Benthic Plastic Debris in Marine and Fresh Water Environments

Patricia L. Corcoran, Department of Earth Sciences, University of Western Ontario, London, Ontario, Canada, N6A 5B7; telephone: 1-519-661-2111; e-mail: pcorcor@uwo.ca

ABSTRACT

This review provides a discussion of the published literature concerning benthic plastic debris in ocean, sea, lake, estuary and river bottoms throughout the world. Although numerous investigations of shoreline, surface and near-surface plastic debris provide important information on plastics types, distribution, accumulation, and degradation, studies of submerged plastic debris have been sporadic in the past and have become more prominent only recently. The distribution of benthic debris is controlled mainly by combinations of urban proximity and its association with fishing-related activities, geomorphology, hydrological conditions, and river input. High density plastics, biofouled products, polymers with mineral fillers or adsorbed minerals, and plastic-metal composites all have the potential to sink. Once deposited on the bottoms of water basins and channels, plastics are shielded from UV light, thus slowing the degradation process significantly. Investigations of the interactions between benthic plastic debris and bottom-dwelling organisms will help shed light on the potential dangers of submerged plastic litter.

Key Words: Benthic plastic debris; distribution, degradation, submersion

1. Introduction

Plastic debris accumulates in the natural environment as litter and spillage, and in landfills as waste materials. Aquatic plastic debris may be lost or discarded directly from vessels, but also may originate on land where it is transported to bodies of water through natural and anthropogenic watercourses during precipitation events and release of wastewater.[1-6] Once transported to oceans, seas and lakes, plastic debris may circulate in surface currents and eventually become deposited along continental or island shorelines, or can sink to the bottom of the water basin.

Counts of plastics in the water column are based mainly upon visual identification from watercrafts or are determined following removal from trawling nets or cores. The resultant counts may vary widely depending on whether an index or estimate of abundance is used.[4] In investigations of marine surface and near-surface waters, examples of maximum plastics abundances ranged from approximately 65,000 pieces/km^2 to 3.5 million pieces/km.[2,7-11] It has recently been estimated that 4.8-12.7 million metric tons of plastic debris entered the ocean in 2010.[12] Typical plastic items identified are fragments, pellets, intact or near-intact products, rubber, fibres, and Styrofoam. Plastics accumulation in fresh surface waters has been investigated to a lesser degree, but example results indicate maximum counts of approximately 44,000 pieces/km^2 and 466,000 pieces/km^2.[13-14] Similar to marine plastics, the most common items identified are pellets, fibres, and fragments, as well as film and microbeads.

Plastics accumulation along marine shorelines has been studied extensively, and is outlined in reviews and references therein.[15-18] Recent investigations carried out on multiple continents show that the pollution of shorelines with plastic debris is occurring on a global scale.[19-24] The distribution of marine shoreline plastics appears to be directly related to their proximity to urban centers, as well as weather conditions, and tide and current patterns.[15, 25-27] There are fewer studies focusing on the distribution of plastics along freshwater shorelines, although the topic has undergone more research in recent years.[6,14,28-33] All shorelines, whether marine or freshwater, contain plastic items similar to those identified in surface waters.

Considerably less attention has been paid to the accumulation of submerged plastic debris on the seabed, and on the bottoms of rivers and lakes. This paper provides a synthesis of plastics accumulation in submerged regions of marine and fresh water basins. Sections discussing the possible causative mechanisms of sinking polymers, and the potential for submerged plastics to degrade are also included.

1.1 Submerged plastics in marine water

Table 1 provides examples of investigations of benthic plastic debris. The presence of plastics on the seabed can result from recreational, agricultural and industrial activities on land in addition to discharge from ships at sea.[34] The global distribution of plastic items submerged in marine water is controlled by several factors, which include proximity to urban centers, water currents, geomorphology, river input and fishing activity. In most cases, a combination of these factors determines the depositional location of benthic plastic debris.

