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Synthetic polymers in the marine environment: A rapidly increasing, long-term threat

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ABSTRACT

Synthetic polymers, commonly known as plastics, have been entering the marine environment in quantities paralleling their level of production over the last half century. However, in the last two decades of the 20th Century, the deposition rate accelerated past the rate of production, and plastics are now one of the most common and persistent pollutants in ocean waters and beaches worldwide. Thirty years ago the prevailing attitude of the plastic industry was that "plastic litter is a very small proportion of all litter and causes no harm to the environment except as an eyesore" [Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44(9), 842–852]. Between 1960 and 2000, the world production of plastic resins increased 25-fold, while recovery of the material remained below 5%. Between 1970 and 2003, plastics became the fastest growing segment of the US municipal waste stream, increasing nine-fold, and marine litter is now 60–80% plastic, reaching 90–95% in some areas. While undoubtedly still an eyesore, plastic debris today is having significant harmful effects on marine biota. Albatross, fulmars, shearwaters and petrels mistake floating plastics for food, and many individuals of these species are affected; in fact, 44% of all seabird species are known to ingest plastic. Sea turtles ingest plastic bags, fishing line and other plastics, as do 26 species of cetaceans. In all, 267 species of marine organisms worldwide are known to have been affected by plastic debris, a number that will increase as smaller organisms are assessed. The number of fish, birds, and mammals that succumb each year to derelict fishing nets and lines in which they become entangled cannot be reliably known; but estimates are in the millions. We divide marine plastic debris into two categories: macro, >5 mm and micro, <5 mm. While macro-debris may sometimes be traced to its origin by object identification or markings, micro-debris, consisting of particles of two main varieties, (1) fragments broken from larger objects, and (2) resin pellets and powders, the basic thermoplastic industry feedstocks, are difficult to trace. Ingestion of plastic micro-debris by filter feeders at the base of the food web is known to occur, but has not been quantified. Ingestion of degraded plastic pellets and fragments raises toxicity concerns, since plastics are known to adsorb hydrophobic pollutants. The potential bioavailability of compounds added to plastics at the time of manufacture, as well as those adsorbed from the environment are complex issues that merit more widespread investigation. The physiological effects of any bioavailable compounds desorbed from plastics by marine biota are being directly investigated, since it was found 20 years ago that the mass of ingested plastic in Great Shearwaters was positively correlated with PCBs in their fat and eggs. Colonization of plastic marine debris by sessile organisms provides a vector for transport of alien species in the ocean environment and may threaten marine biodiversity. There is also potential danger to marine ecosystems from the accumulation of plastic debris on the sea floor. The accumulation of such debris can inhibit gas exchange between the overlying waters and the pore waters of the sediments, and disrupt or smother inhabitants of the benthos. The extent of this problem and its effects have recently begun to be investigated. A little more than half of all thermoplastics will sink in seawater.

1. Introduction

A major unforeseen consequence of the "Plastic Age" is the material's ability to proliferate in innumerable sizes, shapes and colors throughout the marine environment worldwide (Moore, 2003). The physical characteristics of most plastics show high

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resistance to aging and minimal biological degradation. When exposed to the UVB radiation in sunlight, the oxidative properties of the atmosphere and the hydrolytic properties of seawater, these polymers become embrittled, and break into smaller and smaller pieces, eventually becoming individual polymer molecules, which must undergo further degradation before becoming bioavailable. The eventual biodegradation of plastics in the marine environment requires an unknown amount of time (Andrady, 2005). A wide range of undocumented estimates for the time needed to completely mineralize or biodegrade marine plastics—on the order of centuries—have been made; but they are all, at best, educated guesses (Andrady, personal communication). Their persistence contributes to the fact that plastics are accumulating in increasing quantities in the marine environment (Copello and Quintana, 2003; Ogi et al., 1999). Slow biodegradation rates do not mean that plastic polymers and their additives are not bioactive. The process of polymerization of the monomers that form plastics is never 100% complete, and the remaining monomer building blocks of the polymer, such as styrene and bisphenol-A, along with residual catalysts, can migrate from the polymer matrix into compounds with which they come in contact. Polycarbonate plastics, when exposed to the salts in seawater, show accelerated leaching of the bioactive bisphenol-A monomer (Sajiki and Yonekubo, 2003). Many plastic polymers in commercial use have high concentrations of bioactive monomer additives, such as UV stabilizers, softeners, flame retardants, non-stick compounds, and colorants, which leach out at faster or slower rates based on environmental conditions. It is estimated that plastic products overall are composed of about 50% fillers, reinforcements and additives by weight (Colton et al., 1974).

While it is beyond the scope of this paper to delve into the intricacies of polymerization, and the production of thermoset and thermoplastic resins, the leaching of some bioactive substances from commercial plastics will be covered by other papers in this series. Briefly, thermoplastics, the main type of consumer plastics, are formed by melting the plastic raw material and forming it into products, which can be recovered and re-melted. Thermoplastics are distinguished from thermoset plastics; liquids which are "set" by the use of a catalyst, and scorch rather than re-melt when exposed to heat. Thermoset plastics also break into small bits and persist in the environment, and though produced in less quantity than thermoplastics, are recovered or recycled at an even lower rate.

