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Human footprint in the abyss: 30 year records of deep-sea plastic debris

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ABSTRACT

This study reports plastic debris pollution in the deep-sea based on the information from a recently developed database. The Global Oceanographic Data Center (GODAC) of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) launched the Deep-sea Debris Database for public use in March 2017. The database archives photographs and videos of debris that have been collected since 1983 by deep-sea submersibles and remotely operated vehicles. From the 5010 dives in the database, 3425 man-made debris items were counted. More than 33% of the debris was macro-plastic, of which 89% was single-use products, and these ratios increased to 52% and 92%, respectively, in areas deeper than 6000 m. The deepest record was a plastic bag at 10898 m in the Mariana Trench. Deep-sea organisms were observed in the 17% of plastic debris images, which include entanglement of plastic bags on chemosynthetic cold seep communities. Quantitative density analysis for the subset data in the western North Pacific showed plastic density ranging from 17 to 335 items km^{-2} at depths of 1092–5977 m. The data show that, in addition to resource exploitation and industrial development, the influence of land-based human activities has reached the deepest parts of the ocean in areas more than 1000 km from the mainland. Establishment of international frameworks on monitoring of deep-sea plastic pollution as an Essential Ocean Variable and a data sharing protocol are the keys to delivering scientific outcomes that are useful for the effective management of plastic pollution and the conservation of deep-sea ecosystems.

1. Introduction

Plastic pollution is emerging as one of the most serious threats to ocean ecosystems [1], and world leaders, scientists, and communities recognize the need for urgent management measures for the sustainability of marine ecosystem services in the future [2]. Previous studies have reported the accumulation of plastic debris on the coasts [3–5], and ship-based observations have revealed plastic debris accumulation in offshore surface waters [6]. The damage caused by plastic debris in large animals through accidental ingestion and entanglement in floating plastic [7] and the hazards posed by toxic chemicals released from fragmented plastic on the biological function of marine organisms have been well studied [8]. Micro-plastic ingested by zooplankton can be transferred to higher trophic level animals, including commercially important fish species, through the food web [9,10], with potential effects on human health. The United Nations Sustainable Development Goal 14.1 urges the world community to take action to reduce marine pollution by 2025, and one of the indicators to track its progress is the density of floating plastic debris (http://www.un.org/sustainabledevelopment/oceans/).

An increasing number of studies have been conducted on plastic pollution in coastal and surface waters, limited information is available for mesopelagic and deeper layers that occupy a vast area of the global ocean. In those studies, deep-sea debris distribution using bottom sampling [11–15], and video observation *via* remotely operated vehicles (ROVs) and submersibles [12,13,16–21], in regional oceans were revealed. Although pollution in the deep sea was often perceived as being less dependent on land-based human activities, those studies reported that plastic debris were frequently observed in the deep sea, particularly in areas close to highly populated regions, *e.g.* the Mediterranean Sea [12,22,23]. Potential threats of plastic pollution to the biodiversity of deep-sea ecosystems, which are highly endemic and have a very slow growth rate [24], are concerning. However, a majority of the previous studies are based on one-off projects over several years,

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Table 1
Summary of the total and plastic debris occurrences during deep-sea surveys by remotely operated vehicles and submersibles of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in the six oceanic regions for 1982–2015. The information is based on the Deep-sea Debris Database of Global Oceanographic Data Center (GODAC) of JAMSTEC (updated on July 3rd, 2017) (http://www.godac.jamstec.go.jp/dsdebris/e/). Single use plastics are plastic bags, bottles and packages.

Oceanic Region	Year of observation	Geographical range (Latitude - Longitude)	Dive depth range (m)	Debris depth range (m)	Max. depth (m) of plastics	Total dive number	Total debris number	Plastic debris number	% Single use plastic
Western North Pacific	1982–2015	1°15' - 45°34'N 122°42' - 163°15'E	100– 10,899	100–10898	10,898	4552	3370	1108	89
Eastern North Pacific	1998–2002	17°12' - 24°24'N 154°14' - 159°13'W	1714–5569	3879–4684	4684	85	8	2	100
South Pacific	1990–2013	3°10' - 34°53'S 149°52'E - 112112°29'W	499–6498	1846–4460	1986	168	12	1	100
North Atlantic	1994–2013	14°44' - 36°14'N 33°54' - 81°48'W	2265–6024	2300 − 4935	–	68	17	0	N.A.
South Atlantic	2013	20°38' - 31°06'S 34°03' - 41°39'W	921–4219	2493–2721	–	16	5	0	N.A.
Indian Ocean	1998–2013	4°02'N - 32°57'S 57°04' - 105°53'E	1276–5290	1923–3264	2573	121	13	4	100
Total						**5010**	**3425**	**1115**	**89**

at maximum, and on surveys conducted in areas relatively close to the coast. There are only a few cases of long-term observation records on deep-sea plastic pollution [18,25,26] and of surveys conducted at depths greater than the abyssal zone (> 4000 m) [13–15] and in areas more than 1000 km off the coast of the mainland [13,19,27]. Information on deep-sea debris in the western North Pacific Ocean is also very limited [15,28]. Because high concentrations of plastic debris were reported in the shallow coastal waters in East Asia [29–32] and intensive research and management measures have been adopted on the beach and coastal areas of the highly populated East Asian countries [33], investigation regarding a possible link of the coastal plastic pollution to offshore and deep-sea ecosystems in the western North Pacific is urgently needed.

