Water Research 168 (2020) 115121

Contents lists available at ScienceDirect

Water Research

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

The ocean's ultimate trashcan: Hadal trenches as major depositories for plastic pollution

Guyu Peng [a], Richard Bellerby [a, b], Feng Zhang [a], Xuerong Sun [a], Daoji Li [a, *]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, 500 Dongchuan Road, Shanghai, 200241, China
[b] Norwegian Institute for Water Research, Thormølensgate 53D, Bergen, Norway

ARTICLE INFO

Article history:
Received 3 July 2019
Received in revised form
20 September 2019
Accepted 23 September 2019
Available online 24 September 2019

Keywords:
Microplastic
Marine debris
Sediment
Hadal trench
Ecosystems

ABSTRACT

Plastic debris and marine microplastics are being discharged into the ocean at an alarming scale and have been observed throughout the marine environment. Here we report microplastic in sediments of the Challenger Deep, the deepest known region on the planet, abyssal plains and hadal trenches located in the Pacific Ocean (4900 m–10,890 m). Microplastic abundance reached 71.1 items per kg dry weight sediment. That high concentrations are found at such remote depths, knowing the very slow sinking speed of microplastics, suggests that supporting mechanisms must be at-play. We discuss cascading processes that transport microplastics on their journey from land and oceanic gyres through intermediate waters to the deepest corners of the ocean. We propose that hadal trenches will be the ultimate sink for a significant proportion of the microplastics disposed in the ocean. The build-up of microplastics in hadal trenches could have large consequences for fragile deep-sea ecosystems.

1. Introduction

The Earth has experienced drastic changes since the beginning of Anthropocene. A particular period, the so-called Plastic Age, has attracted mass attention (Carpenter and Smith, 1972). Considering their transient hundred-year history (Crawford and Quinn, 2017), plastics have the potential to challenge the productivity, diversity and function of marine ecosystems. The extent that plastic pollution has intruded the ocean is still unknown. An increasing number of observations in different marine environments suggest it is becoming ubiquitous, and accumulating in the ocean. Thompson et al. (2004) found plastic fragments in estuarine sediments around UK, followed by discoveries of microplastics in oceans around the world, including the Polar Regions (Obbard et al., 2014) and the deep sea (Van Cauwenberghe et al., 2013). Extensive studies on the abundance of microplastics in coastal beaches, estuaries, offshore waters and marginal seas have been conducted globally (Lusher, 2015; Browne et al., 2015; Bosker et al., 2017). Since the discovery of the Great Pacific Garbage Patch (GPGP) (Moore et al., 2001) in the center of the North Pacific gyre, the GPGP has been found to accumulate plastics rapidly during the past two decades – four to sixteen times the concentration previously reported, with microplastics consisting 94% of floating pieces (Lebreton et al., 2018). Nevertheless, theoretical estimates of the amount of microplastics in the surface ocean from input estimates heavily outweigh the measured concentrations (Eriksen et al., 2014). This begs the question "where has all the plastics gone".

Investigation into the vertical distribution of microplastics in the water columns (La Daana et al., 2018) suggests that the fate for microplastics is not only the surface ocean, but also the deep sea (Woodall et al., 2014), including the most remote trenches (Jamieson et al., 2019). Although the density of certain types of plastic debris is lighter than seawater, which leads to their initial accumulation in surface water, it is likely that the breakdown of plastic debris causes the formation of microplastics and sinking within the water columns. Sinking factors include not only density of plastic polymers, but also biofouling that leads to the sinking of almost every category of commercial plastics to the seafloor (Engler, 2012). Photodegradation may cause plastics to progressively break down, and a loss of microplastics smaller than 1 mm at the open ocean surface was observed (Cozar et al., 2014) compared to model estimation (Lebreton et al., 2012), indicating mechanisms quickly transferring microplastics from surface to the deep must be at-play. Even buoyant polymers like polyethylene, when incorporated into marine snow, have been shown to sink at a rate of 818 m day^{-1} (Porter et al., 2018). However, the vertical change of

* Corresponding author.
E-mail address: daojili@sklec.ecnu.edu.cn (D. Li).

https://doi.org/10.1016/j.watres.2019.115121

microplastics in water column from sea surface to the ocean floor remains unknown.

The hadal zone is the deepest part of the ocean (6000–11,000 m), which accounts for 45% of the depth range of the ocean (Jamieson et al., 2010). While most studies on microplastics in seabed sediments have mostly been undertaken in coastal areas and continental shelves, very few studies have been done on sediments in the deep-sea or the hadal zone. It has been shown that marine litter is widespread on the deep sea floor, with plastics often being the most common type of marine litter encountered (Mordecai et al., 2011). Compared to microplastics, larger marine debris in deep-sea environments is more frequently reported in deep diving expeditions. Deep-sea trawls in the Gulf of Mexico (at a depth between 250 and 3650 m) revealed that most man-made waste on the seabed were plastics (Wei et al., 2012). The majority of marine debris in the Ryukyu Trench were plastics, especially fragmented plastic bags (Shimanaga and Yanagi, 2016). Based on a video database over 22 years, Schlining et al. (2013) found that anthropic marine debris accumulated on the steepest slopes of the Monterey canyons was mostly plastics. By reviewing images and video clips from Deep-sea Debris Database developed by JAMSTEC, Chiba et al. (2018) found increasing marine debris in the abyss over the past 30 years, with the deepest record of one plastic bag at 10,890 m from Mariana Trench. Miyake et al. (2011) reviewed video surveys of submersible dives in Japan Trench and Ryukyu Trench down to 7216 m and noted plastics were the most common marine debris. Using photographic time-series surveys to investigate the change in concentration of marine litter on seafloor from 2002 to 2014 at depth of 2500 m in the Arctic, there were more litter on the seafloor than at the surface (Tekman et al., 2017). Those findings all support the theory that portions of plastic debris at the sea surface eventually sink to the seafloor, increasing the likelihood of deposition at the deepest and remotest corner of the ocean.

To investigate to what degree microplastics have transported to the hadal zone, and to understand the fate of missing microplastics from sea surface, this study investigated microplastics in sediment samples collected from abyssal plain and some of the deepest trenches in the hadal zone, reviewed the potential cascading processes that transport microplastics to remote hadal trenches, and proposed hadal trenches will be the ultimate sink for a significant proportion of the microplastics.

