Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions

Article *in* Chemosphere · June 2018

DOI: 10.1016/j.chemosphere.2018.06.101

Chemosphere 209 (2018) 298–306

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Microplastic contamination in benthic organisms from the Arctic and sub-Arctic regions

Chao Fang [a], Ronghui Zheng [a], Yusheng Zhang [a], Fukun Hong [a], Jingli Mu [b], Mengyun Chen [a], Puqing Song [a], Longshan Lin [a], Heshan Lin [a], Fengfeng Le [c], Jun Bo [a, *]

[a] Laboratory of Marine Biology and Ecology, Third Institute of Oceanography, State Oceanic Administration, Xiamen 361005, PR China
[b] Division of Marine Chemistry, National Marine Environmental Monitoring Center, Dalian 116023, PR China
[c] Key Laboratory of Marine Ecosystem and Biogeochemistry, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, PR China

HIGHLIGHTS

- First investigation of microplastics (MPs) in benthic organisms from the Arctic.
- MP levels were lower than those found in other regions worldwide.
- The organisms from the northernmost site possessed the highest MP abundances.
- The predator starfish *Asterias rubens* ingested the maximum quantities of MPs.
- Fibers constituted the major type of MPs in each detected species.

ARTICLE INFO

Article history:
Received 4 April 2018
Received in revised form
12 June 2018
Accepted 13 June 2018
Available online 14 June 2018

Handling Editor: Tamara S. Galloway

ABSTRACT

The seafloor is recognized as one of the major sinks for microplastics (MPs). However, to date there have been no studies reported the MP contamination in benthic organisms from the Arctic and sub-Arctic regions. Therefore, this study provided the first data on the abundances and characteristics of MPs in a total of 413 dominant benthic organisms representing 11 different species inhabiting in the shelf of Bering and Chukchi Seas. The mean abundances of MP uptake by the benthos from all sites ranged from 0.02 to 0.46 items g^{-1} wet weight (ww) or 0.04–1.67 items individual^{-1}, which were lower values than those found in other regions worldwide. The highest value appeared at the northernmost site, implying that the sea ice and the cold current represent possible transport mediums. Interestingly, the predator *A. rubens* ingested the maximum quantities of MPs, suggesting that the trophic transfer of MPs through benthic food webs may play a critical role. Fibers constituted the major type (87%) in each species, followed by film (13%). The colors of fibers were classified as red (46%) and transparent (41%), and the film was all gray. The predominant composition was polyamide (PA) (46%), followed by polyethylene (PE) (23%), polyester (PET) (18%) and cellophane (CP) (13%). The most common sizes of MPs concentrated in the interval from 0.10 to 1.50 mm, and the mean size was 1.45 ± 0.13 mm. Further studies about the temporal trends and detrimental effects of MPs remain to be carried out in benthic organisms from the Arctic and sub-Arctic regions.

1. Introduction

As an emerging contaminant of international concern, plastic debris has been recognized as a global environmental problem and poses great threats to a wide range of ecosystems (Jambeck et al., 2015; Lourenco et al., 2017; Lamb et al., 2018). It has been estimated that more than 330 million metric tons (MT) of plastics have been produced globally in 2016, and this amount is predicted to increase to exceed 33 billion MT by 2050 (Crawford and Quinn, 2017). Nevertheless, around 8 million MT of plastic waste was speculated to have been released into the ocean from land in 2015, which is expected to increase to approximately 32 million MT by 2050 (Crawford and Quinn, 2017).

* Corresponding author. Laboratory of Marine Biology and Ecology, Third Institute of Oceanography, State Oceanic Administration, Xiamen 361005, PR China.
E-mail address: bojun@tio.org.cn (J. Bo).

https://doi.org/10.1016/j.chemosphere.2018.06.101
0045-6535/

Among all the plastic debris, the small fragments with diameters of 1 μm–5 mm are defined as microplastics (MPs), which have been reported as the most abundant components by count, and the proportion even can reach above 90% (Thompson et al., 2004; Eriksen et al., 2014; Salvador Cesa et al., 2017; Phuong et al., 2018). This anthropogenic pollutant can be discharged into the ocean either directly from personal care products, washing machines and plastic manufacturing or indirectly from the debris of larger plastics, which can be broken down by various physical, chemical, and biological effects (Napper and Thompson, 2016; Auta et al., 2017). The MPs have drawn increasing concern worldwide as they are pervasive and persistent across the global oceanic ecosystem, including coastal areas (Yu et al., 2018), open ocean (Brach et al., 2018), the world's most remote islands (Lavers and Bond, 2017), and deep-sea sediments (Graca et al., 2017). More recently, the contamination by MPs in the polar regions has attracted broad attention, and accumulating evidence indicates that MPs exist in the Arctic (Lusher et al., 2015) and Antarctic surface waters (Cincinelli et al., 2017; Waller et al., 2017), Arctic sea ice (Obbard et al., 2014) and deep-sea sediments (Bergmann et al., 2017). Of particular concern is the seafloor, which has been hypothesized as one of the major sinks or the final sink for MPs, because the MPs are apt to interact with various microorganisms, macrofauna, nutrients, feces, and organic and inorganic aggregates in the water column, facilitating the deposition of MPs due to biofouling and marine snow (Woodall et al., 2014; Bergmann et al., 2017; Galloway et al., 2017). Besides, the high density MPs can also sink to the sea floor spontaneously (Wright et al., 2013).

However, the current knowledge regarding the abundance, distribution and characterization of MPs in benthic organisms remains scarce (Naji et al., 2018). Most of the associated studies have primarily concentrated on the coastal regions (Van Cauwenberghe et al., 2015; Li et al., 2016; Jabeen et al., 2017; Lourenco et al., 2017; Qu et al., 2017; Naji et al., 2018; Phuong et al., 2018); little attention has been paid to the open and deep-sea ecosystems, and no studies have yet been reported concerning the polar regions (Taylor et al., 2016; Courtene-Jones et al., 2017). A growing number of studies illustrate that MPs are easily accessible to a broad range of marine biota because of their small sizes, posing potential risks to more than 660 marine species worldwide from subcellular to population levels (Auta et al., 2017; Galloway et al., 2017). Therefore, it is urgently required to evaluate the MP contamination in benthic organisms from the polar regions, which is fundamental to assessing the detrimental effects of MPs on the wildlife inhabiting in this pristine ecosystem and determining possible solutions to address this global issue (Cincinelli et al., 2017).