To assess the distribution of deep-sea plastic debris at the global scale, collating and sharing the best available data from past and present surveys will be essential. With such a background, the Global Oceanographic Data Center (GODAC) of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) launched the Deep-sea Debris Database for public use in March 2017 (http://www.godac.jamstec.go.jp/dsdebris/e/). Debris items identified in video footage taken during surveys *via* submersibles and remotely operated vehicles (ROVs) since 1983 were reviewed and recorded in the database, which includes a large amount of plastic debris observed in the abyssal and even the hadal zones (> 6000 m), for which hardly any information on artificial debris distribution is available. Although the data cover the global ocean, the majority of the records are from the western North Pacific and fill the regional knowledge gap on global deep-sea plastic debris pollution.

The aims of this study were to raise awareness about the ubiquitous distribution of macro-plastic debris, particularly of single-use plastic found in the deepest marine trenches and thousands of kilometres from the shore and to suggest effective strategies for scientific research on deep-sea plastic pollution. Using the 30 year worth of records of deep-sea debris available in the Deep-sea Debris Database, the objective of this study was to fill the current knowledge gap by depicting the occurrence of plastic debris in the abyssal and hadal zones of the world's oceans and the density distribution of plastic debris in the western North Pacific. Finally, we discuss how collaboration by the international deep-sea observation community could maximize the benefits of its scientific outcome to knowledge-based action for better conservation and management of the deep-sea environment and ecosystems.

2. Material and methods

2.1. Data

The data used in this study were from the Deep-sea Debris Database updated on July 3rd, 2017 (http://www.godac.jamstec.go.jp/dsdebris/e/). The debris data were obtained by visually analysing video footage taken from 1983 to 2014 by JAMSTEC's manned research submersibles *SHINKAI 2000* and *SHINKAI 6500* and the ROVs *DOLPHIN 3K*, *HYPER-DOLPHIN*, and *KAIKO*, with maximum survey depths of approximately 2000 m (1983–2002), 6500 m (1990–2014), 3000 m (1987–2002), 3000 m (2000–2014), and 11,000 m (1995–2014). For the specifications of these vehicles, refer to the following link to the JAMSTEC website: (http://www.jamstec.go.jp/e/about/equipment/ships/). The database is open to the public for academic use, and users can browse the list of debris photos and videos and other information, such as debris category; date, location, and depth of the observation; observation vehicle; substrate type of the sea floor; and taxonomic information of organisms observed with the debris (if present).

The records for dives conducted in areas deeper than 100 m were selected for analysis. The total number of dives examined was 5010. The diving points were mainly in the western North Pacific: around the Japanese archipelago, including the Japan Trench, and stretching south to the Mariana and Palau Trenches, but a number of dive records, shown in parentheses, were of other oceanic regions: the eastern North Pacific (85), South Pacific (171), Indian Ocean (121), North Atlantic (68), and South Atlantic (13) (Table 1, Fig. 1). In all regions, the maximum survey depth exceeded 4000 m. Many dives were conducted in the open ocean, more than 1000 km off the coast of the mainland, but only 3% of the dives were in the high seas, *i.e.* the areas beyond national jurisdiction.

Records of natural debris and unidentified debris in the database were excluded from the quantitative analysis of this study, and only anthropogenic debris was analysed, which was classified into seven categories: plastic, glass, metal, rubber, cloth/paper/lumber, fishing gear, and other. Plastic debris was sub-categorized into single-use products (bags, bottles, and packages) and other plastics.

2.2. Density analysis

The initial purpose of the dives in the database was to conduct biological and geological investigations, not debris monitoring. Thus, density estimation was possible only for the data subset from the *SHINKAI 6500* dives between 2004 and 2014. Those dives were selected

