Marine Pollution Bulletin 77 (2013) 349–354

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Relationships among the abundances of plastic debris in different size classes on beaches in South Korea

Jongmyoung Lee [a], Sunwook Hong [a], Young Kyung Song [b,c], Sang Hee Hong [b,c], Yong Chang Jang [a], Mi Jang [b,c], Nak Won Heo [b], Gi Myung Han [b], Mi Jeong Lee [a], Daeseok Kang [d], Won Joon Shim [b,c,*]

[a] OSEAN, Our Sea of East Asia Network, 1570-8 Gwangdo-myon, Tongyoung-shi 650-826, South Korea
[b] Oil and POPs Research Group, Korea Institute of Ocean Science & Technology, 391 Jangmok-myon, Geoje-shi 656-834, South Korea
[c] University of Science and Technology, Daejeon 305-320, South Korea
[d] Pukyong National University, 45, Yongso-ro, Nam-Gu, Busan 608-737, South Korea

ARTICLE INFO

Keywords:
Marine debris
Microplastics
Mesoplastics
Macroplastics
Styrofoam

ABSTRACT

Plastic debris on six beaches near the Nakdong River Estuary, South Korea, was sampled in May and September 2012 and classified into three size classes, large microplastics (1–5 mm), mesoplastics (5–25 mm), and macroplastics (>25 mm). The relationships among the abundances of the size classes were then examined. The abundances of each size category in May (before rainy season) and in September (after rainy season) were 8205 and 27,606 particles/m^2 for large microplastics, 238 and 237 particles/m^2 for mesoplastics, and 0.97 and 1.03 particles/m^2 for macroplastics, respectively. Styrofoam was the most abundant item both in microplastic and mesoplastic debris, while intact plastics were most common in macroplastic debris. The abundances of meso- and micro-plastics were the most strongly correlated. There was a higher correlation between the abundances of macro- and meso-plastics than between macro- and micro-plastics.

1. Introduction

Plastics are widely used because of their lightweight nature, durability, potential for diverse applications, and low price (Thompson et al., 2009a). In recent years, annual plastics production has increased drastically, reaching 230 million tonnes in 2009 (PlasticsEurope, 2010). Large amounts of plastic are consigned to landfills, recycled, or are still in use. However, large amounts end up as marine debris as a result of insufficient treatment capacity, accidental inputs, littering, or illegal dumping (Barnes et al., 2009; Hopewell et al., 2009). Numerous studies in recent decades have reported that plastics are the main component of marine debris, regardless of time or location (e.g., Barnes et al., 2010; Ivar do Sul et al., 2009; Matsumura and Nasu, 1997; OSPAR, 2007; Storrier et al., 2007).

Plastic debris causes physical harm to marine life as a consequence of ingestion and entanglement (Good et al., 2009; Hong et al., 2013; Jacobsen et al., 2010; Laist, 1987). Moreover, the debris may be chemically harmful because plastics may contain chemicals added in the manufacturing process or adsorbed from the environment (Browne et al., 2009; Engler, 2012). Plastic debris eventually undergoes fragmentation on beaches or at sea, forming small-sized particles (Barnes et al., 2009; Cooper and Corcoran, 2010). These particles can be widely distributed and with decreasing size are more likely to be ingested by marine life (Andrady, 2011; Ng and Obbard, 2006). Recent studies have investigated the potential for microplastics debris to transport toxic chemicals to organisms including humans (Teuten et al., 2007; Thompson et al., 2009b).

Microplastics are manufactured as small plastic particles to produce resin pellets, scrubbers for cosmetics, or abrasives for blasting (primary microplastics) or they are generated by the fragmentation of larger plastic products (secondary microplastics) (Andrady, 2011; Cole et al., 2011; Gregory, 1996; Mato et al., 2001). Fragmented particles account for the majority of micro-plastics and have various origins (Gregory and Andrady, 2003), which make proper control difficult.

In order to develop management strategies, information about the abundance and spatiotemporal distribution of microplastics is essential. However, relevant data have not been well documented yet because microplastic surveys require much more time, labor, and technical support in comparison with surveys of larger debris (Cole et al., 2011).

If a reasonable correlation exists between microplastics and more easily surveyed larger plastics, this relationship could be

* Corresponding author at: Oil and POPs Research Group, Korea Institute of Ocean Science & Technology, 391 Jangmok-myon, Geoje-shi 656-834, South Korea. Tel.: +82 55 639 8671; fax: +82 55 639 8689.