The effect of urban proximity was evident in an early study by Lenihan et al. (**35**) of the seabed off McMurdo Station, Antarctica. In addition to metals and hydrocarbons, plastic hoses were identified on the seabed near a dumpsite and ice-dock. Therefore, a relationship was clear between the proximity of litter and vessels, and the abundance of marine debris. Similarly, Miller (**36**) reported that abundant marine debris characterize Boston Harbor where sailboats come in to dock. A multibeam sonar, mounted on a remotely operated vehicle enabled researchers to identify plastic cups and tires, in addition to non-plastic debris. Galgani et al. (**37**) recognized a direct relationship between proximity to large cities and plastics abundance in the western Mediterranean Sea. Considerable amounts of plastic debris were found near Marseille, Napoli, Genova and Barcelona compared with locations distal to major urban centers. Hess et al. (**38**) conducted bottom trawl surveys of the seabed around Kodiak Island, Alaska in 1994-1996. The researchers determined that plastic debris items, including fishing line, bait jars and crab pots were most abundant in inlet regions near the town of Kodiak rather than offshore. Other factors controlling the concentration of debris in inlets were fishing activities and water circulation, wherein currents are weaker in the inlet regions than offshore.

Hydrological conditions have been considered important controls on the distribution of plastic debris in benthic regions.[39-41] The movement of water by surface currents, tides, river plumes, or seasonal flooding can redistribute plastic debris following its input from rivers. Galgani et al. (**39**) conducted bottom trawl surveys along the continental shelf of the Bay of Biscay and Seine Bay. The researchers determined that plastics accounted for 80% of all marine debris identified in Seine Bay, and as much as 95% of the debris items identified in the Bay of Biscay. Great amounts of debris in the Gironde Estuary in February could have been a result of the higher water levels caused by spring run-off and/or the northward movement of water masses bringing debris from the south into the estuary. Unexpected low abundances of plastic debris in Seine Bay were attributed to dilution due to strong water circulation. The movement of water currents have also played an important role in plastics distribution in the eastern Mediterranean Sea. A study by Ioakeimidis et al. (**41**) of four gulfs and one bay indicated that 67% of the total benthic debris items were plastics. Although proximity to urban centers, river input and fishing activity played a role in the accumulation of marine debris, water circulation was critical in its distribution. The authors suggested that the abundance of plastics in the western basin of the Saronikos Gulf is due to the surface water circulation that transports debris to the west.

Several investigations have demonstrated that submerged plastic debris distribution is greatly influenced by the geomorphology of the seabed.[42-48] Regions of low topography, such as submarine canyons are often the sites of plastics deposition, although the distribution of plastics may also be controlled by ridges or ledges that are optimal for trapping debris. In their investigation of marine debris along the continental slopes of the Baltic, North and Celtic Seas, and Bay of Biscay, Galgani et al. (**42**) determined that approximately 70% of debris items were plastics. In the Gulf of Lion, northwestern Mediterranean Sea, the greatest concentrations of debris were located in canyons with significantly lower concentrations along continental slopes. The canyons represent accumulation zones for sediment and waste that are transported offshore by high sedimentation rates. Deposition at low seafloor elevations has also been shown in deep rocky habitats of the Mediterranean Sea, where abundant fishing gear was impacting benthic organisms, such as corals and sponges.[47] Along coasts with relatively high gradients, the distribution of marine debris can follow a pattern of increasing concentration away from the shoreline. Keller et al. (**44**) showed that the mean density of marine debris increased with depth along the west coast of the United States, from 30 pieces/km^2 in depths ranging from 55-183 m to 128 pieces/km^2 in depths of 550-1280 m. The effect of seafloor depth was also highlighted in a study of marine debris in Monterey

Bay, California, in which the greatest abundances were found at depths >2000 m.[45] Perhaps most surprisingly, plastic debris has recently been identified in the Kuril-Kamchatka Trench and the adjacent abyssal plain.[48] Collection of box core samples enabled the investigators to determine that abundant microplastics (<1 mm), mainly fibres, were found at depths between approximately 4870-5770 m, and at concentrations as high as 2000 pieces/m^2.

Surveys conducted by SCUBA divers in Gray's Reef National Marine Sanctuary recorded the incidence of marine debris off the east coast of the United States. The results, reported by Bauer et al. (**43**) highlight how the spatial distribution of marine debris is related to bottom features. Ledges were characterized by the greatest concentration of marine debris compared with other bottom types. The predominant type of debris on ledges was derelict fishing gear, in part a result of its tendency to become snagged and trapped in rocky crevices and overhangs.