The shelf of Bering and Chukchi Seas is located in the Arctic and sub-Arctic regions, which represents one of the highest-productivity ecosystems in the world mainly due to the current interactions, seasonal sea ice and changeable weather conditions (Grebmeier et al., 2006). Therefore, this area supports a diverse and distinct ecosystem from pelagic communities to marine mammals including high levels of benthic biomass (Wang et al., 2014; Lusher et al., 2015). In particular, a variety of the benthic organisms in this area are deemed ecologically and commercially important species and thus, the trophic transfer of MPs through these species may also constitute a threat to higher trophic level organisms and even humans (Ryazanova et al., 2016; Nelms et al., 2018). Overall, the aims of this study were to 1) investigate the abundance and characteristics of MPs in the typical benthic organisms inhabiting in the Artic and sub-Artic regions; 2) assess the pollution levels of MPs in the benthic organisms through making a comparison with other results in the literature; and 3) determine whether the quantities of ingested MPs differ among species and which species can serve as the promising sentinel organisms in future monitoring.

2. Materials and methods

2.1. Field sampling

The benthic organisms were sampled using a triangular bottom trawl (2.20 m wide, 0.65 m high, and 6.50 m long; mesh size 20.00 mm) with a geological winch on the Chinese icebreaker Xuelong (Snow Dragon) in late September during "The Eighth Chinese National Arctic Research Expedition (8th CHINARE-Arctic)" from July 20 to October 10, 2017. Four sampling sites named R11, R06, BS05 and B17 were selected, which are located in the shelf of Bering and Chukchi Seas, ranging from 63.1 °N to 73.7 °N. In the light of their latitudes, the former two sites are located in the Arctic region, and the latter ones in the sub-Arctic region. The detail location information for every sampling site is shown in Table 1. The characteristics of seawater from every sampling site, including salinity, depth, temperature and chlorophyll content, were also recorded (Table 1). The trawling of each site was performed at a speed of approximately 3 knots and lasted for 15 min. A total number of 413 dominant benthic organisms were collected, which could be divided into 11 different species belonging to 6 categories, including starfishes (*Asterias rubens*, *Ctenodiscus crispatus*, and *Leptasterias polaris*), shrimp (*Pandalus borealis*), crab (*Chionoecetes opilio*), brittle star (*Ophiura sarsii*), whelks (*Retifusus daphnelloides*, *Latisipho hypolispus* and *Euspira nana*) and bivalves (*Astarte crenata* and *Macoma tokyoensis*) (Table S1, Supplementary material). Following sampling, the organisms were wrapped with aluminum foil and sealed in clean bags, transferred to the laboratory immediately and kept in a −20 °C refrigerator until further analysis. Representative photographs of the above organisms are shown in Fig. S1, Supplementary material.

2.2. Quality assurance/quality control (QA/QC) of analysis

The QA/QC of analysis included how to avoid and monitor the background contamination. Meanwhile, positive controls were also performed referring to a previous study (Hermsen et al., 2017) to examine the recovery rate of MP analysis. The details of above procedures were described in the Supplementary material.

Table 1
The geographical location, seawater characteristics and mean sizes of MPs across all benthic species from every sampling site.

Date	Sites	Longitude (°E)	Latitude (°N)	Salinity	Depth (m)	Water temperature (°C)	Chlorophyll content (mg m^{-3})	Mean size (mm)
2017-09-20	R11	−168.67	73.69	31.72	151.40	0.55	0.06	1.11 ± 0.19
2017-09-21	R06	−168.75	69.59	31.63	53.50	5.93	0.51	1.74 ± 0.20
2017-09-24	BS05	−167.85	64.28	30.82	35.30	6.92	3.17	1.80 ± 0.46
2017-09-25	B17	−173.93	63.10	31.30	78.70	8.50	-[a]	1.70 ± 0.36

[a] The black line "-" means the value was not detected due to the adverse sea condition. The data were expressed as the mean ± S.E.

2.3. Dissection and digestion of benthic organisms

After defrosting, the basic information of the benthic organisms was measured and recorded (Table S1). All the species were dissected and the method of alkaline digestion for the samples with 10% KOH (W/V) solution was established according to previous studies with slight modification (Dehaut et al., 2016; Phuong et al., 2018), which was also described in the Supplementary material.

2.4. Floatation and filtration of MPs

The method of floatation and filtration was chosen from previous studies with slight modification (Li et al., 2015, 2016), which was shown in the Supplementary material.

2.5. Observation and verification of MPs

The filter was thoroughly observed under a Leica M205C stereo microscope and representative photographs were taken with a Leica DFC425 charge-coupled device (CCD) camera. A total of 502 potential MPs found by microscope were classified into 19 different categories based on the colors and shapes (Li et al., 2016; McGoran et al., 2017). Then, a subset of 182 representative potential MPs belonging to each category and each species were picked out and transferred to an alum-coated microscope slide (Thermo Fisher Scientific, USA) for further verifying by micro-Fourier transformed infrared spectroscope (μ-FT-IR, Nicolet iN10, Thermo Fisher Scientific Inc.) (Su et al., 2016). The detailed methods for verifying and calculating the MP abundances in the benthic organisms were presented in the Supplementary material.

2.6. Statistical analysis

Statistical analysis was performed using SPSS 16.0 for Windows software (SPSS Inc., Chicago, IL, USA). The data were first tested for homogeneity of variances using Levene's test, followed by one-way ANOVA analysis of variance. If the homogeneity of the variance was confirmed, a post hoc Tukey's multiple comparison test was performed to examine the significant differences in the abundances and sizes of MPs across species. Otherwise, a non-parametric test followed by the Mann-Whitney *U* test was used. The correlations between the MP pollution (abundances and sizes) and related seawater characteristics (chlorophyll content, water temperature and depth) at every sampling site were analyzed by bivariate correlations followed by Pearson correlation coefficients and two-tailed tests. Significant differences were accepted at $^* = p < 0.05$. The data for the abundances and sizes of MPs in the benthic organisms were expressed as the mean ± S.E.

3. Results

3.1. QA/QC

There were no MPs identified from the procedural blanks. The recovery rates of MPs from two positive controls with PE and PP ranged from 90% to 95% and 95%–115%, respectively.

3.2. The abundances of MP in the benthic organisms

A total of 126 pieces of debris were identified as MPs through the FT-IR spectra. The mean abundance of MPs in all the benthic organisms collected from each site varied from 0.07 ± 0.03 items g^{-1} ww (i.e., 0.17 ± 0.12 items individual^{-1}) to 0.28 ± 0.10 items g^{-1} ww (i.e., 0.83 ± 0.43 items individual^{-1}). The maximum and minimum mean abundances of MPs in the organisms both by weight and individual appeared at sites R11 and B17 ($p < 0.05$), respectively (Fig. 1).

Moreover, it was shown that the *A. rubens*, *P. borealis*, *C. opilio*, *L. Polaris* and *E. nana* possessed relatively higher quantities of MPs than those in other species either calculated by weight or individual at each site (Fig. 2a and b). However, the significant high abundances were only appeared in the *A. rubens* from site R11 (Fig. 2a and b) and *C. opilio* from site R06 (Fig. 2b), respectively.