E-mail address: wjshim@kiost.ac (W.J. Shim).

0025-326X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpolbul.2013.08.013

useful for collecting information on the distribution and abundance of microplastics. A few studies have examined the size-dependent abundance of plastic debris (Claessens et al., 2011; Costa et al., 2010; Martins and Sobral, 2011). To the best of our knowledge, however, relationships among the abundances of beached debris in different size classes have not been reported. This study aimed to determine relationships among the abundances of macro-, meso-, and micro-plastic debris size classes to provide insights for the development of efficient microplastic survey methods.

2. Methods

The study was conducted on a sand bar in the Nakdong River estuary and on five beaches on Geoje Island (Fig. 1). Site Jinwoo (JW) was proximate to the river mouth and five sites were selected with increasing distance from JW.

The Nakdong River, the longest river in South Korea, flows south through highly developed and densely populated Busan metropolitan city. Debris from the Nakdong River watershed occasionally drifts ashore in the northeastern part of Geoje Island during the monsoon season in summer. Initial surveys at the six sites were conducted before rainy season in May 2012 and subsequent surveys at three of the six sites (HN, WH, and MS) took place after rainy season in September 2012 (Fig. 1).

This study classified three size classes of 'large microplastics' (1 to <5 mm) (hereafter microplastics mean large microplastics), 'mesoplastics' (5 to <25 mm), and 'macroplastics' ($\geqslant$25 mm). The United Nations Environment Programme/Intergovernmental Oceanographic Commission (UNEP/IOC) recommends a lower limit of 25 mm for macrodebris in their guidelines (Cheshire et al., 2009). Many researchers have also operationally defined microplastics as particles of up to 5 mm, which are readily ingested by organisms (Kershaw and Leslie, 2012). Particles of which size are smaller than 1 mm cannot be identified and counted without microscopic observation and subsequent spectroscopic confirmation. Thus, the targeted microplastic size range was confined to 1–5 mm in this study.

At each sampling site, we selected two 10 $\times$ 10 m large quadrats (placed in locations that visually appeared to have the maximum and minimum amounts of beached debris) along the strandline (Fig. 2) and collected all macroplastic items (>25 mm) within large quadrats. Within each 10 $\times$ 10 m large quadrat, five small quadrats (0.5 $\times$ 0.5 m) were randomly selected for microplastic and mesoplastic sampling. All natural and artificial debris within a depth of 5 cm in the quadrats was sieved sequentially with 5- and 1-mm Tyler sieves (CISA, Spain) onshore; debris on the sieves was stored in zipper bags and brought to the laboratory. In the case of wet sand samples, sieving was conducted after air drying in the laboratory to avoid contamination of the mesh screen cover.

After removing natural debris, the remnants in each size class were classified into five categories: intact plastics (which have original production form), fragments, Styrofoam (expanded polystyrene), other foamed plastics, and pellets. Styrofoam and other foamed plastics were not counted separately as intact items or fragments because intact samples were rare.

Every count in each size class was recorded. The abundances and relative proportions of the plastic categories were calculated for each size class in a total of 18 large quadrats (six sites $\times$ two large quadrats in May and three sites $\times$ two large quadrats in September). Relationships among the abundances of micro-, meso-, and macro-plastic groups were identified using Spearman's rank correlation (rho). The relationship between the abundances of micro- and meso-plastics was determined using general linear regression analysis.

3. Results

3.1. Abundance and composition of plastic debris

Overall abundances of plastic debris were increased by two or three orders of magnitude with decreasing size class in May and September (Fig. 3). The average abundances of microplastic debris were 8205 particles/m^2 in May and 27,606 particles/m^2 in September (Fig. 3a and Table S1). The highest microplastic abundance (92,217 particles/m^2) among the large quadrats was found in