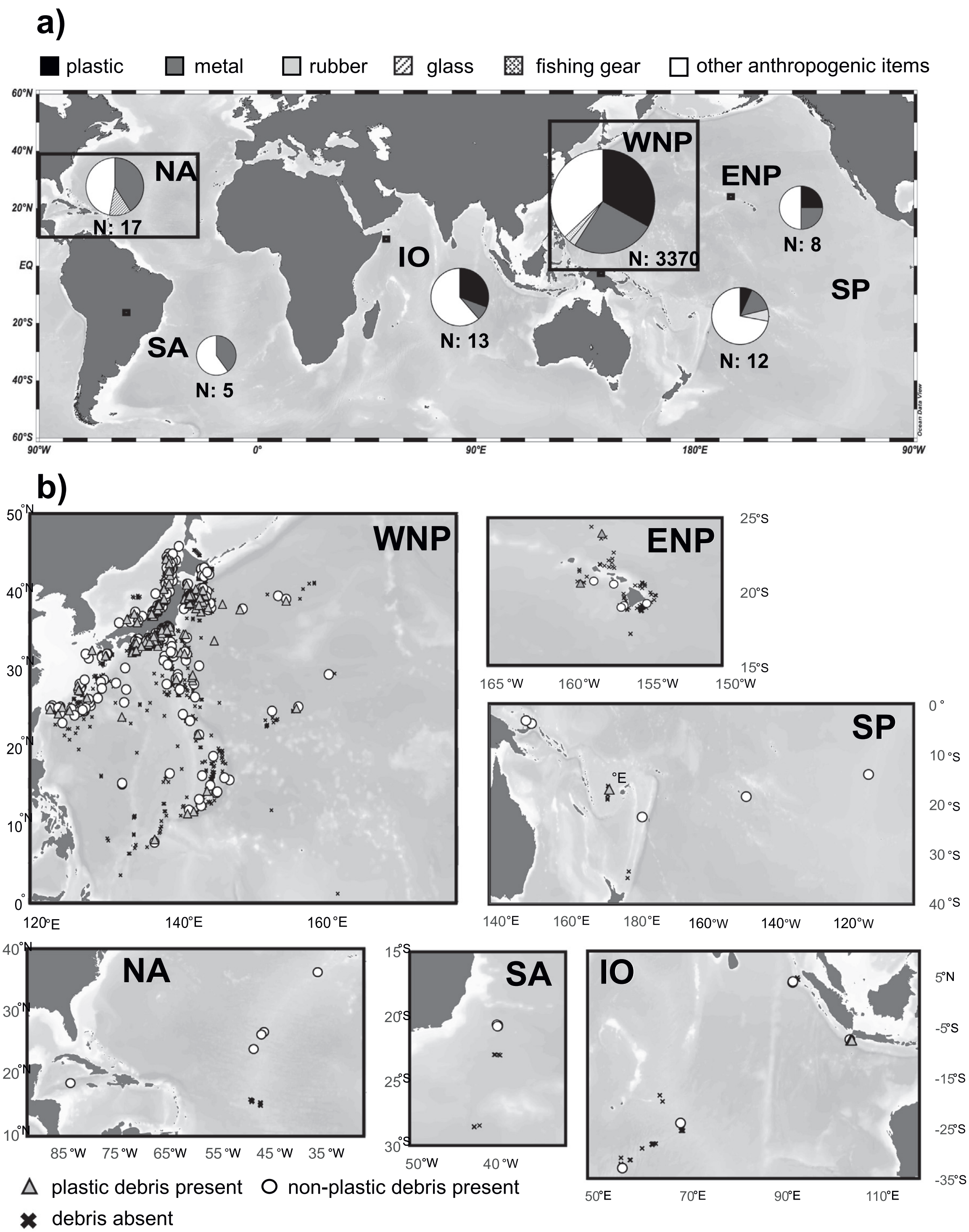

Fig. 1. a) Total number of debris items observed (N) and its composition in the six oceanic regions; WNP: Western North Pacific; ENP: Eastern North Pacific; SP: South Pacific; NA: North Atlantic; SA: South Atlantic; IO: Indian Ocean. Note that the size of circle is not accurately proportional to the number. In WNP, cloth/paper/lumber and glass were also observed, but not visible on the pie chart because their proportions are c.a. 1.0%. b) Location of dive surveys during which at least one item of plastic debris (triangle) or non-plastic debris (circle) were observed. Dives with no debris observed were indicated by cross.

because (1) detailed dive track records with data of altitude and inclination angle of the vehicle were available through the Data and Sample Research System for Whole Cruise Information (DARWIN) (http://www.godac.jamstec.go.jp/darwin/e) and (2) footage was taken by a fixed-angle camera fit to the front of the vehicle. The footage recorded by flexible angle cameras, which were also fit to the front of the vehicle, was not used for the density analysis, as it was difficult to estimate the width of the observation window consistently. As the selected dive records were almost exclusively in the western North Pacific (188 of 198 dives), density analysis was conducted only for the western North Pacific.

The areas observed (km^2) for each dive were estimated from the horizontal distance (km) of the video observation and the width of the video image (m). The horizontal distance of the video observation was estimated by summing the distance calculated from the latitude and longitude for every 10-second interval of each dive. The periods of sea bottom cruising without filming and with low visibility due to turbulence were excluded from distance estimates. The width of the video image was estimated using the distance from the sea bottom to the fixed camera, the angle of the vehicle against the sea bottom also for every 10 s, and the camera's aperture angle [34]. Then, the densities of plastic debris and total debris (number of items km^{-2}) were estimated for 188 dives.

