PERGAMON

Marine Pollution Bulletin 44 (2002) 842–852

MARINE POLLUTION BULLETIN

www.elsevier.com/locate/marpolbul

Review

The pollution of the marine environment by plastic debris: a review

José G.B. Derraik *

Ecology and Health Research Centre, Department of Public Health, Wellington School of Medicine and Health Sciences, University of Otago, P.O. Box 7343, Wellington, New Zealand

Abstract

The deleterious effects of plastic debris on the marine environment were reviewed by bringing together most of the literature published so far on the topic. A large number of marine species is known to be harmed and/or killed by plastic debris, which could jeopardize their survival, especially since many are already endangered by other forms of anthropogenic activities. Marine animals are mostly affected through entanglement in and ingestion of plastic litter. Other less known threats include the use of plastic debris by "invader" species and the absorption of polychlorinated biphenyls from ingested plastics. Less conspicuous forms, such as plastic pellets and "scrubbers" are also hazardous. To address the problem of plastic debris in the oceans is a difficult task, and a variety of approaches are urgently required. Some of the ways to mitigate the problem are discussed.

Keywords: Plastic debris; Pollution; Marine environment

1. Introduction

Human activities are responsible for a major decline of the world's biological diversity, and the problem is so critical that combined human impacts could have accelerated present extinction rates to 1000–10,000 times the natural rate (Lovejoy, 1997). In the oceans, the threat to marine life comes in various forms, such as overexploitation and harvesting, dumping of waste, pollution, alien species, land reclamation, dredging and global climate change (Beatley, 1991; National Research Council, 1995; Irish and Norse, 1996; Ormond et al., 1997; Tickel, 1997; Snelgrove, 1999). One particular form of human impact constitutes a major threat to marine life: the pollution by plastic debris.

1.1. Plastic debris

Plastics are synthetic organic polymers, and though they have only existed for just over a century (Gorman, 1993), by 1988 in the United States alone, 30 million tons of plastic were produced annually (O'Hara et al., 1988). The versatility of these materials has lead to a great increase in their use over the past three decades, and they have rapidly moved into all aspects of everyday life (Hansen, 1990; Laist, 1987). Plastics are lightweight, strong, durable and cheap (Laist, 1987), characteristics that make them suitable for the manufacture of a very wide range of products. These same properties happen to be the reasons why plastics are a serious hazard to the environment (Pruter, 1987; Laist, 1987). Since they are also buoyant, an increasing load of plastic debris is being dispersed over long distances, and when they finally settle in sediments they may persist for centuries (Hansen, 1990; Ryan, 1987b; Goldberg, 1995, 1997).

The threat of plastics to the marine environment has been ignored for a long time, and its seriousness has been only recently recognised (Stefatos et al., 1999). Fergusson (1974) for instance, then a member of the Council of the British Plastics Federation and a Fellow of the Plastics Institute, stated that "plastics litter is a very small proportion of all litter and causes no harm to the environment except as an eyesore". His comments not only illustrates how the deleterious environmental effects of plastics were entirely overlooked, but also that, apparently, even the plastics industry failed to predict the great boom in the production and use of plastics of the past 30 years. In the marine environment, the perceived abundance of marine life and the vastness of the oceans have lead to the dismissal of the proliferation of plastic debris as a potential hazard (Laist, 1987).

---

* Fax: +64-4-389-5319.
E-mail address: jderraik@wnmeds.ac.nz (J.G.B. Derraik).

0025-326X/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0025-326X(02)00220-5

The literature on marine debris leaves no doubt that plastics make-up most of the marine litter worldwide (Table 1). Though the methods were not assessed to ensure that the results were comparable, Table 1 clearly indicates the predominance of plastics amongst the marine litter, and its proportion consistently varies between 60% and 80% of the total marine debris (Gregory and Ryan, 1997).

It is not possible to obtain reliable estimates of the amount of plastic debris that reaches the marine environment, but the quantities are nevertheless quite substantial. In 1975 the world's fishing fleet alone dumped into the sea approximately 135,400 tons of plastic fishing gear and 23,600 tons of synthetic packaging material (Cawthorn, 1989; DOC, 1990). Horsman (1982) estimated that merchant ships dump 639,000 plastic containers each day around the world, and ships are therefore, a major source of plastic debris (Shaw, 1977; Shaw and Mapes, 1979). Recreational fishing and boats are also responsible for dumping a considerable amount of marine debris, and according to the US Coast Guard they dispose approximately 52% of all rubbish dumped in US waters (UNESCO, 1994).

Plastic materials also end up in the marine environment when accidentally lost, carelessly handled (Wilber, 1987) or left behind by beachgoers (Pruter, 1987). They also reach the sea as litter carried by rivers and municipal drainage systems (Pruter, 1987; Williams and Simmons, 1997). There are major inputs of plastic litter from land-based sources in densely populated or industrialized areas (Pruter, 1987; Gregory, 1991), most in the form of packaging. A study on Halifax Harbour

Table 1
Proportion of plastics among marine debris worldwide (per number of items)

Locality	Litter type	Percentage of debris items represented by plastics	Source
1992 International Coastal Cleanups	Shoreline	59	Anon (1990)
St. Lucia, Caribbean	Beach	51	Corbin and Singh (1993)
Dominica, Caribbean	Beach	36	Corbin and Singh (1993)
Curaçao, Caribbean	Beach	40/64	Debrot et al. (1999)
Bay of Biscay, NE Atlantic	Seabed	92	Galgani et al. (1995a)
NW Mediterranean	Seabed	77	Galgani et al. (1995b)
French Mediterranean Coast	Deep sea floor	>70	Galgani et al. (1996)
European coasts	Sea floor	>70	Galgani et al. (2000)
Caribbean coast of Panama	Shoreline	82	Garrity and Levings (1993)
Georgia, USA	Beach	57	Gilligan et al. (1992)
5 Mediterranean beaches	Beach	60–80	Golik (1997)
50 South African beaches	Beach	>90	Gregory and Ryan (1997)
88 sites in Tasmania	Beach	65	Gregory and Ryan (1997)
Argentina	Beach	37–72	Gregory and Ryan (1997)
9 Sub-Antarctic Islands	Beach	51–88	Gregory and Ryan (1997)
South Australia	Beach	62	Gregory and Ryan (1997)
Kodiak Is, Alaska	Seabed	47–56	Hess et al. (1999)
Tokyo Bay, Japan	Seabed	80–85	Kanehiro et al. (1995)
North Pacific Ocean	Surface waters	86	Laist (1987)
Mexico	Beach	60	Lara-Dominguez et al. (1994)
Transkei, South Africa	Beach	83	Madzena and Lasiak (1997)
National Parks in USA	Beach	88	Manski et al. (1991)
Mediterranean Sea	Surface waters	60–70	Morris (1980)
Cape Cod, USA	Beach/harbour	90	Ribic et al. (1997)
4 North Atlantic harbors, USA	Harbour	73–92	Ribic et al. (1997)
Is. Beach State Park, New Jersey, USA	Beach	73	Ribic (1998)
Halifax Harbour, Canada	Beach	54	Ross et al. (1991)
Price Edward Is., Southern Ocean	Beach	88	Ryan (1987b)
Gough Is., Southern Ocean	Beach	84	Ryan (1987b)
Heard Is., Southern Ocean	Beach	51	Slip and Burton (1991)
Macquire Is., Southern Ocean	Beach	71	Slip and Burton (1991)
New Zealand	Beach	75	Smith and Tooker (1990)
Two gulfs in W. Greece	Seabed	79–83	Stefatos et al. (1999)
South German Bight	Beach	75	Vauk and Schrey (1987)
Bird Is., South Georgia, Southern Ocean	Beach	88[a]	Walker et al. (1997)
Fog Bay, N. Australia	Beach	32	Whiting (1998)
South Wales, UK	Beach	63	Williams and Tudor (2001)

Results are arranged in alphabetical order by author.