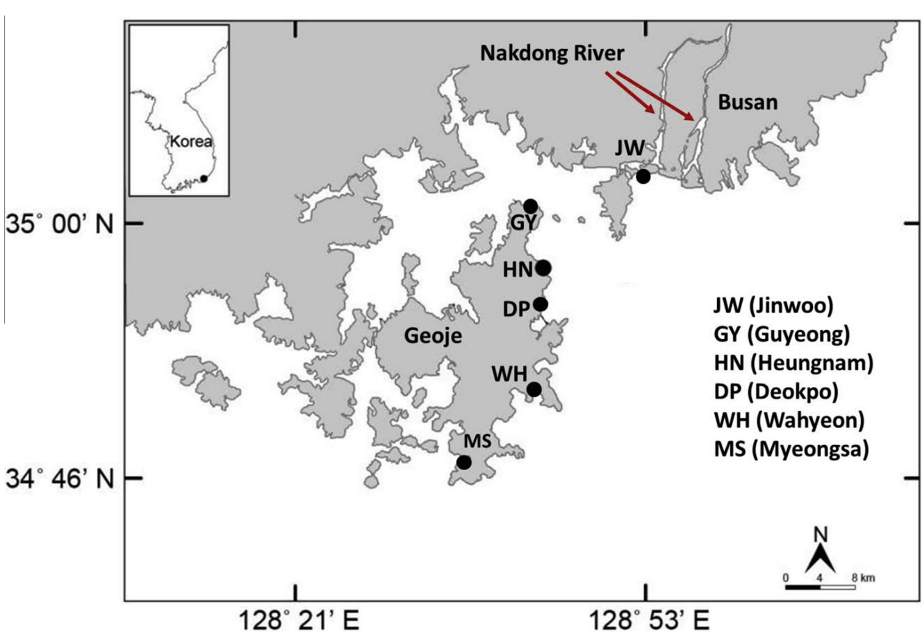

Fig. 1. Sampling locations for beached plastic debris: First sampling campaign was conducted at all sites before rainy season in May 2012, and second sampling was conducted at HN, WH, and MS after rainy season in September 2012.

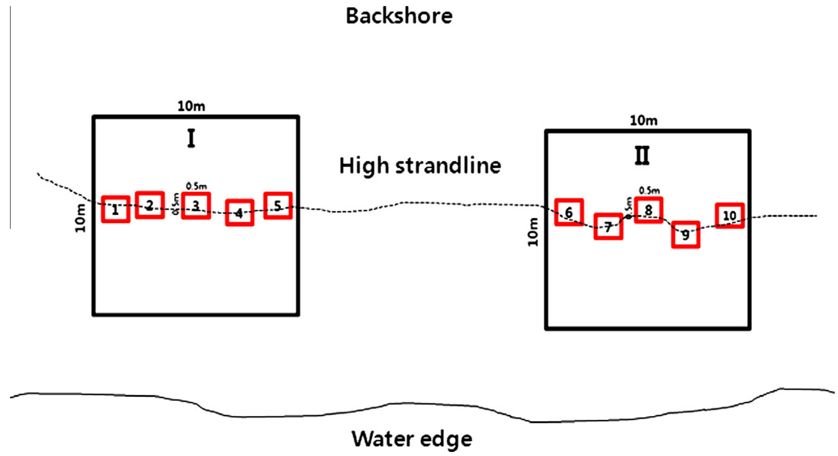

Fig. 2. Scheme of beach plastic debris sampling at each site. Two 10 × 10 m large quadrats were placed along the strandline to quantify macroplastic abundance. Five quadrats (0.5 × 0.5 m) were randomly selected within each large quadrat to determine mesoplastic and microplastic debris abundances.