It is noteworthy that the mean abundances of MPs by weight and individual in *A. rubens* from site R11 were 1.86- to 19.98-fold and 1.43- to 38.71-fold higher, respectively, than those in other species across all sites. Meanwhile, statistical differences ($p < 0.05$) between *A. rubens* and most of other species were also observed (Fig. 2a and b).

To assess the pollution levels of MPs in the benthic organisms

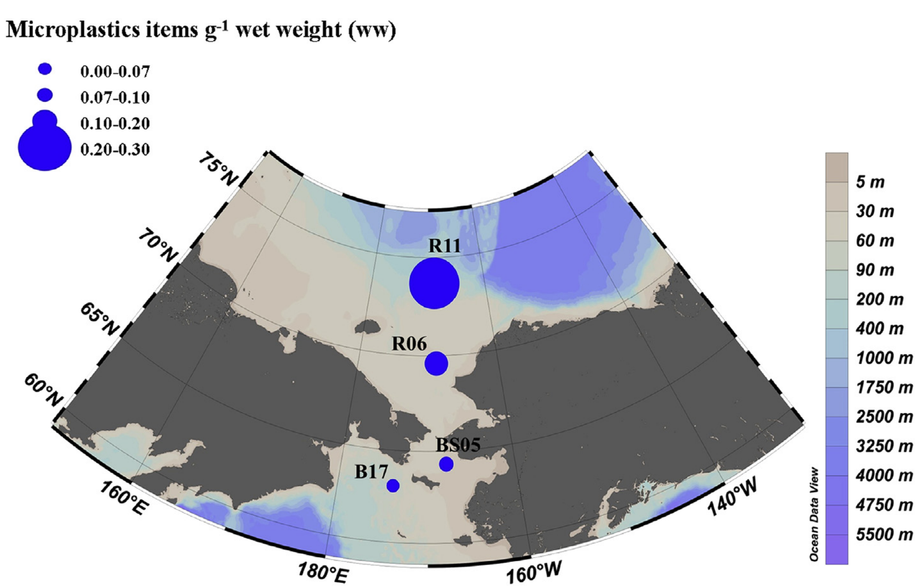

Fig. 1. The graphical representation of the mean abundance of MPs in all the benthic. Organisms collected from each site located in the Bering-Chukchi Seas shelf. The result was expressed as items g^{-1} wet weight (ww), which displayed the same variation as that expressed as items individual^{-1}.

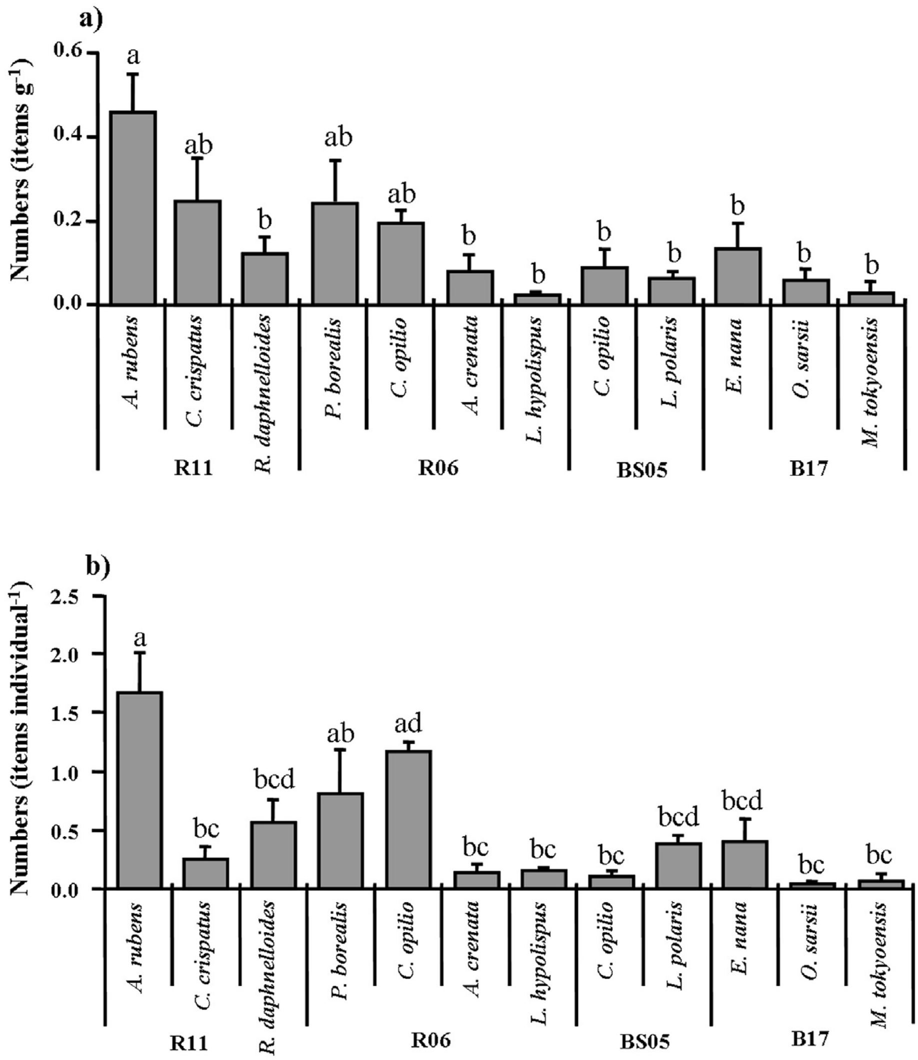

Fig. 2. The mean abundances of MPs a) by weight and b) by individual in every benthic organism from each site. If there was no common alphabet between two entries, then a significant difference existed ($p < 0.05$). The data were expressed as the mean ± S.E.

from this study, we summarized the abundances of MPs in various benthic organisms around the world in Table S2. It was shown that the abundances of MPs in benthic organisms from coastal areas worldwide ranged from 0.18 to 21.00 items g^{-1} ww or 0.50 to 17.70 items individual^{-1}. From the open ocean, the abundances of MPs in benthic organisms varied from 0.36 to 1.58 items g^{-1} ww or 1.00 to 5.00 items individual^{-1}. In this study, the mean abundances of MPs in all the benthic organisms from the Arctic and sub-Arctic regions ranged from 0.02 to 0.46 items g^{-1} ww or 0.04 to 1.67 items individual^{-1}, respectively (Table S2).

