population-level effects can as a

458   consequence cause ecosystem level effects, such as community shifts and changes to ecosystem

459   function, which would result in risks to food security.

460

461   Several articles have shown reduction of growth rates and reproductive function (Cole *et al.*, 2015;

462   Sussarellu *et al.*, 2016), and behavioural changes (Cole *et al.*, 2015; Sussarellu *et al.*, 2016; Ribeiro *et*

463   *al.*, 2017; Woods *et al.*, 2018) in marine organisms as a result of exposure to microplastics. Significant

464   effects from microplastic exposure were observed in laboratory exposure studies with the Pacific

465 oyster (*Crassostrea gigas*) (Sussarellu *et al.*, 2016). Significantly higher algal consumption was
466 observed for oysters exposed to microplastics, possibly in an attempt for the oyster to compensate
467 for lower nutrient intake. Significant reproductive effects were observed; exposed female oysters had
468 fewer, smaller oocytes and a reduction in D-larval yield; exposed male oysters had lower sperm
469 velocity. *C. gigas* larval growth was significantly slower, with a reduction in mean size of 18.6% at 17
470 days post-fertilization and a 6-day lag time to metamorphosis.

471

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

479

480 ### 3.3.3 Risk of disease
481 Once in the marine environment, microplastics are quickly colonised by a variety of organisms termed
482 the plastisphere (Zettler, Mincer and Amaral-Zettler, 2013). The plastisphere is a risk to the marine
483 environment, aquaculture and food security as it has the potential to support pathogenic
484 microorganisms, and allow them to become more bioavailable to the organisms consuming
485 microplastics. Recent research has identified hazardous microorganisms present on microplastics,
486 along with microorganisms usually found in sewage and gut-associated pathogens (Oberbeckmann,
487 Löder and Labrenz, 2015). The microbial biofilms discussed here affect the physical characteristics of
488 the plastic, including size and buoyancy, which could in turn affect the vertical distribution of
489 microplastics within the water column, transporting microplastics to the benthos (Kaiser, Kowalski and
490 Waniek, 2017; Kooi *et al.*, 2017). This, in addition to the horizontal transport of microplastics via ocean
491 currents and wind therefore means that microplastics have the capacity to transport microorganisms
492 to new environments over vast distances, suggesting the potential for microplastics to act as a vector
493 for the transfer of invasive pathogens to new environments.

494

495 High concentrations of microplastic debris in the North pacific subtropical gyre have resulted in an
496 increase in the pelagic insect *Halobates sericeus* and in *H. sericeus* egg densities (Goldstein, Rosenberg
497 and Cheng, 2012). Jiang *et al.* (2018) profiled bacterial communities attached to microplastic samples
498 taken from intertidal locations around the Yangtze estuary in China, and found a wide range of

499   bacterial taxa, including some that are associated with human and animal pathogens: *Vibrio* (0.4% of

500   taxonomic abundance, found at Xiangshan bay); *Leptolyngbya* (1.6% abundance, found at Chongming

501   island), and *Pseudomonas spp.* (<0.01% abundance, all plastics).

502

503   Harmful pathogens travelling large distances could have severe implications for food security. One

504   potential example of this would be the colonisation of marine plastics by HAB (harmful algal bloom)

505   species. When floating plastic debris collected along the North-west Mediterranean were analysed,

506   several potentially harmful dinoflagellates were identified, including *Ostreopsis spp, Coolia spp* and

507   *Alexandrium taylori* (Masó *et al.*, 2003), all of which can cause HABs. *Alexandrium spp.* can cause

508   paralytic shellfish poisoning (PSP), which is hazardous to both marine organisms and humans.

509   *Alexandrium catanella* has caused significant economic losses to the salmon industry in Chile, for

510   example in 2009 when a large bloom was associated with a loss of over $10 million to the Chilean

511   Salmon industry (Mardones *et al.*, 2015). *Alexandrium taylori* has also been shown to produce

512   paralytic shellfish toxins and has recently been identified for the first time in Malaysian waters (Lim *et*

513   *al.*, 2005). Invasive HAB species, potentially transported by microplastics, could therefore be incredibly

514   damaging to global fishery and aquaculture industries.