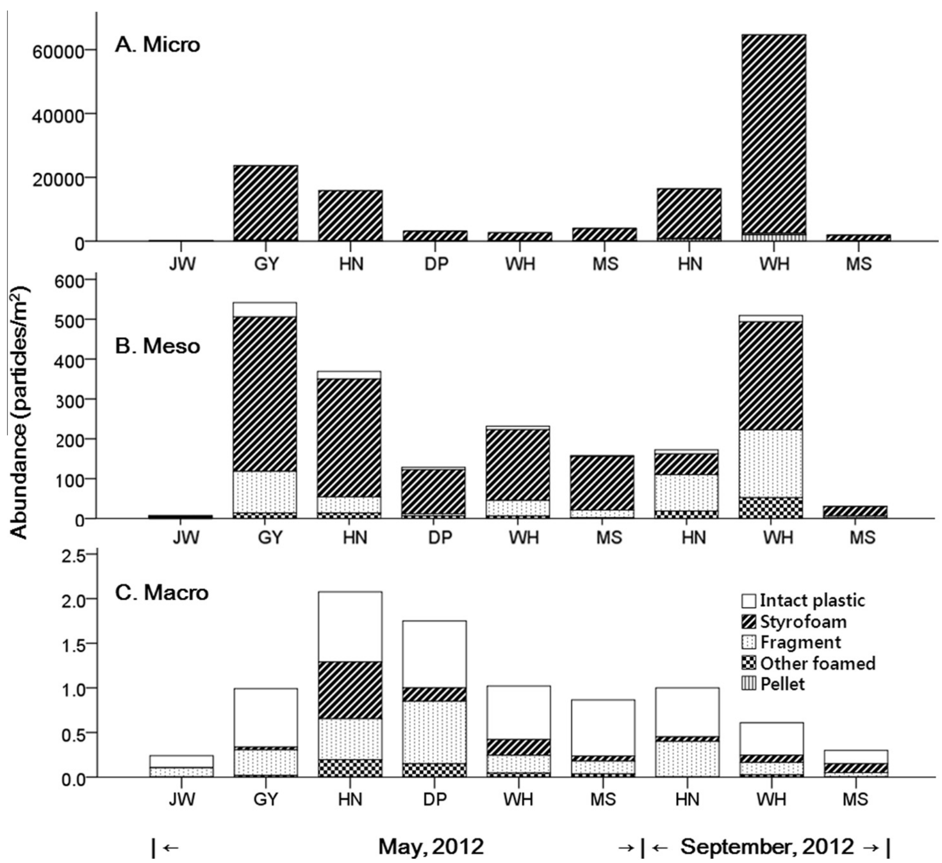

Fig. 3. Abundance and composition of plastic debris on beaches by size category: (a) large microplastics (1–5 mm), (b) mesoplastics (5–25 mm), and (c) macroplastics (>25 mm). Microplastics and mesoplastics are average abundance of ten small quadrats from two large quadrats at each beach and macroplastics are average abundance of two large quadrats at each beach.

Wahyeon (WH) in September and the lowest (1.6 particles/m^2) in Jinwoo (JW) in May. The average abundances of mesoplastic debris were 238 particles/m^2 in May and 237 particles/m^2 in September (Fig. 3b and Table S2). Mesoplastic debris abundance among large quadrats was highest (940 particles/m^2) in Guyeong (GY) in May and lowest (0 particles/m^2) in JW in May. The average abundances of macroplastic debris were 0.97 particles/m^2 in May and 1.03 particles/m^2 in September (Fig. 3c and Table S3). Macroplastic debris showed the highest abundance (2.7 particles/m^2) in Dukpo (DP) in May and the lowest (0.09 particles/m^2) in JW in May.

Microplastic debris was overwhelmingly represented by Styrofoam (99% in May and 96% in September) (Fig. 3a and Table S1). Pellet was drastically increased from 0.1% in May to 3% in September. In mesoplastic debris, Styrofoam was also the most abundant item (68% in May and 49% in September), which was followed by fragment (22% and 37%), other foamed plastics (5% and 10%), and intact plastics (5% and 4%) (Fig. 3b and Table S2). Macroplastics were consisted of intact plastics (55% in May and 47% in September), fragment (23% and 37%), and Styrofoam (17% and 10%) (Fig. 3c and Table S3).

3.2. Correlations among different size classes

Spearman's rank correlation results among the different size classes are shown in Table 1. The total abundance of microplastics was most strongly correlated with the abundance of mesoplastics (0.878, $p < 0.01$). Microplastics and mesoplastics were strongly correlated in all categories (0.806, $p < 0.01$ for Styrofoam, 0.886, $p < 0.01$ for fragments, and 0.911, $p < 0.01$ for other foamed plastics) except for intact plastics (0.353, $p < 0.01$).

The total abundance of macroplastics had a higher correlation (0.804, $p < 0.01$) with mesoplastics than with microplastics (0.593, $p < 0.01$). The correlation between mesoplastics and macroplastics was high for fragments (0.824, $p < 0.01$) and intact plastics (0.748, $p < 0.01$), whereas Styrofoam and other foamed plastics showed no significant correlation within this pair. Microplastics and macroplastics showed no significant correlations, except for fragments (0.637, $p < 0.01$) and other foamed plastics (0.515, $p < 0.05$). Correlations for pellets were not analyzed because they were only included in the microplastics class.