[a] 76% of total consisted of synthetic line for long-line fisheries.

in Canada, for instance, showed that 62% of the total litter in the harbour originated from recreation and land-based sources (Ross et al., 1991). In contrast, in beaches away from urban areas (e.g. Alaska) most of the litter is made up of fishing debris.

Not only the aesthetically distasteful plastic litter, but also less conspicuous small plastic pellets and granules are a threat to marine biota. The latter are found in large quantities on beaches (Gregory, 1978, 1989; Shiber, 1979, 1982, 1987; Redford et al., 1997), and are the raw material for the manufacture of plastic products that end up in the marine environment through accidental spillage during transport and handling, not as litter or waste as other forms of plastics (Gregory, 1978; Shiber, 1979; Redford et al., 1997). Their sizes usually vary from 2–6 mm, though occasionally much larger ones can be found (Gregory, 1977, 1978).

Plastic pellets can be found across the Southwest Pacific in surprisingly high quantities for remote and non-industrialised places such as Tonga, Rarotonga and Fiji (Gregory, 1999). In New Zealand beaches they are found in quite considerable amounts, in counts of over 100,000 raw plastic granules per meter of coast (Gregory, 1989), with greatest concentration near important industrial centres (Gregory, 1977). Their durability in the marine environment is still uncertain but they seem to last from 3 to 10 years, and additives can probably extend this period to 30–50 years (Gregory, 1978).

Unfortunately, the dumping of plastic debris into the ocean is an increasing problem. For instance, surveys carried out in South African beaches 5 years apart, showed that the densities of all plastic debris have increased substantially (Ryan and Moloney, 1990). In Panama, experimentally cleared beaches regained about 50% of their original debris load after just 3 months (Garrity and Levings, 1993). Even subantarctic islands are becoming increasingly affected by plastic debris, especially fishing lines (Walker et al., 1997). Benton (1995) surveyed islands in the South Pacific and got to the alarming conclusion that beaches in remote areas had a comparable amount of garbage to a beach in the industrialized western world.

2. The threats from plastics pollution to marine biota

There is still relatively little information on the impact of plastics pollution on the ocean's ecosystems (Quayle, 1992; Wilber, 1987). There is however an increasing knowledge about their deleterious impacts on marine biota (Goldberg, 1995). The threats to marine life are primarily mechanical due to ingestion of plastic debris and entanglement in packaging bands, synthetic ropes and lines, or drift nets (Laist, 1987, 1997; Quayle, 1992).

Since the use of plastics continues to increase, so does the amount of plastics polluting the marine environment. Robards et al. (1995) examined the gut content of thousands of birds in two separate studies and found that the ingestion of plastics by seabirds had significantly increased during the 10–15 years interval between studies. A study done in the North Pacific (Blight and Burger, 1997) found plastic particles in the stomachs of 8 of the 11 seabird species caught as bycatch. The list of affected species indicates that marine debris are affecting a significant number of species (Laist, 1997). It affects at least 267 species worldwide, including 86% of all sea turtle species, 44% of all seabird species, and 43% of all marine mammal species (Laist, 1997). The problem may be highly underestimated as most victim are likely to go undiscovered over vast ocean areas, as they either sink or are eaten by predators (Wolfe, 1987).

There is also potential danger to marine ecosystems from the accumulation of plastic debris on the sea floor. According to Kanehiro et al. (1995) plastics made up 80–85% of the seabed debris in Tokyo Bay, an impressive figure considering that most plastic debris are buoyant. The accumulation of such debris can inhibit the gas exchange between the overlying waters and the pore waters of the sediments, and the resulting hypoxia or anoxia in the benthos can interfere with the normal ecosystem functioning, and alter the make-up of life on the sea floor (Goldberg, 1994). Moreover, as for pelagic organisms, benthic biota is likewise subjected to entanglement and ingestion hazards (Hess et al., 1999).

2.1. Ingestion of plastics

A study done on 1033 birds collected off the coast of North Carolina in the USA found that individuals from 55% of the species recorded had plastic particles in their guts (Moser and Lee, 1992). The authors obtained evidence that some seabirds select specific plastic shapes and colors, mistaking them for potential prey items. Shaw and Day (1994) came to the same conclusions, as they studied the presence of floating plastic particles of different forms, colors and sizes in the North Pacific, finding that many are significantly under-represented. Carpenter et al. (1972) examined various species of fish with plastic debris in their guts and found that only white plastic spherules had been ingested, indicating that they feed selectively. A similar pattern of selective ingestion of white plastic debris was found for loggerhead sea turtles (*Caretta caretta*) in the Central Mediterranean (Gramentz, 1988). Among seabirds, the ingestion of plastics is directly correlated to foraging strategies and technique, and diet (Azzarello and Van-Vleet, 1987; Ryan, 1987a; Moser and Lee, 1992; Laist, 1987, 1997). For instance, planktivores are more likely to confuse plastic pellets with their prey than do piscivores, therefore the former have a higher incidence of ingested plastics (Azzarello and Van-Vleet, 1987).

Ryan (1988) performed an experiment with domestic chickens (*Gallus domesticus*) to establish the potential effects of ingested plastic particles on seabirds. They were fed with polyethylene pellets and the results indicated that ingested plastics reduce meal size by reducing the storage volume of the stomach and the feeding stimulus. He concluded that seabirds with large plastic loads have reduced food consumption, which limits their ability to lay down fat deposits, thus reducing fitness. Connors and Smith (1982) had previously reached the same conclusion, as their study indicated that the ingestion of plastic particles hindered formation of fat deposits in migrating red phalaropes (*Phalaropus fulicarius*), adversely affecting long-distance migration and possibly their reproductive effort on breeding grounds. Spear et al. (1995) however, provided probably the first solid evidence for a negative relationship between number of plastic particles ingested and physical condition (body weight) in seabirds from the tropical Pacific.

Other harmful effects from the ingestion of plastics include blockage of gastric enzyme secretion, diminished feeding stimulus, lowered steroid hormone levels, delayed ovulation and reproductive failure (Azzarello and Van-Vleet, 1987). The ingestion of plastic debris by small fish and seabirds for instance, can reduce food uptake, cause internal injury and death following blockage of intestinal tract (Carpenter et al., 1972; Rothstein, 1973; Ryan, 1988; Zitko and Hanlon, 1991). The extent of the harm, however, will vary among species. Procellariiformes for example, are more vulnerable due to their inability to regurgitate ingested plastics (Furness, 1985; Azzarello and Van-Vleet, 1987).