3.3. Types and colors of MPs in the benthic organisms

Synthetic fiber was the predominant polymer, followed by film, which accounted for 87% and 13% of the total MPs, respectively. The colors of fibers were classified as red and transparent, which accounted for 46% and 41% of the total MPs, respectively; meanwhile, the colors of film were all gray (Fig. 3a). Comparing the sites, the highest proportions of red fibers, transparent fibers and films appeared at site BS05 (64%), B17 (70%) and R06 (18%), respectively (Fig. 3b). Meanwhile, the highest ratios of red fibers, transparent fibers and films to the total MPs derived from each species were observed in the *A. crenata* (75%) from R06, *M. tokyoensis* (100%) from B17 and *P. borealis* (29%) from R06, respectively (Fig. 3c). Representative photographs of all types of MPs on the filters shown in Fig. 3 d–f.

3.4. Compositions of MPs in the benthic organisms

The composition of MPs across a range of species could be classified into four types, including polyamide (PA), polyethylene (PE), polyester (PET) and cellophane (CP), accounting for 46%, 23%, 18% and 13%, respectively (Fig. 4a). The former three compositions were all contained in the fibers, while CP was only found in the films. With respect to each site, the highest and lowest proportions of PA were recorded at sites BS05 (64%) and B17 (29%), respectively; the highest and lowest proportions of PE were recorded at sites B17 (41%) and R06 (16%), respectively; the highest and lowest proportions of PET were recorded at sites B17 (29%) and BS05 (9%), respectively; whereas the highest and lowest proportions of CP were recorded at sites R06 (18%) and BS05 (9%), respectively (Fig. 4b). In regard to each species, the highest proportions of PA, PE,

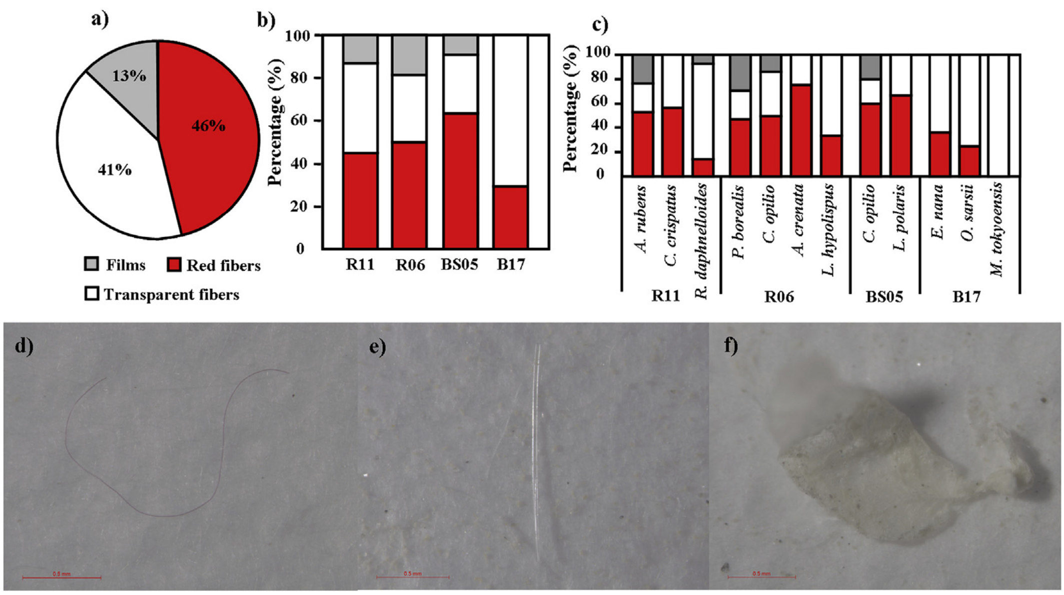

Fig. 3. The types and colors of MPs across all benthic species. a) The proportion of. each type and color to the total MPs from all sites; b) the proportion of each type and color to the total MPs from each site; c) the proportion of each type and color to the total MPs from each species; d) a representative photograph of red fiber; e) a representative photograph of transparent fiber; f) a representative photograph of film. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

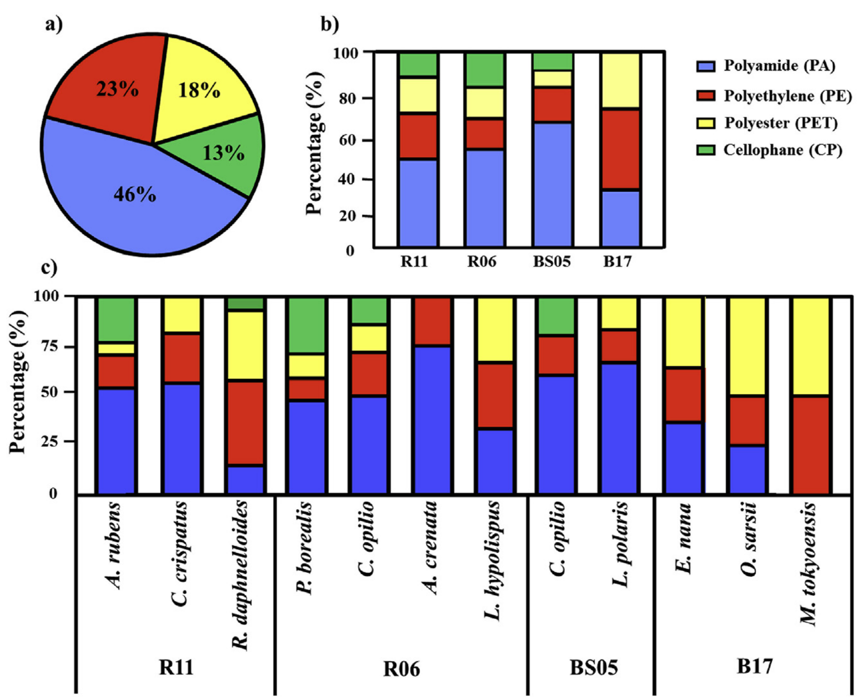

Fig. 4. The compositions of MPs across all benthic species. a) The proportion of each composition to the total MPs from all sites; b) the proportion of each composition to the total MPs from each site; c) the proportion of each composition to the total MPs from each species.

PET and CP were recorded in *A. crenata* (75%), *M. tokyoensis* (50%), *O. sarsii* and *M. tokyoensis* (50%), and *P. borealis* (29%), respectively (Fig. 4c).

3.5. Sizes of MPs in the benthic organisms

The sizes of MPs across all species were divided into four groups ranging from 0.17 to 9.73 mm, and the most common sizes were observed in the interval from 0.10 to 1.50 mm, accounting for 66% of all the sizes (Fig. 5a). Additionally, the smallest sizes of MPs across species from each site were observed in *A. rubens* (54%), *A. crenata* (100%), *L. Polaris* (67%) and *M. tokyoensis* (50%), respectively. The largest sizes of MPs were observed in *A. rubens* (25%), *P. borealis* (40%), *C. opilio* (80%) and *O. sarsii* (50%), respectively (Fig. 5b).