3.3. Regression analysis of abundances of micro- and meso-plastic debris

A significant correlation was found between the total abundances of microplastics and mesoplastics. Microplastics and mesoplastics were significantly correlated for Styrofoam and fragments, and other foamed plastics ($p < 0.01$). When we analyzed the data from May and September separately, the coefficient of determination was much higher in total abundance, Styrofoam and other foamed plastics (Fig 4). The values of r^2 in May were 0.878 ($p < 0.01$) for total abundance, 0.915 ($p < 0.01$) for Styrofoam, 0.885 ($p < 0.01$) for fragments, and 0.590 ($p < 0.01$) for other foamed plastics. The values of r^2 in September were 0.930 ($p < 0.01$) for total abundance, 0.841 ($p < 0.01$) for Styrofoam, 0.859 ($p < 0.01$) for fragments and 0.905 ($p < 0.01$) for other foamed plastics, respectively.

4. Discussion

4.1. Spatial distribution and source of plastic debris

The abundance of macroplastic debris decreased with distance from Heungnam (HN) (Fig. 3c). This pattern appears to be influenced by southward stormwater discharges into the Nakdong River. A simulation model of transport of floating particles load with stormwater discharge in July 2011 revealed that southward movements of river runoff were affected by tides and winds in east–west direction, which caused debris to wash up mainly on the shore of Heungnam (Geoje City, 2013). Heungnam is also exposed to marine debris inputs from nearby fishing grounds and aquaculture facilities. Therefore, all categories of macroplastics debris were present in higher abundance in Heungnam compared to the other sites.

Microplastics and mesoplastics, however, did not show similar trends. This difference may be due to the high abundance of Styrofoam debris at those sizes. Styrofoam accounted for the majority of microplastics and mesoplastics and may have originated from oyster aquaculture facilities near the sampling sites.

More than 90% of oyster products in Korea are harvested along the southeastern coast of the country (Kang et al., 2009). Styrofoam floats are intensively used to sustain buoyancy with oyster growth (Choi, 2008). Styrofoam floats without covers are directly exposed to the environment and are very easily lost or broken down into small spherules. Case studies from Korea, Japan and Chile reported serious pollution of Styrofoam and suggested that oyster and mussel aquacultures were the major sources (Fujieda and Sasaki, 2005; Hinojosa and Thiel, 2009; Heo et al., 2013). Studies outside Korea, Japan, and Chile found comparatively low levels of Styrofoam debris (e.g., Moore et al., 2001).

4.2. Greater abundances in smaller sized debris

The abundance of plastics increased exponentially, by two or three orders of magnitude, with decreasing size class. This was probably caused by the fragmentation of large plastic debris after it washed ashore. Plastic debris on beaches is exposed to UV radiation and the physical effects of wind, currents, waves, and tides lead to chemical or mechanical weathering and eventually result in plastic embrittlement (Corcoran et al., 2009; Cooper and Corcoran, 2010). In this study, Styrofoam was expanded lower density material, which can break down more readily than other plastics, accounting for its dominance among microplastics.

Plastics smaller than 5 mm seemed to be more abundant than larger plastics in previous studies that were conducted at the sea surface (Lattin et al., 2004; Moore et al., 2001) or in the water column (Doyle et al., 2011). Fragments in seawater represent potential inputs to beaches and can result in higher abundances of fragments in beach surveys. Some studies that were undertaken on beaches (Ivar do Sul et al., 2009; Martins and Sobral, 2011; Zurcher, 2009) found relatively high abundances of plastics in the <5 mm size class. However, these results were primarily due to the abundance of pellets (Hidalgo-Ruz et al., 2012).

4.3. Relationships among abundances in different size classes

The correlation analysis results suggest that microplastics were abundant in areas where the mesoplastics abundance was high. A similar relationship was also found between the abundances of mesoplastics and macroplastics. However, it is difficult to state that microplastics are abundant in locations where the macroplastic abundance is high.

Macro-Styrofoam debris was not significantly correlated with meso- and micro-sized particles. The selective cleanup of larger Styrofoam debris on beaches could explain this result. Intact plastic was the only category that did not show a significant correlation

Table 1
Spearman's rank correlation among abundances of beach plastic debris by size category and type.

Pair	Total	Styrofoam	Fragments	Intact plastics	Other foamed plastics
Micro–Meso	0.878**	0.806**	0.886**	0.353	0.911**
Micro–Macro	0.593**	0.167	0.637**	0.282	0.515*
Meso–Macro	0.804**	0.430	0.824**	0.748**	0.433

* $p < 0.05$.
** $p < 0.01$.