Bauer et al. (**43**) suggested that in addition to the trapping properties of ledges, the abundance of fishing-related items could be explained by this bottom type being targeted by fishermen. This leads to the fourth factor controlling benthic plastics distribution, which is fishing-related activity. Fishing gear contributes greatly to the pollution of the seafloor, and the majority of these items are composed of polymers. Moore and Allen (**49**) described the amount and types of marine debris found in the Southern California Bight in 1994. Fishing-related items and other plastics were the most common types of debris, and were found on the outer, middle and inner shelf zones. A separate study based on bottom trawls of the East China Sea and South Sea of Korea conducted from 1996 to 2005 indicated that fishing-related items, such as pots, nets and lines accounted for 37-72% of all marine debris in both locations.[22] Ioakeimidis et al. (**41**) showed a clear correlation between the abundance of fishing-related items and recorded number of professional fishing boats in their sampling regions of the eastern Mediterranean and Black Seas. Strafella et al. (**50**) in their study of marine debris in the northern and central Adriatic Sea, interpreted the types and distribution to be a function of river inflow, urban proximity and hydrological conditions. The urban proximity results in extremely high levels of fishing activity. Approximately 50% of the debris items identified were derived from fishing and aquacultural activities, as the Adriatic Sea is a major fishing ground in the Mediterranean.

The proximity of river input is also significant because rivers are considered major pathways for land-based plastic debris into seas and oceans. In a study of the Gulfs of Patras and Echinadhes, the concentration of debris on the seafloor was 240 and 89 pieces/km^2, respectively.[51] The authors attributed the greater abundance of debris in the Gulf of Patras to the higher number of rivers and streams flowing through villages compared with those draining into the Gulf of Echinadhes. Galgani et al. (**42**) demonstrated that the concentration of marine debris in the Bay of Biscay was greatest near the Loire, Gironde and Adour estuaries compared with increased distance from the coast. In addition, the authors determined that high concentrations of debris accumulate in submarine extensions of major rivers.

1.2 Submerged plastics in fresh/brackish water

Investigations of benthic plastic debris in freshwater ecosystems are rare compared with their marine counterparts, but the results suggest that plastics distribution is controlled by the same parameters, mainly proximity to urban centers and river input, geomorphology of the basin, and the behaviour of water circulation.[6, 51-55] Lewis et al. (**51**) conducted a multibeam sonar study of western Lake Ontario, Canada in 1993 and discovered anomalous lineaments between Toronto and Welland Canal, and Toronto and the Niagara River mouth. The authors interpreted this acoustic response to be a product of shipping debris that has accumulated along historical, major shipping lines. Grab samples from the lakebed mud indicated the presence of anthropogenic particles including plastics, coal, oil, fly ash and chemicals. A more recent investigation of box core samples taken from Lake Ontario indicates that microplastics (<5 mm) are becoming incorporated into the lakebed sediment to depths of 8 cm.[6] Given the sediment accumulation rates, the plastics are inferred to have begun accumulating no more than 38 years ago. The results also show that microplastics are more abundant in the center of the lake than at the Niagara River mouth, in contrast to the results from marine benthic surveys in European seas. The authors attribute the low abundance of microplastics at the Niagara River mouth as a function of a 10^{o} slope off the Niagara bar and the presence of a river plume that is diverted to the east as it empties into the lake.

Submerged plastic items have also been discovered in river systems. Morritt et al. (**53**) collected bottom debris from eel fyke nets anchored to the river bed of the upper Thames estuary. Their results indicated that 20-25% of all debris items were composed of plastic, with the main plastic components being wrappers, containers, sanitary products, utensils and bags. The abundance of sanitary products was interpreted as a direct result of the proximity of sewage treatment plants to the sampling locations. A recent investigation of sediments in the St. Lawrence River, Canada, has uncovered abundant microbeads

(<2.16 mm) in 10 sampling sites over 320 km.[54] A mean concentration of approximately 13,800 microbeads/m^2 was determined by the investigators. Size variations were evident, with small microbeads found in regions receiving industrial and municipal effluent, in contrast to larger microbeads in non-effluent areas.

Although river bottom sediment was not sampled in a study of French rivers, Sanchez et al. (**55**) proved the presence of benthic microplastics by examining the digestive tracts of bottom-feeding gudgeons. Of the fish dissected, 12% contained microplastics, including fibres and pellets.