2. Materials and methods

2.1. Sampling

Sediment samples from abyssal plain and hadal trenches were collected by Lander (sites except E3) or a box corer (site E3) during sea trials of Autonomous and Remotely-operated Vehicle (ARV) Rainbowfish in December 2016 (Fig. 1). The 4800-tonnes Scientific Research Ship Zhang Jian is the main supporting vessel for Rainbowfish. Samples were collected from one abyssal plain near the Philippines (4800 m), the Challenger Deep in the Mariana Trench (10,890 m), Marceau Trench (7190 m), and the New Britain Trench (5800 m, 8225 m, 8930 m). Detailed information on geographical coordinates, sediment description, and grain size distribution of sediment samples can be found in Table 1. Landers were equipped with a multitude of deep-sea apparatuses, which took samples of hadal settings including water, sediment and macro organisms. Tubes are equipped on the Lander to collect hadal sediment samples. Only top layers of samples from each sampling sites were taken for microplastic analysis (refer to Fig. S1 for photos of sampling tools). Back in the Mobile Hadal Science Laboratory, sediment samples were carefully wrapped with aluminum foil, after which they were put into clean lunch boxes and stored at −80 °C in the fridge.

2.2. Density separation and numeration

For each site, about 500 g wet weight sediment were used for the analysis of microplastics. Samples were firstly weighted using analytical balance (TB-2002, Denver Instrument, USA), freeze-dried at −80 °C using Christ Alpha 1–4 LDplus (Germany) and dry weight was determined. An aliquot of 25 g dry weight sediment per sample

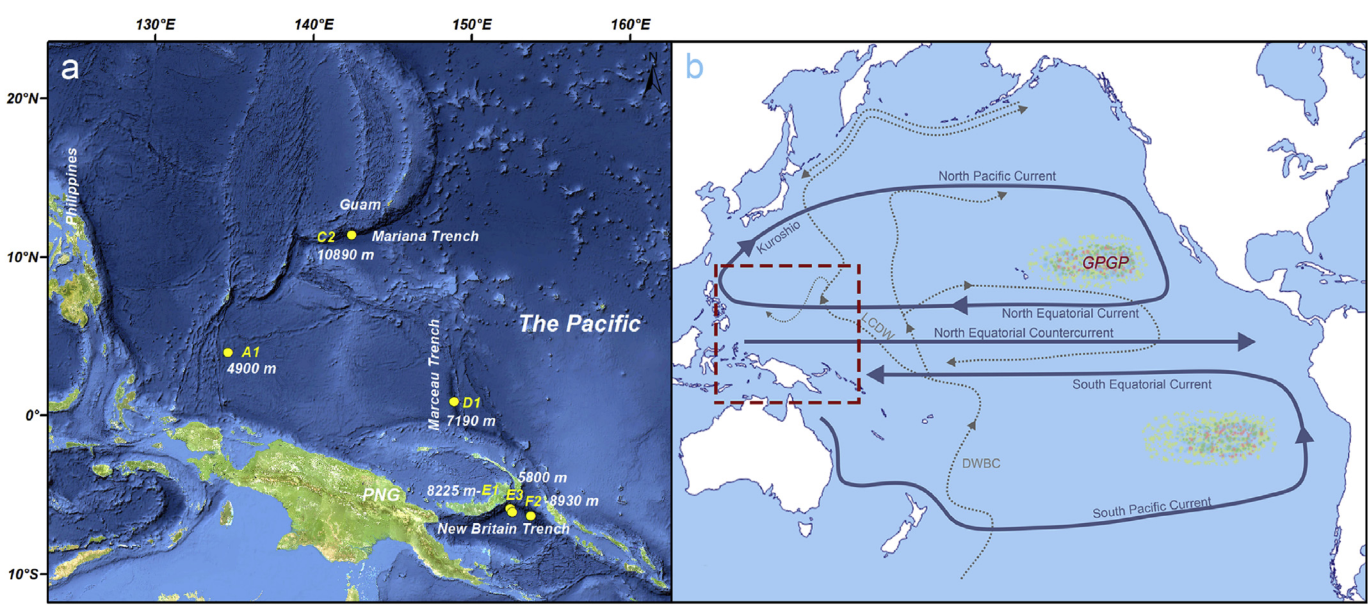

Fig. 1. Map of the six sampling sites and a schematic of ocean circulation in surface and deep water in the Pacific Ocean (modified from Talley et al., 2011). (a) Sampling sites are marked with yellow dots. C1: Challenger Deep, Mariana Trench; A1: north of Papua New Guinea (PNG), east of the Philippines, abyssal plain; D1: Marceau Trench; E1, E2 and F2 are located in the New Britain Trench. (b) Red dotted square shows the location of (a). Surface circulation are marked by blue solid lines and abyssal circulation are marked by grey dotted lines. GPGP: Great Pacific Garbage Patch; DWBC: Deep Western Boundary Current; LCDW: Lower Circumpolar Deep Water. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Detailed information on geographical coordinates, sediment description, and grain size distribution of sediment samples from six sampling sites.

Sampling site	Location	Depth [m]	Longitude [degrees_east]	Latitude [degrees_north]	Sampler	Sediment Description	Sand [%]	Silt [%]	Clay [%]
A1	Abyssal plain east of Philippines	4900	134.6021	3.9954	Lander	Brown, Soft	9.4	47.8	42.8
E3	New Britain Trench	5800	152.5609	−6.1006	Box corer	Deep Brown, Soft	7.7	58.0	34.3
D1	Marceau Trench	7190	148.8887	0.8975	Lander	Deep Brown, Soft	2.7	51.5	45.8
E1	New Britain Trench	8225	152.4252	−5.8662	Lander	Deep Brown, Soft	3.5	64.4	32.1
F2	New Britain Trench	8930	153.7430	−6.3258	Lander	Yellow, Soft, with tephros	9.9	74.3	25.8
C2	Challenger Deep, Mariana Trench	10,890	142.4041	11.3537	Lander	Deep Brown, Soft	4.3	66.4	29.3

from six sites (3 replicates for each site) were utilized for density separation (18 samples in total). Microplastics were extracted from the sediments according to Peng et al. (2017). Saturated sodium iodide solution (NaI, 1.8 g mL^{-1}) was applied for density separation to improve extraction efficiency. The solution was added to a beaker with 25 g dry sediment, stirred for 2 min with a clean glass rod and settled down for 24 h. The supernatant was filtered using a vacuum pump, and microplastic particles were collected onto a filter membrane (RAWP04700-MF-Millipore™ Membrane Filter, 1.2 μm pore size). The filter was dried in room temperature until constant weight. The filter was then observed under dissecting microscopes (Leica M165 FC, Germany) for numeration. Shape, size and color of microplastics were categorized.

2.3. Microplastic identification

Because only thin particles can be compressed in the diamond cell for the μ-FT-IR instrument, one fragment was too big, and was tested using the FT-IR instrument (Fig. 2c). All the other particles were identified by μ-FT-IR. ATR mode of μ-FT-IR instrument (Thermo Fisher Nicolet iN10) were used to identify microplastic polymer types and Transmittance mode of FT-IR instrument (Thermo Fisher Nicolet iS5) was applied in one big particle based on different size limit for the two types of FT-IR instruments. Grain size distribution was performed using laser particle analyzer (Coulter LS13 320). Field-emission Scanning Electron Microscopy (SEM, FEI Sirion 200) was used to characterize morphology of microplastics.