3. Results

3.1. Global distribution

A total of 3425 anthropogenic debris items were detected in 5010 dive records, among which plastic was the most frequently observed category, accounting for 33% of all debris items, followed by metal (26%), rubber (1.8%), fishing gear (1.7%), glass (1.4%), cloth/paper/lumber (1.3%), and and other anthropogenic items (35%). Of the plastic items, 89% were single-use products. The overall composition of debris resembled that of the western North Pacific (plastic: 33%) due to its large proportion of dive numbers (4552 out of 5010 dives). Plastic was also the most abundant category in the eastern North Pacific (25%), South Pacific (8%), and the Indian Ocean (31%), and single-use plastic accounted for 100% of the plastic debris in all three regions (Table 1, Fig. 1). Metal debris was most frequently observed in the North (41%) and South Atlantic (40%). Debris items were observed in areas deeper than 4000 m in the western and eastern North Pacific, South Pacific, and North Atlantic. The maximum depth record of plastic debris was a plastic bag at 10898 m in the Mariana Trench in the western North Pacific (Fig. 2). In terms of horizontal distribution, plastic debris as well as non-plastic debris reached the open sea over 1000 km off the coast (Fig. 1).

Total debris as well as plastic debris was observed mostly in the depth range of 1000–2000 m, where the number of dives conducted was the greatest (Fig. 3). The ratio of plastic to total debris markedly increased from the depth range shallower than 1000 m to that greater than 1000 m, from 18% to 22% to 34–63%, respectively, and was 52% at depths greater than 6000 m. Most of plastic items observed below 1000 m were single-use plastic (88–100%) and the ratio is 92% below 6000 m.

At least one organism was identified in 124 out of 759 images with a plastic item(s) (16%), among which at least one organism was attached to a plastic(s) in 53 images (43%) either merely physically contacted, entangled by plastics (4 images), or settled on plastics (5 images) (Supplementary Table 1). Among the 41 taxa detected, the most frequently observed were actiniarians (sea anemones): in 26 images with 11 attached on plastics including 5 settled; actinopterygians (ray-finned fish): in 20 images with 3 attached to plastics; and ophiuroids (brittlestars) in 17 images with 8 attached to plastics. Plastic bags were observed in chemosynthetic cold seep communities in Sagami Bay, Japan Trench and Java Sea with beard worms (Siboglinidae), *Calyptogena* spp. and *Bathymodiolus* spp. Entanglements of a plastic bag on *Bathymodiolus* spp. and bead worms were observed in Sagami Bay and Java Sea, respectively (Supplementary Table 1). More detailed study on interaction between organisms and all debris types will be conducted later.

3.2. Density analysis in the western North Pacific

Among the 188 dive records used for the quantitative density analysis, debris was detected during 41 dives, with densities ranging from 11 to 342 items km^{-2} at depths of 1085–6037 m (Supplementary Table 2). Plastic debris was observed during 19 dives, and its density ranged from 17 to 335 items km^{-2} at depths of 1092–5977 m. The maximum density was observed at 4670 m for total debris and 5977 m for plastic debris. Debris density significantly decreased as the dive depth increased, for both the total debris (Spearman rank correlation $R = -0.226$, $p < 0.01$, $N = 187$) and plastic debris ($R = -0.150$, $P < 0.05$, $N = 187$). Although the horizontal distribution of debris showed high debris density near the Japanese archipelago, the density did not gradually decrease from the coast to offshore, *e.g.* the highest density was observed at the offshore diving point off east Japan (Fig. 4). Because the dive locations varied between 2004 and 2014, it was difficult to examine temporal variation of the debris density.

4. Discussion

4.1. Plastic debris at great depths

Consistent to the previous deep-sea debris studies in the Mediterranean Sea [12,22,23], North Atlantic [14,15], eastern North Pacific [17,22], Bering Sea [11], Arctic Ocean [17] and global summary [5], in this study, plastic debris was the most dominant deep-sea debris in the western North Pacific, eastern North Pacific, and Indian Ocean. Whereas those previous surveys were conducted on the sea floor at depths shallower than 4000 m, excluding the one off the west coast of Portugal [16], in this study, evidence of distribution of plastic debris was shown in the abyssal zone (4000–6000 m) and for the first time in the hadal zone (> 6000 m), in the world's deepest trench at over 10,000 m deep. It is noteworthy that the relative dominance of plastic debris was larger at depths greater than 6000 m (52%) than at shallower depths (18–22% at > 1000 m) and it was almost exclusively single-use plastic. In a study off the California coast, the relative occurrence of plastic debris increased in the 2000–4000 m depth range compared to that in the upper 1500 m [18], The same study also reported dominance of single-use plastic among the plastic debris. It is plausible that single-use plastic, having high buoyancy, tends to be transported far distances *via* oceanic currents and other physical mechanisms from coastal regions before settling and accumulating on the deep-sea floor.

The total debris density per dive observed in this study, 11–342 items km^{-2}, was 1–2 orders of magnitude smaller than that of previous deep-sea debris surveys (> 100 m) by ROVs or submersibles conducted in regions relatively close to the coast, *e.g.* 1329 items km^{-2} in the Arctic Ocean [17], 320 items km^{-2} off Southern California [25], 100–1100 items km^{-2} items in European waters [13], and 3210 items km^{-2} in the Mediterranean Sea [13], and also in offshore regions > 600 km away from the mainland, *e.g.* 100–1700 items km^{-2} in the Indian Ocean [19] and 100–1200 items km^{-2} in the South Atlantic [19]. As debris density was 0 items km^{-2} for 146 out of 187 dive records used for density analysis in this study, the area average density in the western North Pacific was much smaller. This study indicated that debris density significantly decreased with greater depth. The low density was possibly because the target survey depth of *SHINKAI 6500* is up to 6500 m and much greater than that in other studies.