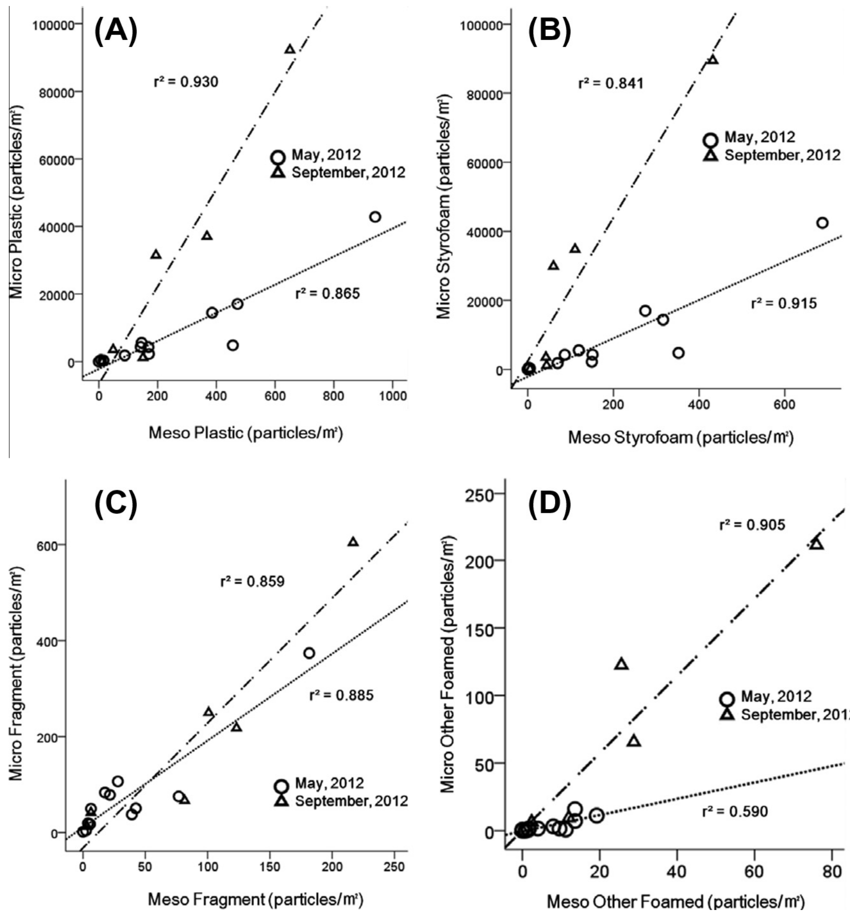

Fig. 4. Linear regressions of (a) total plastics abundance, (b) Styrofoam abundance, (c) fragments abundance and (d) other foamed plastic abundance in between the mesoplastics and the microplastics groups ($p < 0.01$ in all regression analyses).

between meso- and micro-classes possibly because these plastics persist without fragmentation. Macro other foamed plastics showed significant correlation not with meso- but with micro-sized group. The correlation coefficient was not that high (0.515) and the number of collected other foamed plastics was low compared to other categories. It can be considered as an exceptional case.

Regression analysis showed that the slope of the trend line between micro- and meso-Styrofoam and other foamed plastic debris increased more dramatically during the second survey than in the first survey. It is likely that foamed plastic debris was more seriously fragmented by high physical energy during typhoons that occurred between in May and September surveys. It is also possible that Styrofoam spherules from surrounding aquaculture farms and environments were relocated and deposited at the sampling sites during typhoon events. On the other hand, fragments showed no distinct increase in the second survey.

4.4. Applications and limitations of the results and further research

Mesoplastics (5–25 mm) surveys could serve as surrogates for microplastics (1–5 mm) monitoring. Surveys of mesoplastics debris can be easily conducted by volunteers, who have played important roles in many marine debris monitoring programs (Cheshire et al., 2009; OSPAR, 2007; Rees and Pond, 1995; Ribic et al., 2011; Ribic et al., 2012; Sheavly, 2007). Mesoplastics surveys could be used to identify hot spots of microplastic pollution in large geographical areas with limited resources.