Furthermore, the mean sizes of MPs varied across all species, ranging from a maximum of 2.65 ± 0.88 mm recorded in *O. sarsii* to a minimum of 0.53 ± 0.09 mm recorded in *A. crenata* (Fig. 5c). Concerning each site, there were no significant differences in the

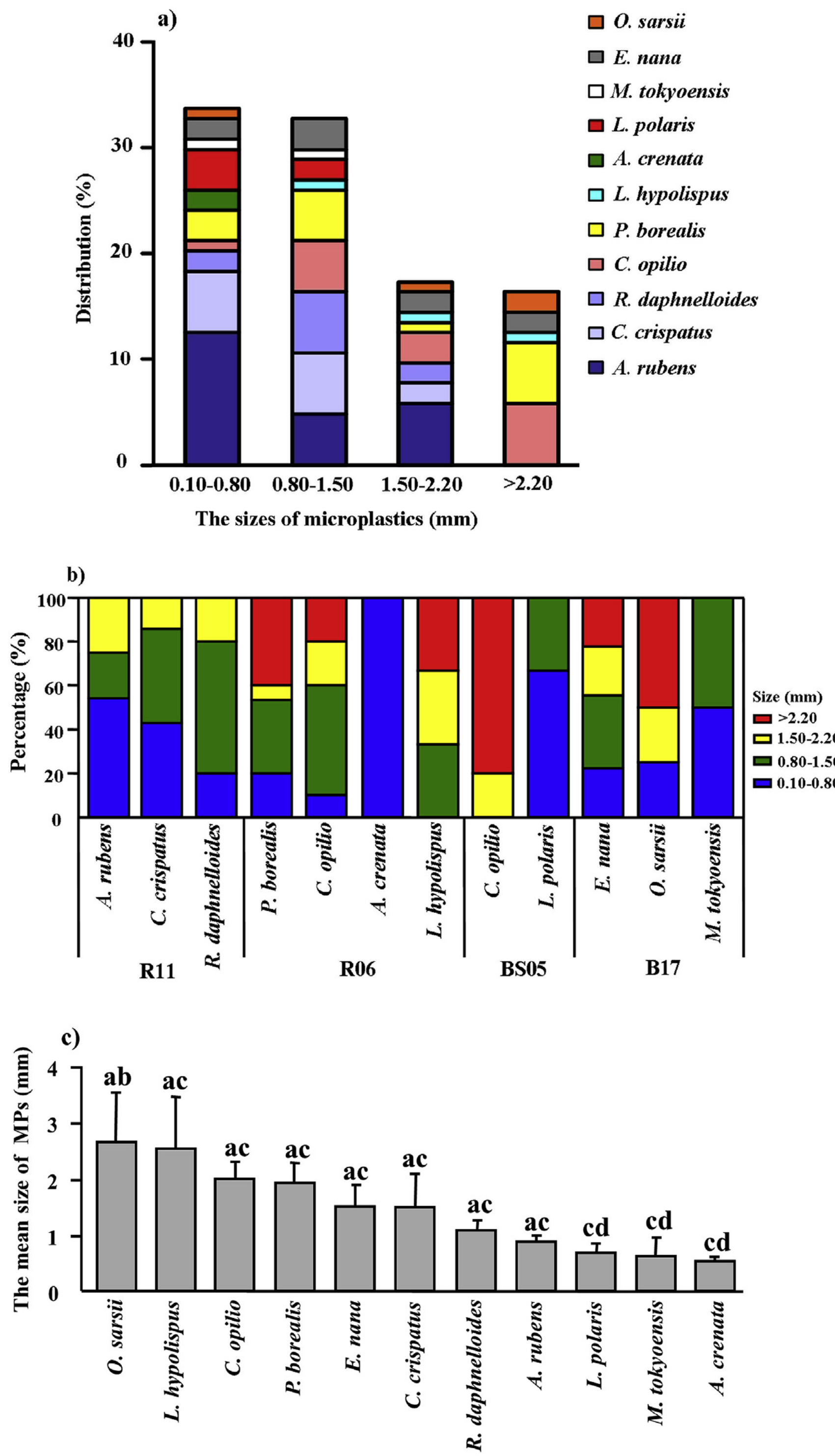

Fig. 5. The sizes of MPs across all benthic species. a) The distribution proportion of every size from each species; b) the proportion of every size across species from each site; c) the mean size from each species. If there was no common alphabet between two entries, then a significant difference existed ($p < 0.05$). The data were expressed as the mean ± S.E.

mean sizes of MPs across species except for the *O. sarsii* and *M. tokyoensis* at site B17 (Fig. 5c). In general, the mean sizes were 1.11 ± 0.19 mm, 1.74 ± 0.20 mm, 1.80 ± 0.46 mm and 1.70 ± 0.36 mm in all the benthic species from sites R11, R06, BS05 and B17, respectively (Table 1). Overall, the mean size was 1.45 ± 0.13 mm across all the benthic organisms from the Arctic and sub-Arctic regions (Table S2).

3.6. The correlations between MP pollution and seawater characteristics

There is a negative correlation between the mean abundances of MPs (expressed as items g^{-1}) in the benthic organisms and water temperature (Pearson correlation = −0.983, $p = 0.017$, 2-tailed) at every sampling site. The mean sizes of MPs in the benthic organisms and water depth also have negative correlations (Pearson correlation = −0.975, $p = 0.025$, 2-tailed). The mean abundances (items g^{-1}) and sizes of MPs have a trend of being negatively correlated (Pearson correlation = −0.947, $p = 0.053$, 2-tailed).

4. Discussion

The present study represents the first report of MP ingestion by benthic organisms caught in the Arctic and sub-Arctic regions, highlighting the global distribution of these anthropogenic pollutants. In comparison with other studies across different coastal and open ocean ecosystems, the MP abundances in the benthic organisms of this study were at relatively lower levels. It is speculated that the study region is far from densely populated or industrialized districts, receiving a lower input of MPs from the land-based sources.