4.2. Impacts on deep-sea ecosystem in the western North Pacific

There is a growing concern that deep-sea ecosystems have already been and will be seriously impacted by direct exploitation of biological and non-biological resources, deep-sea trawling and mining, and infrastructure development, such as hydrocarbon plants and submarine cables [35,36]. In addition to those direct impacts, the observed distribution of plastic debris clearly indicates that land-based human activities have also been affecting deep-sea ecosystems. This present study showed that association of plastic debris and deep-sea biota occurs at a relatively high frequency considering the low biomass and/or sporadic distribution of deep-sea ecosystems: 17% of debris images were found with at least one organisms. Entanglement of plastic bags were detected even in the cold seep communities and its negative impact on these rare ecosystems is concerned.

In the western North Pacific, tectonic activities are common on the sea floor, particularly around the Japanese archipelago, and allow the

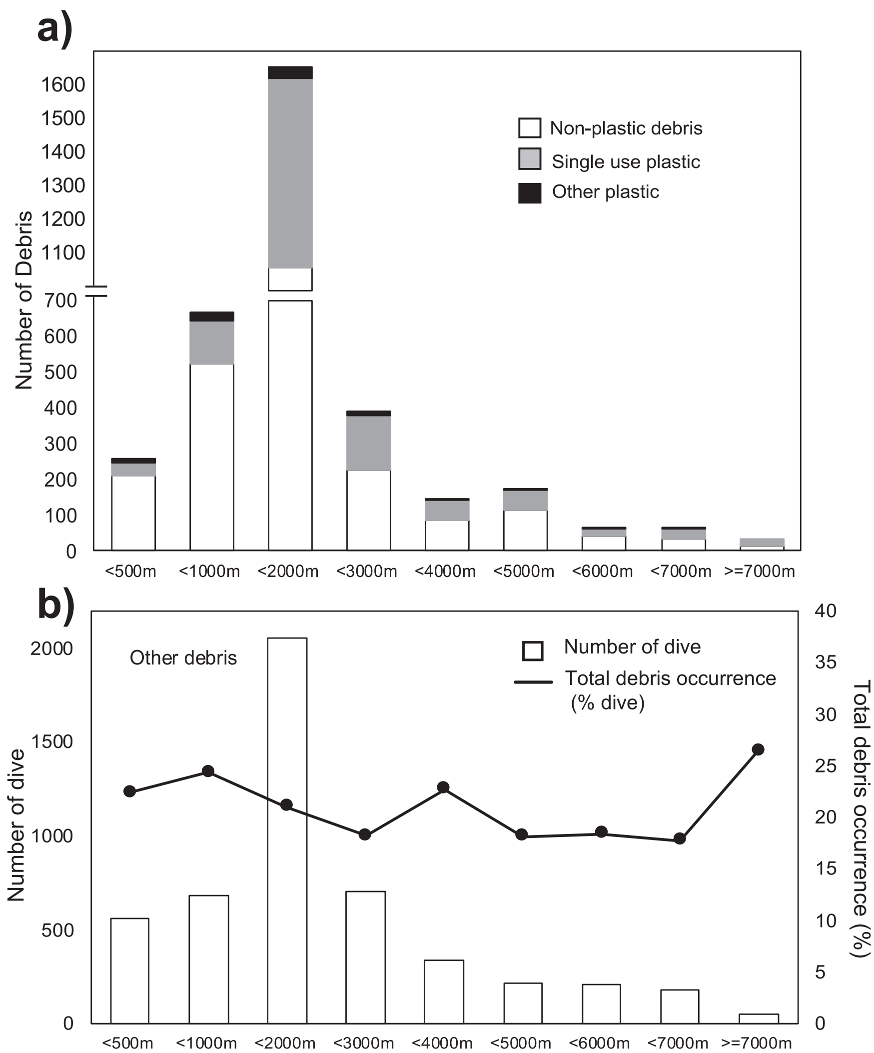

Fig. 2. Plastic debris detected on the sea bottom at the Mariana Trench (10,898 m, 11°21′N, 142°12′E) observed by ROV KAIKO on May 20th, 1998. The photo was downloaded from the JAMSTEC Deep-sea Debris Database (http://www.godac.jamstec.go.jp/dsdebris/e/).

sporadic formation of unique chemosynthetic communities, such as hydrothermal vent and cold seep communities [24]. In these communities, chemosynthetic bacteria play the role of primary producers to sustain highly endemic and diverse ecosystems. Because of their uniqueness, several parts of these deep-sea areas around the Japanese archipelago were reported to the Convention of Biological Diversity (CBD) as Ecologically or Biologically Significant Marine Areas (EBSAs) of Japan [37] and the areas covered by the Deep-sea Debris Database largely overlap the Japanese EBSAs. Although hazards of the chemical substances released from plastic to the biological and ecological functions of individual organisms and communities have been reported [38,39], actual impacts of plastic debris on deep-sea ecosystems have been less studied. However, with their slow growth rate and endemic distribution [24], recovery of deep-sea ecosystems will be difficult once they are severely damaged.