Examples of benthic plastic debris in both marine and freshwater/brackish systems indicate that plastics pollution is not only prevalent along shorelines and in near-surface waters. The publications listed in Table 1 provide information on plastics submerged in rivers and estuaries, on lakebeds, along continental slopes and shelves, in submarine canyons, and regions as deep as oceanic trenches. This leads to the following questions: How are plastics submerged, and what is their potential for degradation?

1.3 How are Plastics Submerged?

Plastics with densities greater than water (>1 g/cm^3; e.g. nylon, polyvinyl chloride, acrylic) are expected to sink in marine and fresh water environments. In addition, low density plastics that are combined with heavier materials (e.g. metals) to form whole products will easily become submerged below the surface. However, some studies have shown that low density polymers, including polyethylene (PE) and polypropylene (PP) are deposited on the substrates of aquatic basins.[6,56-57] Although these polymers have a tendency to float, several reasons can be considered for their submersion. Biofouling by bacteria, algae and other organisms may cause some plastics to sink.[7,15,56] Moret-Ferguson et al. (**57**) cited biofouling as the cause for increased density in plastics sampled from the Atlantic Ocean compared with their virgin plastic counterparts. A later study of plastics density by Lobelle and Cunliffe (**58**) involved submersion of PE plastic bags off the coast of Plymouth, U.K. over a 3 week interval. The researchers found an increase in density of the bags caused by attachment of biofilms. Recent work by Cole et al. (**59**) suggests that microplastics could sink if they form part of faecal pellets. Through laboratory experiments, the authors showed that zooplankton ingest polystyrene beads in the absence of other food sources, and these beads are eventually egested in faecal pellets.

The density of plastics could also increase where minerals adhere to hydrophobic organic material that covers a plastic particle.[18,34] In addition, clay minerals have negative charges on the surfaces of their silicate layers, which enables their direct adsorption onto polymers. Minerals may also play a role in density increase during production. Many plastics are injected with functional fillers that enhance a variety of properties, including the improvement of structural and impact strength, scratch resistance, and brightness.[60-61] Example fillers are talc, mica, calcium carbonate, silica and kaolin. Corcoran et al. (**6**) suggested that silica, mica, and calcium carbonate were fillers in PP and PE benthic microplastics of Lake Ontario based on Fourier transform infrared spectroscopy (FTIR).

1.4 What is the potential for degradation of submerged debris?

The degradation of polymers in natural environments has been estimated at hundreds to thousands of years[15], and is controlled mainly by weathering reactions caused by exposure to photo-oxidation, biodegradation and mechanical erosion.[2,62-64] In addition, if a polymer is exposed to high temperature and is consequently damaged during processing, it has a greater potential to weather when exposed to photo-oxidative processes in nature.[62] However, the chances of rapid degradation are extremely low, and this is especially the case for plastics buried beneath the water column. In natural settings, beaches are optimal sites for plastics degradation where a combination of physical and oxidative weathering takes place.[15,64] In contrast, benthic plastic debris is either resting directly on the sea or lake bottom, or is buried in sediment. In addition, shallow benthic plastic particles may be fouled by organisms, which could protect them from the UV-B radiation needed for photo-oxidative breakdown.[65] Therefore, the longevity of plastic is greater in aquatic environments than on land or in surface waters. Although benthic plastics will eventually degrade via biological action, the process will be significantly slower than photo-oxidative degradation.[17] The cooler temperatures associated with aquatic environments also slows the thermal degradation process, as has been shown in studies comparing the breakdown of plastics in air and seawater.[66-67] The majority of the investigations cited in Table 1 were conducted by visual estimate or bottom trawls, which suggests that most of the plastic debris was not buried. However, the studies reporting microplastics in bottom sediments indicate that burial could be an additional inhibitor of plastics degradation on seafloors and lakebeds. The overlying sediment would, in addition to the water column itself, shield the plastics from UV light and warm temperatures, possibly leading to preservation of polymers in the future sedimentary record.[6,68]

