

## The Occurrence, Effects and Fate of Small Plastic Debris in the Oceans

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### Purpose

This white paper reviews the literature and synthesizes the various topics that will be discussed at the workshop to be held September 9-10, 2008. Topics include (1) the occurrence of microplastics in the environment; (2) the documented effects of microplastics on marine fauna; (3) the potential interactions between persistent organic pollutants (POPs) and microplastics; and (4) the global fate of persistent organic pollutants (POPs). The workshop is a joint venture between the University of Washington Tacoma and the National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program. The NOAA Marine Debris Program (MDP) leads efforts within the United States to address marine debris, especially as it affects living marine resources. This document is the initial draft of the synthesis paper resulting from the workshop.

### Introduction

**Definition:** *Marine Debris.* Any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment or the Great Lakes.

**Definition:** *Microplastic (or 'microdebris' or 'small plastics').* Marine debris composed primarily of plastic materials smaller than 10 cm in the longest dimension.

Carpenter *et al.* (1972) first described small bits of plastic floating in the surface waters of the Northwest Atlantic more than 35 years ago. These microplastics are also routinely found in seabirds and, less frequently, in marine turtles and mammals. Despite increasing interest in 'macro' marine debris, especially plastics concentrated within convergence zones and gyres, there is no systematic monitoring or evaluation of marine microplastics. In the past year, the increased attention to small plastic debris in the marine environment has highlighted the limited information and research on the amount, location, and environmental impacts of marine microplastics. The purpose of this review is to summarize what is known about the occurrence and distribution of microplastics in the oceans, the effects of these plastics on marine organisms, and the role these plastics may play in the global cycling and marine exposure of persistent organic pollutants. Specific goals are:

1. To summarize our current understanding of the spatial and temporal distribution of microplastics in the world's oceans.
2. To review what is known about the effects of microplastics on marine organisms
3. To evaluate the predictive capabilities to model microplastic fate and transport in the ocean
4. To explore linkages between marine microplastics and the cycling and exposure of persistent organic pollutants.
5. To identify gaps in understanding and to describe potential research and monitoring initiatives.

### I. Occurrence of small plastic debris in the marine environment

#### *Purpose*

Small plastic debris has been found in surface seawater and along coastlines, with an increasing number of reported observations in many of the world's oceans. While there has been some speculation about

potential impact of marine microplastics, the details of this issue have not been systematically studied and are not well-documented in peer-reviewed literature. Small particles of plastic may be ingested by filter-feeders while in the water column and by benthic organisms after settling. Microplastics also accumulate in marine surface layers, where they may be ingested by birds and other consumers who rely on these food-rich environments. This leads to a concern that small plastics, and their associated chemical contaminants, may become incorporated into the marine food webs. The consequences of this are largely unknown.

### Sources

Sources of small plastic debris to the oceans are difficult to determine, but fall into three categories: (1) larger pieces of plastic debris undergo a slow weathering process in the ocean, and may break apart into increasingly smaller bits; (2) inadvertent or accidental release of small, unweathered industrial plastic bits called nurdles during production, shipping, and storage; and (3) discharge of wastewater that contains microplastics purposefully added to consumer products. Nurdles have been documented in the oceans since the 1970s (Carpenter *et al.* 1972, Colton *et al.* 1974), and may be a source of leachable components into seawater. Smaller polyethylene, polypropylene or polystyrene particles on the order of 0.5 mm are increasingly being used by the cosmetics industry as exfoliants in soaps and scrubs as well as for microabrasion cleaning of mechanical parts (Gregory 1996). Microplastics in consumer products are designed to be used once and then enter domestic wastewater, and it is unclear whether wastewater treatment plants are able to collect these particles before they enter rivers and oceans (Gregory 1996). The absolute and relative importance of these three sources (breakdown of larger plastic items, industrial plastic bits, and plastic additives to cosmetics) of microplastics are unknown, but likely vary spatially throughout the world's oceans and temporally as manufacturing, marine transportation, and consumer products change.

### Occurrence

Small plastics have been found across the world in the open ocean, on beaches, and in sediments. However, most surveys of marine debris in the open ocean focus on large plastics and on derelict fishing gear. Recently there has been an increased interest in plastic bags as debris, and surveys of marine debris are more and more often including plastic bags as a debris category. While plastic bags (and pieces of plastic bags) are a type of marine debris, they are not considered microplastics in this paper as dimensions of bags are generally not given.

The scarcity of microplastics data is due to the difficulty of quantifying microplastics in the world's oceans (Table 1). Large sampling efforts and tedious sorting and enumeration methods are required. Carpenter *et al.* (1972) made perhaps the first such effort by conducting plankton tows in the waters of southern New England. Clear and opaque spheres, measuring 0.5 mm in diameter, were observed with a maximum concentration of 14 spheres per cubic meter and a mean concentration of one sphere per cubic meter. Based on the description in Carpenter *et al.* (1972), these spheres were most likely industrial plastic pellets (nurdles). Importantly, these spheres were found in white perch, winter flounder, silversides, and one chaetognath sampled from those same waters.

Colton *et al.* (1974) performed a major sampling effort in the Northwestern Atlantic Ocean, from Cape Cod to the Caribbean, during a summer 1972 Marine Resources Monitoring Assessment and Prediction (MARMAP) cruise. During this cruise, they conducted plankton tows that retained opaque and clear polystyrene spheres, opaque polyethylene cylinders, Styrofoam, sheets of flexible plastic, and fragments. There were geographical differences in plastic abundance along transects, with fewer particles present around the Caribbean than near Cape Cod, which the authors attributed to greater plastic use and production in the United States.