2.4. QA/QC

Quality assurance and quality control must follow the strictest procedures to prevent any contamination, especially airborne contamination (Woodall et al., 2014). All analyses were conducted in a laminar flow cabinet (Airtech SW-CJ-1FD). All the glassware and metal utensils were muffled at 450 °C for 3 h before usage to prevent microfiber contamination. Chemicals and Milli Q water were filtered prior to usage. Filter membranes were examined under microscopes to check for possible contamination before usage. Procedural blanks were performed at each step of density separation of each single sample. Blank 1 was set during the preparation of saturated NaI solution. Blank 2 was set during the filtration of each sediment sample. Blank 3 was set for the same volume of Milli Q water during density separation. In all the 24 procedural blanks during the experiment, no fiber or other contamination was found under microscopic inspection.

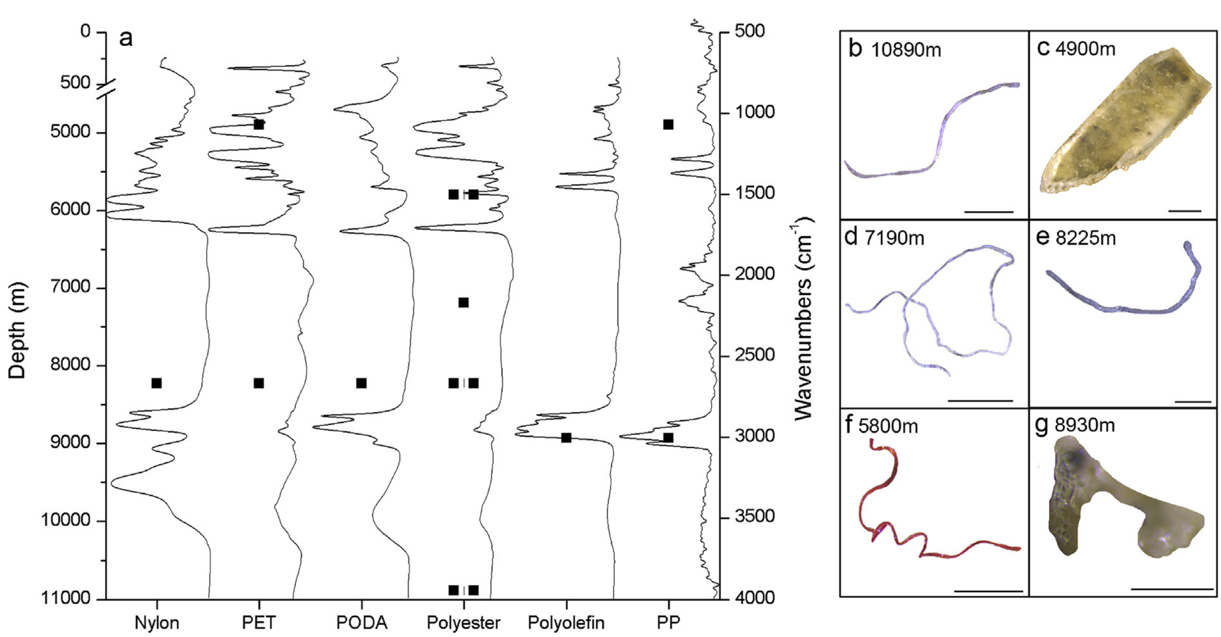

Fig. 2. Microplastics in sediments in the abyssal plain and hadal trenches, and imaged examples of microplastics from each site at various depth. (a) Distribution of microplastics categorized by polymer type (excluding rayon, marked as black squares) and infrared spectra of six kinds of polymers identified using FT-IR instruments. (b) Fiber (ID: C2-2-2, polyester), (c) fragment (A1-1-2, PP), (d) fiber (D1-2-1, polyester), (e) fiber (E1-2-3, nylon), (f) fiber (E3-3-1, polyester), and (g) film (F2-1-3, polyolefin).

Table 2
A total of 14 identified microplastics (excluding rayon) in six sampling sites in abyssal plain and hadal trenches, illustrating the characteristics of microplastics.

Sampling site	Location	Depth [m]	Abundance [items/L dry weight]	Abundance [items/kg dry weight]	Microplastic ID	Shape	Color	Size [μm]	Polymer [Match %]	Polymer Density [g/cm^3]
A1	Abyssal plain east of Philippines	4900	67.2	53.3	A1-1-1	Fragment	Red	115	PET (94.73)	1.30–1.50
					A1-1-2	Fragment	Transparent	6068	PP (82.10)	0.88–1.23
E3	New Britain Trench	5800	67.2	53.3	E3-2-2	Fiber	Blue	1760	Polyester (96.49)	1.30–1.50
					E3-3-1	Fiber	Red	2895	Polyester (91.83)	1.30–1.50
D1	Marceau Trench	7190	33.6	26.7	D1-2-1	Fiber	Transparent	8298	Polyester (97.09)	1.30–1.50
E1	New Britain Trench	8225	168.0	133.3	E1-2-1	Fragment	Blue	105	Polyester (82.62)	1.30–1.50
					E1-2-3	Fiber	Transparent	1204	Nylon (98.38)	1.13–1.38
					E1-3-2	Fiber	Transparent	1009	Polyester (95.67)	1.30–1.50
					E1-3-4	Fragment	Red	73	PET (99.01)	1.30–1.50
					E1-3-5	Film	Transparent	491	Poly(octadecyl acrylate) (98.32)	0.90
F2	New Britain Trench	8930	84.0	66.7	F2-1-3	Film	Transparent	422	Polyolefin (85.51)	0.86
					F2-1-4	Fiber	Transparent	774	PP (97.25)	0.88–1.23
C2	Challenger Deep, Mariana Trench	10,890	117.6	93.3	C2-2-2	Fiber	Transparent	1058	Polyester (83.40)	1.30–1.50
					C2-2-5	Fiber	Transparent	12,376	Polyester (98.30)	1.30–1.50

2.5. Recovery rate and statistical analysis

Recovery rate experiments were conducted using commercial PP resin pellets (4.37 ± 0.29 mm), lab-made PP fibers (1.66 ± 0.59 mm) and lab-made PET fibers (1.07 ± 0.52 mm). This consideration of particle shape and size used for recovery test took environmental abundance, microplastic size and actual polymer composition into consideration. PP resin pellets, lab-made PP and PET fibers were spiked into soft hadal sediments collected where microplastics had been removed using density separation. Statistical analysis was done using IBM SPSS Statistics 22.