Besides the obviously hazardous impacts, plastic debris often provides benthic organisms with new habitats [18,25]. In this study, settlements of deep-sea anemones on plastic bags were observed on the muddy sea floor during several dives. Because those animals need hard substrates to attach to and thus cannot inhabit soft bottoms, deep-sea plastic debris possibly plays the role of a stepping stone for sessile animals to expand their original distribution. In addition to the "hitchhiking" of the organisms on floating debris from the shallow waters [40], this stepping stone effect may alter the food web and biogeochemical function of the deep-sea ecosystems [28].

The Deep-sea Debris database only shows information of the sea floor, and a majority of the survey areas are within the Exclusive Economic Zone (EEZ) of certain countries. However, as the deep sea is likely to be the final destination of floating plastic debris, the frequent occurrence and widespread distribution of plastic debris in the deep sea, far away from populated coastal areas, indicate that large numbers of plastic debris pieces are distributed throughout the water column and in the high seas. The western North Pacific is known for its high biological diversity [41] and holds large ecologically and biologically important areas [42]. Although several studies have reported on the cumulative impacts of plastic debris on populations of large vertebrates, such as sea turtles [43], whales [44], and commercially important fish [45] living in offshore waters, the current study suggests that all pelagic, mesopelagic, and deep-sea species in the western North Pacific may be at risk.

4.3. Recommendations for effective knowledge-based action

The highlight of this study was the ubiquitous distribution of single-use plastic, even to the greatest depths of the Mariana Trench, indicating a clear link between daily human activities and remote environments where no direct human activities occur. Establishing Marine Protection Areas (MPAs) is a potentially effective measure to protect deep-sea ecosystems against the threats of direct resource exploitation and industrialization [35]; *e.g.* the Mariana Trench is designated as a

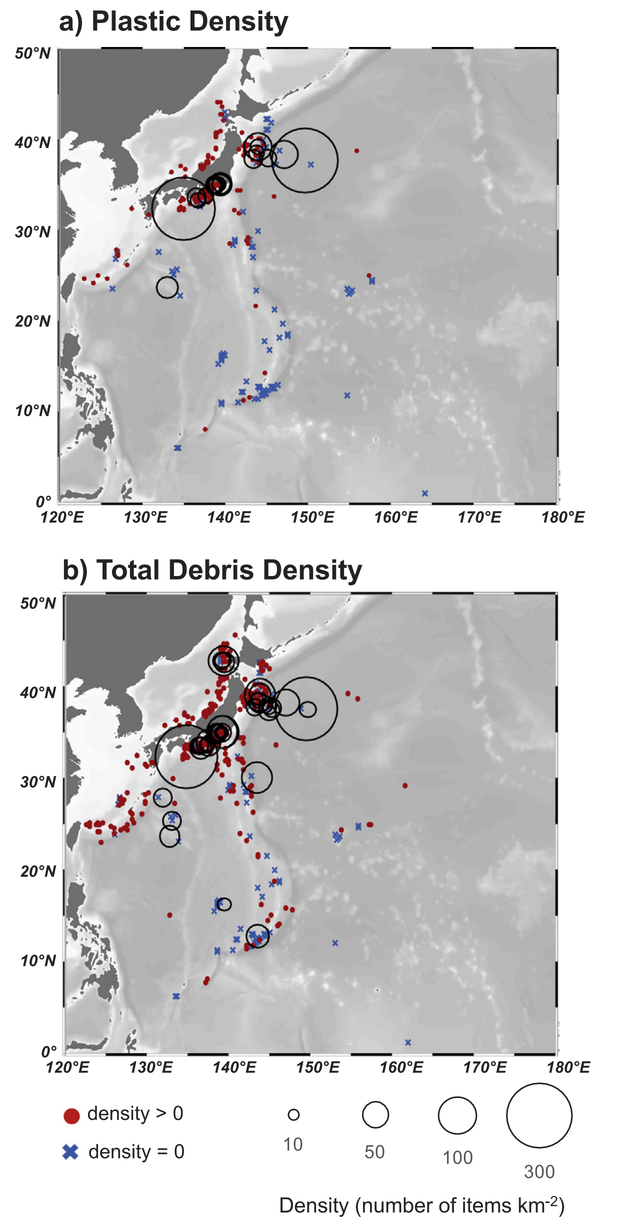

Fig. 3. a) Depth distribution of debris for 1983–2014. Bar indicates number of total debris and plastic debris items observed in each depth range. Single use plastics are plastic bags, bottles, and packages. b) Total dive number in each depth range. The solid line indicates percentage of dives during which at least one debris was observed.