Day and Shaw (1987) provided an in-depth survey of the North Pacific Ocean for small debris, and found the highest density in the subtropical North Pacific (96,100 objects km<sup>-2</sup>) when compared with the subarctic North Pacific (mean density 3370 objects km<sup>-2</sup>) and Bering Sea (mean density 80 objects km<sup>-2</sup>) during towed neuston samples collected in 1985. More recently, Moore *et al.* (2001) sampled in the

subtropical North Pacific during August 1999 and found a mean density of 334,271 plastic pieces  $\text{km}^{-2}$  with a mean mass of 5114 g plastic  $\text{km}^{-2}$ . Moore *et al.* (2001) encountered thin plastic films, polypropylene and monofilament line, and unidentified plastic fragments most often. This is an increase of approximately 350% in plastic density for that area of the Pacific in a little over one decade (Day and Shaw 1987, Moore *et al.* 2001).

Thompson *et al.* (2004) investigated historic continuous plankton recorder samples routinely collected since the 1960s from Aberdeen, Scotland to the Shetlands, and from Skule Skerry, Scotland to Iceland. Thompson *et al.* (2004) found a significant increase in small plastics along these transects from the 1960s to 1990s (Figure 1).

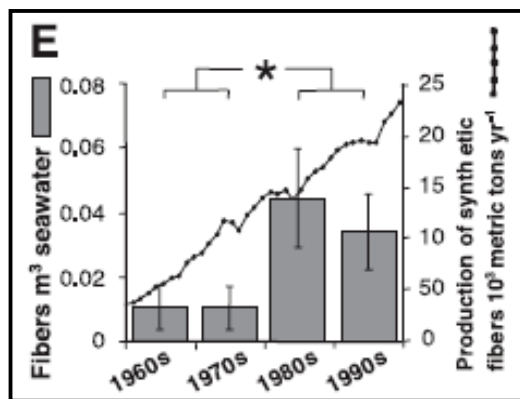


Figure 1. "Microscopic plastic in CPR samples revealed a significant increase in abundance when samples from the 1960s and 1970s were compared to those from the 1980s and 1990s (\*,  $F_{3,3}=14.42$ ,  $P<0.05$ ). Approximate global production of synthetic fibers is overlain for comparison. Microplastics were also less abundant along oceanic route CPR 1 than along CPR 2 ( $F_{1,24}=5.18$ ,  $P<0.05$ )." Reproduced from Thompson *et al.* 2004.

One of the first beach surveys that examined accumulation and distribution of industrial pellets was published by Gregory (1978) for New Zealand beaches. Most pellets were virgin polyolefins, and were clustered near cities but they were also found in remote areas (Gregory 1978). Beach surveys have become more prevalent in the last forty years, with efforts to quantify beach debris spanning the globe. However, most beach surveys are not structured to methodically sample sediments for microplastics, instead focusing on larger debris items. Quantitative information on microplastics is generally not collected or published. There are several possible explanations for this. Often the smaller debris particles are not a priority for clean ups, the surveyors must be apprised of the potential for microplastics to occur in sand and sediments, and collecting sediment samples to analyze for plastics can be labor- and time-intensive.

Abu-Hilal and Al-Najjar (2004) found more than 50% of the litter they surveyed from 1994-1995 on the shores of Jordan was small plastic pieces or bags, mostly from local sources. Recently, Ng and Obbard (2006) detailed the presence and abundance of microplastics (defined as  $>1.6 \mu\text{m}$ ) in Singapore. They found microplastics in four of seven beaches surveyed in the top centimeter of sediment and in the sea surface microlayer, likely due to poor waste disposal practices and ship discharges. A similar study of microplastics in sediment from the Alang-Sosiya shipyard in India identified polyurethane, nylon, polystyrene, polyester and glass wool fragments with Fourier transform infrared (FT-IR) spectroscopy (Reddy *et al.* 2006). These polymers are all used in ship construction, and thus it is not surprising to find these types of fragments in one of the largest ship-breaking zones in the world. In a field investigation to complement data from historic open ocean samples, Thompson *et al.* (2004) showed significantly higher amounts of synthetic polymers in subtidal sediment than on sandy beaches around Plymouth, UK (Figure 2).

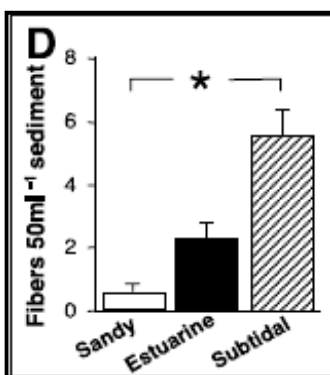


Figure 2. "Microplastics were more abundant in subtidal habitats than on sandy beaches (\*,  $F_{2,3} = 13.26$ ,  $P < 0.05$ ), but abundance was consistent among sites within habitat types." Reproduced from Thompson *et al.* 2004.

### Monitoring of plastics in seabirds

Ingestion of plastic by seabirds has been monitored over the past forty years, providing evidence of not only the occurrence of plastics over large foraging areas but also the ability of small plastics to effect the biological environment (Kenyon and Kridler 1969, Baltz and Morejohn 1976, Fry *et al.* 1987, Pettit *et al.* 1981, Ryan 1988, Auman *et al.* 1997, van Franeker *et al.* 2004, 2005). Documentation of microplastics in some of the most remote regions of the marine environment stem from surveys of seabird regurgitations or stomach contents. Baltz and Morejohn (1976) confirm that six species of seabird ingest polyethylene cylinders off central California: short-tailed shearwater (*Puffinus tenuirostris*), sooty shearwater (*Puffinus griseus*), pink-footed shearwater (*Puffinus creatopus*), northern fulmar (*Fulmarus glacialis*), black-legged kittiwake (*Rissa tridactyla*) and Heermann's gull (*Larus heermanni*). Plankton tows in Monterey Bay did not collect these pellets, which perhaps points to a land source of the polyethylene cylinders (Baltz and Morejohn 1976).