The modern trend is for nearly all consumer goods to contain and/or be contained by plastic, and recovery of the material often does not provide readily realizable profits, or options for reuse (Unnithan, 1998); therefore, plastics are the fastest growing component of waste. Some of this waste reaches disposal sites, but much of it litters the landscape. Since the ocean is downhill and downstream from virtually everywhere humans live, and about half of the world's human population lives within 50 miles of the ocean, lightweight plastic trash, lacking significant recovery infrastructure, blows and runs off into the sea. There, it moves to innumerable habitats, where it causes at least eight complex problems, none of which is well understood: (1) plastic trash foul beaches worldwide, devaluing the experience of beachgoers, with a concomitant impact on the tourism industry. Medical waste, plastic diapers and sanitary waste often found among this debris constitute a public health hazard. (2) Plastic entangles marine life and kills through drowning, strangulation, dragging, and reduction of feeding efficiency. So-called "ghost nets" continue to fish after being lost or abandoned by their owners, and kill untold numbers of commercial species. (3) Ingestion of plastic items that mimic natural food fails to provide nutrition proportionate to its weight or volume. It weakens and may kill seabirds through starvation and false feelings of satiation, irritation of the stomach lining, and failure to put on fat stores necessary for migration and reproduction. Sea turtles and marine mammals with ingested plastic have been found washed up or floating dead, but linking mortality unequivocally to the ingested debris is difficult. (4) Petroleum-based plastic polymers do not readily biodegrade, and are long-lived and slow moving in the ocean. As such, they provide substrata for "bryozoans, barnacles, polychaete worms, hydroids and mollusks (in order of abundance)," and may present a more effective invasive species dispersal mechanism than ship hulls or ballast water (Barnes, 2005), and are implicated in the northward range extension of the large barnacle *Perforatus perforatus* (Rees and Southward, 2008). In some areas, e.g. the central Pacific gyre, these plastic substrates are so numerous that their ready availability is likely to alter the species composition of sessile organisms. (5) Plastic resin pellets and fragments of plastic broken from larger objects are sources and sinks for xenoestrogens and persistent organic pollutants (POPs) in marine and aquatic environments (Moore et al., 2005a; Mato et al., 2001; Rios et al., 2007), and can be readily ingested by invertebrates at the base of the food web (Thompson et al., 2004). (6) Since the majority of consumer plastics are neutrally buoyant (within 0.1 g/mL of seawater density, USEPA, 1992), grains of sand caught in their seams or fouling matter make many plastics sink to the sea floor. Much of this material consists of thin packaging film and has the potential to inhibit gas exchange, possibly interfering with CO_2 sequestration (Goldberg, 1997). Plastic deposited on the sea floor also has the potential to change the composition, interfere with or smother inhabitants of the sediments (Katsanevakis et al., 2007; Uneputty and Evans, 1997; Goldberg, 1997). (7) Marine litter threatens coastal species by filling up and destroying nursery habitat where new life would otherwise emerge (UNEP, 2001). (8) Marine plastic litter fouls vessel intake ports, keels and propellers, and puts crew at risk while working to free the debris; incurring significant damage to vessels, with economic losses estimated by Takehama (1990) to be 6.6 billion Yen/yr in Japanese fishing vessels $<$1000 gross tons. According to the US National Oceanographic and Atmospheric Administration's (NOAA's) office of Response and Restoration, in 2005, the US Coast Guard found that floating and submerged objects caused 269 boating accidents resulting in 15 deaths, 116 injuries and $US 3 million in property damage.

Given the variety of problems caused by plastic debris, it is important to gauge its rate of change. In the early 1970s, a study in the Atlantic Ocean of 247 surface plankton samples from Cape Cod to the Caribbean found plastic in 62% of samples (Colton et al., 1974). A similar study in the Pacific during the mid-1980s of 203 samples from the Japan Sea to the Bering Sea and north of Hawaii found plastic in 59% (Day et al., 1990). Evidence from archived plankton samples taken from the 1960s–1990s off Great Britain showed that microscopic marine plastics increased significantly in the North Atlantic. (Thompson et al., 2004). During the decade of the 1990s, plastics in the US municipal waste stream tripled (USEPA, 2003) and researchers found increased levels in the marine environment. Plastic was found in all trawl samples in studies from 1999 to 2007 in the north Pacific (Moore C.J., et al., 2001, and unpublished data from 2002 to 2007). Moore C.J., et al. (2001) found maximum neuston (surface) plastic levels three times greater than Day et al. (1990) had found a decade earlier. From 1994 to 1998, debris levels around the United Kingdom coastline doubled (Barnes, 2002), "and in parts of the Southern Ocean it increased 14–15 fold during the early 1990s" (Walker et al., 1997). Ogi et al. (1999) found that neuston plastic increased 10-fold in coastal areas of Japan during the 1970s–1980s, but that during the 1990s, densities increased 10-fold every 2–3 years.