515

516   Marine plastic debris collected from multiple locations in the North Atlantic was analysed and bacterial

517   assemblage sequenced to characterize the plastisphere community (Zettler, Mincer and Amaral-

518   Zettler, 2013). In this diverse community, the bacteria genus *Vibrio* and dinoflagellate genus

519   *Alexandrium* were identified. Both of these genii contain species that are pathogenic to both humans

520   and animals. Several strains of *Vibrio spp.* including potentially pathogenic *Vibrio parahaemolyticus*

521   were also detected on microplastics and in seawater from the North and Baltic sea by Kirstein *et al.*

522   (2016). Microplastics samples from a transect taken along the Slovenian coast of the North Adriatic

523   Sea were subjected to DNA extraction, amplification and phylogenetic analysis, and the bacterial

524   pathogen *Aeromonas salmonicida* was identified on the particles (Viršek *et al.*, 2017). This species is

525   pathogenic to several commercially important species, such as salmonids.

526

527   ***3.3.4 Chemical additives and adhered contaminants***

528   Microplastics contain chemicals added during plastic manufacture to enhance certain properties, and

529   have also been shown to adsorb and concentrate contaminants from the environment such as PCBs,

530   PAHs, and metals (Teuten *et al.*, 2007; Brennecke *et al.*, 2016). Many of these contaminants can be

531   toxic to marine organisms. Several researchers have therefore investigated whether microplastics can

532   act as a vector for contaminant transfer to marine organisms, and whether this is a significant pathway

533   compared to other methods of contaminant ingestion.

534

535   *3.3.4a Chemical additives*

536   Chemical additives in plastics enhance the different properties that make plastics so useful; some act

537   as fire retardants, while others may act as stabilisers, foaming agents or strength enhancers. When

538   plastic pollution occurs, these additives slowly leach from plastics into their surrounding media, for

539   example seawater. This has led to concerns that they may enter biological systems and affect the

540   health of exposed organisms, however, there is also a growing set of evidence that the overall

541   exposure of organisms to these chemicals from plastics is negligible compared to other sources.

542

543   The potential for leaching of nonylphenol (NP) and bisphenol A (BPA) in the GIT of *Arenicola marina*

544   (lugworm) and *Gadus morhua* (Atlantic cod), and a comparison of exposure to these two substances

545   by microplastics alone and total environmental exposure, was investigated utilising a biodynamic

546   model by Koelmans, Besseling and Foekema (2014). They suggest that for cod, ingestion of

547   microplastic is highly unlikely to lead to negative effects from NP and BPA and is negligible compared

548   to uptake from water and prey. For lugworms, though ingestion of microplastic was hypothesised to

549   be a substantial exposure pathway in certain conditions, the low concentrations of NP and BPA

550   involved would not cause a risk to the lugworm.

551

552   *3.3.4b Adhered contaminants*

553   In addition to leaching chemical additives, plastic particles can sorb contaminants from the

554   environment, giving a possible route for the concentration of these chemicals, potentially increasing

555   their toxicity if they are released into a marine organism. Teuten *et al.*, (2007) investigated the uptake

556   and release of the hydrophobic organic contaminant phenanthrene by three virgin plastic polymers:

557   polyethylene, polypropylene, and polyvinyl chloride. All three sorbed phenanthrene with varying

558   efficiency, however all three plastics greatly exceeded the sorption of phenanthrene onto two natural

559   sediments.

560

561   Ašmonaitė *et al.* (2018) investigated the effect of ingestion of large (100-400 µm) polystyrene

562   microplastics (PS-MPs) on the rainbow trout (*Oncorhynchus mykiss*). Trout were exposed to virgin

563   microplastics as well as microplastics exposed to either sewage effluent or environmental water in a

564   harbour. All three sets of PS-MPs contained chemical contaminants including PAHs, plasticizers and

565   surfactants, however, a wider variety of compounds were detected after exposure to sewage and

566 harbour water, confirming the ability for PS-MPs to sorb contaminants from the aquatic environment.

567 Rainbow trout were experimentally exposed to these microplastics following a dietary-exposure

568 protocol, however no significant changes in hepatic biomarker responses were observed, suggesting

569 that PS-MPs did not induce adverse hepatic stress in rainbow trout; however, Ašmonaitė *et al.* (2018)

570 theorize that this may be due to the size of the PS-MPs used, as oxidative stress effects have been

571 observed for smaller polystyrene particles (Jeong *et al.*, 2016; Lei *et al.*, 2018). Ašmonaitė, Sundh, *et*

572 *al.* (2018) also show that PS-MPs did not affect intestinal health in the same species.

573

574 A review and reinterpretation of the available literature by Koelmans *et al.* (2016) and a modelling

575 study by Bakir *et al.* (2016), both investigating the relative importance of microplastics as a pathway

576 for the transfer of adhered contaminants from microplastics to biota, suggest that this is not a

577 significant route for exposure to adhered contaminants when compared to bioaccumulation from

578 natural prey and water.