3. Results and discussion

3.1. Characteristics of microplastics in hadal trenches

Microplastics were found at all six sampling sites in hadal trenches and abyssal plain. In total, 32 microplastic particles were extracted from the 3 kg sediment samples (wet weight) and the average abundance of microplastics in sediments was 1.78 items per 25 g dry weight sediment, i.e., 71.1 items per kg dry weight sediment. Assuming the density of sediments from the Mariana Trench to be 1.26 g cm^{-3} (Glud et al., 2013), the average abundance by volume was 89.6 items per L dry weight sediment. The highest abundance was found at E1 in the New Britain Trench, with 3.33 items per 25 g dry weight sediment (i.e., 133.3 items per kg dry weight sediment). The lowest abundance was 0.67 items per 25 g dry weight at station D1 in the Marceau Trench (i.e., 26.7 items per kg dry weight sediment). The properties of the microplastics (excluding rayon) from six sites are shown in Table 2. Rayon fibers and fragments from six sites were also identified (Table S1), and because procedural blanks indicated no microfiber contamination occurred, rayon fibers are listed in the result as a reference recognizing the debate on whether rayon should be classified as microplastics (Peeken et al., 2018). Transparent particles (excluding rayon) constituted 64.3% of total particles, followed by red particles (21.4%) and blue particles (14.3%). Fibers (excluding rayon) were the major shape of microplastics, constituting of 57.1% of all the particles, while fragments constituted 42.8% of total microplastics, a significant higher percentage than those in coastal sediments (Frias et al., 2016). Size of microplastics ranged from 73 to 12,376 μm (Table 2). The most prevalent type of polymers was polyester (50%). Only one polypropylene (PP) fragment (Fig. 2c) from A1 had to be identified by FT-IR due to its relatively larger size, which led to the slightly different spectrum compared to other polymer spectra obtained by μ-FT-IR (Fig. 2a). The surface texture of this PP fragment was characterized by SEM analysis (Fig. 3) and shows attached organic matter and apparent signs of degradation, suggesting that plastic particles may sink due to biofouling and continue to fragment into microplastics through ingestion (Dawson et al., 2018) even in the deep-sea floor. In this study, recovery rates for PP pellets, PP fibers and PET fibers were 100%, 94.4 ± 4.8% and

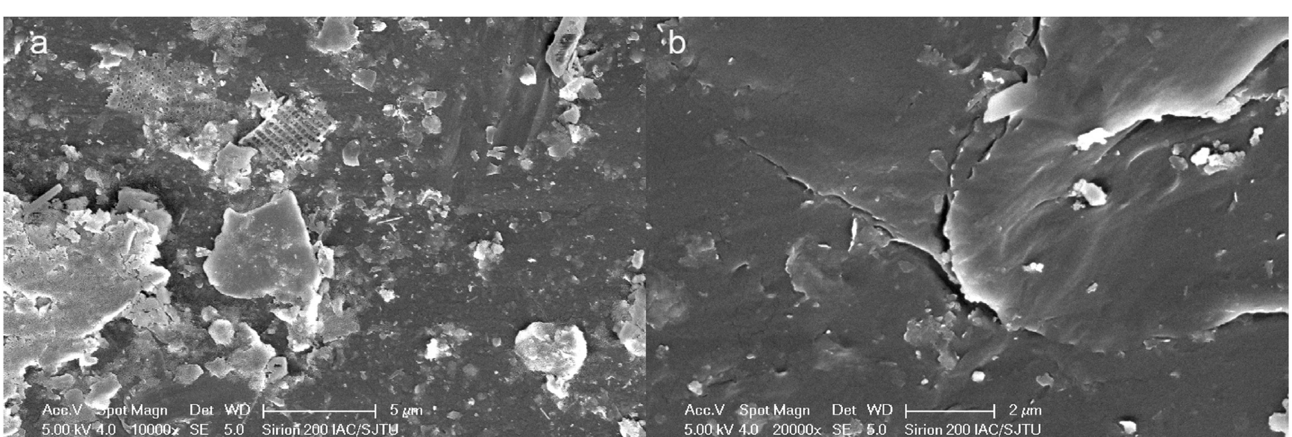

Fig. 3. SEM images of the surface texture of one PP fragment (ID: A1-1-2). (a) showing organic matter attached to the surface of microplastic particle with magnification of 10000x, and (b) showing signs of degradation on the surface with magnification of 20000x.

89.8 ± 5.8% (mean ± SD, n = 3, CI = 95%), respectively (Table S2).

3.2. Microplastic abundance

This study found that microplastics were present in sediments from some of the deepest corners on earth, including the Mariana Trench, Marceau Trench and New Britain Trench at depths from 4900 to 10,890 m. The highest abundance of microplastics was 133.3 items per kg dry weight sediment. The high concentration of microplastics in three deepest hadal trenches of the planet suggests that microplastics pollution has reached the full ocean depth and deposit at a high concentration, making hadal trenches the major depositories and ultimate sink for microplastics.

High hydrostatic pressure and extreme environments make hadal trenches out of reach by most human activities except anthropogenic pollutants. While some deep-sea surveys have visually identified marine litter on the deep-sea floor (Miyake et al., 2011), few have successfully sampled and quantified microplastics due to the technical challenges of collection and retrieval of samples from the hadal zone below 6500 m (Cui et al., 2014), e.g., the development of full ocean depth ROV/ARV/HOV, and the collection and preservation of hadal samples under 110 MPa. Therefore, sinking mechanisms for microplastics entering the hadal environment remain largely unknown due to limited research on microplastic distribution in the deep-sea and hadal environments and lack of knowledge on hadal science. Here we propose sources and potential pathways for microplastics to enter the hadal trenches from land and sea-based sources, which contributing to microplastics export to the seafloor, making hadal trenches as major depositories and ultimate sink for microplastics.

Our results illustrate that microplastics in sediments from hadal trenches are even higher than those identified from the conventional “deep-sea”. Microplastic particles have been found in sediments in the Atlantic Ocean at depth from 1100 to 5000 m with an average abundance of 0.5 items per 25 cm^2 (Van Cauwenberghe et al., 2013). In the Kuril-Kamchatka trench in the North-West Pacific, fiber was the dominant type of microplastics in sediment samples at depth from 4869 to 5766 m (Fischer et al., 2015). Deep-sea cores from the Mediterranean, South-West Indian Ocean and North-East Atlantic Ocean at a depth down to 3500 m revealed that the abundance of microplastic fibers in sediments was several orders of magnitude higher than that in surface waters (Woodall et al., 2014).

Recently, microplastics were also found in water and sediment samples in the Mariana Trench. According to Peng et al. (2018), microplastic abundance reached as high as 13.51 pieces L^{-1} in bottom waters, and 2200 pieces L^{-1} in sediments. They compared microplastic abundance at 10,903 m with 8 other studies, and found that the abundance is four times higher than that in the offshore waters near Vancouver, and twenty times higher than deep-sea sediments from Atlantic (Peng et al., 2018). This may be an example of hadal trenches as the sink for microplastics, however, compared to the abundance in our study which collected samples from several hadal trenches with larger sample quantity (500 g wet weight from each site), such high concentration may attribute to direct conversion from 5 mL to 1000 mL for each sediment sample in their study (Peng et al., 2018). While studies attempt to make comparisons among microplastic abundance worldwide, comparison should be made among studies with same sampling method and reporting units, as stressed in GESAMP WG40 report (GESAMP, 2016).