Once plastic debris reaches the ocean, the floating component is dispersed in various ways. Onshore winds force debris back to

Fig. 1. Trawl Sample, August, 2005, AMRF survey: 40° North Latutude, 140° West Longitude. Photo: Capt. Charles Moore.

the shore, while offshore winds push debris toward major ocean current transport systems. Both types of wind have a greater effect on objects that have appendages above the sea surface, such as fishing floats and bathtub toys. In the deep ocean, large high-pressure systems known as gyres tend to accrete the debris, while low-pressure systems tend to disperse it (Ingraham and Ebbesmeyer, 2000). In the largest gyre, located in the central North Pacific, neuston trawls lined with 0.333 mm mesh yielded the astounding figure of six kilos of plastic fragments for every kilo of zooplankton >0.333 mm in size (Moore C.J., et al., 2001, Fig. 1).

2. Plastic debris concerns

It was inevitable that a lightweight, long-lived (slow biodegrading) product that fills so many commodity niches, and which is often used only once and discarded, would eventually cause problems for the marine and terrestrial environments where it accumulates.

2.1. Aesthetics

According to the World Health Organization, a clean beach is one of the most important characteristics sought by visitors (Bartram and Rees, 2000). The negative effects of debris, defined as solid materials of human origin, are: loss of tourist days, resultant damage to leisure/tourism infrastructure, damage to commercial activities dependent on tourism, damage to fishery activities, and damage to the local, national and international image of a resort. "Such effects were experienced in New Jersey, USA in 1987 and Long Island, USA in 1988 where the reporting of medical waste, such as syringes, vials and plastic catheters, along the coastline resulted in an estimated loss of between 121 and 327 million user days at the beach and between US$ 1.3×10^9 and US$ 5.4×10^9 in tourism related expenditure" (Bartram and Rees, 2000). Clean beaches, free from debris, are a thing of the past. In the 20 years since the US-based organization, Ocean Conservancy organized the first annual International Coastal Cleanup Day, 6 million volunteers from 100 countries have removed 100 million pounds of litter from 170,000 miles of beaches and inland waterways. Reports of groups finding nothing to pick up do not exist. While the International Cleanup Day effort expands each year, so does the amount of debris recovered. Between 1996 and 2006, at Escondido Beach, California, 310 total debris items were removed, but 182 of those were found in 2005, representing 59% of the total recovered in the last year of the 10-year effort. At Torrey Pines State Beach, California, in the four quarters of 2005, 136 items were removed, but in the second quarter of 2006 alone, 189 items were found (Ocean Conservancy, 2007).

It must be remembered that beach cleanups focus on macro-debris. Numerous studies have found micro-debris on beaches and in their sediments worldwide, many of the beaches remote from human activity. (McDermid and McMullen, 2004; Moore S.L., et al., 2001; Gregory, 1977, 1978, 1983, 1991, 1996, 1999; Thompson et al., 2004; Ng and Obbard, 2006). In a study of a beach, near an urban river mouth, Moore et al. (unpublished data) found the sand to be 1% plastic by volume down to a depth of 20 cm.

Floating debris is an aesthetic issue for swimmers, mariners, coastal and inland water body dwellers, and submerged debris is an aesthetic issue for divers.

2.2. Entanglement

In the 1980s, researchers estimated that there were approximately 100,000 marine mammal deaths per year in the North Pacific related to entanglement in plastic nets and fishing line (Wallace, 1985). Currently in the US, the NOAA is using digitally enhanced photos of wounds suffered by marine mammals to identify the type of line they were entangled in (National Oceanic and Atmospheric Administration). Lost and abandoned nets, termed "ghost nets", continue to fish and destroy resources. A report by Canada's Food and Agriculture Organization (FAO, 1991) estimates that 10% of all static fishing gear is lost, and that this results in a loss of 10% of the target fish population. Efforts to remove this gear are growing, but are not widespread, and the great cost of removal of derelict gear is not borne by those who manufacture it or lose it. Such costs could threaten the economic viability of commercial fishing.

Documentation of entanglement of seabirds and other marine species in six-pack rings used to hold cans and bottles has resulted in changes to the plastic formula to speed up disintegration in the environment. The polymer can be changed chemically during manufacture so that it absorbs UV-B radiation from sunlight and breaks down into a very brittle material in a fairly

short period of time; however, the resulting particles are no more biodegradable than the untreated polymer (Gregory and Andrady, 2003). Such embrittlement accelerators are not used in nets and lines, however; and volunteer groups worldwide are regularly called on to free entangled cetaceans and other sea life.