579

580 *3.3.4c Metals*

581 Heavy metal pollution within the marine environment is increasingly becoming a serious threat to

582 ecosystems (Naser, 2013) and may therefore become a risk to food security in the near future.

583 Brennecke *et al.* (2016) examined the adsorption of two heavy metals, copper and zinc, leached from

584 antifouling paint, to virgin polystyrene beads and aged polyvinylchloride fragments in seawater. Both

585 heavy metals adsorbed onto the two microplastic types, with concentrations of Cu and Zn increasing

586 significantly on PVC and PS over the 14-day experiment. Significantly greater adsorption of Cu onto

587 PVC fragments was observed, with the authors theorizing this was due to the higher surface area and

588 polarity of PVC.

589

590 The effect of exposure to microplastic (0.26 and 0.69 mg/L), mercury (0.010 and 0.016 mg/L) and

591 mixtures of the two substances (same concentrations) on the gills and liver of juvenile European bass

592 (*Dicentrarchus labrax*) over a 96-hour period showed that, while both alone caused oxidative stress in

593 the gills and liver, the concentration of mercury in both gills and liver was significantly higher in the

594 presence of microplastics than their absence (Barboza *et al.*, 2018b). This result is therefore indicative

595 of a synergistic effect of microplastics on the accumulation of mercury within fish tissue. Heavy metals

596 are proven environmental contaminants, and their interaction with microplastic debris therefore has

597 potential to significantly alter the toxicity of microplastics within the marine environment.

598

599

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

634 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).
635 This is the first time that fragmentation of microplastics to nanoplastics has been reported in
636 planktonic crustaceans, and could be indicative of a mechanism for microplastic translocation to
637 tissues in crustaceans where initially they may have been too large.

638

639

640 **4. Discussion**

641

642 ***4.1 What does the data show?***

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

650

651

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

663

664 The data presented in Fig. 2 and Table 5 suggests that microplastics do not biomagnify. Comparing
665 microplastic concentrations within the GIT of different marine organisms to Hg concentrations within
666 similar organisms (Fig. 2), normalizing by organism weight, shows contrasting trendlines; Hg presence
667 in organism tissues (ppm) biomagnifies with increasing trophic level whereas the number of

668 microplastics g^{-1} w. w. decreases with increasing trophic level. Whilst the data presented here suggests
669 that microplastics within marine organisms do not biomagnify, this may not be the case for
670 nanoplastics. These particles are small enough to possibly pass through the gut lining and into the
671 tissues of organisms (Al-Sid-Cheikh *et al.*, 2018), therefore they may be more likely to bioaccumulate
672 in animal tissues and may potentially biomagnify through the food chain (although there is no data as
673 of yet to support this hypothesis).

674

675 ***4.2 What factors influence microplastic consumption?***

676 Feeding strategy and environmental prevalence are primary drivers for microplastic consumption.
677 Generally, lower trophic level organisms appear to ingest more microplastics due to feeding strategy,
678 as observed by our biomagnification data (Fig. 2 and Table 5). However, there can be huge variations,
679 for example although they occupy the same ecological niche, 76.6% Japanese anchovy were found
680 with microplastics within their GIT (Tanaka and Takada, 2016), but only 0.9% Peruvian anchovy (Ory
681 *et al.*, 2018). This is most likely due to the location where the fish were caught and the sample
682 digestion methodology utilised. The Japanese anchovy were caught in Tokyo bay, which is in extremely
683 close proximity to a very large level of anthropomorphic activity, with a drainage basin population of
684 29 million people, whereas the Peruvian anchovy were caught in further offshore locations in
685 proximity to smaller population centres, therefore less microplastic pollution may be expected.
686 Tanaka and Takada (2016) also removed and digested the entire GIT, whereas Ory *et al*. (2018) instead
687 removed and digested only the gut contents; such differences in methodology may lead to differing
688 identification efficacies. These differences, in sampling site and methodology, may have resulted in
689 the large difference in the number of anchovy caught containing microplastics, and care should always
690 be taken when comparing ingestion studies to identify any sampling bias such as identified here.