2. Conclusions

The accumulation of benthic plastic debris is occurring on a global scale. Although many of the investigations concerning the distribution and degradation of plastics in the environment focus on shoreline and surface water surveys, information from bottom surveys of oceans, seas, rivers, lakes and estuaries is becoming more readily available. These surveys are conducted using a variety of techniques, including bottom trawls, SCUBA diving, remotely operated vehicle surveying, submersible surveying, box core sampling, grab sampling, and multibeam sonar. The majority of the marine debris recovered from bottom trawls is represented by plastic products and their broken down equivalents. The main plastic items include fishing nets and lines, industrial pellets, fragments, and microbeads. The distribution of these items is largely controlled by proximity to urban centres and associated fishing-related activity, geomorphology and hydrological conditions, as well as river input. Although many plastic items are composed of low density polymers, biofouling and mineral adsorption may be responsible for their submersion. Many plastics may also contain mineral fillers that have increased the density of the polymer, causing it to sink once in the water column. The potential for degradation of benthic plastics is quite low because the water column and any overlying sediment act as a shield from UV light and subsequent photo-oxidation. Benthic plastic debris poses a threat to bottom dwelling organisms by reducing their nutrient supply either through limiting natural prey or affecting the natural gas exchange between the substrate and overlying water column.

References

1 A.T. Williams, and S.L. Simmons, S.L., *Water Air Soil Pollut.*, 1997, **98,** 119–139.

2 M.R. Gregory and A.L. Andrady, *Plastics and the Environment*, Wiley, New Jersey, 2003, p. 379.

3 R.C. Thompson, Y. Olsen, R.P. Mitchell, A. Davis, S.J. Rowland, A.W.G. John, D. McGonigle, and A.E. Russell, *Science,* 2004, **304,** 838.

4 P.G. Ryan, C.J. Morre, J.A. van Franeker, and C.L. Moloney, *Phil. Trans. R. Soc. B,* 2009, **364,** 1999-2012.

5 S. Rech, V. Macaya-Caquilpan, J.F. Pantoja, M.M. Rivadeneira, D. Jofre Madariaga, and M. Thiel, *Mar. Pollut. Bull.,* 2014, **82,** 66-75.

6 P.L. Corcoran, T. Norris, T. Ceccanese, M. Walzak, P.A. Helm, and C.H. Marvin, *Environ. Pollut.,* 2015, **204,** 17-25.

7 C.J. Moore, S.L. Moore, M.K. Leecaster, and S.B. Weisberg, *Mar. Pollut. Bull.,* 2001, **42,** 1297-1300.

8 M. Thiel, I. Hinojosa, N. Vásquez, and E. Macava, *Mar. Pollut. Bull.,* 2003, **46,** 224-231.

9 R. Yamashita, and A. Tanimura, *Mar. Pollut. Bull.,* 2007, **54,** 485-488.

10 K.L. Law, S. Moret-Ferguson, N.A. Maximenko, G. Proskurowski, E.E Peacock, et al., *Science*, 2010, **329,** 1185–1188

11 M.C. Goldstein, A.J. Titmus, M. Ford, *PLoS ONE*, 2013, **8,** e80020.

12 J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, R. Narayan, and K.L. Law, *Science,* 2015, **347,** 768-771.

13 M. Eriksen, S. Mason, S. Wilson, C. Box, A. Zellers, W. Edwards, H. Farley, and S. Amato, *Mar. Pollut. Bull.,* 2013, **77,** 177–182.

14 C.M. Free, O.P. Jensen, S.A. Mason, M. Eriksen, N.J. Williamson, and B. Boldgiv, *Mar. Pollut. Bull.,* 2014, **85,** 156-163.

15 D.K.A. Barnes, F. Galgani, R.C. Thompson, and M. Barlaz, *Philos. Trans. R. Soc. B,* 2009, **364,** 1985-1998.

16 R.C. Thompson, C.J. Moore, F.S. vom Saal, and S.H. Swan, *Philos. Trans. R. Soc. B*, 2009, **364,** 2153-2166.

17 A.L. Andrady, *Mar. Pollut. Bull.,* 2011, **62,** 1596-1605.

18 M.A. Browne, P. Crump, S.J. Niven, E. Teuten, A. Tonkin, T. Galloway, and R. Thompson, *Envir. Sci. Technol.*, 2011, **45,** 9175-9179.

19 C. Eriksson, H. Burton, S. Fitch, M. Schulz, and J. Van den Hoff, *Mar. Pollut. Bull.,* 2013, **66,** 199-208.

20 V. Hidalgo-Ruz and M. Thiel, *Mar. Envir. Res.,* 2013, **87-88,** 12-18.

21 H.B. Jayashiri, C.S. Purushothaman, and A. Vennila, *Mar. Pollut. Bull.,* 2013, **77,** 107-112.

22 J. Lee, S. Hong, Y.K. Song, S.H. Hong, Y.C. Jang, M. Jang, N.W. Heo, G.M. Han, M.J. Lee, D. Kang, W.J. Shim, *Mar. Pollut. Bull.,* 2013, **77,** 349-354.