However, there is extremely little information available concerning the sources of MPs in the polar regions. Long-range transport by ocean currents, wind, sea ice, migratory species and atmospheric transport may play pivotal roles in transporting MPs to this remote and pristine realm (Obbard, 2018). Since it was difficult to sample the same species across sites through random trawling, we took all the benthic species from every site as a whole to make comparisons across sites. It was found that the mean quantities of MPs in the benthic organisms from the shelf of the Chukchi Sea were higher than those from the Bering Sea and that the highest quantities were observed in the northernmost site (R11), which was close to the marginal ice zone and under the impact of a cold current (Arctic Ocean, 2013). The negative correlation between the water temperature and MP quantities in the benthic organisms may also be associated with the above geographic patterns. A previous study has noted a similar phenomenon in Arctic deep-sea sediments, suggesting that sea ice and the cold current represent possible transport vehicles for MPs in the Arctic region (Bergmann et al., 2017). The explanation for this inference lies in the observations that the Arctic sea ice has been documented to contain high levels of MPs and that the decreasing sea ice could release the MPs to the seawater especially in the context of global warming (Obbard et al., 2014). Likewise, the MP abundances in the surface water at site R11 were also relatively higher than those from other study sites (unpublished data, personal communication with Prof. Mu). In future study, the MP contamination in the habitats of benthic organisms, including seawater, sediment and sea ice, are also required to be further investigated.

Through comparison of the MP abundances within the same site across species, it was indicated that the carnivorous or omnivorous species exhibited considerable abundances of MP ingestion, especially for the *A. rubens* and *C. opilio* (Nakata et al., 2003; Ortega et al., 2011). Another recent study has also documented that higher levels of MPs existed in predatory species among several molluscan shellfish (Naji et al., 2018).

Moreover, it was interesting to find that *A. rubens* from site R11 ingested the highest quantities of MPs across species regardless of the different units used, which was probably due to the site itself containing relatively greater MP pollution. On the other hand, it should be noted that the starfish is found to be at the highest trophic level in the deep-sea benthic food web from Arctic, which can prey on numerous benthic organisms including bivalves, gastropods, barnacles and so on (Bergmann et al., 2009; Ortega et al., 2011). A previous study has also shown that the starfish *H. pellucidus* collected from the North Atlantic Ocean contained the highest number of MPs among the three benthic species, including starfish, brittle star and whelk (Courtene-Jones et al., 2017).

Accordingly, we hypothesized that the trophic transfer of MPs through benthic food webs might be an important route for MP ingestion by predatory benthos, which needs to receive more attention in future field monitoring. However, empirical evidence related to the trophic transfer of MPs is still lacking, and more research must be carried out (Naji et al., 2018).

On the other hand, the factors affecting vertical transport of MPs to the benthos have not yet been well understood. It has been stated that the sinking process of MPs could be influenced by a range of factors in terms of plastic size, shape and polymer density (Courtene-Jones et al., 2017). In this study, the highest composition of MPs was PA, whose density is greater than seawater, making it possible to sink spontaneously, which may also be true for PET and CP (Lusher et al., 2013). In addition to their own properties, the involvement of MPs in various physical and biological processes in the marine ecosystem could further affect their vertical transport (Galloway et al., 2017). A previous study found that MP abundances were positively correlated with the chlorophyll *a* contents in the Arctic deep-sea sediments around Fram Strait and speculated that the deposited ice algae may promote the sinking of MPs (Bergmann et al., 2017). By contrast, we have not observed this correlation between MP quantities in the benthos and chlorophyll contents in the seawater, implying that other interrelated factors may take effects and that the related parameters in the sediments should be considered in future studies to explore the underlying correlation.

In agreement with most of previous studies in other investigated regions, fibers constituted the major type of MPs identified in the benthic organisms (Table S2). Of note, we took measures to strictly avoid contamination with fibers from the air and found no fibers present in the procedural blanks. Meanwhile, it has been found that fibers were also the most abundant type in the seawater and sea ice cores from Arctic regions (Obbard et al., 2014; Lusher et al., 2015). Therefore, we can conclude that the benthic organisms in this study ingested fibers from their habitats rather than from airborne contamination during the process of experiment.

Although the underlying causes contributing to the high frequency of fiber uptake by the benthos remain elusive, three possible reasons may be involved. First, fibers are recognized as a predominant category of MPs in varying marine environments due to multiple sources, such as releasing from domestic washings or the fragmentation of large textile fibers, ropes, lines, fishing nets and other synthetic fibers (Salvador Cesa et al., 2017). Therefore, the ubiquity of fibers may increase their availability to a wider range of organisms. Second, the fibers or their parent materials may be more likely to interact with the kinds of biotic and abiotic sinking mediums through twining, wrapping or biofouling, but this requires further investigation. Third, there is a data gap concerning the kinetics of fibers related to uptake, accumulation and egestion in the benthos, which may affect the residence time, distribution and abundances of fibers *in vivo* (Jemec et al., 2016; Naji et al., 2018). Further studies are needed to compare the kinetics of fibers with other types of MPs in the benthos in order to understand whether this is a cause for the high bioavailability of fibers.

The most frequent colors of fibers in the benthos were divided into red and transparent in the present study, both of them are common colors observed in a great diversity of ecosystems by numerous field investigations (Lusher et al., 2013; Graca et al., 2017). The interspecific difference in the ingestion of MPs with different colors was observed and it was reported that some seabirds demonstrated preferences for preying on certain colors in marine ecosystems, but little is known about the benthic organisms, which remains to be elucidated (Lavers and Bond, 2017).

It is noteworthy that the four compositions of MPs in the benthos of this study were also commonly observed in other benthos around the world, which may be due to their high production, extensively used and global transportation (Salvador Cesa et al., 2017). The compositions of MPs varied greatly in each species, highlighting the need for more laboratory studies to reveal whether there are interspecific differences in the ingestion or egestion of MPs with different compositions. Although the MP abundances in the benthos from BS05 and B17 were relatively lower, they ingested the highest ratios of PA, PE and PET. In consideration of the application fields of these compositions, it appears that food packaging, textiles, fishing nets and nylon ropes originated from the coastal areas of southwest Alaska, fishing and shipping activities in the Bering Sea or oceanic current may be the primary sources of MPs in this study region (Doyle et al., 2011; Li et al., 2016; Phuong et al., 2018). Meanwhile, the two most common compositions of MPs detected in the benthos of this study were PA and PE, which have also been detected in the surface waters, sediments and ice cores from Arctic regions (Obbard et al., 2014; Lusher et al., 2015; Bergmann et al., 2017), indicating the surrounding environment may provide possible sources for the MPs observed in the benthos of this study. In future study, the compositions of MPs in different habitats of benthos should be surveyed.

It is also worth noting that the size of MP is a critical factor influencing the uptake and detrimental effects of MP (Phuong et al., 2018; Ziajahromi et al., 2018). The most common sizes for MPs detected in the benthic organisms of this study fell into the smallest size groups and were within the ranges (0.01–2.00 mm) observed by other studies (Lusher et al., 2013; Bellas et al., 2016; Naji et al., 2018; Phuong et al., 2018). Meanwhile, the mean size of MPs was also comparable with that found in the aforementioned three benthic species from North Atlantic Ocean (Courtene-Jones et al., 2017). Moreover, the evidently negative correlation between the sizes of MPs and water depth at every site in this study may also support the recent viewpoint suggesting that smaller MPs sink more easily than larger ones, which probably increases the possibility of ingestion of the smaller MPs by the benthos (Fazey and Ryan, 2016; Bergmann et al., 2017).