2.3. Ingestion

The term "plastic" means "capable of being formed into any shape." The plastic objects that populate the marine and aquatic environments, with the exception of fishing lures, are not made to look like natural food to marine creatures. However, thin plastic shopping bags balloon out in water and resemble jellyfish, and are regularly consumed by sea turtles (Lutcavage et al., 1997), especially critically endangered leatherbacks (Barreiros and Barcelos, 2001; Karla McDermid, personal communication). It is probable that the infinite ways in which the mega-tons of multi-colored plastic debris break down in the marine environment create mimics for virtually every natural food source. Bern (1990) found that a crustacean zooplankton, *Bosmina coregoni*, when offered polystyrene beads of 2 and 6 μm and ^{14}C-labelled alga of equal size, ingested both non-selectively within combinations. Andrady (personal communication) reported on feeding studies by Alldredge at UC Santa Barbara, using Ivlev's Electivity Index (designed to quantify prey-selection by predators, especially planktivores), showing that two common species of crustaceans, *Euphausia pacifica* (krill) and the copepod *Calanus pacificus*, had values of the index that suggested the ingestion of contaminant-free, uncolonized plastic particles, versus natural prey, from a mixture of these, appeared to be non-preferential. Most feeding that takes place in the ocean, is accomplished by indiscriminate feeders with mucus bodies or appendages, which trap anything of an appropriate size with which the organism comes in contact. Collection of salps in the North Pacific Central Gyre by Algalita Marine Research Foundation (AMRF) (2006), using both plankton trawls and hand nets, found individuals with plastic particles and fishing line embedded in their tissue (Moore C.J., et al., 2001). The optimum size class of plastic for filter feeder ingestion appears to be less than 1 mm in diameter, although larger particles have been found in some individuals. A 1999 AMRF study of 27,448 plastic particles trawled from the surface of the North Pacific Central Gyre found 9470 particles near 1 mm in size, 4646 near 0.5 mm, and 2626 near 0.3 mm, suggesting that smaller particles are being removed, or are leaving the system by some unknown mechanism (Moore C.J., et al., 2001). Thompson et al. (2004) kept intertidal invertebrates in aquaria with microscopic plastic particles <2 mm in diameter. The microscopic plastics were ingested by polychaete worms, barnacles, and amphipods during these laboratory trials. Documentation of transmission of these types of particles up the food web has been provided by Eriksson and Burton (2003), who surveyed Southern fur seal scat on Macquarie Island. They found that scats contained plastic particles from the night-feeding myctophids (Lantern fish), active near the sea surface, and consumed by the seals.

When plastic debris enters the sea, the proportion that floats, heads for surface accumulation zones. Modeling done by Ingraham and Ebbesmeyer (2000), using the Ocean Surface Current Simulator (OSCURS), seeded 113 drifters uniformly over the North Pacific from the US Coast to China. The model showed that after 12 years, winds and currents had gathered 75% of the drifters into an area of the Central Gyre equal to 28% of the total area seeded. The five enormous high-pressure gyres in the oceans comprise 40% of the sea surface, or 25% of the area of the entire earth (Koblentz-Mishke et al., 1970). The mountains of air that create the highs, force the sea level lower near their centers and create accumulation zones described as "gentle maelstroms" (Moore, 2003). These areas are over the deep ocean and are oligotrophic, oceanic deserts (Koblentz-Mishke et al., 1970). Thus, the ratio of plastic particles to plankton is highest near the center of high-pressure gyres on average, although after heavy rains, which cause runoff of plastic particles from urban areas, higher ratios are found near urban coastal zones (Moore et al., 2002; Lattin et al., 2004). Detritus feeders, like the Laysan albatross, have been demonstrated to feed primarily in and around the north Pacific subtropical gyre (Henry, 2004), and the stomach contents of their chicks, receiving nutriment only by regurgitation from adult birds, contain alarming quantities of plastic (Auman et al., 1997), as shown in Fig. 2. Sileo et al. (1990) documented 80 species of seabirds that ingest plastic. Carpenter et al. (1972) found plastic pellets in eight of 14 species of fish and one chaetognath off Southern New England. In USEPA (1992), it was reported that pellet ingestion was more common in lobster than winter flounder in the New York Bight in 1991.

Plastics as a means to transport pollutants to organisms in aquatic and marine ecosystems have become the focus of scientific research as levels of macro- and micro-plastics in these environments increase (Thompson et al., 2004). Mato et al. (2001) studied how polypropylene (PP) pellets in the marine environment adsorb (with adsorption coefficients of 10^5–10^6 from ambient seawater), and transport PCBs, DDE and nonylphenols (NP). Field and laboratory studies of the physiological effects on seabirds that ingest contaminated plastic resin pellets by this group are in press. Moore et al. (2005a) found polycyclic aromatic hydrocarbons and phthalates in samples of pre-production plastic pellets, and post consumer fragments of the same general size (<5 mm), from rivers and marine beaches near urban centers. Ryan et al. (1988) found that the mass of ingested plastic in Great Shearwaters was positively correlated with PCBs in their fat tissue and eggs.