691

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

702

4.3 What are the issues with current studies?

704 Problems with laboratory analysis of microplastics remain, with several papers likely underestimating
705 the amount of microplastics found in organic material due to worries about contamination and the
706 use of filters with pore sizes too large to catch smaller microplastics. Microplastic fibres are commonly
707 removed from analysis due to concerns about contamination (Rochman *et al.*, 2015; Rummel *et al.*,
708 2016; Ory *et al.*, 2018). Fibres are one of the most common types of microplastic debris worldwide
709 (Lusher *et al.*, 2014; Barrows, Cathey and Petersen, 2018), therefore it is critical that research should
710 utilise methodology to reduce contamination (laminar flow cabinets, non-synthetic laboratory
711 consumables and clothing etc.), to allow for more robust and realistic analyses of environmental
712 microplastic concentrations, as concentrations are very likely to be under-represented without the
713 inclusion of microplastic fibres in results. Smaller microplastics are often missed from analysis due to
714 equipment constraints, both in collection and analysis. Foekema *et al.*, (2013) and Rummel *et al.*
715 (2016) only analysed particles larger than 0.2 and 0.5 mm respectively, due to the diameter of the
716 sieve mesh used. Both Güven *et al.* (2017) and Foekema *et al.* (2013) investigated microplastic in the
717 GIT of *Trachurus spp.;* Güven *et al.* filtered digested *Trachurus mediterraneus* stomach and intestine
718 content through a 26 µm mesh, with the resulting percentage of *Trachurus* shown to ingest
719 microplastics as 68% of the population; Foekema *et al.* filtered digested *Trachurus trachurus* samples
720 through a 0.2 mm seive and found microplastics in 1% of the population. Güven *et al.* also included
721 microplastic fibres in their results, while Foekema *et al.* did not. Mean microplastic size identified by
722 Güven *et al.* was 656.18 µm ± 803.31 SD, median particle size observed by Foekema *et al*. was 800
723 µm. Extrapolation of observed environmental concentrations of microplastics compared to their size
724 shows that as mesh size or bead diameter decreases, the number of microplastics found per litre
725 seawater increases by several orders of magnitude (Lenz, Enders and Nielsen, 2016). This shows a
726 clear bias of microplastics identified due to methodology, and without standardization it is very
727 difficult to accurately compare microplastic studies in a rigorous manner.

728

729 Methodological differences are also clear in the preparation of samples for microplastic analysis.
730 When preparing fish digestive tracts for microplastic analysis, some researchers inspect the entire GIT,
731 while others opt to inspect only the stomach contents. Both of these methods involve manually
732 inspecting GIT contents for microplastics once scraped from their respective lining, while another
733 method more commonly in use in newer studies is to digest the entire GIT, filtering this solution to
734 remove most of the organic matter and make microplastics more visible and easier to quantify.
735 Common solvents used to digest the organic material are H_2O_2, KOH, HNO_3 and $HClO_4$ (Foekema *et al.*,

736 2013; Li *et al.*, 2015, 2016; Van Cauwenberghe *et al.*, 2015; Davidson and Dudas, 2016; Jabeen *et al.*,

737 2017; Phuong *et al.*, 2018; Qu *et al.*, 2018; Waite, Donnelly and Walters, 2018), with combinations of

738 these solvents sometimes used to increase digestion efficacy (De Witte *et al.*, 2014; Devriese *et al.*,

739 2015). Some of these treatments have been shown to have a destructive effect on microplastic

740 particles (Cole *et al.*, 2014; Lusher *et al.*, 2017) therefore care should be taken to ensure microplastics

741 are not damaged or eliminated due to the digestion protocol utilised. One option is to use digestive

742 enzymes; for example Cole *et al*. (2014) and Courtene-Jones *et al.* (2017) have utilised enzymatic

743 digestion with proteinase K and trypsin, respectively, with no observed impacts on microplastics.

744 However, the methods utilized to effectively measure microplastics whilst avoiding microplastic

745 alteration or destruction must be balanced against the cost, speed and effort required.

746

747 ***4.4 What are the risks of microplastics to fisheries and aquaculture?***

748 Measuring the cost of microplastic pollution to ecosystem services, such as food provisioning through

749 fisheries and aquaculture, is very challenging, and research into this is still in its infancy. Measuring

750 the economic cost of marine litter is complex due to the wide range of impacts on the environment,

751 social and economic sectors (Newman *et al.*, 2015), and it can be expected to be even more

752 challenging to look at the cost of only microplastics as a proportion of this. The close relationship

753 between ecosystem services and the marine environment means that adverse environmental effects

754 from microplastic pollution will have impacts on food provisioning, which could add risk to global food

755 security. Research has been done to attempt to put a cost to large marine debris. A survey of Scottish

756 fish vessels reported that 86% of vessels reported reduced catch and 95% reported snagging on their

757 nets on seafloor debris, with an estimated cost of €11.7-13 million per year; the equivalent of 5% of