Quite a bit of research has investigated ingestion of plastic debris by the Laysan albatross, *Phoebastria immutabilis*. Kenyon and Kridler (1969) provided one of the very first published reports of plastic ingestion in Laysan albatross. Seventy-four of one hundred dead fledglings had swallowed plastic, mostly as caps and miscellaneous fragments, and it was assumed these were picked up from the local beaches of the Hawaiian Islands National Wildlife Refuge. In 1981, Pettit *et al.* suggested adult albatross may offload plastic via regurgitations to chicks; however, chicks are not able to regurgitate the plastic until just prior to fledging. Reports agree that the most likely venue for plastic ingestion in adult albatross is offshore feeding, namely inadvertent consumption of floating plastic while surface-skimming for fish egg casings (Pettit *et al.* 1981, Fry *et al.* 1987, Kinan and Cousins 2000). Forty-five of fifty albatross chicks sampled in the Hawaiian Islands during the mid-1980s had ingested plastic. Twelve of twenty wedge-tailed shearwaters had ingested plastics, most of which were industrial pellets (Fry *et al.* 1987). Though obstruction of the digestive tract was not common, Fry *et al.* (1987) believe chicks are at greater risk because they can pick up plastics from parental regurgitations and from their own inexperienced foraging trips.

This greater threat to chicks is augmented by an increasing trend for plastic ingestion in the Laysan albatross, with only 6 of 251 albatross chicks sampled on Midway Atoll devoid of plastics in their gut according to a survey from the mid-1990s (Auman *et al.* 1997). High incidence of plastic ingestion is also documented by Kinan and Cousins (2000), who noted all of the 43 black-footed and Laysan albatross examined on Kure Atoll had ingested plastics. Plastic pellets were observed in Laysan albatross samples; coupled with the high incidence of cigarette lighters and glowsticks on this beach but lack thereof in stomach content samples (Kinan and Cousins 2000), these data point to offshore sources of plastics that albatross carry as a burden until regurgitation or death.

Auman *et al.* (2004) cataloged the first incidence of plastic ingestion by seabirds at sub-Antarctic Heard Island. Two Antarctic prions, *Pachyptila desolata*, contained plastics in their digestive tracts. Plastic was not thought to be the cause of mortality. Out of 396 sub-Antarctic skua (*Catharacta antarctica*)

regurgitated pellets, 2 contained small plastics that were on the order of less than one centimeter. However, this area is far from any anthropogenic inputs and the plastic debris must have been transported over long distances.

Plastics were sampled in 15 of 24 species of seabird from 1988-1990 in the sub-Arctic North Pacific, another location far from anthropogenic inputs of plastic debris (Robards *et al.* 1995). Surface feeders and planktivorous divers ingested more plastic debris than birds that use other foraging methods, and approximately 76% of ingested plastic was composed of industrial pellets (Robards *et al.* 1995). Data were compared with a similar study in the same area conducted from 1969-1977, and the comparison (increasing number of species that ingested plastics, increasing frequency of occurrence, and increasing mean number of plastics per individual) demonstrates an increasing presence of plastics in seabirds from the sub-Arctic North Pacific (Robards *et al.* 1995).

This historic use of seabirds to document occurrence of plastic debris in marine ecosystems has been lately augmented with a new strategy of using seabirds as indicators of plastic pollution in the North Sea and North Pacific Ocean (Nevins *et al.* 2005; van Franeker *et al.* 2004, 2005). Van Franeker *et al.* (2004, 2005) tracked plastic pollution in the North Sea via northern fulmar (*Fulmarus glacialis*) stomach contents from 1982 to 2003 as part of a Save the North Sea initiative. This study has effectively shown a decreasing occurrence of industrial plastics and increasing occurrence of user plastics in northern fulmars across the North Sea during the twenty year study period; overall abundance of plastics has not changed. Northern fulmars show a gradient of pollution, with the most plastics present in the southeast and fewest in the northwest North Sea; this points to a smaller fulmar range than was expected, and also points to the importance of local sources of debris in determining fulmar plastic levels (van Franeker *et al.* 2004, 2005).

Nevins *et al.* (2005) investigated the use of pelagic seabirds as indicators of plastic pollution in the North Pacific Ocean, but warn that seabirds' utility as indicators will depend on species ecology and life history characteristics, such as foraging method, lifespan, habitat use, body size and ability to regurgitate. These authors conclude that when used correctly, seabirds give valuable information about the extent of small plastic debris distribution across the North Pacific because they routinely traverse large spatial scales (Nevins *et al.* 2005).

#### *Modeling the Sources, Transport and Spatial Distribution of Marine Microplastics*

The above studies highlight both local and global sources of microplastic pollution. The findings demonstrate spatial gradients, with generally higher microplastic concentrations closer to populated areas. However, marine microplastic debris also occurs in extremely remote areas far away from possible point-sources. These plastics likely travel long distances via surface ocean currents to arrive on islands with no human settlement, implying that microplastics are quite persistent in marine surface waters. Convey *et al.* (2002) noted that synthetic plastic and polystyrene debris accounted for greater than 70% of the debris littering the shores of Scotia Arc, Antarctica from 1990 to 2002. This area encompasses several beaches in the Southern Ocean, including South Georgia, the South Sandwich archipelago and Adelaide Island, all of which are far from any anthropogenic inputs.

Deterministic models could predict the spatial and temporal distribution of microplastics in the oceans if we adequately understood the (1) the magnitude and locations of their sources, (2) their persistence and behavior in seawater, and (3) the general surface water circulation patterns in the world's oceans. In fact, observations of marine debris have been used to calibrate and verify ocean surface circulation models. To date, there is no systematic inventory of microplastic releases into the marine environment, which greatly limits the ability to model global distributions. Microplastic debris washes from the land to the sea directly, and is released into the marine environment as ship-generated discharge (Pruter 1987). It is nearly impossible to predict debris inputs to the oceans from ships. According to regulations in Annex V of MARPOL 1973/78 from the International Maritime Organization, discharge of any plastics is strictly prohibited under all circumstances. These regulations are difficult to enforce and it is certain that some microplastics enter the marine environment in this manner. Thus sources of microplastics are difficult to

ascertain, and the growing trend is to rely on models to predict where debris will accumulate in lieu of surveying marine plastic debris.