23 B.J.L. Laglbauer, R.M. Franco-Santos, M. Andreu-Cazenave, L. Brunelli, M. Papadatou, A. Palatinus, M. Grego, and T. Deprez, *Mar. Pollut. Bull.,* 2014, **89,** 356-366.

24 S.D.A. Smith, C.L. Gillies, and H. Shortland-Jones, *Mar. Pollut. Bull.,* 2014, **88,** 188-193.

25 J.G.B. Derraik, *Mar. Pollut. Bull.,* 2002, **44,** 842-852.

26 K.L. Storrier, D.J. McGlashen, S. Bonellie, and K. Velander, *J. Coast. Res.,* 2007, **23,** 813-822.

27 A.S. Leite, L.L. Santos, Y. Costa, and V. Hatje, *Mar. Pollut. Bull.,* 2014, **81,** 242-247.

28 M. Zbyszewski and P.L. Corcoran, *Wat. Air Soil Poll,* 2011, **220,** 365-372.

29 M. Zbyszewski, P.L. Corcoran, and A. Hockin, *J. Great Lakes Res.,* 2014, **40,** 288-299.

30 F. Faure, M. Corbaz, H. Baecher, and L.F. de Alencastro, *Archeol. Sci.,* 2012, **65,** 157–164.

31 H.K. Imhof, N.P. Ivleva, J. Schmid, R. Niessner, and C. Laforsch, *Curr. Biol.,* 2013, **23,** R867–R868.

32 A.G.J. Driedger, H.H. Dürr, K. Mitchell, and P. Van Cappellen, *J. Great Lakes Res.,* 2015, **41,** 9-19.

33 T.J. Hoellein, M. Westhoven, O. Lyandres, and J. Cross, *J. Great Lakes Res.,* 2015, **41,** 78-86.

34 E.D. Goldberg, *Environ. Technol.,* 1997, **18,** 195-202.

35 H.S. Lenihan, J.S. Oliver, J.M. Oakden, and M.D. Stephenson, *Mar. Pollut. Bull.,* 1990, **21,** 422-430.

36 R.Z. Miller, *Sea Technol.,* 2012, **53,** 58-60.

37 F. Galgani, S. Jaunet, A. Campillo, X. Guenegen, and E. His, *Mar. Pollut. Bull.,* 1995a, **30,** 713-717.

38 N.A. Hess, C.A. Ribic, and I. Vining, *Mar. Pollut. Bull.,*1999, **38,** 885-890.

39 F. Galgani, T. Burgeot, G. Bocquene, F. Vincent, J.P. Leaute, J. Labastie, A. Forest, and R. Guichet, *Mar. Pollut. Bull.,* 1995b, **30,** 58–62.

40 F. Galgani, A. Souplet, Y. Cadiou, Mar. Ecol. Prog. Ser., 1996, **142,** 225-234.

41 C. Ioakeimidis, C. Zeri, H. Kaberi, M. Galatchi, K. Antoniadis, N. Streftaris, F. Galgani, E. Papathanassiou, and G.A. Papatheodorou, *Mar. Pollut. Bull.,* 2014, **89,** 296-304.

42 F. Galgani, F., J.P. Leauté, P. Moguedet, A. Souplet, Y. Verin, A. Carpentier, H. Goraguer, D. Latrouite, B. Andral, Y. Cadiou, J.C. Mahe, J.C. Poulard, and P. Nerisson, *Mar. Pollut. Bull.,* 2000, **40,** 516-527.

43 L.J. Bauer, M.S. Kendall, and G. McFall, *NOAA Technical Memorandum NOS NCCOS 113.*, 40 pp.

44 A.A. Keller, E.L. Fruh, M.M. Johnson, V. Simon, and C. McGourty, *Mar. Pollut. Bull.,* 2010, **60,** 692-700.

45 K. Schlining, S. von Thun, L. Kuhnz, B. Schinling, L. Lundsten, N. Jacobsen Stout, L. Chaney, and J. Connor, *Deep-Sea Res. Part I: Ocean Res. Pap.* 2013, **79,** 96-105.