In the ocean, degraded and fragmented bits of polymeric material are assuming the characteristics of a new class of sediments. Such fragments are floating on the surface, mixed into the water column, and embedded in bottom sediments and beach sand (Colton et al., 1974; Rios et al., 2007). Studies by Gregory (1996), Moore et al. (2005c), and Zitco and Hanlon (1991) have drawn attention to small fragments of plastic derived from hand cleaners, cosmetic preparations, airblast cleaning media, and production waste from plastic processing plants. The quantities and effects of these contaminants on the marine environment have yet to be fully determined, but in a study conducted on the

Fig. 2. Laysan albatross chick, Kure Atoll, 2002, photo: Cynthia Vanderlip, AMRF.

Los Angeles and San Gabriel Rivers in 2004–2005, sample analysis with extrapolation found 2 billion plastic particles of all types, <5 mm in size, flowing toward the ocean in 3 days of sampling (Moore et al., 2005b). Teuten et al. (2007) found that a priority pollutant, phenanthrene, was transmitted to the lugworm, *Arenicola marina*, by polyethylene contaminated with phenanthrene absorbed from seawater mixed into sediments inhabited by the worm. According to Andrady (2003) "… plasticizers tend to migrate slowly to the surface of the product and can therefore enter the environment or come into human contact. Common plasticizers are indeed found in low levels dispersed in the environment in most parts of the world and generally believed to be even ingested routinely along with food… Another more recent health concern is endocrine disruption by chemicals, and plasticizers are included in the class of relevant chemical agents." Whether or to what extent estrogenic compounds in plasticizers added to plastics at the time of manufacture, or absorbed from the environment, are linked to findings such as a high percentage of intersex in Mediterranean swordfish (De Metrio et al., 2003), has not been investigated; but the presence of micro-plastics in the sea surface microlayer where xenoestrogens are known to accumulate, has been documented by Ng and Obbard (2006). Some phthalate plasticizers have been banned by the European Commission (Andrady, 2005), and numerous studies have found deleterious effects from another common plasticizer, bisphenol-A (vom Saal and Welshons, 2005).

2.4. Collateral concerns

Just as plastics are widely variable in structure and use, so are the concerns raised by their ubiquitous presence as poorly controlled non-degradable waste. Foremost among these concerns is the recent explosion in what may be termed "pelagic plastics." For most of their history, synthetic, petroleum-based polymers were used and discarded principally in Europe and the United States, and more recently, Japan. Levels of plastic pollution off these coasts increased similarly to the level of plastic production until recently (Ogi et al., 1999; Moore C.J., et al., 2001). During the last decade of the 20th century, and continuing to the present, proliferation of plastic packaging and products accelerated worldwide. Sales of PET plastic water bottles in the US alone rose from a million tons in 1996, to 2.5 million tons in 2005 (Beck, 2005). Many of these bottles are shipped around the world for disaster relief and other purposes, where no recycling infrastructure exists. Dr. Curtis Ebbesmeyer, of the Beachcombers and Oceanographers International Association (personal communication), has estimated that a single, 1 l plastic water bottle will photodegrade into enough small pieces to put one piece on every mile of beach in the world. Two studies in the North Pacific reveal a rapid rise in micro-plastic marine debris. Moore C.J., et al. (2001) found the maximum abundance of plastic particles to be three times that found by Day et al. (1990). Ogi et al. (1999) found plastic particle abundance to be increasing by a factor of 10 every 2–3 years in the most extreme case off of Japan during the decade of the 1990s. There are now 65,000 plastic processors in India and China, consuming nearly as much plastic resin, 49.8 mt/yr, as the United States (Mehta, 2007). Exports of primary plastic resins from the Middle East are growing rapidly in every global market except North and South America (Al-Sheaibi, 2002). Consumer plastics are going global. Tracking their fate is difficult. Based on statistics compiled in a 2003 California "Plastics White Paper," that included amounts of plastics made, disposed of, and recycled nationwide, approximately 25% of all disposable plastics remain unaccounted for (CIWMB, 2003). With total US thermoplastic resin sales at 50×10^6 tons, 25×10^6 tons (50%) are disposed of as municipal waste, 5% is recycled and an estimated 20% is made into durable goods. That leaves 12.5 million tons (25%) unaccounted for, which could make its way via rivers to the sea. In 3 days of sampling on the Los Angeles and San Gabriel Rivers, AMRF found 60 tons of plastic debris flowing towards the sea, representing 2.3 billion individual pieces of plastic trash of all size classes >1 mm (Moore et al., 2005b).