Ocean current models are generally employed to explain distribution of debris to remote areas. For example, Kubota (1994) studied a series of climatological data to evaluate the relative contribution of north of Hawaii. In addition, they examined the movement of floating buoys in the North Pacific to test the apparent convergence of debris in a zone near the Northwestern Hawaiian Islands. Another study using debris to study ocean currents employed an Ocean Surface Current Simulator (OSCURS) model (Ingraham and Ebbesmeyer 2001). The authors placed floaters in the North Pacific and tracked movement from 1965 to 1977, and developed numerical models from these data. Models developed from these data predict approximately 86% of debris released into the North Pacific Ocean would accumulate in the mid-latitudes within six years of release (Ingraham and Ebbesmeyer 2001). Recently, a Debris Estimated Likelihood Index (DELI) was developed using aerial flyover surveys in the North Pacific that documented debris accumulations just north of the North Pacific Transition Zone Chlorophyll Front (TZCF) (Pichel *et al.* 2007). DELI maps were created based on significant correlations among presence of debris, sea surface temperature, chlorophyll *a* content, and chlorophyll *a* gradient in the assumption that these maps will be useful for tracking conditions in which marine debris is likely to aggregate (Pichel *et al.* 2007).

Weathering of plastic in seawater will affect its properties (density, size) and, therefore, its persistence and transport distance. In general, marine plastic debris degrades very slowly (Pruter 1987). Weathering of plastics creates smaller pieces of microplastic, but the essential polymer remains intact. Weathering rates, including photodegradation, are lower in seawater than on land (Andrady *et al.* 1998). Degradation rates depend on the amount of processing and the addition of pigments, extenders, photo-stabilizers and thermal-stabilizers; the purity of the resin is directly related to its decomposition time (Andrady *et al.* 1998). The effects of partially-degraded plastic polymers on marine ecosystems are largely unknown. If microplastic particles are more dense than seawater (or become incorporated in dense aggregates), they will settle through the water column and be sequestered in marine sediments. Plastic incorporation into sediments could be detrimental if these plastic particles enter the benthic food web.

## **II. Impact of small plastic debris on the natural environment**

### *Purpose*

Microplastics may impact the marine environment in several ways: (1) direct impacts on marine organisms by ingestion of microplastic particles, such as irritation of the gastrointestinal tract or blockage of feeding structures (2) indirect impacts through disruption of feeding behavior and nutrition, and (3) altered exposure to chemical contaminants associated with microplastics. Several studies have examined the direct interactions between small plastics and marine organisms, typically species that are threatened or endangered. Most of this research has focused on ingestion of small plastics by pelagic seabirds and the effects of mistaking plastic for prey items. This section highlights pertinent studies, mainly from the wealth of literature on seabird–small plastic interactions, which have investigated the direct effects of small plastic ingestion on biota. Entanglement is mentioned here for completeness only, as no research has yet focused on the potential for small plastics to entangle marine organisms.

### *Invertebrates*

One paper that focuses on the interactions between microorganisms and microplastics compares plastic and zooplankton in the Pacific Ocean, close to the California coast in an area of high productivity and expansive human development (Moore *et al.* 2002). This study showed an increase in abundance of plastic debris after a runoff event compared to plastic levels during a dry spell; plastics were collected along with plankton samples. Moore *et al.* (2002) collected a higher plastic density but lower mass than was found in a high pressure convergence zone in the North Pacific subtropical gyre, though many factors could have affected this comparison (Moore *et al.* 2001).

It is important to note the rarity of studies focusing on the impact of plastic debris on invertebrate organisms. Two studies are available on this topic. One shows that microplastics in dosed aquaria sediment were ingested by amphipods, lugworms and barnacles despite their differences in feeding method (detritivore, deposit feeder and filter feeder, respectively; Thompson *et al.* 2004). The second shows that microplastics were taken up by the mussel *Mytilus edulis* in aquaria dosed with microplastics; these plastics persisted in the circulatory system for more than 48 d and greater numbers of smaller plastics were found embedded in circulatory tissue (Browne *et al.* 2008). Thus interactions between microplastics and small invertebrate sediment fauna have been demonstrated, and this type of interaction is likely happening in sediments contaminated with microplastics. Thompson *et al.* (2005) suggest more research focusing on toxicity of microplastic ingestion and bioaccumulation in food chains, in order to better understand the effects of interactions on the level of the organism before extrapolating to ecosystem-level effects of microplastics.

#### *Vertebrates - Seabirds*

A wealth of information on plastic ingestion in seabirds exists in scientific literature. Most is useful to document occurrence of plastics that have been incorporated from the marine environment into marine food webs (see "Occurrences" section above). Few studies have determined the effects of ingestion on elements of seabird health, such as survival and reproductive potential.

Some studies have integrated temporal trends in seabird plastic ingestion as an assessment of continued impact to populations. Ryan (1988) published results on intraspecific variation in plastic ingestion among seabirds in the Southern Ocean, focusing on long-term variation, which showed an increase in plastic ingestion over time; geographic variation, which presented more incidences of plastic ingestion in the northern part of the Southern Ocean than in the southern; sex-related variation, which showed no differences between male and female plastic ingestion; and age-related variation, which is likely due to gradual accumulation in time for Procellariid birds that are unable to regurgitate indigestible items as a bolus. Age-related variation in which chicks have larger plastic loads than parents is explained by the hypothesis of an intergenerational transfer in species that can regurgitate to chicks. Ryan (1988) concludes that plastic ingestion is a phenomenon that has the most dramatic effect on young of the species.

Spear *et al.* (1995) completed a comprehensive review of plastic ingestion in 36 species of seabirds of the tropical Pacific Ocean from 1984 to 1991. Two main findings emerged from this study: (1) birds that weigh more (given life history characteristics) were more likely to have plastic in their gut; (2) plastic-containing individuals had a negative correlation between number of plastic particles and body weight (Spear *et al.* 1995).