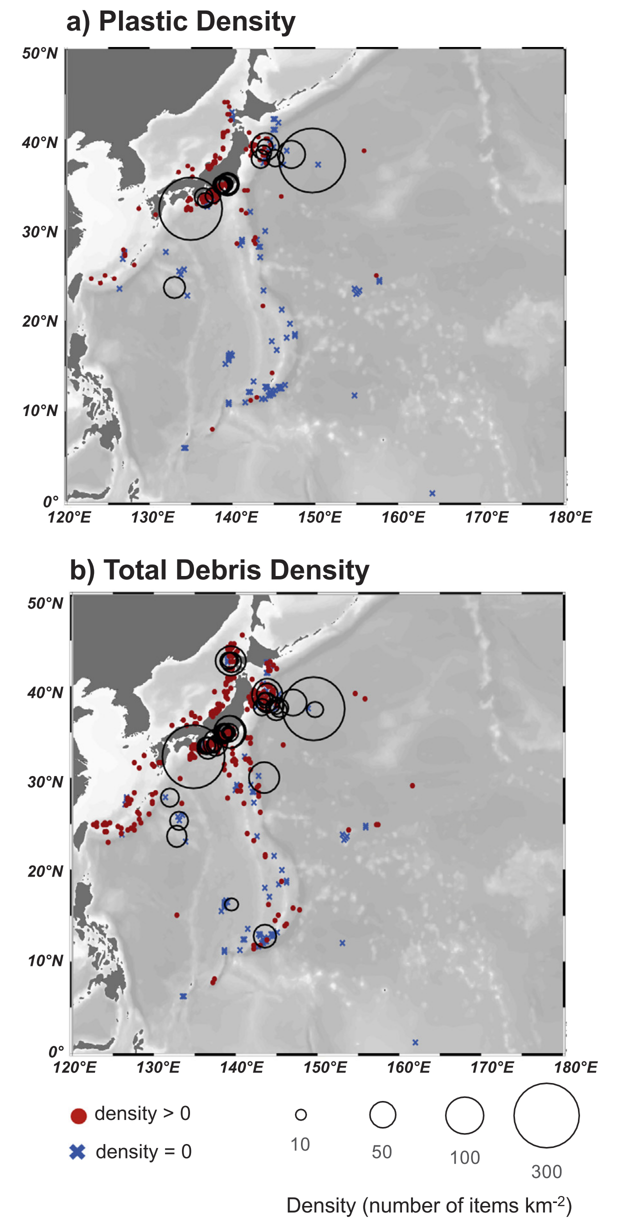

Fig. 4. Density (number of items Km^{-2}) of plastic debris a) and total debris b) in the western North Pacific. Density was estimated for selected dives of SHINKAI 6500 for 2004–2014. Red dots indicate location of dives during which at least one plastic debris a) or any debris b) was observed (number of debris items $Km^{-2} > 0$) but areas (Km^{-2}) of dives were unknown. Blue crosses indicate location of dives which areas were estimated but no debris was observed (number of debris items $Km^{-2} = 0$).

Marine National Monument MPA by the United States [46]. However, MPA designation cannot prevent the hazards of plastic pollution in the deep sea because the source of plastic pollution is exclusively land-based. Even if it is assumed that a small percentage of plastic debris originates from illegal or accidental deposition from ships and offshore infrastructures, all of the plastic is produced on land. Moreover, plastic debris tends to accumulate in canyons and depressions, where the threats of direct exploitation are less. Although deep-sea ecosystem services are less recognized compared to coastal and offshore ecosystem services, human society largely benefits from deep-sea biodiversity through provisional services (genetic and other bioprospecting resources), regulatory services, (nutrient regeneration), and cultural services (educational and scientific literacy) [47]. Plastic is estimated to potentially remain for hundreds to thousands of years once they are deposited in the deep sea where there is no UV light and less turbulence [6].

Despite the beach cleaning and public literacy campaigns conducted by volunteers, NGOs, and local and national governments worldwide, *e.g.* [33,48,49], the global source of plastic wastes is enormous. For example, the amount of global plastic waste produced from 1950 to 2015 is estimated as c.a. 6300 million tons, of which nearly 80% has been left in landfills or in the natural environment without being recycled or incinerated [50]. Minimizing the production of plastic waste and its flow into the coastal areas and the ocean is the only fundamental solution to the problem of deep-sea plastic pollution. Awareness of the needs for regulations on plastic waste is already high in the international community; *e.g.* the UN Environment Clean Seas campaign (www.cleanseas.org), launched at the Economist World Ocean Summit in 2017, aims at drastic reduction of single-use plastic and is attracting the attention of mass media and the public. Despite such momentum, it will take a considerable amount of effort for the world's nations to reach agreement in terms of international response to this challenge.

To protect deep-sea ecosystems from existing threats of plastic pollution and to sustain their service to human society in the future, it is important for ocean scientists to provide the international community with sound scientific evidence for the effective management of plastic pollution. The major challenge in the assessment of plastic debris effects on deep-sea ecosystems is the scarcity of spatially and temporally quantified data, and therefore globally comparable data on the density of plastic debris. Non-destructive type surveys *via* ROVs and other deep-sea vehicles are ideal for monitoring the debris and its influence on deep-sea organisms. As such high-technology surveys are expensive and only a limited number of organizations in the world are capable of conducting them, international initiatives to standardize survey methods [51], prioritize research subjects, and integrate those observation efforts [52] are necessary for effective utilization of the limited research capability. Some recommendations for the ocean science community are discussed in the following sections.