Laist (1987) and Fry et al. (1987) observed that adults that manage to regurgitate plastic particles could pass them onto the chicks during feeding. The chicks of Laysan albatrosses (*Diomedea immutabilis*) in the Hawaiian Islands for instance, are unable to regurgitate such materials which accumulate in their stomachs, becoming a significant source of mortality, as 90% of the chicks surveyed had some sort of plastic debris in their upper GI tract (Fry et al., 1987). Even Antarctic and sub-Antarctic seabirds are subjected to this hazard (Slip et al., 1990). Wilson's storm-petrels (*Oceanites oceanicus*) for instance, pick up plastic debris while wintering in other areas (Van Franeker and Bell, 1988). A white-faced storm-petrel (*Pelagodroma marina*) found dead at the isolated Chatham Islands (New Zealand) at a breeding site, had no food in its stomach while its gizzard was packed with plastic pellets (Bourne and Imber, 1982).

The harm from ingestion of plastics is nevertheless not restricted to seabirds. Polythene bags drifting in ocean currents look much like the prey items targeted by turtles (Mattlin and Cawthorn, 1986; Gramentz, 1988; Bugoni et al., 2001). There is evidence that their survival is being hindered by plastic debris (Duguy et al., 1998), with young sea turtles being particularly vulnerable (Carr, 1987). Balazs (1985) listed 79 cases of turtles whose guts were full of various sorts of plastic debris, and O'Hara et al. (1988) cited a turtle found in New York that had swallowed 540 m of fishing line. Oesophagus and stomach contents were examined from 38 specimens of the endangered green sea turtle (*Chelonia mydas*) on the south of Brazil, 23 of which (60.5%) had ingested anthropogenic debris, mainly plastics (Bugoni et al., 2001). Among other *C. mydas* washed ashore in Florida, 56% had anthropogenic debris in their digestive tracts (Bjorndal et al., 1994). Tomás et al. (2002) found that 75.9% of 54 loggerhead sea turtles (*C. caretta*) captured by fishermen had plastic debris in their digestive tracts.

At least 26 species of cetaceans have been documented to ingest plastic debris (Baird and Hooker, 2000). A young male pygmy sperm whale (*Kogia breviceps*) stranded alive in Texas, USA, died in a holding tank 11 days later (Tarpley and Marwitz, 1993). The necropsy showed that the first two stomach compartments were completely occluded by plastic debris (garbage can liner, a bread wrapper, a corn chip bag and two other pieces of plastic sheeting). The death of an endangered West Indian manatee (*Trichechus manatus*) in 1985 in Florida was apparently caused by a large piece of plastic that blocked its digestive tract (Laist, 1987). Deaths of the also endangered Florida manatee (*Trichechus manatus latirostris*) have too been blamed on plastic debris in their guts (Beck and Barros, 1991). Secchi and Zarzur (1999) blamed the fate of a dead Blainville's beaked whale (*Mesoplodon densirostris*) washed ashore in Brazil to a bundle of plastic threads found in the animals' stomach. Coleman and Wehle (1984) and Baird and Hooker (2000) cited other cetaceans that have been reported with ingested plastics, such as the killer whale (*Orcinus orca*).

Some species of fish off the British coast were found to contain plastic cups within their guts that would eventually lead to their death (Anon, 1975). In the Bristol Channel in the summer of 1973, 21% of the flounders (*Platichthyes flesus*) were found to contain polystyrene spherules (Kartar et al., 1976). The same study found, that in some areas, 25% of sea snails (*Liparis liparis*) (a fish, despite its common name) were heavily contaminated by such debris. In the New England coast, USA, the same type of spherules were found in 8 out of 14 fish species examined, and in some species 33% of individuals were contaminated (Carpenter et al., 1972).

2.2. Plastics ingestion and polychlorinated biphenyls

Over the past 20 years polychlorinated biphenyls (PCBs) have increasingly polluted marine food webs, and are prevalent in seabirds (Ryan et al., 1988). Though their adverse effects may not always be apparent, PCBs lead to reproductive disorders or death, they increase risk of diseases and alter hormone levels (Ryan et al., 1988; Lee et al., 2001). These chemicals have a detrimental effect on marine organisms even at very low levels and plastic pellets could be a route for PCBs into marine food chains (Carpenter and Smith, 1972; Carpenter et al., 1972; Rothstein, 1973; Zitko and Hanlon, 1991; Mato et al., 2001).

Ryan et al. (1988) studying great shearwaters (*Puffinus gravis*), obtained evidence that PCBs in the birds' tissues were derived from ingested plastic particles. Their study presented the first indication that seabirds can assimilate chemicals from plastic particles in their stomachs, indicating a dangerous pathway for potentially harmful pollutants. Bjorndal et al. (1994) worked with sea turtles and came to a similar conclusion, that the absorption of toxins as sublethal effects of debris ingestion has an unknown, but potentially great negative effect on their demography.

Plastic debris can be a source of other contaminants besides PCBs. According to Zitko (1993) low molecular weight compounds from polystyrene particles are leached by seawater, and the fate and effects of such compounds on aquatic biota are not known.

2.3. Entanglement in plastic debris

Entanglement in plastic debris, especially in discarded fishing gear, is a very serious threat to marine animals. According to Schrey and Vauk (1987) entanglement accounts for 13–29% of the observed mortality of gannets (*Sula bassana*) at Helgoland, German Bight. Entanglement also affects the survival of the endangered sea turtles (Carr, 1987), but it is a particular problem for marine mammals, such as fur seals, which are both curious and playful (Mattlin and Cawthorn, 1986).

Young fur seals are attracted to floating debris and dive and roll about in it (Mattlin and Cawthorn, 1986). They will approach objects in the water and often poke their heads into loops and holes (Fowler, 1987; Laist, 1987). Though the plastic loops can easily slip onto their necks, the lie of the long guard hairs prevents the strapping from slipping off (Mattlin and Cawthorn, 1986). Many seal pups grow into the plastic collars, and in time as it tightens, the plastic severs the seal's arteries or strangles it (Weisskopf, 1988). Ironically, once the entangled seal dies and decomposes, the plastic band is free to be picked up by another victim (DOC, 1990; Mattlin and Cawthorn, 1986), as some plastic articles may take 500 years to decompose (Gorman, 1993; UNESCO, 1994).

Once an animal is entangled, it may drown, have its ability to catch food or to avoid predators impaired, or incur wounds from abrasive or cutting action of attached debris (Laist, 1987, 1997; Jones, 1995). According to Feldkamp et al. (1989) entanglement can greatly reduce fitness, as it leads to a significant increase in energetic costs of travel. For the northern fur seals (*Callorhinus ursinus*), for instance, they stated that net fragments over 200 g could result in 4-fold increase in the demand of food consumption to maintain body condition.