Many islands, which act as sieves for ocean-borne plastics, have already been heavily impacted by plastic debris originating far from their shores. On the surface of one square foot of beach sand on Kamilo Beach, Hawaii, 2500 plastic particles >1 mm were found, and the fact that 500 of them were pre-production plastic pellets, with no processors located in Hawaii, lends credence to the concept that these particles are of distant origin (Moore, unpublished data). McDermid and McMullen (2004) collected 19,100 plastic particles from nine remote Hawaiian beaches separated by 1500 miles, and 11% were pre-production pellets by count. These pellets come in a variety of shapes, including rounded, flattened oval, and cylindrical, and are normally <5 mm in diameter. Plastic producers make these pellets and ship them to plastic manufacturers or processors to be melted into consumer products. A 1998 study of Orange County Beaches in Southern California showed plastic pellets to be the most abundant items, with an estimated count of over 105 million, comprising 98% of the total debris (Moore S.L., et al., 2001). Southern California has the largest concentration of plastic processors in the western United States. A 2005 study by AMRF (Moore et al., 2005b) of the two main rivers draining the Los Angeles, California basin found in one dry and two rainy days of sampling, over 2.3×10^9 plastic objects and fragments being transported to the Pacific Ocean at San Pedro Bay. Macro-debris >5 mm accounted for 10% of the total. Of the identifiable objects, the largest single component was pre-production plastic pellets at 2.3×10^8. Ignoring such inputs results in underestimates of the total number of pieces of litter entering the ocean worldwide on a daily basis. A widely quoted figure of 8 million pieces per day given in UNEP (2001) is, in reality, only 1% of the total number of plastic pieces flowing to the sea from the Los Angeles area in a single day, based on AMRF's 3-day totals. AMRF's figures do not include anthropogenic debris other than plastic.

Plastics form a stable substratum for colonization by marine organisms, including bacteria, with larger floating items generally having one side exposed to the sun, and one side ballasted with fouling organisms (Moore, unpublished data). Less than 10% of the micro-debris in a 1999 North Pacific Central Gyre study, however, appeared to host multicellular fouling organisms at all (Moore C.J., et al., 2001). This may be due to their frequency of tumbling in wavelets and changing the side exposed to the sun. Barnes (2005) estimates "that rubbish of human origin in the sea has roughly doubled the propagation of fauna in the subtropics and more than tripled it at high (>50°) latitudes." Globally, the proportion of plastic among marine debris ranges from 60% to 80%, although it has reached over 90–95% in some areas (Derraik, 2002). Bartram and Rees (2000) point out certain exceptions to the percentages, found during United Kingdom beach surveys, and state that "litter sourcing seems to be highly site specific."

Plastics made up 80–85% of the seabed debris in Tokyo Bay (Kanehiro et al., 1995). The consequences of partially covering the seabed with materials resistant to gas and water transport have not been fully investigated, although Katsanevakis et al. (2007) found a deviation in the community structure of the impacted benthic surface from their control and a clear successional pattern of change in benthic community composition. Goldberg (1997) speculated that benthic debris may interfere with carbon cycling in the ocean. Moore (2003) estimated that the weight of plastic debris on the surface, in an area of the North Pacific Central Gyre

known as the "Eastern Garbage Patch," an area 1000 km in diameter, was about three million tons, based on an average of 5114 g/km^2. (Moore C.J., et al., 2001). Andrady (2000) found that plastic fishing gear "would initially increase in density because of copious fouling," and become negatively buoyant until it descended below the photic zone where the foulant colony would likely die due to lack of sunlight, allowing the plastic material to float again. This implies that as buoyant plastic fragments become mixed into marine "snow" (the natural detritus of the marine environment), the marine snow may be prevented from reaching the sea floor where it is a major sequestration vector for atmospheric CO_2.

3. Solutions

Because of the enormous diversity of plastic waste, the solutions to the plastic debris pollution problem will also have to be diverse. Despite the recent upsurge in development of solutions to prevent plastic pollution, the author is not aware of reports showing measurable overall reductions to this rapidly increasing despoiler of marine and aquatic environments.

3.1. Structural controls

Devices to capture plastic debris before it reaches rivers and oceans are being installed at urban catch basins, storm drains and pumping stations, and debris booms are being placed across rivers draining urban areas. Containment structures cover only a small percentage of debris conduits, and during heavy storms, these devices break or overflow, and release debris. Nevertheless, these devices are being relied upon by municipalities required to reduce trash input to urban waterways by regulations called total maximum daily loads (TMDLs), used by Water Resource Control Boards to regulate pollutants entering urban waterways. Structural controls typically capture macro-debris (>5 mm) only, as the legal definition of trash under the TMDL is anthropogenic debris that can be trapped by a 5 mm mesh screen (California Regional Water Quality Control Board, Los Angeles Region). Based on a study of the Los Angeles watershed, 90% of plastic debris by count, and 13% by weight are micro-debris <5 mm (Moore et al., 2005b).

3.2. Beach and reef cleanups

While beach cleanups by civic groups raise awareness among the general public of the plastic debris problem, they are infrequent and do not stem the tide of debris. In the Northwestern Hawaiian Islands, NOAA spends 2 million US dollars per year to remove 50–60 tons of derelict fishing nets and gear in an effort to save the critically endangered Hawaiian Monk Seal, over 200 of which have become entangled since records were kept (Foley and Veenstra, 2006; Pichel et al., 2007). The amount retrieved does not diminish significantly, year to year, and efforts are currently being made to find accumulation zones where the nets can be retrieved at sea before they damage coral reef habitat (Pichel et al., 2007). Recently, civic groups have begun to focus clean up efforts on storm drains and catch basins upstream from outlets to the sea, which will prevent the debris removed from reaching the ocean.