Additionally, the discrepancies in the proportions of different sizes of MPs within the same site across species may be partially attributed to the different feeding habits of MPs; the carnivorous and omnivorous benthos are supposed to have more changes and strategies to actively take in relatively longer MPs than bivalves, which display filter feeding habits leading to the acquisition of MPs with limited sizes (Lourenco et al., 2017; Phuong et al., 2018). Besides, as a top predator, the starfish may have more chances to acquire both small and large sizes of MPs through trophic transfer from contaminated prey (Bergmann et al., 2009; Nelms et al., 2018). Accordingly, the mean sizes of MPs taken up by starfishes and bivalves were relatively smaller than those consumed by other species, especially for the brittle star. Likewise, a previous study conducted in the North Atlantic Ocean also found the longest fiber uptake by brittle stars (Courtene-Jones et al., 2017). The brittle star prefers to live in or on the sea floor and can utilize a variety of feeding methods (Feder, 1981; Brogger et al., 2016). A previous study has observed that the maximum length of food items ingested by brittle star could range up to 17.5 or 30.0 mm depended on the prey types (Feder, 1981). In this regard, the long fiber seems easy to be ingested by brittle star.

5. Conclusions

This study provided the first data on the MP ingestion by benthic organisms from the Arctic and sub-Arctic regions, raising our concern about MP pollution in this remote and vulnerable ecosystem. The predator starfish *A. rubens* ingested the highest quantities of MPs, suggesting it could be considered as a promising candidate for monitoring MP contamination and the trophic transfer of MPs through benthic food webs. The benthos from the northernmost site possessed the highest MP levels, implying that the sea ice and the cold current represent possible transport mediums. Fibers constituted the major type of MPs, emphasizing that more researches needs to be carried out regarding how they transport vertically to the seafloor and become available to the benthos. The interspecific differences in the ingestion of MPs with different characteristics may be attributed to the diverse feeding habits or capacities for MP ingestion and egestion of benthic organisms. However, this hypothesis requires more empirical evidence. Although the MP abundances in benthic organisms from the Arctic and sub-Arctic regions present lower levels, more information on the temporal trends of MP contamination in these ecologically and economically valuable species and their habitats is needed, and the associated harmful effects deserve further study.

Acknowledgements

This research was sponsored by the Natural Science Foundation of Fujian Province, China (Nos. 2016J01191, 2015Y0033, 2016Y0062); the Scientific Research Foundation of the Third Institute of Oceanography, State Oceanic Administration (SOA) (Nos. 2015034, 2016013); the National Key Research and Development Program of China (2017YFA0604902); the Program on Monitoring, Risk Assessment and Prevention Measures of Marine Debris in Xiamen, China (No. 2016-ZS159); and the National Natural Science Foundation of China (No. 41306116).

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.chemosphere.2018.06.101.

References

Arctic Ocean, 2013. Figure 3: Surface circulation and sea ice extent in the Arctic Ocean. http://www.marbef.org/wiki/Arctic_Ocean.
Auta, H.S., Emenike, C.U., Fauziah, S.H., 2017. Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environ. Int. 102, 165–176.
Bellas, J., Martinez-Armental, J., Martinez-Camara, A., Besada, V., Martinez-Gomez, C., 2016. Ingestion of microplastics by demersal fish from the Spanish Atlantic and Mediterranean coasts. Mar. Pollut. Bull. 109, 55–60.
Bergmann, M., Dannheim, J., Bauerfeind, E., Klages, M., 2009. Trophic relationships along a bathymetric gradient at the deep-sea observatory HAUSGARTEN. Deep-Sea Res. Pt I 56, 408–424.
Bergmann, M., Wirzberger, V., Krumpen, T., Lorenz, C., Primpke, S., Tekman, M.B., Gerdts, G., 2017. High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN observatory. Environ. Sci. Technol. 51, 11000–11010.
Brach, L., Deixonne, P., Bernard, M.F., Durand, E., Desjean, M.C., Perez, E., van Sebille, E., Ter Halle, A., 2018. Anticyclonic eddies increase accumulation of microplastic in the North Atlantic subtropical gyre. Mar. Pollut. Bull. 126, 191–196.
Brogger, M.I., Martinez, M.I., Cadierno, M.P., Penchaszadeh, P.E., 2016. Tooth microstructure and feeding biology of the brittle star *Ophioplocus januarii* (Echinodermata: ophiuroidea) from northern Patagonia, Argentina. Rev. Biol. Trop. 63, 353–360.
Cincinelli, A., Scopetani, C., Chelazzi, D., Lombardini, E., Martellini, T., Katsoyiannis, A., Fossi, M.C., Corsolini, S., 2017. Microplastic in the surface waters of the Ross Sea (Antarctica): occurrence, distribution and characterization by FTIR. Chemosphere 175, 391–400.
Courtene-Jones, W., Quinn, B., Gary, S.F., Mogg, A.O.M., Narayanaswamy, B.E., 2017. Microplastic pollution identified in deep-sea water and ingested by benthic invertebrates in the Rockall Trough, North Atlantic Ocean. Environ. Pollut. 231, 271–280.
Crawford, C.B., Quinn, B., 2017. Plastic production, waste and legislation. In: Crawford, C.B., Quinn, B. (Eds.), Microplastic Pollutants. Elsevier Inc., Netherlands, pp. 39–56.
Dehaut, A., Cassone, A.L., Frere, L., Hermabessiere, L., Himber, C., Rinnert, E., Riviere, G., Lambert, C., Soudant, P., Huvet, A., Duflos, G., Paul-Pont, I., 2016. Microplastics in seafood: benchmark protocol for their extraction and characterization. Environ. Pollut. 215, 223–233.
Doyle, M.J., Watson, W., Bowlin, N.M., Sheavly, S.B., 2011. Plastic particles in coastal pelagic ecosystems of the Northeast Pacific ocean. Mar. Environ. Res. 71, 41–52.
Eriksen, M., Lebreton, L.C., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F.,

Ryan, P.G., Reisser, J., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9, e111913.

Fazey, F.M., Ryan, P.G., 2016. Biofouling on buoyant marine plastics: an experimental study into the effect of size on surface longevity. Environ. Pollut. 210, 354–360.

Feder, H.M., 1981. Aspects of the feeding biology of the brittle star *Ophiura texturata*. Ophelia 20, 215–235.

Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol. 1, 116.