Generalized relationships between paired groups may not be directly applicable to other geographic areas because this study was conducted in an area where Styrofoam was a dominant source of plastic debris. Variation in the abundance of plastic debris among adjacent quadrats on the same beach was high, and therefore additional research is needed to determine methods to select representative sampling areas (e.g., Ryan et al., 2009). The classification of macro-, meso-, and micro-size classes is also controversial when dealing with small-sized debris. Many researchers have used different size limits for microplastics: <10 mm (Graham and Thompson, 2009), <5 mm (Barnes et al., 2009), 2–6 mm (Derraik, 2002), <2 mm (Ryan et al., 2009), and <1 mm (Browne et al., 2010; Claessens et al., 2011). Additional research on correlations between abundances in further sub-divided size classes (1–25 mm) would provide good references for size classifications. In addition, small microplastics less than 1 mm in size may show different types, sources, or relationships with larger size classes of plastic debris.

Acknowledgement

This study was supported by grants-in-aid from Korea Institute of Ocean Science and Technology (PE 99153).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2013.08.013.

References

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of the plastic debris in global environments. Phil. Trans. R. Soc. B: Biologic. Sci. 364, 1985–1998.

Barnes, D.K., Walters, A., Gonçalves, L., 2010. Macroplastics at sea around Antarctica. Mar. Environ. Res. 70, 250–252.

Browne, M.A., Galloway, T.S., Thompson, R.C., 2009. Microplastic—an emerging contaminant of potential concern? Integr. Environ. Assess. Manage. 3, 559–561.

Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. Environ. Sci. Technol. 44, 3404–3409.

Cheshire, A., Adler, E., Barbière, J., Cohen, Y., Evans, S., Jarayabhand, S., Jeftic, L., Jung, R., Kinsey, S., Kinsui, E., 2009. UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter. United Nations Environment Programme, Regional Seas Programme, p. 120.

Choi, K.-S., Oyster capture-based aquaculture in the Republic of Korea. FAO Rome, 2008. pp. 271–286.

Claessens, M., Meester, S.D., Landuyt, L.V., Clerck, K.D., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199–2204.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597.

Corcoran, P.L., Biesinger, M.C., Grifi, M., 2009. Plastics and beaches: a degrading relationship. Mar. Pollut. Bull. 58, 80–84.

Cooper, D.A., Corcoran, P.L., 2010. Effects of mechanical and chemical processes on the degradation of plastic beach debris on the Island of Kauai, Hawaii. Mar. Pollut. Bull. 60, 650–654.

Costa, M.F., Ivar do Sul, J.A., Silva-Cavalcanti, J.S., Araújo, M.C.B., Spengler, A., Tourinho, P.S., 2010. On the importance of size of plastic fragments and pellets on the strandline a snapshot of a Brazilian beach. Environ. Monit. Assess. 168, 299–304.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852.

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.

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

Fujieda, S., Sasaki, K., 2005. Stranded debris of foamed plastics on the coast of Eta Island and Kurahashi Island in Hiroshima Bay. Nippon Suisan Gakkaishi 71, 755–761.

Geoje City, 2013. Research on the pathway of Nakdong River-based marine debris and preventive responses, Geoje, South Korea, pp. 168. (in Korean).

Good, T.P., June, J.A., Etnier, M.A., Broadhurst, G., 2009. Ghosts of the Salish Sea: threats to marine birds in Puget Sound and the Northwest Straits from derelict fishing gear. Mar. Ornithol. 37, 67–76.

Graham, E.R., Thompson, J.T., 2009. Deposit- and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. J. Exp. Mar. Biol. Ecol. 368, 22–29.

Gregory, M., 1996. Plastic 'scrubbers' in hand cleansers: a further (and minor) source for marine pollution identified. Mar. Pollut. Bull. 32, 867–871.

Gregory, M.R., Andrady, A.L., 2003. Plastics in the marine environment. In: Andrady, Anthony L. (Ed.), Plastics and the Environment. John Wiley and Sons, ISBN 0-47-09520-6.

Heo, N.W., Hong, S.H., Han, G.M., Hong, S., Lee, J., Song, Y.K., Jang, M., Shim, W.J., 2013. Distribution of small plastic debris in cross-section and high strandline on Heungnam Beach, South Korea. Ocean Sci. J. 48, 225–233.

Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075.

Hinojosa, I.A., Thiel, M., 2009. Foating marine debris in fjords, gulfs and channels of southern Chile. Mar. Pollut. Bull. 58, 341–350.

Hong, S., Lee, J., Jang, Y.C., Kim, Y.J., Kim, H.J., Han, D., Hong, S.H., Kang, D., Shim, W.J., 2013. Impacts of marine debris on wild animals in the coastal area of Korea. Mar. Pollut. Bull. 66, 117–124.