The decline in the populations of the northern sea lion (*Eumetopias jubatus*), endangered Hawaiian monk seal (*Monachus schauinslandi*) (Henderson, 1990, 2001) and northern fur seal (Fowler, 1987) seems at least aggravated by entanglement of young animals in lost or discarded nets and packing bands. In the Pribiloff Islands alone, in the Bering Sea west of Alaska, the percentage of northern fur seals returning to rookeries entangled in plastic bands rose from nil in 1969 to 38% in 1973 (Mattlin and Cawthorn, 1986). The population in 1976 was declining at a rate of 4–6% a year, and scientists estimated that up to 40,000 fur seals a year were being killed by plastic entanglement (Weisskopf, 1988). A decline due to entanglement also seems to be occurring with Antarctic fur seals (*Arctocephalus gazella*) (Croxall et al., 1990). Pemberton et al. (1992) and Jones (1995) both reported similar concern for Australian fur seals (*Arctocephalus pusillus doriferus*). At South-east Farallon Island, Northern California, a survey from 1976–1988 observed 914 pinnipeds entangled in or with body constrictions from synthetic materials (Hanni and Pyle, 2000).

Lost or abandoned fishing nets pose a particular great risk (Jones, 1995). These "ghost nets" continue to catch animals even if they sink or are lost on the seabed (Laist, 1987). In 1978, 99 dead seabirds and over 200 dead salmon were counted during the retrieval of a 1500 m ghost net south of the Aleutian Islands (DeGange and Newby, 1980). In a survey done in 1983/84 off the coast of Japan, it was estimated that 533 fur seals were entangled and drowned in nets lost in the area (Laist, 1987). Whales are also victims, as "they sometimes lunge for schools of fish and surface with netting caught in their mouths or wrapped around their heads and tails" (Weisskopf, 1988).

2.4. Plastic "scrubbers"

Studies (Gregory, 1996; Zitko and Hanlon, 1991) have drawn attention to an inconspicuous and previously overlooked form of plastics pollution: small fragments of plastic (usually up to 0.5 mm across) derived from hand cleaners, cosmetic preparations and airblast cleaning media. The environmental impact of these particles, as well as similar sized flakes from degradation of larger plastic litter, has not been properly established yet.

In New Zealand and Canada, polyethylene and polystyrene scrubber grains respectively were identified in the cleansing preparations available in those markets, sometimes in substantial quantities (Gregory, 1996). In airblasting technology, polyethylene particles are used for stripping paint from metallic surfaces and cleaning engine parts, and can be recycled up to 10 times before they have to be discarded, sometimes significantly contaminated by heavy metals (Gregory, 1996). Once discarded they enter into foul water or reticulate sanitary systems, and though some may be trapped during sewage treatment, most will be discharged into marine waters; and as they float, they concentrate on surface waters and are dispersed by currents (Gregory, 1996).

There are many possible impacts of these persistent particles on the environment (Zitko and Hanlon, 1991). For instance, heavy metals or other contaminants could be transferred to filter feeding organisms and other invertebrates, ultimately reaching higher trophic levels (Gregory, 1996).

2.5. Drift plastic debris: possible pathway for the invasion of alien species

The introduction of alien species can have major consequences for marine ecosystems (Grassle et al., 1991). This biotic mixing is becoming a widespread problem due to human activities, and it is a potential threat to native marine biodiversity (McKinney, 1998). According to some estimates, global marine species diversity may decrease by as much as 58% if worldwide biotic mixing occurs (McKinney, 1998).

Plastics floating at sea may acquire a fauna of various encrusting organisms such as bacteria, diatoms, algae, barnacles, hydroids and tunicates (Carpenter et al., 1972; Carpenter and Smith, 1972; Minchin, 1996; Clark, 1997). The bryozoan *Membranipora tuberculata*, for instance, is believed to have crossed the Tasman Sea, from Australia to New Zealand, encrusted on plastic pellets (Gregory, 1978). The same species together with another bryozoan (*Electra tenella*) were found on plastics washed ashore on the Florida coast, USA, and they seem to be increasing their abundance in the region by drifting on plastic debris from the Caribbean area (Winston, 1982; Winston et al., 1997). Minchin (1996) also describes barnacles that crossed the North Atlantic Ocean attached to plastic debris.

Drift plastics can therefore increase the range of certain marine organisms or introduce species into an environment where they were previously absent (Winston, 1982). Gregory (1991, 1999) pointed out that the arrival of unwanted and aggressive alien taxa could be detrimental to littoral, intertidal and shoreline ecosystems. He emphasised the risk to the flora and fauna of conservation islands, for instance, as alien species could arrive rafted on drifting plastics.

3. Discussion and recommendations

Though the seas cover the majority of our planet's surface, far less is known about the biodiversity of marine environments then that of terrestrial systems (Ormond et al., 1997). Irish and Norse (1996) examined all 742 papers published in the journal Conservation Biology and found that only 5% focused on marine ecosystems and species, compared with 67% on terrestrial and 6% on freshwater. As a result of this disparity, marine conservation biology severely lags behind the terrestrial counterpart (Murphy and Duffus, 1996), and this gap of knowledge poses major problems for conservation of marine biodiversity and must be addressed.

This study shows that there is overwhelming evidence that plastic pollution is a threat to marine biodiversity, already at risk from overfishing, climate change and other forms of anthropogenic disturbance. So far however, that evidence is basically anecdotal. There is a need for more research (especially long term monitoring) to assess the actual threat posed by plastic debris to marine species. The research information would provide input for conservation management, strengthen the basis for educational campaigns, and also provide marine scientists with better evidence that could be used to demand from the authorities more effort to mitigate the problem. Due to the long life of plastics on marine ecosystems, it is imperative that severe measures are taken to address the problem at both international and national levels, since even if the production and disposal of plastics suddenly stopped, the existing debris would continue to harm marine life for many decades.

3.1. Plastics pollution and legislation

There have been nevertheless some attempts to promote the conservation of the world's oceans through international legislation, such as the establishment of the 1972 Convention on the Prevention of Marine Pollution by Dumping Wastes and Other Matter (the London Dumping Convention or LDC). The most important legislation addressing the increasing problem of marine pollution is probably the 1978 Protocol to the International Convention for the Prevention of Pollution from Ships (MARPOL), which recognised that vessels present a significant and controllable source of pollution into the marine environment (Lentz, 1987).

The Annex V of MARPOL is the key international authority for controlling ship sources of marine debris (Ninaber, 1997), and came into effect in 1988 (Clark, 1997). It "restricts at sea discharge of garbage and bans at sea disposal of plastics and other synthetic materials such as ropes, fishing nets, and plastic garbage bags with limited exceptions" (Pearce, 1992). More importantly, the Annex V applies to all watercraft, including small recreational vessels (Nee, 1990). Seventy-nine countries have so far ratified the Annex V (CMC, 2002), and the signatory countries are required to take steps to fully implement it. Annex V also refers to "special areas", including the Mediterranean Sea, the Baltic Sea, the Black Sea, the Red Sea and the "Gulfs" areas, where discharge regulations are far more strict (Lentz, 1987).