46 A.R. Eryaşar, H. Özbilgin, A.C. Gücü, and S. Sakinan, *Mar. Pollut. Bull.,* 2014, **81,** 80-84.

47 M. Angiolillo, B. Di Lorenzo, A. Farcomeni, M. Bo, G. Bavestrello, G. Santangelo, A. Cau, V. Mastascusa, A. Cau, F. Sacco, and S. Canese, *Mar. Pollut. Bull.,* 2015, **92,** 149-159.

48 V. Fischer, N.O. Elsner, N. Brenke, E. Schwabe, and A. Brandt, *Deep-Sea Res. Part II,* 2015, **111,** 399-405.

49 S.L. Moore and M.J. Allen, *Mar. Pollut. Bull.,* 2000, **40,** 83-88.

50 P. Strafella, G. Fabi, A. Spagnolo, F. Grati, P. Polidori, E. Punzo, T. Fortibuoni, B. Marceta, S. Raicevich, I. Cvitkovic, M. Despalatovic, and G. Scarcella, *Mar. Pollut. Bull.,* 2015, **91,** 120-127.

51 A. Stefatos, M. Charalampakis, G. Papatheodorou, and G. Ferentinos, *Mar. Pollut. Bull.,* 1999, **36,** 389-393.

52 C.F.M. Lewis, L.A. Mayer, P.K. Mukhopadhyay, M.A. Kruge, J.P. Coakley, *Int. J. Coal Geol.,* 2000, **43,** 307-324.

53 D. Morritt, P.V. Stefanoudis, D. Pearce, O.A. Crimmen, and P.F. Clark, *Mar. Pollut. Bull.,* 2014, **78,** 196-200.

54 R.A. Castañeda, S. Avlijas, M.A. Simard, and A. Ricciardi, *Can. J. Fish. Aquat. Sci.,* 2014, **71,** 1767-1771.

55 W. Sanchez, C. Bender, and J.-M. Porcher, *Environ. Res.,* 2014, **128,** 98-100.

56 S. Ye, and A.L. Andrady, *Mar. Pollut. Bull.,*1991, **22,** 608-613.

57 S. Moret-Ferguson, K.L. Law, G. Proskurowski, E.K. Murphy, E.E. Peacock, and C.M. Reddy, *Mar. Pollut. Bull.,* 2010, **60,** 1873-1878.

58 D. Lobelle and M. Cunliffe, *Mar. Pollut. Bull.,* 2011, **62,** 197-200.

59 M. Cole, P. Lindeque, E. Fileman, C. Halsband, R. Goodhead, J. Moger, and T.S. Galloway, *Environ. Sci. Technol.,* 2013, **47,** 6646-6655.

60 D. Sekutowski, D., *Plastics Additives and Modifiers Handbook*, 1992, Springer, 491-556.

61 K.K. Mathur and D.B. Vanderheiden, D.B., *Polymer Modifiers and Additives,* 2001, Marcel Dekker, Inc., New York, 125-171.

62 J.R. White and A. Turnbull, *J. Mat. Sci.,* 1994, **29,** 584-613.

63 J.F. Rabek, *Photodegradation of Polymers,* Springer-Verlag, Berlin, 1996.

64 P.L. Corcoran, M.C. Biesinger, M. Grifi, M., *Mar. Pollut. Bull.,* 2009, **58,** 80-84.

65 M.R. Gregory, *Ocean Coast. Manag.,* 1999, **42,** 603-615.

66 A.L. Andrady, *J. Appl. Polym. Sci.,* 1990, **39,** 363-370.

67 A.L. Andrady, J.E. Pegram, and Y. Tropsha, *J. Environ. Polym. Degrad.,* 1993, **1,** 171-179.

68 P.L. Corcoran, C.J. Moore, and K. Jazvac, *GSA Today,* 2014, **24,** 4-8.

69 F. Bingel, D. Avsar, and M. Unsal, *Meeresforschung,* 1987, **31,** 227-233.

70 J.A. June, J. A., *Proc. Second Int. Conf. Marine Debris*, 1990, **NMFS-SWF-SC-154,** 279 –301.

71 B.S. Galil, A. Golik, and M. Turkay, *Mar. Pollut. Bull.,* 1995, **30,** 22-24.

72 E. Acha, W. Hermes, A. Mianzan, C. Iribarne, A. Domingo, C. Gagliardini, A. Carlos Lasta, and D. Pedro Daleo, *Mar. Pollut. Bull.,* 2003, **46,** 197-202.