3.3. Deposits, fees

Ten of 52 US states have implemented "bottle bills" which require a deposit on certain plastic bottles to aid in their recovery and recycling, and in 2005, only 17% of the over 50 billion polyethylene terephthalate (PET) plastic water bottles consumed in the US were recycled. The number of plastic bottles as a percentage of total debris recovered in beach cleanups is rising (Beck, 2005). Thin high-density polyethylene (HDPE) and thicker LDPE shopping bags are recycled at a rate of around 1% in the US (USEPA, 2003), with trillions being produced worldwide. Many become airborne and soar on the wind to distant waterways and seas. Recently, a BBC photographer (Rebecca Hosking, personal communication), after documenting the effects of plastic waste on the Hawaiian Archipelago, returned to her hometown of Modbury, UK, and succeeded in getting the town's merchants to stop using plastic bags. This movement has spread to other towns and the Mayor of London is now considering a 10 pence tax on the bags. The movement to tax or restrict the use of plastic shopping bags is growing, with new initiatives being reported from around the world on a regular basis, but the author has not been able to locate a summary report where details of these efforts can be found.

3.4. Source reduction, take-back schemes

Because plastic packaging extends the shelf life of products by providing an air and moisture barrier, it is increasingly used in global trade. In some applications, where space is a major concern, bulk packaging, rather than individual containers are preferred, but the trend is for more individual packaging. Producers of consumer plastics in the United States have little incentive to minimize the use of their products, or to design them for ease of recycling. The prevailing attitude among US manufacturers is that they are responding to the demands of the market, and that it is the responsibility of individuals and governments to create infrastructure for dealing with the resultant waste. Rarely are US processors required to subsidize the cost of land filling or otherwise disposing of their manufactured plastic products, which often become fast-track waste. A few US companies have adopted a "zero waste" policy, which requires that their suppliers take-back packaging and provide take-back programs for their customers, but these companies remain a small part of industry as a whole.

European countries, however, are responding to so-called "green dot" initiatives with some packaging reductions. In December 1994, the European Union issued the "Directive on Packaging and Packaging Waste." This legislation places direct responsibility and specific packaging waste reduction targets on all manufacturers, importers and distributors of products on the EU market. To meet the requirements of this legislation, manufacturers, importers and distributors must either develop their own take-back scheme or join industry-driven non-profit organizations, such as the Green Dot Program, to collect, sort and recycle used packaging. Green Dot is currently the standard take-back program in 19 European countries and Canada. Such programs encourage product and packaging design that gives waste value when it is recycled as another product in a "cradle to cradle" system (McDonough and Braungart, 2002). Such schemes may help to reduce plastic waste that ends up in the ocean, but they are far from universal.

3.5. Industry housekeeping

Plastic resin pellets, powders and fragments are widely dispersed from their places of origin. The impacts of powders and plastic debris smaller than pellets are not known, but ingestion by plankton (Bern, 1990; Moore C.J., et al., 2001) and several species of meso-pelagic myctophid fish does occur (Eriksson and Burton, 2003; Moore, C.J., unpublished data). The impacts of pelletized and powdered plastic additives,

including colorants and conditioning chemicals in the marine environment are not well understood, as research is in the initial phases, but Teuten et al. (2007) states that …"plastics may be important agents in the transport of hydrophobic contaminants to sediment-dwelling organisms."

Pre-production plastics (in the form of pellets, powders and production scrap) are accidentally discharged to waterways during the transport, packaging, and processing of plastics when Best Management Practices (BMPs, i.e., proper housekeeping practices) are not adequately employed. For pellets transported by rail, cars are emptied via a valve that connects to a conveyance suction hose. The valve should be capped when not in use. Caps are often not replaced, causing pellet loss within the rail yard adjacent to a facility. A similar conveyance system exists for resins transported by hopper trucks. Pellets and powders escape when hoppers are emptied through pipes connected to valves at the bottom of the truck. When handled improperly, resin pellets and powders are also released from conveyance mechanisms on site. In addition to plastic resins, additives used for coloring or creating specific characteristics of processed plastics are also delivered in pellet and powder form. The discharges to local waterways include colorants and additives, not just plastic resins. Grindings, cuttings and fragments from the processing of plastics, known as production scrap, are often part of the mix of debris that is conveyed by wind and storm water as runoff from plastics facilities to storm drains and nearby waterways (Moore et al., 2005c).