Nevertheless, the legislation is still widely ignored, and ships are estimated to discard 6.5 million tons per year of plastics (Clark, 1997). Observers on board foreign fishing vessels within Australian waters, for instance, found that at least one-third of the vessels did not comply with the MARPOL regulations on the disposal of plastics (Jones, 1995). As Kirkley and McConnell (1997) pointed out, the compliance of individuals with laws is partly a question of economics. They believe most people (or companies) would not change their attitude if stopping the dumping of plastics into the ocean were economically costly. Henderson (2001) assessed the impact of Annex V and found reduction neither in the accumulation of marine debris nor in the entanglement rate of Hawaiian monk seals in the Northwestern Hawaiian Islands. Amos (1993) and Johnson (1994) however, found that it has been of some effect in reducing plastic litter in the oceans.

Legislation at the national level also plays an important role. Individual countries can be effective through their own legislation, such as laws that require degradability standards or that encourage recycling (Bean, 1987). In the USA, for instance, the Marine Plastics Pollution Research and Control Act of 1987 not only adopted Annex V, but also extended its application to US Navy vessels (Nee, 1990; Bentley, 1994). Ports and ocean carriers have to adapt to these regulations prohibiting the disposal of plastics at sea (Nee, 1990). The biggest difficulty however when it comes to legislation, is to actually enforce it in an area as vast as the world's oceans. It is therefore essential that neighbouring countries work together in order to ensure that all vessels comply with Annex V.

3.2. Other issues and ways to prevent marine pollution

Education is also a very powerful tool to address the issue, especially if it is discussed in schools. Youngsters not only can change habits with relative ease, but also be able to take their awareness into their families and the wider community, working as catalysts for change. Since land-based sources provide major inputs of plastic debris into the oceans, if a community becomes aware of the problem, and obviously willing to act upon it, it can actually make a significant difference. The power of education should not be underestimated, and it can be more effective than strict laws, such as the Suffolk County Plastics Law (in New York, USA) that banned some retail food packaging and was unsuccessful in reducing beach and roadside litter (Ross and Swanson, 1995). There may also be a need for financial incentives as Ray and Grassle (1991) stressed "no effort to conserve biological diversity is realistic outside the economics and public policies that drive the modern world".

There are also more complicated aspects of the problem of plastic pollution. As it could be seen as a "side-effect" of progress, those countries undergoing economic development will seek their share of growth, putting an increasing pressure on the environment. It is unlikely that such nations would take any steps to reduce the use of plastics or their disposal into the oceans, if that would compromise any short-term economic gain. Especially when nations from the developed world are being careless themselves, and still failing to comply with the requirements of Annex V.

One possibility to mitigate the problem is the development and use of biodegradable and photodegradable plastics (Wolf and Feldman, 1991; Gorman, 1993). The US Navy, for instance, was working on a promising biopolymer (regenerated cellulose) for the fabrication of marine-disposable trash bags (Andrady et al., 1992). Unfortunately, the effects of the final degradation products of those materials are not yet known, and there is the danger of substituting one problem for another (Horsman, 1985; Wolf and Feldman, 1991; Quayle, 1992). Therefore studies were being done, for example, to monitor the degradation of polymers in natural waters under real-life conditions (Mergaert et al., 1995) and assess the impact of degradation products on estuarine benthos (Doering et al., 1994).

3.3. Final remarks

Ultimately, all sectors of the community should take their individual steps. *Thinking globally and acting locally* is a fundamental attitude to reduce such an environmental threat. A combination of legislation and the enhancement of ecological consciousness through education is likely to be the best way to solve such environmental problems. The general public and the scientific community have also the responsibility of ensuring that governments and businesses change their attitudes towards the problem. It is nevertheless certain that the environmental hazards that threaten the oceans' biodiversity, such as the pollution by plastic debris, must be urgently addressed.

> "The last fallen mahogany would lie perceptibly on the landscape, and the last black rhino would be obvious in its loneliness, but a marine species may disappear beneath the waves unobserved and the sea would seem to roll on the same as always" (Ray, 1988, p. 45).

Acknowledgements

I would like to thank Jenny Smith for her thorough proof reading. Special thanks must go to Eduardo Secchi (Department of Zoology, University of Otago, New Zealand) and Gilberto Fillmann (CCMS—Plymouth Marine Laboratory, United Kingdom) for their valuable input.

References

Anon, 1975. Plastic cups found in fish. Marine Pollution Bulletin 6, 148.

Anon, 1990. Garbage. Center for Marine Conservation, Washington DC.

Amos, A.F., 1993. Solid waste pollution on Texas beaches: a post MARPOL annex V study, vol. 1. OCS Study MMS 93-0013. United States Department of Interior, New Orleans.

Andrady, A.L., Pegram, J.E., Olson, T.M., 1992. Research and development of two marine-degradable biopolymers. Report, David-Taylor Research Centre, Research Triangle Park, Northern Carolina, USA.

Azzarello, M.Y., Van-Vleet, E.S., 1987. Marine birds and plastic pollution. Marine Ecology Progress Series 37, 295–303.

Baird, R.W., Hooker, S.K., 2000. Ingestion of plastic and unusual prey by a juvenile Harbour Porpoise. Marine Pollution Bulletin 40, 719–720.

Balazs, G., 1985. Impact of ocean debris on marine turtles: entanglement and ingestion. In: Shomura, R.S., Yoshida, H.O. (Eds.), Proceedings of the Workshop on the Fate and Impact of Marine Debris, 27–29 November 1984, Honolulu. US Department of Commerce, pp. 387–429. NOAA Technical Memorandum NMFS SWFC-54.

Bean, M.J., 1987. Legal strategies for reducing persistent plastics in the marine environment. Marine Pollution Bulletin 18, 357–360.

Beatley, T., 1991. Protecting biodiversity in coastal environments: introduction and overview. Coastal Management 19, 1–19.

Beck, C.A., Barros, N.B., 1991. The impact of debris on the Florida manatee. Marine Pollution Bulletin 22, 508–510.

Bentley, R., 1994. Evaluation of environmentally acceptable packaging for Navy use. In: Marine Technology Society: Challenges and Opportunities in the Marine Environment—Conference Proceedings, pp. 656–662.

Benton, T.G., 1995. From castaways to throwaways: marine litter in the Pitcairn Islands. Biological Journal of the Linnean Society 56, 415–422.

Bjorndal, K.A., Bolten, A.B., Lagueux, C.J., 1994. Ingestion of marine debris by juvenile sea turtles in coastal Florida habitats. Marine Pollution Bulletin 28, 154–158.

Blight, L.K., Burger, A.E., 1997. Occurrence of plastic particles in seabirds from the eastern North Pacific. Marine Pollution Bulletin 34, 323–325.

Bourne, W.R.P., Imber, M.J., 1982. Plastic pellets collected by a prion on Gough Island, Central South Atlantic Ocean. Marine Pollution Bulletin 13, 20–21.