At Midway Atoll, Auman *et al.* (1997) found an increasing number of Laysan albatross chicks were ingesting plastic. This study compared anthropogenic mortality chicks (e.g., chicks that died as a result of car-induced injuries) and natural mortality chicks (e.g., found dead without probable cause of death). Natural mortality chicks had more plastic in their proventriculus and gizzard than did chicks killed by cars and also had lower mass and fat indices, which serve as indicators of health (Auman *et al.* 1997).

Van Franeker *et al.* (2004, 2005) noted an increasing trend of plastic ingestion in the North Sea, using northern fulmars (*Fulmarus glacialis*) as an ecological indicator of plastic pollution in the Netherlands. One major difference between this study and many of the studies mentioned above is that the North Sea is a heavily polluted area near dense European populations. Another difference is that this effort is international in scope to better understand and integrate temporal and spatial trends in northern fulmar debris ingestion (Van Franeker *et al.* 2005). Results from a study spanning 1982 to 2003 show a trend of shifting ingested plastic particles in *F. glacialis*, with increasing consumer (also termed "user") plastics and a smaller contribution (but not number) of industrial pellets to debris composition in northern fulmar digestive tracts (Van Franeker *et al.* 2005).

Another study that addresses the topic of temporal changes in ingestion and does not find an increase in frequency of ingestion is Vlietstra and Parga (2002). There has been a change in the type of plastic

particles found in short-tailed shearwaters (*Puffinus tenuirostris*) in the Southeast Bering Sea, but not in the frequency of occurrence or amount per individual. Type of plastic has shifted from industrial plastic pellets to consumer plastics when comparing birds from the 1970s to 2001.

It is interesting to note that Moser and Lee (1992) found industrial pellets in 92% of northern fulmars (*F. glacialis*) and 91% of greater shearwaters (*Puffinus gravis*) located off the Atlantic coast of North Carolina, USA, during a fourteen-year study spanning 1975 to 1989. Very recently, Mallory *et al.* (2006) observed plastic debris in Northern fulmars from Davis Strait, Nunavut, Canada. Out of a total sample size of 42 fulmars, no industrial pellets were observed; consumer plastics were found in 15 samples, most of which were less than one centimeter along the longest dimension (Mallory *et al.* 2006). These temporal trends in fewer industrial pellets suggest that management controls may have been put in place to reduce the accidental loss of pellets to the environment. Although this is a promising sign, Pierce *et al.* (2004) argue that plastic ingestion is very likely underestimated as a direct cause of mortality, as dead seabirds sink or are scavenged. Even if a necropsy is performed, it can be difficult to prove the cause of death (Pierce *et al.* 2004) or directly connect plastic ingestion with mortality.

#### Vertebrates – Sea turtles

Quite a few studies have documented plastic ingestion in sea turtles, though as with seabirds it is very difficult to bridge the gap between presence of foreign debris and cause of mortality. Carr (1987) wrote that juvenile sea turtles are often drawn to convergence zones, as these zones tend to collect prey organisms. Unfortunately, convergence zones also collect anthropogenic debris. Small plastic pieces could be confused with the tiny floats present on Sargassum, and Carr (1987) observes that early life stages are at higher risk than adults. After surveying loggerhead sea turtles (*Caretta caretta*) off the east coast of Florida, Carr (1987) observed “ubiquitous plastic beads that are delivered to the sea by the millions in industrial waste water” that floated in the same habitat as juvenile loggerhead sea turtles.

One of the most comprehensive reviews of plastic ingestion in sea turtles is the paper George Balazs (1985) presented at the Workshop on the Fate and Impact of Marine Debris, 27-29 November 1984 in Honolulu, Hawaii. Balazs compiled 79 reports of debris ingestion and suggested that obstruction of the digestive pathway and chemical release by plastics were the two major threats of marine debris to these threatened and endangered reptiles. Plastic particles were seen in green (*Chelonia mydas*), loggerhead (*C. caretta*) and hawksbill (*Eretmochelys imbricata*) turtles and not in leatherback (*Dermochelys coriacea*) or olive ridley (*Lepidochelys olivacea*) sea turtles. Plastic and Styrofoam particles comprised 18.9% of ingested debris from the compiled records of ingestion.

Balazs (1985) also infers some possible impacts of eating plastic, including blocked intestines, loss of nutrition, reduced nutrient absorption in the gut, possible absorption of polychlorinated biphenyls (PCBs) from plastics, engulfment of microscopic particles in the intestines, and effects on buoyancy if too much low-density plastic is ingested. The following explanations for the palatability of plastics are explored: small plastic debris could be encrusted with other wildlife; prey could have ingested the plastic, thus causing bioaccumulation through the food chain; or possibly habitat could lack nutritious food sources (Balazs 1985).

More recently, Tomas *et al.* (2002) documented plastic debris ingested by juvenile loggerhead sea turtles illegally caught for consumption in the western Mediterranean. Plastics accounted for the highest percentage of anthropogenic debris recovered from the digestive tracts of 41 of 54 turtles surveyed. Mascarenhas *et al.* (2004) documented plastic ingestion in two sea turtles in Brazil, one female *C. mydas* that defecated 10 small pieces of hard plastic and plastic bags, and one adult male *L. olivacea* with 9 small pieces of hard plastic. Tomas *et al.* (2002) are in agreement with Bjorndal *et al.* (1994) that sea turtles are resistant to mortality from ingesting small foreign debris, though with the increasing number of turtles containing plastics, small plastics can be a major concern if they occlude the digestive tract. Barreiros and Barcelos (2001) observed several pieces of soft plastic and a hard plastic cap in one leatherback sea turtle (*D. coriacea*) intestine. This particular turtle was by-caught in a long-line fishery near the Azores; the plastic did not cause the turtle apparent harm. Bugoni *et al.* (2001) identified marine debris and human impacts to green sea turtles in Brazil. Plastics were the most frequently encountered

form of debris in the digestive tract, though hard plastics were present in only four turtles and plastic bags and ropes were the most prevalent forms of plastic debris, at 50% and 39.5%, respectively (Bugoni *et al.* 2001). There are very few, if any, published records of small plastics as the direct cause of mortality in sea turtles.