3.3. Sources and sinks

We propose cascading processes that transport microplastics on their journey from land and oceanic gyres through intermediate waters to the deepest corners of the ocean (Fig. 4), making hadal trenches the ultimate sink for plastic pollution. The most significant source of all sizes of plastic debris is the input from land-based sources, especially river discharge, and concentration of microplastics positively correlates with the amount of mismanaged plastic waste in river catchments (Lebreton et al., 2017). Papua New Guinea in the West Pacific, a region regarded as major plastic waste input into the ocean in the world (Jambeck et al., 2015), was more populated in recent years, putting pressure on the waste treatment facilities in growing informal settlements in coastal cities (Smith, 2012). This may explain the higher abundance of microplastics found in New Britain Trench in this study. A recently identified

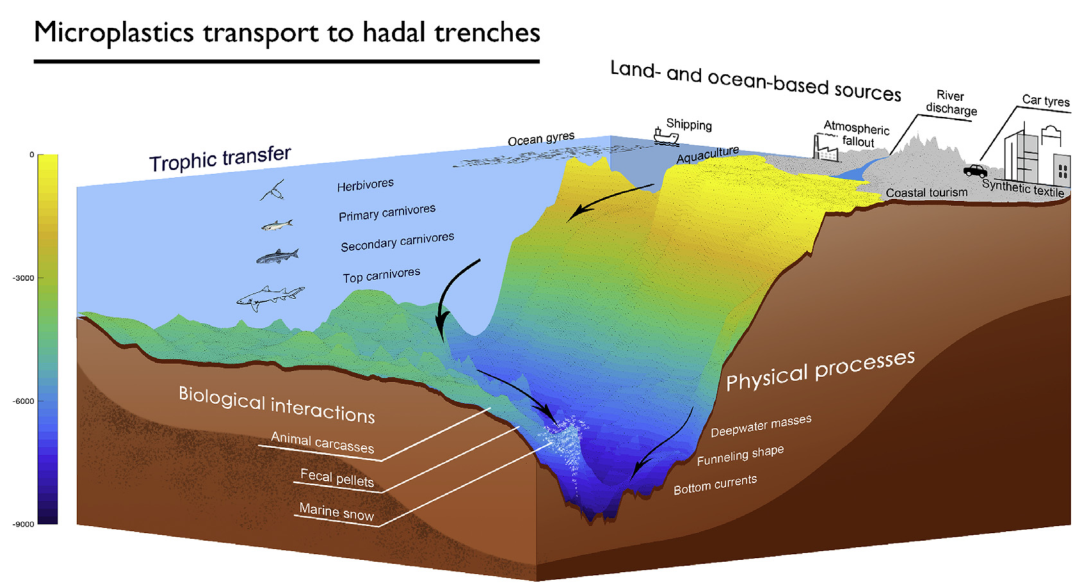

Fig. 4. A schematic of pathways of microplastics from various sources entering the hadal trenches (taking the New Britain Trench as an example), making the deepest spots on Earth the ultimate sink and depository for microplastics. Microplastics from land and ocean sources may enter the marine environments and transfer through the food chains. Through biological interactions (e.g., marine snow), microplastics increase density and sink to deeper layers. Once entering the hadal zone, physical processes facilitate microplastics to deposit in the hadal trenches and bioavailable for benthic organisms.

source of marine microplastics is atmospheric fallout (Dris et al., 2016). Through wind transfer, airborne microfibers may account for 7% of marine microplastic pollution (Boucher and Friot, 2017). The heavily populated NW Pacific and the rapidly expanding Great Pacific Garbage Patch (GPGP) may contribute to the quantity of microplastics at the ocean surface (Moore et al., 2001; Lebreton et al., 2018). Ocean-based sources, including maritime activities, aquaculture and fishery, still contribute to a great portion of plastic marine debris, although dumping at sea has been banned by MARPOL Annex V since 1988 (Borrelle et al., 2017).

Although an increasing amount of plastics was found accumulating at the surface (Lebreton et al., 2018), the eventual fate of microplastics, however, still lacks investigation. The mechanisms that assist vertical transport of microplastics from the surface to the deep ocean has only been investigated under lab conditions (Long et al., 2015) or in the shallow seas (Katija et al., 2017). It is likely the high concentrations of microplastics in this study indicate that the deep ocean (Woodall et al., 2014), especially the hadal trenches (Jamieson et al., 2019), may be a significant resting ground for microplastics pouring into the ocean. But how do they get there? Direct sinking of microplastic particles alone may take hundreds or thousands of years to reach the hadal trenches. The presence of microplastics in the hadal zone requires there to be mechanisms that promote the rapid descent from surface to full ocean depth. It cannot be gravitational sinking - spherical microplastics may spend 10–15 years in the euphotic zone before sinking, while for fibers it is 6–8 months (Chubarenko et al., 2016). Biofouling will increase the density of microplastics, leading to loss of buoyancy and vertical transportation to the seafloor (Chubarenko et al., 2016). Marine snow, or particulate organic matter (POM) synthesized in the euphotic zone, is the main food supply of life in hadal environments (Long et al., 2015; Taylor et al., 2016), and an important component of biological pump (Miyake et al., 2011). As microplastics are detected in marine snow (Zhao et al., 2017), the pathways and fluxes of marine snow from ocean surface to the deeper waters can predict possible mechanisms of microplastic occurrence even in the deepest hadal trenches (Ichino et al., 2015). Based on the equations from laboratory tests (Long et al., 2015), we calculated the time for microplastics incorporated into marine aggregates to reach the hadal sediments in our study (Fig. S2). A minimum of 14 days is enough for a polypropylene fragment to reach 4900 m if aggregated in phytoplankton aggregates. Once marine snow is removed to the deep, its quantity and quality is reduced by large extent (Jamieson et al., 2010). A video showcasing marine snow at 8930 m in the New Britain Trench was recorded during sample collection (Movie S1). A possible mechanism for microplastics to reach the seafloor may be the formation of “ecocorona”, which increases the density of microplastics (Galloway et al., 2017). The formation of ecocorona on the surface of microplastics by macromolecules or microorganisms alters the size, hydrophobicity and other chemical properties of microplastics (Rillig et al., 2017). This has been proven by the high concentration of nitrogen (N) on microplastics collected from surface waters, as N is not a content for consumer plastics, but crucial proxy for biomass (Morét-Ferguson et al., 2010). Using SEM analysis, we found organic matter attached to the surface of microplastics (Fig. 3).

Supplementary data related to this article can be found at https://doi.org/10.1016/j.watres.2019.115121.