Bugoni, L., Krause, L., Petry, M.V., 2001. Marine debris and human impacts on sea turtles in Southern Brazil. Marine Pollution Bulletin 42, 1330–1334.

Carpenter, E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P., Peck, B.B., 1972. Polystyrene spherules in coastal waters. Science 178, 749–750.

Carpenter, E.J., Smith, K.L., 1972. Plastics on the Sargasso Sea surface. Science 175, 1240–1241.

Carr, A., 1987. Impact of nondegradable marine debris on the ecology and survival outlook of sea turtles. Marine Pollution Bulletin 18, 352–356.

Cawthorn, M., 1989. Impacts of marine debris on wildlife in New Zealand coastal waters. In: Proceedings of Marine Debris in New Zealand's Coastal Waters Workshop, 9 March 1989, Wellington, New Zealand. Department of Conservation, Wellington, New Zealand, pp. 5–6.

Clark, R.B., 1997. Marine Pollution. Clarendon Press, Oxford.

CMC—Center for Marine Conservation, 2002. MARPOL/MPPRCA. Available online on http://www.cmc-ocean.org/mdio/marpol.php3.

Coleman, F.C., Wehle, D.H.S., 1984. Plastic pollution: a worldwide problem. Parks 9, 9–12.

Connors, P.G., Smith, K.G., 1982. Oceanic plastic particle pollution: suspected effect on fat deposition in red phalaropes. Marine Pollution Bulletin 13, 18–20.

Corbin, C.J., Singh, J.G., 1993. Marine debris contamination of beaches in St. Lucia and Dominica. Marine Pollution Bulletin 26, 325–328.

Croxall, J.P., Rodwell, S., Boyd, I.L., 1990. Entanglement in man-made debris of Antarctic fur seals at Bird Island, South Georgia. Marine Mammal Science 6, 221–233.

Debrot, A.O., Tiel, A.B., Bradshaw, J.E., 1999. Beach debris in Curaçao. Marine Pollution Bulletin 38, 795–801.

DeGange, A.R., Newby, T.C., 1980. Mortality of seabirds and fish in a lost salon driftnet. Marine Pollution Bulletin 1, 322–323.

DOC—Department of Conservation, 1990. Marine Debris. Wellington, New Zealand.

Doering, P.H., Sullivan, B.K., Jeon, H., 1994. Effects of biodegradable plastic components on metabolism of an estuarine benthos. Journal of Environmental Polymer Degradation 2, 271–275.

Duguy, R., Moriniere, P., Lemilinaire, C., 1998. Factors of mortality of marine turtles in the Bay of Biscay. Oceanologia Acta 21, 383–388.

Feldkamp, S., Costa, D., DeKrey, G.K., 1989. Energetics and behavioural effects of net entanglement on juvenile northern fur seals *Callorhinus ursinus*. Fisheries Bulletin 87, 85–94.

Fergusson, W.C., 1974. Summary. In: Staudinger, J.J.P. (Ed.), Plastics and the Environment. Hutchinson and Co, London, p. 2.

Fowler, C.W., 1987. Marine debris and northern fur seals: a case study. Marine Pollution Bulletin 18, 326–335.

Fry, D.M., Fefer, S.I., Sileo, L., 1987. Ingestion of plastic debris by Laysan albatross and wedge-tailed shearwaters in the Hawaiian Islands. Marine Pollution Bulletin 18, 339–343.

Furness, R.W., 1985. Plastic particle pollution: accumulation by Procellariiform seabirds at Scottish colonies. Marine Pollution Bulletin 16, 103–106.

Galgani, F., Burgeot, T., Bocquene, G., Vincent, F., Leaute, J.P., Labastie, J., Forest, A., Guichet, R., 1995a. Distribution and abundance of debris on the continental shelf of the Bay of Biscay and in Seine Bay. Marine Pollution Bulletin 30, 58–62.

Galgani, F., Jaunet, S., Campillo, A., Guenegen, X., His, E., 1995b. Distribution and abundance of debris on the continental shelf of the north-western Mediterranean Sea. Marine Pollution Bulletin 30, 713–717.

Galgani, F., Souplet, A., Cadiou, Y., 1996. Accumulation of debris on the deep sea floor of the French Mediterranean Coast. Marine Ecology Progress Series 142, 225–234.

Galgani, F., Leaute, J.P., Moguedet, P., Souplets, A., Verin, Y., Carpenter, A., Goraguer, H., Latrouite, D., Andral, B., Cadiou, Y., Mahe, J.C., Poulard, J.C., Nerisson, P., 2000. Litter on the sea floor along European coasts. Marine Pollution Bulletin 40, 516–527.

Garrity, S.D., Levings, S.C., 1993. Marine debris along the Caribbean coast of Panama. Marine Pollution Bulletin 26, 317–324.

Gilligan, M.R., Randal, S.P., Richardson, J.P., Kozel, T.R., 1992. Rates of accumulation of marine debris in Chatham County, Georgia. Marine Pollution Bulletin 24, 436–441.

Goldberg, E.D., 1994. Diamonds and plastics are forever? Marine Pollution Bulletin 28, 466.

Goldberg, E.D., 1995. The health of the oceans—a 1994 update. Chemical Ecology 10, 3–8.

Goldberg, E.D., 1997. Plasticizing the seafloor: an overview. Environmental Technology 18, 195–202.

Golik, A., 1997. Debris in the Mediterranean Sea: types, quantities, and behavior. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris—Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 7–14.

Gorman, M., 1993. Environmental Hazards—Marine Pollution. ABC-CLIO Inc, Santa Barbara.

Gramentz, D., 1988. Involvement of loggerhead turtle with the plastic, metal, and hydrocarbon pollution in the Central Mediterranean. Marine Pollution Bulletin 19, 11–13.

Grassle, J.F., Lassere, P., McIntyre, A.D., Ray, G.C., 1991. Marine biodiversity and ecosystem function. Biology International Special Issue 23, 1–19.

Gregory, M.R., 1977. Plastic pellets on New Zealand beaches. Marine Pollution Bulletin 8, 82–84.

Gregory, M.R., 1978. Accumulation and distribution of virgin plastic granules on New Zealand beaches. New Zealand Journal of Marine and Freshwater Research 12, 399–414.

Gregory, M.R., 1989. Accumulation of plastic debris in New Zealand's coastal waters and exclusive economic zone. In: Proceedings of Marine Debris in New Zealand's Coastal Waters Workshop, 9 March 1989, Wellington, New Zealand. Department of Conservation, Wellington, New Zealand, pp. 3–4.

Gregory, M.R., 1991. The hazards of persistent marine pollution: drift plastics and conservation islands. Journal of the Royal Society of New Zealand 21, 83–100.

Gregory, M.R., 1996. Plastic "scrubbers" in hand cleansers: a further (and minor) source for marine pollution identified. Marine Pollution Bulletin 32, 867–871.

Gregory, M.R., 1999. Plastics and South Pacific Island shores: environmental implications. Ocean and Coastal Management 42, 603–615.

Gregory, M.R., Ryan, P.G., 1997. Pelagic plastics and other seaborne persistent synthetic debris: a review of Southern Hemisphere perspectives. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris—Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 49–66.