Hopewell, J., Dvorak, R., Kosior, E., 2009. Plastics recycling: challenges and opportunities. Phil. Trans. R. Soc. B: Biol. Sci. 364, 2115–2126.

Ivar do Sul, J.A., Spengler, A., Costa, M.F., 2007. Here, there and everywhere: small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). Mar. Pollut. Bull. 58, 1236–1238.

Jacobsen, J.K., Massey, L., Gulland, F., 2010. Fatal ingestion of floating net debris by two sperm whales (*Physeter macrocephalus*). Mar. Pollut. Bull. 60, 756–767.

Kang, C., Choy, E., Hur, Y., Myoung, J., 2009. Isotopic evidence of particle size-dependent food partitioning in cocultured sea squirt *Halocynthia roretzi* and Pacific oyster *Crassostrea gigas*. Aquatic Biol. 6, 289–302.

Kershaw, P.J., Leslie, H. (eds.), 2012. GESAMP Working Group 40 – Sources, fate and effects of micro-plastics in the marine environment- a global assessment: Report of the Inception Meeting, 13–15th March 2012, UNESCO-IOC, Paris, pp. 45.

Laist, D.W., 1987. Overview of the biological effects of lost and discarded plastic debris in the marine-environment. Mar. Pollut. Bull. 18, 319–326.

Lattin, G.L., Moore, C.J., Zellers, A.F., Moore, S.L., Weisberg, S.B., 2004. A comparison of neustonic plastic and zooplankton at different depths near the southern California shore. Mar. Pollut. Bull. 49, 291–294.

Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., Kaminuma, T., 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ. Sci. Technol. 35, 318–324.

Martins, J., Sobral, P., 2011. Plastic marine debris on the Portuguese coastline: a matter of size? Mar. Pollut. Bull. 62, 2649–2653.

Matsumura, S., Nasu, K., 1997. Distribution of floating debris in the North Pacific Ocean: sighting surveys 1986–1991. Springer Series on Environmental Management.

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.

Ng, K.L., Obbard, J.P., 2006. Prevalence of microplastics in Singapore's coastal marine environment. Mar. Pollut. Bull. 52, 761–767.

OSPAR, 2007. Monitoring of marine litter on beaches in the OSPAR region.

PlasticsEurope, 2010. Plastics – The Facts 2010: An Analysis of European Plastics Production, Demand and Recovery for 2009. Plastics, Belgium, p. 32.

Rees, G., Pond, K., 1995. Marine litter monitoring programmes—a review of methods with special reference to national surveys. Mar. Pollut. Bull. 30, 103–108.

Ribic, C.A., Sheavly, S.B., Rugg, D.J., 2011. Trends in marine debris in the US Caribbean and the Gulf of Mexico 1996–2003. J. Integr. Coastal Zone Manage. 11, 7–19.

Ribic, C.A., Sheavly, S.B., Rugg, D.J., Erdmann, E.S., 2012. Trends in marine debris along the US Pacific Coast and Hawai'i 1998–2007. Mar. Pollut. Bull. 64, 994–1004.

Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Phil. Trans. R. Soc. B: Biologic. Sci. 364, 1999–2012.

Sheavly, S.B., 2007. National Marine Debris Monitoring Program: Final Program Report, Data Analysis and Summary. Prepared for US Environmental Protection Agency by Ocean Conservancy, Grant Number X83053401-02. pp. 76.

Storrier, K.L., McGlashan, D.J., Bonellie, S., Velander, K., 2007. Beach litter deposition at a selection of beaches in the Firth of Forth, Scotland. J. Coastal Res. 23, 813–822.

Thompson, R.C., Swan, S.H., Moore, C.J., vom Saal, F.S., 2009a. Our plastic age. Phil. Trans. R. Soc. B: Biologic. Sci. 364, 2153–2166.

Thompson, R.C., Moore, C.J., vom Saal, F.S., Swan, S.H., 2009b. Plastics, the environment and human health: current consensus and future trends. Phil. Trans. R. Soc. B: Biol. Sci. 364, 2153–2166.

Teuten, E.L., Rowland, S.J., Galloway, T.S., Thompson, R.C., 2007. Potential for plastics to transport hydrophobic contaminants. Environ. Sci. Technol. 41, 7759–7764.

Zurcher, N., 2009. Small plastic debris on beaches in Hong Kong: an initial investigation. Thesis for the degree of Master of Science in Environmental Management, University of Hong Kong.