758 the total revenue of affected fisheries (Mouat, Lozano and Bateson, 2010). Estimated values such as

759 this are not available to look at the cost of microplastic pollution, however the risks of microplastics

760 identified in this review may all add a cost to fisheries and aquaculture that we cannot currently

761 quantify. Microplastics carrying pathogenic microbes or invasive species may decimate native

762 populations of commercially important organisms such as shellfish and crustaceans. Increasing

763 concentrations of microplastic within the marine environment may put a stress on the energetic

764 burden of marine organisms if organisms have to spend more energy to consume nutritionally

765 valuable food this will decrease the energy available for growth and reproduction, and could decrease

766 mean population size and reproductive output. This would mean that commercially exploited

767 organisms could take longer to reach a harvestable size, leading to decreased profits in the fisheries

768 and aquaculture sector, and smaller organism size would lower the nutritional value of seafood.

769

770   Currently, there is no evidence that significant amounts of microplastics can translocate to the tissues

771   of fish from e.g. the digestive tract or gills, and as most fish are consumed gutted or as processed

772   pieces (e.g. fillets), there is little evidence that larger fish will transfer microplastics to humans through

773   diet. However, in the case of smaller fish such as anchovies, as well as shellfish and edible seaweeds,

774   where the whole organism is often consumed, there is a greater risk of humans consuming

775   microplastics, with implications for food safety and food security. Studies have suggested that

776   European consumers may consume 11,000 microplastics per year (Van Cauwenberghe and Janssen,

777   2014) or 4620 microplastics per year (Catarino *et al.*, 2018) through seafood. Although it has been a

778   concern that microplastics may leach additives or adsorbed chemical contaminants into humans upon

779   ingestion, the estimated chemical exposure to humans of persistent organic pollutants and plastic

780   additives following consumption of seafood is expected to be negligible, at <0.1% of total dietary

781   exposure (FAO, 2017). Although risks from seafood ingestion are not currently clear, it is possible that

782   studies such as these will affect the perception of consumers, leading to a change in consumer habits

783   and diet, before robust studies can be performed to give a clear picture of the effects of plastic

784   pollution (Koelmans *et al.*, 2017) on food safety and food security. The results of a survey by the

785   German Environment Agency found that 62% of the population studied felt that they were strongly

786   (39%) or moderately (23%) contaminated by plastic particles in food and drinking water (SAPEA, 2019);

787   microplastics research that is reported whilst failing to address human health and food security

788   concerns may heavily alter public perceptions in similar ways. This may cause a lowering of seafood

789   value and reduced profits in the seafood and aquaculture sector, potentially impacting public health

790   in areas which rely heavily on seafood diets. In addition to researching the prevalence and effect of

791   microplastics that are ingested by organisms in the marine environment, significant numbers of

792   microplastics may be added to seafood during processing stages and packaging; such concerns should

793   be researched through analysing microplastic content throughout the production process, to

794   eliminate any potential areas of contamination that may occur.

795

796   Microplastics are present in commonly consumed aquatic species sourced from both aquaculture and

797   the marine environment. Processing steps may remove some microplastics, e.g. by removing the GIT

798   of fish, or washing shellfish and molluscs, however microplastics have been identified in processed

799   aquatic biota that is being sold for consumption (Karami *et al.*, 2017, 2018). The effect pathways of

800   microplastics on the health of commercially important marine organisms, and possible risks to human

801   health from consuming these organisms, must therefore be researched more thoroughly, to evaluate

802   the potential effect of microplastic pollution to food security.

803

804 **5. Conclusion**

805

806 This review examined the presence of microplastics within commercially important marine organisms,

807 and the risks they may have on organism health. All commercially important organisms analysed in

808 this review were shown to contain microplastics. Investigation of microplastic concentrations at

809 different trophic levels suggests that microplastics do not biomagnify, and organisms at lower trophic

810 levels are at greater risk of microplastic contamination. While organisms higher up the food chain may

811 not contain as many microplastics per gram body weight, risks are still present from contaminant

812 transfer and chronic effects, potentially including increased feeding pressure as a result of the higher

813 risk to lower trophic level organisms. This review highlights that some marine organisms that are

814 important to global food security are omitted from current microplastics research, and that

815 microplastics are a risk to the health of marine organisms worldwide. As fisheries and aquaculture are

816 critical for global food security, this has implications for food security and food safety. Microplastics

817 present an added risk to an already stressed environment, and further research on the effects of

818 microplastic pollution is required to be able to perform comprehensive risk assessments on the effect

819 of microplastics on food security.

820

825

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827

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