Hanni, K.D., Pyle, P., 2000. Entanglement of pinnipeds in synthetic materials at South-east Farallon Island, California, 1976–1998. Marine Pollution Bulletin 40, 1076–1081.

Hansen, J., 1990. Draft position statement on plastic debris in marine environments. Fisheries 15, 16–17.

Henderson, J.R., 1990. A review of Hawaiian monk seal entanglement in marine debris. In: Shomura, R.S., Yoshida, H.O. (Ed.), Proceedings of the Workshop on the Fate and Impact of Marine Debris, 27–29 November 1984, Honolulu. US Department of Commerce, pp. 326–336.

Henderson, J.R., 2001. A pre- and post-MARPOL Annex V summary of Hawaiian monk seal entanglements and marine debris accumulation in the Northwestern Hawaiian Islands, 1982–1988. Marine Pollution Bulletin 42, 584–589.

Hess, N.A., Ribic, C.A., Vining, I., 1999. Benthic marine debris, with an emphasis on fishery-related items, surrounding Kodiak Island, Alaska, 1994–1996. Marine Pollution Bulletin 38, 885–890.

Horsman, P.V., 1982. The amount of garbage pollution from merchant ships. Marine Pollution Bulletin 13, 167–169.

Horsman, P.V., 1985. Garbage kills. BBC Wildlife 3, 391–393.

Irish, K.E., Norse, E.A., 1996. Scant emphasis on marine biodiversity. Conservation Biology 10, 680.

Johnson, S.W., 1994. Deposition of trawl web on an Alaska beach after implementation of MARPOL Annex V Legislation. Marine Pollution Bulletin 28, 477–481.

Jones, M.M., 1995. Fishing debris in the Australian marine environment. Marine Pollution Bulletin 30, 25–33.

Kanehiro, H., Tokai, T., Matuda, K., 1995. Marine litter composition and distribution on the seabed of Tokyo Bay. Fisheries Engineering 31, 195–199.

Kartar, S., Abou-Seedo, F., Sainsbury, M., 1976. Polystyrene spherules in the Severn Estuary—a progress report. Marine Pollution Bulletin 7, 52.

Kirkley, J., McConnell, K.E., 1997. Marine debris: benefits, costs and choices. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris—Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 171–185.

Laist, D.W., 1987. Overview of the biological effects of lost and discarded plastic debris in the marine environment. Marine Pollution Bulletin 18, 319–326.

Laist, D.W., 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris—Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 99–139.

Lara-Dominguez, A.L., Villalobos-Zapata, G.J., Rivera-Arriaga, E., Vera-Herrera, F., Alvarez-Guillen, H., 1994. Source of solid garbage in Campeche beaches, Mexico. Revista de la Sociedad Mexicana de Historia Natural 45, 133–142.

Lee, K., Tanabe, S., Koh, C., 2001. Contamination of polychlorinated biphenyls (PCBs) in sediments from Kyeonggi Bay and nearby areas, Korea. Marine Pollution Bulletin 42, 273–279.

Lentz, S.A., 1987. Plastics in the marine environment: legal approaches for international action. Marine Pollution Bulletin 18, 361–365.

Lovejoy, T.E., 1997. Biodiversity: what is it? In: Reaka-Kudla, M.K., Wilson, D.E., Wilson, E.O. (Eds.), Biodiversity II: Understanding and Protecting our Biological Resources. Joseph Henry Press, Washington DC, pp. 7–14.

Madzena, A., Lasiak, T., 1997. Spatial and temporal variations in beach litter on the Transkei coast of South Africa. Marine Pollution Bulletin 34, 900–907.

Manski, D.A., Gregg, W.P., Cole, C.A., Richards, D.V., 1991. Annual Report of the National Park Marine Debris Monitoring Program: 1990 Marine Debris Surveys. National Park Services, Washington DC.

Mattlin, R.H., Cawthorn, M.W., 1986. Marine debris—an international problem. New Zealand Environment 51, 3–6.

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

McKinney, R.L., 1998. On predicting biotic homogenization—species-area patterns in marine biota. Global Ecology and Biogeography Letters 7, 297–301.

Mergaert, J., Wouters, A., Anderson, C., Swings, J., 1995. In situ biodegradation of poly(3-hydroxybutyrate) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) in natural waters. Canadian Journal of Microbiology 41, 154–159.

Minchin, D., 1996. Tar pellets and plastics as attachment surfaces for *Lepadid cirripedes* in the North Atlantic Ocean. Marine Pollution Bulletin 32, 855–859.

Morris, R.J., 1980. Floating plastic debris in the Mediterranean. Marine Pollution Bulletin 11, 125.

Moser, M.L., Lee, D.S., 1992. A fourteen-year survey of plastic ingestion by western North Atlantic seabirds. Colonial Waterbirds 15, 83–94.

Murphy, D.D., Duffus, D.A., 1996. Conservation biology and marine biodiversity. Conservation Biology 10, 311–312.

National Research Council, 1995. Understanding marine biodiversity. National Academy Press, Washington DC.

Nee, J., 1990. What do you do when the nearest trashcan is 2000 miles away? Seafarer 39, 8–9.

Ninaber, E., 1997. MARPOL Annex V, commercial ships, and port reception facilites: making it work. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris—Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 239–243.

O'Hara, K., Iudicello, S., Bierce, R., 1988. A Citizen's Guide to Plastics in the Ocean: More than a Litter Problem. Center for Marine Conservation, Washington DC.

Ormond, R.F.G., Gage, J.D., Angel, M.V., 1997. Marine biodiversity: patterns and processes. Cambridge University Press, Cambridge.

Pearce, J.B., 1992. Marine vessel debris: a North American perspective. Marine Pollution Bulletin 24, 586–592.

Pemberton, D., Brothers, N.P., Kirkwood, R., 1992. Entanglement of Australian fur seals in man-made debris in Tasmanian waters. Wildlife Research 19, 151–159.

Pruter, A.T., 1987. Sources, quantities and distribution of persistent plastics in the marine environment. Marine Pollution Bulletin 18, 305–310.

Quayle, D.V., 1992. Plastics in the marine environment: problems and solutions. Chemical Ecology 6, 69–78.

Ray, G.C., 1988. Ecological diversity in coastal zones and oceans. In: Wilson, E.O., Peter, F.M. (Eds.), Biodiversity. National Academy Press, Washington DC, pp. 36–50.

Ray, G.C., Grassle, J.F., 1991. Marine biological diversity. BioScience 41, 453–457.

Redford, D.P., Trulli, H.K., Trulli, W.R., 1997. Sources of plastic pellets in the aquatic environment. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris—Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 335–343.

Ribic, C.A., 1998. Use of indicator items to monitor marine debris on a New Jersey Beach from 1991 to 1996. Marine Pollution Bulletin 36, 887–891.

Ribic, C.A., Scott, W.J., Cole, C.A., 1997. Distribution, type, accumulation, and source of marine debris in the United States, 1989–1993. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris—Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 35–47.