Microplastic and plastic debris have been shown to be ingested and entangled by 395 marine species (Gall and Thompson, 2015), from herbivores (e.g., zooplankton, Moore et al., 2001; Cole et al., 2013; Frias et al., 2014; Hall et al., 2015; Sun et al., 2017; Frydkjær et al., 2017), primary carnivores (e.g., bivalves, Taylor et al., 2016; Murray and Cowie, 2011; von Moos et al., 2012), secondary carnivores (e.g., fish, Dantas et al., 2012; Bråte et al., 2016; Jabeen et al., 2017; Anastasopoulou et al., 2013) to top carnivores (e.g., large shark, Lusher et al., 2015; Alomar and Deudero, 2017). Transfer of microplastics in food webs had been proven in both field and lab experiments, including the transfer within planktonic food web from mesozooplankton to macrozooplankton (Setälä et al., 2014), natural transfer from mussels to crabs (Farrell and Nelson, 2013), and from fish to top predators (Nelms et al., 2018). Microplastics were found in stranded whales (Lusher et al., 2015), and whale fall could support significant food source in deep-sea floor (Smith and Baco, 2003). Giant larvaceans transport microplastics and carbon into deep sea either by sinking of fecal pellets or discarded mucus houses at rates of 300 m day^{-1} and 800 m day^{-1}, respectively (Katija et al., 2017). Microplastic particles with increased density due to biofouling will sink to deeper layers in the ocean. By transferring through marine food webs, aggregating into marine snows, fecal pellets, or animal carcasses, microplastics are vertically transported to the deeper layers.

But export from the surface and intermediate ocean does not explain fully why the microplastics are focused in the trenches. Microplastic abundance in different layers has distinct distribution patterns, with the surface layer and the deep water at higher concentrations (La Daana et al., 2018), indicating vertical change in microplastics in water columns. Trenches are well ventilated due to the overflow of dense water currents (Johnson, 1998), which brings in oxygen and nutrition (Ichino et al., 2015), as well as some pollutants (Jamieson et al., 2017). The unique topography of trenches increases the likelihood of microplastic accumulation. Similar to submarine canyons, funneling mechanism of trenches tend to accumulate organic matter and other substances in the hadal ecosystem with little opportunity for dispersal. Steep slope of trenches and occasional seismic activity accelerate the accumulation of substances along the trench axis, or “trench resource accumulation depth” (Jamieson et al., 2010). The Atacama trench at 7800 m functions as a deep oceanic trap, or a “depocentre”, for organic matter, which accelerates benthic microbial processes in hadal environment (Danovaro et al., 2003). Microplastics that undergo the funneling effects will eventually sink to the bottom along the axis of a trench. Compared to gravity-driven transport of marine snow, bottom currents play a greater role in the transport of organic matter, and leads to higher biomass along the axis of a trench (Ichino et al., 2015). The maximum of current velocity at 10,890 m can reach 8.1 cm s^{-1} (Johnson, 1998), making the lateral transport of sediments, dissolved oxygen and other substances possible within the trench. In this study, microplastics showed a relatively high abundance in surface sediments in hadal trenches, which may reflect accumulation along the axis of hadal trenches, thus more sampling efforts should be focused in this area.

3.4. Ecological effects

Ecological theory for littoral zones is applicable for characteristics in trench communities, albeit the elevated hydrostatic pressure (Jamieson et al., 2010). The ecological effects of microplastics include acting as “Trojan horse” for hydrophobic organic chemicals (HOCs) in food webs (Diepens and Koelmans, 2018), and as carrier for foreign species (Miyake et al., 2011). Different accumulation patterns for biomagnification of PCBs and PAHs were revealed by feeding zooplankton, fish and top predators in Arctic food web with HOCs contaminated microplastics (Diepens and Koelmans, 2018). In six deepest trenches including the Mariana Trench, three species of amphipod were found to ingest microplastics, indicating microplastics are bioavailable in hadal ecosystems (Jamieson et al., 2019). With the discovery of POPs in hadal amphipod species (Jamieson et al., 2017), similar “Trojan horse” effect may apply to hadal food webs.

Once entering the hadal food webs, microplastics might be perpetually locked in the trophic cycling due to both surface-derived carcasses and hadal-derived amphipod as food sources by amphipods (Jamieson et al., 2010). At the deepest corner on earth, amphipods are hungry necrophages, cannibals, detritivores and carnivores, which ingest nutrient-poor POM from above (Jamieson et al., 2010). Dawson et al. (2018) found a new pathway for plastics to transfer in biogeochemical cycling. Ingested microplastics may fragment into nanoparticles and pass physical barriers of krill or other marine species. It is very likely that hadal species facilitate microplastic fragmentation through ingestion and translocation, thus securing microplastics and nanoplastics in the hadal zone, making hadal trenches the ultimate sink for plastics. However, even comprehensive understanding of ecological impact of plastic pollution in coastal area is still lacking. More research efforts are required for the risk assessment of microplastics in the hadal zone to inform policy makers.

4. Conclusions

Microplastics found in sediments in the three deepest hadal trenches show that microplastics are already accumulating at the bottom of deepest corners on the planet, with an average abundance of 71.1 items per kg dry weight sediment (i.e., 89.6 items per L dry weight). Our study provides essential baseline data on microplastic pollution in hadal environments (down to 10,890 m), which confirms that microplastics have reached full-ocean depth. The potential cascading processes that transport microplastics to hadal trenches provides an answer to how microplastics are transported from sea surface to seafloor, including land and ocean-based input sources (e.g., maritime activities), ingestion by marine biota and trophic transfer, biological interactions with microplastics (e.g., marine snow) and physical processes (e.g., deep water currents) in the hadal trenches. These processes make the hadal trenches major depositories and the ultimate sink for microplastics. The understanding of sinking mechanisms and ecological effects of microplastics in the hadal zone will hopefully enhance the understanding for the remediation and prevention measures of microplastic pollution for relevant stakeholders.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study is funded by National Key Research and Development Program (2016YFC1402205), National Natural Science Foundation of China (41676190), a graduate fellowship from the Chinese Scholarship Council (CSC: 201806140234) to Guyu Peng and “Future Scientist” PhD Incubation Program from East China Normal University to Guyu Peng.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.watres.2019.115121.

References

Alomar, C., Deudero, S., 2017. Evidence of microplastic ingestion in the shark Galeus melastomus Rafinesque, 1810 in the continental shelf off the western Mediterranean Sea. Environ. Pollut. 223, 223–229.

Anastasopoulou, A., Mytilineou, C., Smith, C.J., Papadopoulou, K.N., 2013. Plastic debris ingested by deep-water fish of the Ionian sea (eastern Mediterranean). Deep Sea Res. Oceanogr. Res. Pap. 74, 11–13.