Graca, B., Szewc, K., Zakrzewska, D., Dolega, A., Szczerbowska-Boruchowska, M., 2017. Sources and fate of microplastics in marine and beach sediments of the Southern Baltic Sea-a preliminary study. Environ. Sci. Pollut. Res. Int. 24, 7650–7661.

Grebmeier, J.M., Cooper, L.W., Feder, H.M., Sirenko, B.I., 2006. Ecosystem dynamics of the pacific-influenced northern bering and Chukchi seas in the amerasian arctic. Prog. Oceanogr. 71, 331–361.

Hermsen, E., Pompe, R., Besseling, E., Koelmans, A.A., 2017. Detection of low numbers of microplastics in North Sea fish using strict quality assurance criteria. Mar. Pollut. Bull. 122, 253–258.

Jabeen, K., Su, L., Li, J., Yang, D., Tong, C., Mu, J., Shi, H., 2017. Microplastics and mesoplastics in fish from coastal and fresh waters of China. Environ. Pollut. 221, 141–149.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771.

Jemec, A., Horvat, P., Kunej, U., Bele, M., Krzan, A., 2016. Uptake and effects of microplastic textile fibers on freshwater crustacean *Daphnia magna*. Environ. Pollut. 219, 201–209.

Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., True, J.D., Kelly, L.A., Ahmad, A., Jompa, J., Harvell, C.D., 2018. Plastic waste associated with disease on coral reefs. Science 359, 460–462.

Lavers, J.L., Bond, A.L., 2017. Exceptional and rapid accumulation of anthropogenic debris on one of the world's most remote and pristine islands. Proc. Natl. Acad. Sci. U.S.A. 114, 6052–6055.

Li, J., Qu, X., Su, L., Zhang, W., Yang, D., Kolandhasamy, P., Li, D., Shi, H., 2016. Microplastics in mussels along the coastal waters of China. Environ. Pollut. 214, 177–184.

Li, J., Yang, D., Li, L., Jabeen, K., Shi, H., 2015. Microplastics in commercial bivalves from China. Environ. Pollut. 207, 190–195.

Lourenco, P.M., Serra-Goncalves, C., Ferreira, J.L., Catry, T., Granadeiro, J.P., 2017. Plastic and other microfibers in sediments, macroinvertebrates and shorebirds from three intertidal wetlands of southern Europe and west Africa. Environ. Pollut. 231, 123–133.

Lusher, A.L., McHugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar. Pollut. Bull. 67, 94–99.

Lusher, A.L., Tirelli, V., O'Connor, I., Officer, R., 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Sci. Rep. 5, 14947.

McGoran, A.R., Clark, P.F., Morritt, D., 2017. Presence of microplastic in the digestive tracts of European flounder, *Platichthys flesus*, and European smelt, *Osmerus eperlanus*, from the River Thames. Environ. Pollut. 220, 744–751.

Naji, A., Nuri, M., Vethaak, A.D., 2018. Microplastics contamination in molluscs from the northern part of the Persian Gulf. Environ. Pollut. 235, 113–120.

Nakata, H., Sakai, Y., Miyawaki, T., Takemura, A., 2003. Bioaccumulation and toxic potencies of polychlorinated biphenyls and polycyclic aromatic hydrocarbons in tidal flat and coastal ecosystems of the Ariake Sea, Japan. Environ. Sci. Technol. 37, 3513–3521.

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112, 39–45.

Nelms, S.E., Galloway, T.S., Godley, B.J., Jarvis, D.S., Lindeque, P.K., 2018. Investigating microplastic trophic transfer in marine top predators. Environ. Pollut. 238, 999–1007.

Obbard, R.W., 2018. Microplastics in Polar Regions: the role of long range transport. Curr. Opin. J. Environ. Sci. Health 1, 24–29.

Obbard, R.W., Sadri, S., Wong, Y.Q., Khitun, A.A., Baker, I., Thompson, R.C., 2014. Global warming releases microplastic legacy frozen in Arctic Sea ice. Earth's Future 2, 315–320.

Ortega, I., Martin, A., Diaz, Y., 2011. Distribution, population parameters, and diet of *Astropecten marginatus* (asteroidea: astropectinidae) in the venezuelan atlantic coast. Rev. Biol. Trop. 59, 53–69.

Phuong, N.N., Poirier, L., Pham, Q.T., Lagarde, F., Zalouk-Vergnoux, A., 2018. Factors influencing the microplastic contamination of bivalves from the French Atlantic coast: location, season and/or mode of life? Mar. Pollut. Bull. 129, 664–674.

Qu, X., Su, L., Li, H., Liang, M., Shi, H., 2017. Assessing the relationship between the abundance and properties of microplastics in water and in mussels. Sci. Total Environ. 621, 679–686.

Ryazanova, T.V., Fedotov, P.A., Kharlamenko, V.I., 2016. The bitter crab syndrome in commercial crabs in the Western part of the Bering and Chukchi Seas. Russ. J. Mar. Biol. 42, 409–413.

Salvador Cesa, F., Turra, A., Baruque-Ramos, J., 2017. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Sci. Total Environ. 598, 1116–1129.

Su, L., Xue, Y., Li, L., Yang, D., Kolandhasamy, P., Li, D., Shi, H., 2016. Microplastics in taihu lake, China. Environ. Pollut. 216, 711–719.

Taylor, M.L., Gwinnett, C., Robinson, L.F., Woodall, L.C., 2016. Plastic microfibre ingestion by deep-sea organisms. Sci. Rep. 6, 33997.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304, 838.

Van Cauwenberghe, L., Claessens, M., Vandegehuchte, M.B., Janssen, C.R., 2015. Microplastics are taken up by mussels (*Mytilus edulis*) and lugworms (*Arenicola marina*) living in natural habitats. Environ. Pollut. 199, 10–17.

Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O., Hughes, K.A., 2017. Microplastics in the Antarctic marine system: an emerging area of research. Sci. Total Environ. 598, 220–227.

Wang, J., Lin, H., Xuebao, H.E., Lin, J., Huang, Y., Rongguan, L.I., Zheng, C., Zheng, F., Jiang, J., 2014. Biodiversity and community structural characteristics of macrobenthos in the Chukchi Sea. Acta Oceanol. Sin. 33, 82–89.

Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2014. The deep sea is a major sink for microplastic debris. R. Soc. Open. Sci. 1, 140317.

Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492.

Yu, X., Ladewig, S., Bao, S., Toline, C.A., Whitmire, S., Chow, A.T., 2018. Occurrence and distribution of microplastics at selected coastal sites along the southeastern United States. Sci. Total Environ. 613–614, 298–305.

Ziajahromi, S., Kumar, A., Neale, P.A., Leusch, F.D.L., 2018. Environmentally relevant concentrations of polyethylene microplastics negatively impact the survival, growth and emergence of sediment-dwelling invertebrates. Environ. Pollut. 236, 425–431.