#### *Vertebrates – Marine mammals*

Marine mammals are also at risk for ingestion of small marine plastic debris due to possible occlusion of the digestive tract and subsequent starvation. However, there are very few reports of small plastics in marine mammals. This is likely because most marine debris research centering on marine mammals focuses on the more visual problem of entanglement in floating and submerged debris.

However, two recent papers highlight the small plastics problem. Baird and Hooker (2000) published what they state is the third record of plastic ingestion for harbor porpoises, *Phocoena phocoena*. One juvenile harbor porpoise was found dead on a beach in Nova Scotia, with no net markings or obvious cause of death. A small piece of black plastic, 5x7 cm<sup>2</sup>, occluded the esophageal connection to the stomach in this individual; incidentally, unusual prey items were also found in the digestive tract, thus perhaps the porpoise ingested plastic due to inexperienced foraging (Baird and Hooker 2000).

Eriksson and Burton (2003) examined fur seal (*Arctocephalus* spp.) scat on Macquarie Island. They recovered 164 plastic pieces from 145 scats with plastic present. No industrial plastic pellets were found. The authors assume transfer of plastics from fish prey to fur seals must have been the source of plastics in fur seal diet (Eriksson and Burton 2003).

#### *Discussion*

In a seminal review article of the biological effects of plastic debris on marine ecosystems, Laist (1987) describes the two main issues as mechanical, those being entanglement and ingestion of plastics. As entanglement generally does not refer to microplastics, ingestion is the only effect that fits in this overview paper. Hence it makes sense that none of the above studies have noted entanglement in small plastics; as stated previously, this could be possible but on such small scales that it is not probable to encounter microplastic entanglement in the open ocean. Laist (1987) cautions persistent plastic debris should be considered a major form of ocean pollution, as it is long-lasting, buoyant and increasingly ubiquitous in the marine environment. This sentiment was echoed many years later by Derraik (2002).

A breadth of information exists on microplastics in seabirds. While marine mammals and sea turtles may be impacted by entanglement as well as ingestion, seabirds are most likely affected by plastic ingestion, especially chicks fed via regurgitation (Laist 1987). Seabirds can also be more accessible for study than sea turtles and marine mammals. Thus, serious research gaps exist on the effects of microplastic debris on the majority of marine organisms. In some cases, as with Laysan albatross, it is easier to see the cause-and-effect relationship of plastic ingestion, occlusion of digestive tract, and eventual death. With most other marine organisms, such direct links may be difficult to make in enough cases to be scientifically convincing. Finally, the subtle effects of microplastics, such as the possibility of unloading bound toxic chemicals to the organism, have yet to be thoroughly investigated. The next section of this paper elaborates on the chemistry of microplastics and the potential to adsorb and desorb contaminants, namely persistent organic pollutants, to the marine environment.

### **III. Impacts of small plastic debris exposure to persistent organic pollutants**

#### *Purpose*

This section highlights the current and expanding literature on plastic pollution in marine environments, and the indirect effect this may be having on dispersal of lipophilic chemicals that are able to adsorb to plastics. The chemistry of small plastic debris is an advancing field of research, as is evidenced by the

growing number of peer-reviewed publications that investigate the very specific connection between persistent organic pollutants and small plastic debris in the oceans.

The first report of chemicals sorbed to small plastic marine debris was Carpenter *et al.* (1972). Aroclor 1254 (a polychlorinated biphenyl (PCB) mixture) was extracted at 5 parts per million from plastics spherules found floating in Niantic Bay, Long Island Sound. The authors infer that small plastics are able to adsorb these particles from the marine environment because unlike some PCBs that served as plastics additives, the mixture Aroclor 1254 was never added to virgin plastics and must have sorbed to spherules in the environment (Carpenter *et al.* 1972). In the western Sargasso Sea, Carpenter and Smith (1972) found many brittle industrial plastic pellets and suggest that the PCB-containing plasticizers could have been lost to the marine environment, which would account for the loss of elasticity in the pellets.

Small ingested plastics and organic contaminants were examined in tandem for the first time in great shearwaters, *Puffinus gravis*, from Gough Island (Ryan *et al.* 1988). Nineteen of twenty breeding females had ingested plastics. Total organic contaminant load was highly correlated with amount of fatty tissue present in females, and variation in PCB load was explained via a significant, positive correlation with plastic load. Positive correlations with other organic contaminants were not significant; thus Ryan *et al.* (1988) surmise that ingested plastics are the source of PCBs in *P. gravis* tissues. Thirty years later, this study is still one of the only direct field comparisons of plastics and contaminants in marine organisms.

More recently, studies have focused on the uptake potential of organic contaminants from the marine environment to plastic debris. Mato *et al.* (2001) present data that define industrial plastic pellets (nurdles) as a transport medium for organic contaminants in seawater. Polychlorinated bi-phenyls, DDE, and nonylphenols were all detected in polypropylene pellets collected from the Japanese coast. An apparent adsorption coefficient of  $10^5$ – $10^6$  was determined for polypropylene pellets, based on a field experiment with virgin pellets placed in seawater for six days (Mato *et al.* 2001). Adsorption during this six-day experiment was two orders of magnitude lower than chemical concentrations found in nurdles from the Japanese coast; thus equilibrium with oceanic waters was not reached after six days (Mato *et al.* 2001).

An in-depth analysis of PCBs in industrial plastic pellets shows high variability among regions sampled in Japan, ranging from a concentration of <28 to 2300 ng/g (Endo *et al.* 2005; reproduced in Figure 3).