Borrelle, S.B., Rochman, C.M., Liboiron, M., Bond, A.L., Lusher, A., Bradshaw, H., Provencher, J.F., 2017. Opinion: why we need an international agreement on marine plastic pollution. Proc. Natl. Acad. Sci. 114, 9994–9997.

Bosker, T., Behrens, P., Vijver, M.G., 2017. Determining global distribution of microplastics by combining citizen science and in-depth case studies. Integr. Environ. Assess. 13, 536–541.

Boucher, J., Friot, D., 2017. Primary Microplastics in the Oceans: a Global Evaluation of Sources. IUCN Gland, Switzerland.

Bråte, I.L.N., Eidsvoll, D.P., Steindal, C.C., Thomas, K.V., 2016. Plastic ingestion by Atlantic cod (Gadus morhua) from the Norwegian coast. Mar. Pollut. Bull. 112, 105–110.

Browne, M.A., Chapman, M.G., Thompson, R.C., Amaral Zettler, L.A., Jambeck, J., Mallos, N.J., 2015. Spatial and temporal patterns of stranded intertidal marine debris: is there a picture of global change? Environ. Sci. Technol. 49, 7082–7094.

Carpenter, E.J., Smith, K.L., 1972. Plastics on the Sargasso sea surface. Science 175, 1240–1241.

Chiba, S., Saito, H., Fletcher, R., Yogi, T., Kayo, M., Miyagi, S., Ogido, M., Fujikura, K., 2018. Human footprint in the abyss: 30 year records of deep-sea plastic debris. Mar. Policy 96, 204–212.

Chubarenko, I., Bagaev, A., Zobkov, M., Esiukova, E., 2016. On some physical and dynamical properties of microplastic particles in marine environment. Mar. Pollut. Bull. 108, 105–112.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., Galloway, T.S., 2013. Microplastic ingestion by zooplankton. Environ. Sci. Technol. 47, 6646–6655.

Cozar, A., Echevarria, F., Gonzalez-Gordillo, J.I., Irigoien, X., Ubeda, B., Hernandez-Leon, S., Palma, A.T., Navarro, S., Garcia-de-Lomas, J., Ruiz, A., Fernandez-de-Puelles, M.L., Duarte, C.M., 2014. Plastic debris in the open ocean. Proc. Natl. Acad. Sci. 111, 10239–10244.

Crawford, C.B., Quinn, B., 2017. The emergence of plastics. Microplast. Pollutants 1–17, 118.

Cui, W., Hu, Y., Guo, W., Pan, B., Wang, F., 2014. A preliminary design of a movable laboratory for hadal trenches. Methods Oceanogr. 9, 1–16.

Danovaro, R., Della Croce, N., Dell Anno, A., Pusceddu, A., 2003. A depocenter of organic matter at 7800m depth in the SE Pacific Ocean. Deep Sea Res. Oceanogr. Res. Pap. 50, 1411–1420.

Dantas, D.V., Barletta, M., Da Costa, M.F., 2012. The seasonal and spatial patterns of ingestion of polyfilament nylon fragments by estuarine drums (Sciaenidae). Environ. Sci. Pollut. Res. 19, 600–606.

Dawson, A.L., Kawaguchi, S., King, C.K., Townsend, K.A., King, R., Huston, W.M., Bengtson Nash, S.M., 2018. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. Nat. Commun. 9.

Diepens, N.J., Koelmans, A.A., 2018. Accumulation of plastic debris and associated contaminants in aquatic food webs. Environ. Sci. Technol. 52, 8510–8520.

Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104, 290–293.

Engler, R.E., 2012. The complex interaction between marine debris and toxic chemicals in the ocean. Environ. Sci. Technol. 46, 12302–12315.

Eriksen, M., Lebreton, L.C.M., 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.

Farrell, P., Nelson, K., 2013. Trophic level transfer of microplastic: Mytilus edulis (L.) to Carcinus maenas (L.). Environ. Pollut. 177, 1–3.

Fischer, V., Elsner, N.O., Brenke, N., Schwabe, E., Brandt, A., 2015. Plastic pollution of the Kuril–Kamchatka trench area (NW pacific). Deep Sea Res. Part II Top. Stud. Oceanogr. 111, 399–405.

Frias, J.P.G.L., Gago, J., Otero, V., Sobral, P., 2016. Microplastics in coastal sediments from Southern Portuguese shelf waters. Mar. Environ. Res. 114, 24–30.

Frias, J.P.G.L., Otero, V., Sobral, P., 2014. Evidence of microplastics in samples of zooplankton from Portuguese coastal waters. Mar. Environ. Res. 95, 89–95.

Frydkjær, C.K., Iversen, N., Roslev, P., 2017. Ingestion and egestion of microplastics by the Cladoceran Daphnia magna: effects of regular and irregular shaped plastic and sorbed phenanthrene. Bull. Environ. Contam. Toxicol. 99, 655–661.

Gall, S.C., Thompson, R.C., 2015. The impact of debris on marine life. Mar. Pollut. Bull. 92, 170–179.

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

GESAMP, 2016. Sources, fate and effects of microplastics in the marine environment: part two of a global assessment. In: Kershaw, P.J., Rochman, C.M. (Eds.), Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, vol. 93. Rep. Stud. GESAMP No., p. 220. IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP.

Glud, R.N., Wenzhöfer, F., Middelboe, M., Oguri, K., Turnewitsch, R., Canfield, D.E., Kitazato, H., 2013. High rates of microbial carbon turnover in sediments in the deepest oceanic trench on Earth. Nat. Geosci. 6, 284.

Hall, N.M., Berry, K.L.E., Rintoul, L., Hoogenboom, M.O., 2015. Microplastic ingestion by scleractinian corals. Mar. Biol. 162, 725–732.

Ichino, M.C., Clark, M.R., Drazen, J.C., Jamieson, A., Jones, D.O.B., Martin, A.P., Rowden, A.A., Shank, T.M., Yancey, P.H., Ruhl, H.A., 2015. The distribution of