73 S. Katsanevakis and A. Katsarou, *Wat. Air Soil Pollut.,* 2004, **159,** 325-337.

74 A. Koutsodendris, G. Papatheodorou, O. Kougiourouki, and M. Georgiadis, *Estuar. Coastal Shelf Sci.,* 2008, **77,** 501-512.

75 L. Van Cauwenberghe, A. Vanreusel, J. Mees, and C.R. Janssen, *Environ. Pollut.* 2013, **182,** 495–499.

76 O. Güven, H. Gülyavuz, M.C. Deval, *Turk. J. Fish. Aquat. Sci.,* 2013, **13,** 43-49.

77 E. Ramirez-Llodra, B. De Mol, M. Coll, F. Sardà, *Progr. Ocean.* 2013, **118,** 273-287.

Locality	Method	Source
Marine		
Mediterranean Sea	Bottom trawl surveys	Bingel et al. (1987)[69]
Bering Sea, Norton Sound, East Pacific Ocean	Bottom trawl surveys	June (1990)[70]
Winter Quarters Bay, Antarctica	SCUBA diving	Lenihan et al. (1990)[35]
Mediterranean Sea	Bottom trawl surveys	Galgani et al. (1995a)[37]
Bay of Biscay, Seine Bay	Bottom trawl surveys	Galgani et al. (1995b)[39]
Bay of Marseille, Gulf of Lion, western Mediterranean Sea	Bottom trawl surveys	Galgani et al. (1996)[40]
Mediterranean Sea	Bottom trawl surveys	Galil et al. (1995)[71]
Gulf of Alaska	Bottom trawl surveys	Hess et al. (1999)[38]
Patras Gul, Echinadhes Gulf	Bottom trawl surveys	Stefatos et al. (1999)[51]
Baltic Sea, North Sea, Celtic Sea, Mediterranean Sea, Adriatic Sea, Bay of Biscay	Bottom trawl surveys Submersible surveys	Galgani et al. (2000)[42]
Southern California Bight	Bottom trawl surveys	Moore and Allen (2000)[49]
Rio de la Plata Estuary	Bottom trawl surveys	Acha et al. (2003)[72]
Mediterranean Sea	SCUBA diving	Katsanevakis and Katsarou (1994)[73]
East China Sea, South Sea of Korea	Bottom trawl surveys	Lee et al. (2006)[22]
South Atlantic Bight	SCUBA diving	Bauer et al. (2008)[43]
Mediterranean Sea	Bottom trawl surveys	Koutsodendris et al. (2008)[74]
Pacific Ocean off western U.S.A.	Bottom trawl surveys	Keller et al. (2010)[44]
Boston Harbor	Multibeam sonar on remotely operated vehicle	Miller (2011)[36]
Atlantic Ocean, Mediterranean Sea	Multicoring, Remotely operated vehicle surveys	Van Cauwenberghe et al. (2013)[75]
Antalya Bay, Mediterranean Sea	Bottom trawl surveys	Güven et al. (2013)[76]
Mediterranean Sea	Bottom trawl surveys	Ramirez-Llodra et al. (2013)[77]
Monterey Bay	Remotely operated vehicle surveys	Schlining et al. (2013)[45]
Mediterranean Sea, Black Sea	Bottom trawl surveys; Remotely operated vehicle surveys	Ioakeimidis et al. (2014)[41]
Mediterranean Sea	Demersal trawl surveys	Eryasar et al. (2014)[46]
Thames estuary	Eel fyke nets anchored to river bed	Morritt et al. (2014)[53]
Tyrrhenian Sea	Remotely operated vehicle surveys	Angiollilo et al. (2015)[47]
Kuril-Kamchatka Trench	Box core sampling	Fischer et al. (2015)[48]
Adriatic Sea	Modified beam trawl	Strafella et al. (2015)[49]
Fresh/Brackish Water		
Lake Ontario	Multibeam sonar; grab sampling	Lewis et al. (2000)[52]
Rivers in France	Examination of digestive tracts of gudgeons	Sanchez et al. (2014)[55]
St. Lawrence River	Grab sampling	Castañeda et al. (2014)[54]
Lake Ontario	Box core sampling	Corcoran et al. (2015)[6]