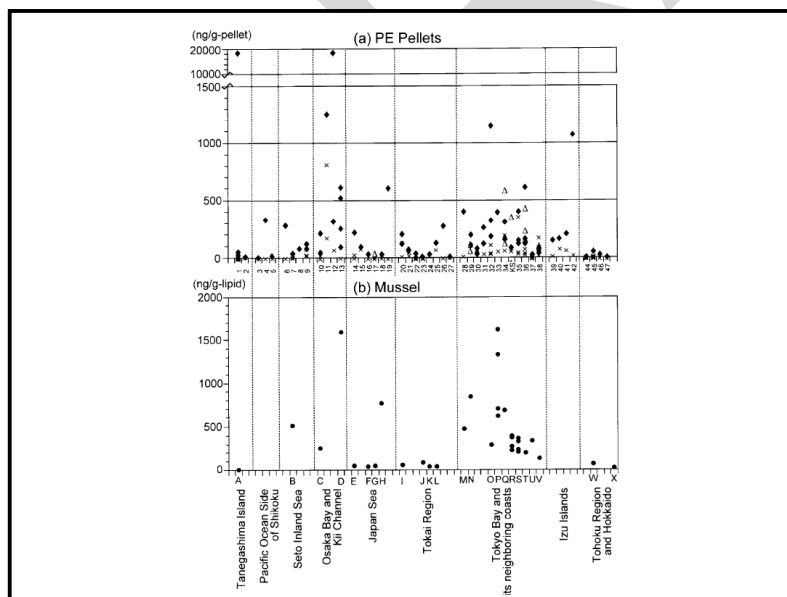


Figure 3. “(a) PCBs concentration in PE resin pellets from 47 Japanese beaches, (b) PCBs concentrations in mussel samples from Japanese coasts. Location numbers on X-axis correspond to Fig. 1, Tables 1 and 2. Solid diamonds: discolored and fouled (“fy”) pellets; open triangles: discolored and non-fouled (“y”) pellets; crosses: non-discolored and fouled (“f”) pellets.” Reproduced from Endo *et al.* 2005.

Concentrations in pellets were comparable to mussel tissue PCBs and Endo *et al.* (2005) propose pellets as monitors of organic chemicals in the marine environment. High concentrations of PCBs were found in remote areas with no localized source; thus, the authors suggest pellets could be a major route of PCB exposure for organisms in remote areas.

A similar study collected small plastics from the North Pacific Subtropical Gyre, coastal waters of Hawaii and southern California, and from Laysan albatross regurgitations on Guadalupe Island, Mexico (Rios *et al.* 2007). Of the PCBs, polycyclic aromatic hydrocarbons (PAHs), DDTs and aliphatic hydrocarbons detected on pellets, PCBs were the most frequently encountered organic contaminant, and total PCBs on plastic pieces ranged from 27 to 980 ng/g (Rios *et al.* 2007). Concentrations were not mapped by location or plastic type, and trends based on these two parameters were not assessed (Rios *et al.* 2007).

Teuten *et al.* (2007) reach the same conclusion as Mato *et al.* (2001) that plastics can transport organic contaminants in the oceans. Phenanthrene, a polycyclic aromatic hydrocarbon (PAH), was noted to bind to three types of plastic (polyethylene, polypropylene and polyvinyl chloride). Compared to uptake of phenanthrene by natural sediments, uptake and binding by plastics was much higher. Teuten *et al.* (2007) show that addition of virgin plastics decreases phenanthrene availability in sediments, with a dramatic effect on sediments low in organic carbon. It was estimated that 1 ng/g contaminated polyethylene or 14 ng/g contaminated polypropylene added to sediments would cause an 80% increase in lugworm (*Arenicola marina*) tissue phenanthrene concentrations (Teuten *et al.* 2007). These exposure estimates were derived from partition coefficient calculations and not actual experiments. Data from a study in Greece are in agreement that of the plastics tested, polyethylene has the highest apparent distribution coefficient (a measure of how much contaminant binds to a surface) for phenanthrene (Karapanagioti and Klontza 2008).

#### *Discussion*

Plastic debris can serve as a sorbent for contaminants in the natural environment with different effects based on the type of plastic and properties of the contaminant. Plastics may also serve the reverse role as a source of contaminants to organisms upon ingestion. Based on the potential for plastics to adsorb contaminants, Takada (2006) put out a call for beached pellets from around the world to aid in mapping global distributions of persistent organic pollutants. It remains to be seen whether enough useful information can be gleaned from floating bits of plastic to be useful in determining global cycles of persistent organic pollutants. But it is certain that plastics have the potential to both adsorb organic contaminants from the marine environment and desorb these contaminants to biota that ingest plastics.

#### **IV. Effect of small plastic debris on biogeochemical cycling of POPs**

No research has yet taken plastic debris into account in determining global POP distribution and contribution to global cycles. Due to the complex nature of biogeochemical research, integrating plastics into the most up-to-date models will be a challenge. Yet it is crucial to determine if plastics can be accurately described as sources or sinks of POPs to the marine environment. If plastics are playing a source or sink role it is necessary to factor plastic debris into global models of persistent organic pollutant cycling in the oceans.

The so-called "Dirty Dozen" or legacy persistent organic pollutants, named and controlled by the Stockholm Convention in 1995, are as follows: aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans, toxaphene. This list has been expanded to include the carcinogenic polycyclic aromatic hydrocarbons, brominated flame retardants, and some organometallics. These pollutants are set as the highest priority compounds for environmental removal and remediation efforts.

While persistent organic pollutants are composed of similar molecules (e.g., a carbon-hydrogen backbone), specific structures and functional groups largely determine differences in POP movement and behavior in the environment. Wania and Daly (2002) estimate global lifetimes of PCBs to be on the order

of decades, but even within this class of compounds there is quite a bit of variability in degradation and environmental transfer that depends on the specific compound, or PCB congener. Binding to organic particles in the deep sea is the dominant loss process (or sink) of highly chlorinated PCB congeners (Wania and Daly, 2002). Determining presence of POPs in remote locations such as the deep sea is a major difficulty to overcome in developing a global mass balance model for persistent organic pollutants (Lohmann *et al.* 2007). The manner in which persistent organic pollutants interact with plankton in the water column and with the oceanic microbial loop is largely unknown, making it difficult to assess persistent organic pollutants in the deep sea (Lohmann *et al.* 2007).