Evidence suggests that pre-production plastic resin pellets accidentally released from plastic processors contribute approximately 10% by count to the plastic debris problem (Moore et al., 2005b; McDermid and McMullen, 2004). In response, the American Plastics Council (APC) and the Society of the Plastics Industry (SPI) in the United States have adopted a voluntary program of BMPs known as "Operation Clean Sweep" (OCS). OCS was first developed in 1980 by SPI. It was recently revised and improved by a collaborative effort between AMRF, APC, and SPI. Measurements of industrial discharge before and after implementation of the program showed reductions of approximately 50% in pellet discharge (Moore et al., 2005c), but recruiting participants from the thermoplastic processing sector has proved challenging (American Plastics Council, personal communication).

3.6. Recycling

Plastic is hard to clean due to the penetration of contaminants into the polymer matrix. It is also difficult to separate composites and mixed plastic waste into the many different plastic types that require different reprocessing technologies. Furthermore, many thermoplastics melt at temperatures not far above the boiling point of water. Therefore, contaminants are not driven off during remanufacture. The price of recycled plastic materials often exceeds the current price of virgin plastic resin (Brandrup, 2003). Because of contamination, recycled plastics can rarely be used in true "closed-loop" recycling; for example, a layer of virgin plastic must be added onto the recycled material for food contact applications. Plastic bags are often used to make plastic "wood", rather than more bags. Plastic wood is not widely recycled and most will end up as land fill or otherwise discarded. In spite of separation schemes for households, only about 5% of plastics in the US are recycled in any way (CIWMB, 2003).

3.7. Bans, legislation

Bans typically focus on high profile waste, such as thin plastic shopping bags and expanded polystyrene cups and clamshell food service containers (commonly but incorrectly called Styrofoam, which is a patented insulation made by Dow Chemical Co.). Bans on some bags and foamed plastics have been adopted by several municipalities in the United States and by some other countries, but most types of plastic packaging and consumer products are unregulated and continue to litter the landscape, and make their way to the ocean.

3.8. Biodegradables

All polymers that occur in nature are biodegradable (Swift, 2003).

Many synthetic "bio-polymers" originate from non-petroleum sources. These include cellulose-based cellophane and rayon, as well as the more modern polylactic acid (PLA) and polyhydroxyalkanoate (PHA), which are derived from fermentation. In general, these plastics biodegrade more rapidly than their petroleum-based counterparts. However, typical tests for biodegradability rely on hot, aerated composting media, based on the metabolism of bacteria, fungi and insects. The marine environment is much colder, and many compostable "bioplastics" degrade very slowly at sea, and hardly at all in the deep ocean (Wirsen, 1971). Currently, substitution for conventional plastics is limited by the cost of bioplastics, which is five to ten times greater than for petroleum-based resins. A 1999 projection of the world biodegradables market was that it would grow from 30 to 250×10^6 pounds per year, while petroleum plastics sell at 1000 times that rate, or 250×10^9 pounds annually (New York Times, 1999). While bioplastics may offer a more sustainable industry product with reduced environmental effects, Swift (2003, p. 499) states: "…modification of natural polymers either by grafting synthetic polymers or by chemical conversions such as oxidation and esterification, changes their properties and biodegradation characteristics significantly. Therefore, polymers produced by any of these modifications must be evaluated for biodegradability in the same manner as purely synthetic polymers."

4. Recommendations

In 2002, the State of California Water Resources Control Board awarded a half million dollar US grant to AMRF and the California Coastal Commission (CCC) to assess the amount of plastic debris entering the ocean from the Los Angeles Basin's two largest watersheds. The grant provided for a process to develop recommendations to reduce these inputs. In 2005, during the first international conference on plastic debris, called "Plastic Debris, Rivers to Sea," sponsored by the CCC and AMRF (www.plasticdebris.org), the participants were encouraged to participate in writing these recommendations. The result was a comprehensive booklet (Gordon, 2006). It included 63 recommendations for action which were grouped into the following categories:

1. the need for improved coordination
2. research needs
3. specific sources of land-based discharges
4. product wastes.

In part as a result of these recommendations, the California Ocean Protection Council (2007) adopted a resolution on marine debris, which listed many of the recommendations found in AMRF and the CCC's Action Plan. Certain California legislators then proposed, under the mantle of "The Pacific Protection Initiative," two Assembly bills and two Senate bills to address marine debris issues. Assembly Bill 258 requires the State Water Board and

Regional Water Boards to implement a program to control discharges of pre-production plastic pellets, which are used to make plastic products, into rivers and streams. The bill was signed into law by Governor Swarzenegger on October 1, 2007. Three other bills are still pending. Assembly Bill 904 would require that takeout food packaging be made from recyclable or compostable materials starting July 1, 2012. Senate Bill 898 would require the California Integrated Waste Management Board to address derelict (abandoned) fishing gear, and assign resin code labeling for bioplastics. Senate Bill 899 would implement a phased-ban of toxic additives in plastic packaging, such as Bisphenol-A. Details of international legal and other actions to deal with marine debris are beyond the scope of this review, and the author has not been able to locate a comprehensive report that lists and updates this type of international data, but such a compilation would be of benefit to those seeking solutions to the problems caused by persistent plastic debris.

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