Robards, M.D., Piatt, J.F., Wohl, K.D., 1995. Increasing frequency of plastic particles ingested by seabirds in the subarctic North Pacific. Marine Pollution Bulletin 30, 151–157.

Ross, S.S., Parker, R., Strickland, M., 1991. A survey of shoreline litter in Halifax Harbour 1989. Marine Pollution Bulletin 22, 245–248.

Ross, S.S., Swanson, R.L., 1995. The impact of the Suffolk County, New York, plastics ban on beach and roadside litter. Journal of Environmental Systems 23, 337–351.

Rothstein, S.I., 1973. Plastic particle pollution of the surface of the Atlantic Ocean: evidence from a seabird. Condor 75, 344–345.

Ryan, P.G., 1987a. The incidence and characteristics of plastic particles ingested by seabirds. Marine Environment Research 23, 175–206.

Ryan, P.G., 1987b. The origin and fate of artefacts stranded on islands in the African sector of the Southern Ocean. Environmental Conservation 14, 341–346.

Ryan, P.G., 1988. Effects of ingested plastic on seabird feeding: evidence from chickens. Marine Pollution Bulletin 19, 125–128.

Ryan, P.G., Connell, A.D., Gardner, B.D., 1988. Plastic ingestion and PCBs in seabirds: is there a relationship? Marine Pollution Bulletin 19, 174–176.

Ryan, P.G., Moloney, C.L., 1990. Plastic and other artefacts on South African beaches: temporal trends in abundance and composition. South African Journal of Science 86, 450–452.

Schrey, E., Vauk, G.J.M., 1987. Records of entangled gannets (*Sula bassana*) at Helgoland, German Bight. Marine Pollution Bulletin 18, 350–352.

Secchi, E., Zarzur, S., 1999. Plastic debris ingested by a Blainville's beaked whale, *Mesoplodon densirostris*, washed ashore in Brazil. Aquatic Mammals 25, 21–24.

Shaw, D.G., 1977. Pelagic tar and plastic in the Gulf of Alaska and Bering Sea: 1975. Science of the Total Environment 8, 13–20.

Shaw, D.G., Mapes, G.A., 1979. Surface circulation and the distribution of pelagic tar and plastic. Marine Pollution Bulletin 10, 160–162.

Shaw, D.G., Day, R.H., 1994. Colour- and form-dependent loss of plastic micro-debris from the North Pacific Ocean. Marine Pollution Bulletin 28, 39–43.

Shiber, J.G., 1979. Plastic pellets on the coast of Lebanon. Marine Pollution Bulletin 10, 28–30.

Shiber, J.G., 1982. Plastic pellets on Spain's 'Costa del Sol' beaches. Marine Pollution Bulletin 13, 409–412.

Shiber, J.G., 1987. Plastic pellets and tar on Spain's Mediterranean beaches. Marine Pollution Bulletin 18, 84–86.

Slip, D.J., Burton, H.R., 1991. Accumulation of fishing debris, plastic litter, and other artefacts, on Heard and Macquarie Islands in the Southern Ocean. Environmental Conservation 18, 249–254.

Slip, D.J., Green, K., Woehler, E.J., 1990. Ingestion of anthropogenic articles by seabirds at Macquarie Island. Marine Ornithology 18, 74–77.

Smith, P., Tooker, J., 1990. Marine debris on New Zealand coastal beaches. Greenpeace, Auckland.

Snelgrove, P.V.R., 1999. Getting to the bottom of marine biodiversity: sedimentary habitats. BioScience 49, 129–138.

Spear, L.B., Ainley, D.G., Ribic, C.A., 1995. Incidence of plastic in seabirds from the Tropical Pacific, 1984–91: relation with distribution of species, sex, age, season, year and body weight. Marine Environmental Research 40, 123–146.

Stefatos, A., Charalampakis, M., Papatheodorou, G., Ferentinos, G., 1999. Marine debris on the seafloor of the Mediterranean Sea: examples from two enclosed gulfs in Western Greece. Marine Pollution Bulletin 36, 389–393.

Tarpley, R.J., Marwitz, S., 1993. Plastic debris ingestion by cetaceans along the Texas coast: two case reports. Aquatic Mammals 19, 93–98.

Tickel, C., 1997. The value of biodiversity. In: Ormond, R.F.G., Gage, J.D., Angel, M.V. (Eds.), Marine Biodiversity: Patterns and Processes. Cambridge University Press, Cambridge, pp. xiii–xxii.

Tomás, J., Guitart, R., Mateo, R., Raga, J.A., 2002. Marine debris ingestion in loggerhead sea turtles, *Caretta caretta*, from the Western Mediterranean. Marine Pollution Bulletin 44, 211–216.

UNESCO, 1994. Marine Debris: Solid Waste Management Action Plan for the Wider Caribbean. IOC Technical Series 41, Paris.

Van Franeker, J.A., Bell, P.J., 1988. Plastic ingestion by petrels breeding in Antarctica. Marine Pollution Bulletin 19, 672–674.

Vauk, G.J.M., Schrey, E., 1987. Litter pollution from ships in the German Bight. Marine Pollution Bulletin 18, 316–319.

Walker, T.R., Reid, K., Arnould, J.P.Y., Croxall, J.P., 1997. Marine debris surveys at Bird Island, South Georgia 1990–1995. Marine Pollution Bulletin 34, 61–65.

Weisskopf, M., 1988. Plastic reaps a grim harvest in the oceans of the world (plastic trash kills and maims marine life). Smithsonian 18, 58.

Whiting, S.D., 1998. Types and sources of marine debris in Fog Bay, Northern Australia. Marine Pollution Bulletin 36, 904–910.

Wilber, R.J., 1987. Plastic in the North Atlantic. Oceanus 30, 61–68.

Williams, A.T., Simmons, S.L., 1997. Estuarine litter at the river/beach interface in the Bristol Channel, United Kingdom. Journal of Coastal Research 13, 1159–1165.

Williams, A.T., Tudor, D.T., 2001. Litter burial and exhumation: spatial and temporal distribution on a cobble pocket beach. Marine Pollution Bulletin 42, 1031–1039.

Winston, J.E., 1982. Drift plastic—an expanding niche for a marine invertebrate? Marine Pollution Bulletin 13, 348–357.

Winston, J.E., Gregory, M.R., Stevens, L.M., 1997. Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biogeographical, environmental, and conservation issues. In: Coe, J.M., Rogers, D.B. (Eds.), Marine Debris—Sources, Impacts and Solutions. Springer-Verlag, New York, pp. 81–97.

Wolf, N., Feldman, E., 1991. Plastics—America's packaging dilemma. Environmental Action Coalition. Island Press, Washington DC.

Wolfe, D.A., 1987. Persistent plastics and debris in the ocean: an international problem of ocean disposal. Marine Pollution Bulletin 18, 303–305.

Zitko, V., 1993. Expanded polystyrene as a source of contaminants. Marine Pollution Bulletin 26, 584–585.

Zitko, V., Hanlon, M., 1991. Another source of pollution by plastics: skin cleaners with plastic scrubbers. Marine Pollution Bulletin 22, 41–42.