### *Modeling*

Global biogeochemical POPs models include cycling of organic contaminants through every compartment of the ecosystem, including both abiotic (e.g., air and water columns, sediments, and soils) and biotic (e.g., the flora and fauna that comprise the ecosystem) compartments. Chemicals are “recycled” on a global scale. However, environmental sinks have a tendency to efficiently bind and transport a chemical or compound out of the system, so that it is removed from the recycling process. It is important to know the specifics of environmental sinks to accurately model the movement of chemicals on a global scale. Global biogeochemical models include bioaccumulation of contaminants in tissues of plants and animals, and biomagnification of those contaminants in a food web structure. Thus, obtaining accurate biogeochemical models requires knowledge of how chemicals move on a small scale between particles, how chemicals are moved through the environment via geologic and meteorological forces, how chemicals are incorporated into tissues of biota, and how chemicals and compounds are degraded over time.

### *Links between POPS and microplastics.*

Several studies have demonstrated that persistent organic pollutants, due to their hydrophobic nature, have strong affinities for microplastic particles. This is not surprising, as the standard analytical method to isolate POPs from natural waters employs passing the water through beds of polymeric resin, trapping the POP analytes. What is less clear is (1) whether the quantity and composition of microplastics in the oceans are sufficient to alter the global cycling of POPs, (2) whether leaching of chemicals from weathering microplastics is an important source of POPs to the world's oceans, and (3) whether microplastics play a role of accumulating POPs to high concentrations in a form that is ingested by marine organisms.

## **V. Conclusions**

The main sources of microplastic marine debris likely include: (1) larger pieces of plastic debris breaking into smaller bits during weathering; (2) inadvertent or accidental release of small, unweathered industrial plastic bits (“nurdles”) during production, shipping, and storage; and (3) discharge of wastewater that contains microplastics purposefully added to consumer products. Effects of these types of microplastic debris on marine organisms are not easily determined, and have not been systematically investigated. Microplastics have the potential to adsorb persistent organic pollutants, which may account in part for observed POP concentrations in seawater and marine organisms that contain microplastics. Microplastics also may serve as a transport mechanism for contaminants, not only as a vector for contaminants into organisms, but also as a transport medium for contaminants to move around the globe. Often POPs reach remote locations through atmospheric transport and adversely effect ecosystems that are far from the source of the contaminant. The ubiquity of plastic coupled with its ability to adsorb hydrophobic contaminants could be another major introductory route for contaminants into marine ecosystems.

Table 1. Occurrences of microplastic debris in the marine environment.

Location	Year (s)	Mean Abundance (pieces/km <sup>2</sup> )	Mean Abundance (pieces/m <sup>3</sup> )	Range (pieces/km <sup>2</sup> )	Citation
<b>Surface Sea Water</b>					
Western Sargasso Sea	1971	3,500	0.00035	50 - 12,000	Carpenter and Smith 1972
southern New England, USA (Niantic Bay)	1972	1000000*	1.0	0 - 140,000,000*	Carpenter et al. 1972
southern New England, USA (Long Island Sound)	1972	700000*	0.070		Carpenter et al. 1972
southern New England, USA (east of Block Island)	1972	300000*	0.030		Carpenter et al. 1972
southern New England, USA (west of Great Salt Pond)	1972	200000*	0.020		Carpenter et al. 1972
NW Atlantic (Oregon II - Caribbean)	1972	61	0.0000061	0 - 166,991	Colton et al. 1974
NW Atlantic (Albatross IV - north of Caribbean)	1972	184	0.000018		Colton et al. 1974
NW Atlantic (Delaware II - continental shelf NY to FL)	1972	2,773	0.00028		Colton et al. 1974
Subtropical North Pacific	1985	96,100	0.0096		Day and Shaw 1987
Subarctic North Pacific	1985	3,370	0.00034		Day and Shaw 1987
Bering Sea	1985	80	0.0000080		Day and Shaw 1987
Subtropical North Pacific	1999	334,271	0.033	31,982 - 969,777	Moore et al. 2001
southern California, USA (mouth of San Gabriel River)	2000	3000000*	0.30		Moore et al. 2002
Singapore	2004			0-2 particles L <sup>-1</sup> seawater	Ng and Obbard 2006
NE Atlantic Ocean	1960-1980	100000*	0.010		Thompson et al. 2004
NE Atlantic Ocean	1980-2000	400000*	0.040		Thompson et al. 2004
<b>Beaches</b>					
New Zealand	1972-1976	10-100 m <sup>-1</sup> *		0 - 100,000 m <sup>-1</sup> *	Gregory 1978
Jordan	1994	5 items m <sup>-2</sup> **		0.35-0.81 items m <sup>-2</sup>	Abu-Hilal and Al-Najjar 2004
Jordan	1995	3 items m <sup>-2</sup> **		0.15-0.62 items m <sup>-2</sup>	Abu-Hilal and Al-Najjar 2004
South Georgia, Candlemas Island, Saunders Island, Adelaide Island	1993-2002			0-0.3 items m <sup>-1</sup> **	Convey et al. 2002
<b>Sediment</b>					
Plymouth, UK (sandy)	~2000	.001 fibers cm <sup>-3</sup> *			Thompson et al. 2004
Plymouth, UK (estuarine)	~2000	.05 fibers cm <sup>-3</sup> *			Thompson et al. 2004
Plymouth, UK (subtidal)	~2000	0.11 fibers cm <sup>-3</sup> *			Thompson et al. 2004
Singapore	2004			0-4 particles 250g <sup>-1</sup> sediment	Ng and Obbard 2006
Alang-Sosiya, India	2004	81.43 +/- 4.03 mg kg <sup>-1</sup>			Reddy et al. 2006
*estimated from published data					
**calculations include all debris found					

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