benthic biomass in hadal trenches: a modelling approach to investigate the effect of vertical and lateral organic matter transport to the seafloor. Deep Sea Res. Oceanogr. Res. Pap. 100, 21–33.
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. Marine pollution. Plastic waste inputs from land into the ocean. Science 347, 768–771.
Jamieson, A.J., Brooks, L., Reid, W., Piertney, S.B., Narayanaswamy, B.E., Linley, T.D., 2019. Microplastics and synthetic particles ingested by deep-sea amphipods in six of the deepest marine ecosystems on earth. R. Soc. Open Sci. 6, 180667.
Jamieson, A.J., Fujii, T., Mayor, D.J., Solan, M., Priede, I.G., 2010. Hadal trenches: the ecology of the deepest places on Earth. Trends Ecol. Evol. 25, 190–197.
Jamieson, A.J., Malkocs, T., Piertney, S.B., Fujii, T., Zhang, Z., 2017. Bioaccumulation of persistent organic pollutants in the deepest ocean fauna. Nat. Ecol. Evol. 1, 0051.
Johnson, G.C., 1998. Deep water properties, velocities, and dynamics over ocean trenches. J. Mar. Res. 56, 329–347.
Katija, K., Choy, C.A., Sherlock, R.E., Sherman, A.D., Robison, B.H., 2017. From the surface to the seafloor: how giant larvaceans transport microplastics into the deep sea. Sci. Adv. 3, e1700715.
La Daana, K.K., Gårdfeldt, K., Lyashevska, O., Hassellöv, M., Thompson, R.C., O'Connor, I., 2018. Microplastics in sub-surface waters of the Arctic central basin. Mar. Pollut. Bull. 130, 8–18.
Lebreton, L.C.M., van der Zwet, J., Damsteeg, J., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8, 15611.
Lebreton, L., Greer, S.D., Borrero, J.C., 2012. Numerical modelling of floating debris in the world's oceans. Mar. Pollut. Bull. 64, 653–661.
Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A., Noble, K., Debeljak, P., Maral, H., Schoeneich-Argent, R., Brambini, R., Reisser, J., 2018. Evidence that the great pacific garbage Patch is rapidly accumulating plastic. Sci. Rep. 8.
Long, M., Moriceau, B., Gallinari, M., Lambert, C., Huvet, A., Raffray, J., Soudant, P., 2015. Interactions between microplastics and phytoplankton aggregates: impact on their respective fates. Mar. Chem. 175, 39–46.
Lusher, A.L., Hernandez-Milian, G., O'Brien, J., Berrow, S., O'Connor, I., Officer, R., 2015. Microplastic and macroplastic ingestion by a deep diving, oceanic cetacean: the True's beaked whale Mesoplodon mirus. Environ. Pollut. 199, 185–191.
Lusher, A., 2015. Microplastics in the marine environment: distribution, interactions and effects. In: Marine Anthropogenic Litter. Springer, Cham, pp. 245–307.
Miyake, H., Shibata, H., Furushima, Y., 2011. Deep-sea litter study using deep-sea observation tools. Interdiscipl. Stud. Environ. Chem.-Marine Environ. Model. Anal.: Terra 261–269.
Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A comparison of plastic and plankton in the north Pacific central gyre. Mar. Pollut. Bull. 42, 1297–1300.
Mordecai, G., Tyler, P.A., Masson, D.G., Huvenne, V.A.I., 2011. Litter in submarine canyons off the west coast of Portugal. Deep Sea Res. Part II Top. Stud. Oceanogr. 58, 2489–2496.
Morét-Ferguson, S., Law, K.L., Proskurowski, G., Murphy, E.K., Peacock, E.E., Reddy, C.M., 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Mar. Pollut. Bull. 60, 1873–1878.
Murray, F., Cowie, P.R., 2011. Plastic contamination in the decapod crustacean Nephrops norvegicus (Linnaeus, 1758). Mar. Pollut. Bull. 62, 1207–1217.
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., 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.
Peeken, I., Primpke, S., Beyer, B., Gütermann, J., Katlein, C., Krumpen, T., Bergmann, M., Hehemann, L., Gerdts, G., 2018. Arctic sea ice is an important temporal sink and means of transport for microplastic. Nat. Commun. 9, 1505.
Peng, G., Zhu, B., Yang, D., Su, L., Shi, H., Li, D., 2017. Microplastics in sediments of the Changjiang estuary, China. Environ. Pollut. 225, 283–290.
Peng, X., Chen, M., Chen, S., Dasgupta, S., Xu, H., Ta, K., Bai, S., 2018. Microplastics contaminate the deepest part of the world's ocean. Geochem. Perspect. Lett. 9, 1–5.
Porter, A., Lyons, B.P., Galloway, T.S., Lewis, C., 2018. Role of marine snows in microplastic fate and bioavailability. Environ. Sci. Technol. 52, 7111–7119.
Rillig, M.C., Ingraffia, R., de Souza Machado, A.A., 2017. Microplastic incorporation into soil in agroecosystems. Front. Plant Sci. 8, 1805.
Schlining, K., von Thun, S., Kuhnz, L., Schlining, B., Lundsten, L., Jacobsen Stout, N., Chaney, L., Connor, J., 2013. Debris in the deep: using a 22-year video annotation database to survey marine litter in Monterey Canyon, central California, USA. Deep Sea Res. Oceanogr. Res. Pap. 79, 96–105.
Setälä, O., Fleming-Lehtinen, V., Lehtiniemi, M., 2014. Ingestion and transfer of microplastics in the planktonic food web. Environ. Pollut. 185, 77–83.
Shimanaga, M., Yanagi, K., 2016. The Ryukyu Trench may function as a "depocenter" for anthropogenic marine litter. J. Oceanogr. 72, 895–903.
Smith, C.R., Baco, A.R., 2003. Ecology of whale falls at the deep-sea floor. Oceanogr. Mar. Biol. 41, 311–354.
Smith, S.D., 2012. Marine debris: a proximate threat to marine sustainability in Bootless Bay, Papua New Guinea. Mar. Pollut. Bull. 64, 1880–1883.
Sun, X., Li, Q., Zhu, M., Liang, J., Zheng, S., Zhao, Y., 2017. Ingestion of microplastics by natural zooplankton groups in the northern South China Sea. Mar. Pollut. Bull. 115, 217–224.
Talley, L.D., Pickard, G.L., Emery, W.J., Swift, J.H., 2011. Descriptive Physical Oceanography: an Introduction, sixth ed. Elsevier, London, pp. 303–362.
Taylor, M.L., Gwinnett, C., Robinson, L.F., Woodall, L.C., 2016. Plastic microfibre ingestion by deep-sea organisms. Sci. Rep. 6.
Tekman, M.B., Krumpen, T., Bergmann, M., 2017. Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory. Deep Sea Res. Oceanogr. Res. Pap. 120, 88–99.
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., Vanreusel, A., Mees, J., Janssen, C.R., 2013. Microplastic pollution in deep-sea sediments. Environ. Pollut. 182, 495–499.
von Moos, N., Burkhardt-Holm, P., Köhler, A., 2012. Uptake and effects of microplastics on cells and tissue of the blue MusselMytilus edulis L. After an experimental exposure. Environ. Sci. Technol. 46, 11327–11335.
Wei, C., Rowe, G.T., Nunnally, C.C., Wicksten, M.K., 2012. Anthropogenic "litter" and macrophyte detritus in the deep northern Gulf of Mexico. Mar. Pollut. Bull. 64, 966–973.
Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L.J., 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, 140317-140317.
Zhao, S., Danley, M., Ward, J.E., Li, D., Mincer, T.J., 2017. An approach for extraction, characterization and quantitation of microplastic in natural marine snow using Raman microscopy. Anal. Methods 9, 1470–1478.