4.3.1. Priority areas of monitoring

As it is impossible to survey the vast areas in the deep sea thoroughly, observation should be focused on the habitat of rare or vulnerable ecosystems, such as chemosynthetic communities and deep-sea corals. Besides, defining the regions of major land sources of plastics and deep-sea sinks, and understanding of transportation mechanism of plastics from the sources to sinks are prioritized. Deep-sea debris is not randomly distributed on the sea floor but tends to accumulate in certain areas owing to anthropogenic and natural factors. Plastic debris is more abundant on the sea floor near highly populated and industrial coastal regions [6,16] and along submarine canyons and in depressions rather than on sea mounts and ridges [13,18]. These areas are the deep-sea “sinks” of plastic and also have relatively high biological production rates owing to sedimentation of rich organic matter.

Oceanic currents [53–55] and other physical mechanisms, such as Ekman transport [56], play a major role in the transport of plastic debris at the global scale. Major “sources” of plastic debris and the trajectory of plastic debris to deep-sea “sinks” can be detected using high resolution ocean circulation models, which are capable of simulating oceanic currents in mesopelagic and deeper layers. Plastic debris load in open surface water are very large in the North Pacific due to the size of its gyre which functions to accumulate debris [57]. Because Southeast and East Asia are undergoing rapid industrialization and population growth, they are considered the largest source of plastic, based on the solid waste production rates and the population and economic status of countries in these areas in 2010. China alone is estimated to produce 3530 kt of plastic waste per year; two other countries generating large amounts of plastic waste (1290 and 730 kt per year) are also in Southeast Asia [58]. Plastic waste that flows to the coast is spread not only in the marginal eastern Asian seas, as observed from the high density of such in the East China Sea [30] and Japan Sea [59,60], but is also potentially transported to offshore surface waters in the western and central North Pacific *via* intensive oceanic currents [61] (see “Sailing Seas of Plastic”: http://app.dumpark.com/seas-of-plastic − 2/). Ocean circulation modelling studies reveal the floating debris concentration in the North Pacific subtropical gyre and particularly along the convergence zone known as the “garbage patches” [62], which is suggested as one of the potential mechanisms of sinking surface plastic debris to deep-sea environments [57].

4.3.2. Global monitoring network and data sharing

International initiatives and/or networks promote deep-sea research from various aspects. The Deep Ocean Observing Strategy (DOOS) (http://www.deepoceanobserving.org) is being developed under the auspices of the Global Ocean Observation System (GOOS), with the aim of promoting and integrating physical, biogeochemical, and biological observation in the deep sea (> 2000 m) of the global ocean. In accordance with the guideline of the Framework for Ocean Observation [52], agreed upon by the global ocean science community at the OceanObs’09 meeting in 2009, DOOS is preparing to identify Essential Ocean Variables (EOVs) to measure deep-sea environments globally (http://www.goosocean.org/index.php?option = com_content&view = article&id = 14&Itemid = 114). The density or occurrence of plastic is one of the possible deep-sea EOVs. It is particularly recommended to develop micro-plastic EOVs because the impact of micro-plastic on deep-sea ecosystems is largely unknown [63–65]. Development of deep-sea plastic EOV and its implementation will be the most challenging process compared to other EOVs. It will be possible only by maximizing utilization of available observation platforms and both hard and soft infrastructures through close collaboration of existing deep-sea observation communities and networks.

Establishment of international protocols for collation and sharing of the best available data regarding marine plastic from coastal to deep seas is recommended along with the observation strategies. For example, biology and ecosystem EOVs of GOOS are being developed based on the close cooperation of the GOOS panel and the Ocean Biogeographic Information Service (OBIS) (http://www.iobis.org) [66]. There are a few integrated information services on marine debris, *e.g.* LITTERBASE [5]. Yet, many online data sources, including JAMSTEC's Deep-sea Debris Database, are based on national or regional surveys and the data are archived following the respective protocols. It would be ideal if the geographic information of deep-sea plastic and of all coastal and marine debris observed and archived by various organizations for different purposes were classified and registered in a standardized manner, which is a more simplified version of the Darwin Core standard applied by OBIS.

5. Conclusions

This study shows that plastic debris, particularly single-use products, has reached the deepest parts of the ocean. Whereas regulation on the production of single-use plastic and the flow of such debris into the coast are the only effective ways to prevent further threats to deep-sea ecosystems, successful management of plastic waste is possible through internationally harmonized practices based on scientifically sound knowledge. Because deep-sea surveys are expensive and require most advanced technology, the function of existing deep-sea observation networks and data sharing protocols should be strengthened. It is recommended that impact assessment surveys be prioritized for the biologically and ecologically important areas with high plastic debris concentrations, and for the detection of the trajectories from land sources to deep-sea sinks *via* high-resolution ocean circulation models.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2018.03.022.

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