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Accumulation and fragmentation of plastic debris in global environments

David K. A. Barnes[1, *] François Galgani[2], Richard C. Thompson[3] and Morton Barlaz[4]

[1] British Antarctic Survey, NERC, High Cross, Madingley Road, Cambridge CB3 OET, UK
[2] IFREMER, Laboratoire Environnement Ressources, Provence Azur Corse (LER/PAC), Ifremer Centre de Méditerranée, ZP de Bregaillon, BP no. 330, 83507 La Seyne sur Mer, France
[3] Marine Biology and Ecology Research Centre, Marine Institute, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK
[4] Department of Civil, Construction and Environmental Engineering, North Carolina State University, PO Box 7908, Raleigh, NC 27695-7908, USA

*: Corresponding author : David K. A. Barnes, email address : dkab@bas.ac.uk

Abstract:

One of the most ubiquitous and long-lasting recent changes to the surface of our planet is the accumulation and fragmentation of plastics. Within just a few decades since mass production of plastic products commenced in the 1950s, plastic debris has accumulated in terrestrial environments, in the open ocean, on shorelines of even the most remote islands and in the deep sea. Annual clean-up operations, costing millions of pounds sterling, are now organized in many countries and on every continent. Here we document global plastics production and the accumulation of plastic waste. While plastics typically constitute approximately 10 per cent of discarded waste, they represent a much greater proportion of the debris accumulating on shorelines.

Mega- and macro-plastics have accumulated in the highest densities in the Northern Hemisphere, adjacent to urban centres, in enclosed seas and at water convergences (fronts). We report lower densities on remote island shores, on the continental shelf seabed and the lowest densities (but still a documented presence) in the deep sea and Southern Ocean. The longevity of plastic is estimated to be hundreds to thousands of years, but is likely to be far longer in deep sea and non-surface polar environments. Plastic debris poses considerable threat by choking and starving wildlife, distributing non-native and potentially harmful organisms, absorbing toxic chemicals and degrading to micro-plastics that may subsequently be ingested. Well-established annual surveys on coasts and at sea have shown that trends in mega- and macro-plastic accumulation rates are no longer uniformly increasing: rather stable, increasing and decreasing trends have all been reported. The average size of plastic particles in the environment seems to be decreasing, and the abundance and global distribution of micro-plastic fragments have increased over the last few decades. However, the environmental consequences of such microscopic debris are still poorly understood.

Keywords: persistent organic pollutants, marine debris, plastic production, landfill, microplastic

1. INTRODUCTION

In the last half century there have been many drastic changes on the surface of the planet, but one of the most instantly observable is the ubiquity and abundance of plastic debris. Like many anthropogenic impacts on natural systems, it is one that, despite widespread recognition of the problem, is still growing and even if stopped immediately will persist for centuries. From what started as a perceived aesthetic problem of plastics littering towns, countryside, shores and even far out into the ocean soon emerged as causing the choking and entanglement of wildlife. The number of potentially harmful implications of plastic debris that have been identified has escalated and it is now realised that these items may also transport persistent organic pollutants (POPs – Mato *et al*. 2001), non-indigenous species to new locations (Barnes 2002) and distribute algae associated with red tides (Maso *et al*. 2003). Reports of accumulation of plastics spread rapidly in terms of the taxa influenced, geography and bathymetry of affected sites, and countries beginning monitoring and beach clean-up operations. Schools and voluntary organisations have made annual coastal collections of stranded plastics an important educational issue even on many of the planet's most remote islands. In some areas though, notably on the sea-bed, assessment of plastic accumulation has been relatively neglected (Goldberg 1994). Since 1990, the dumping of rubbish at sea from ships has been prohibited under the international shipping regulation MARPOL annex V. A reduction of ship derived plastic debris should therefore be expected, even if global use of plastics continues to increase. To gain an accurate and meaningful assessment of plastics and their influence, large scale and long-term monitoring is needed across debris sizes (here termed mega [>1 cm diameter], macro [1-10 mm] and micro [>1 mm]), countries and environments, including the sea floor (see Ryan *et al*. this volume).

Natural marine debris of some type (e.g. pumice) has floated on the surface of the global ocean for longer than life itself, but life greatly increased this through floating algae, shells, seeds, fruits and wood. Human activities and travel by water must have further greatly increased flotsam (e.g. by timber) but by far the biggest change in the potential for transport by debris came with the mass production of plastics. The accumulation of both macro- and microplastics, has consistently increased on shores and in sediments for the last four decades (see Barnes 2005 and Thompson *et al*. 2004, respectively). Their inexpensive, lightweight and durable properties have made plastic much more single use and 'throw-away' than previous synthetic artefacts. Such compounds do deteriorate in Ultra Violet (UV) light but haline environments and the cooling effect of the sea mean degradation requires very long exposure times (Gregory 1999). Because plastics become fouled by marine organisms relatively quickly, the debris may also become shielded to some extent from UV and the persistence of this debris was recently illustrated by accounts that plastic swallowed by an albatross had originated from a plane shot down 60 years previously some 9600 km away (Weiss *et al*. 2006).

Mega-debris at sea was highlighted by tens of thousands of each of basketball shoes, hockey gloves and bath-toys released from containers washed off of ships (Weiss *et al*. 2006). There are many sources for plastics accumulating in the environment from direct dropping and dumping of litter on land or at sea to blowing from landfill sites, losses in transport and accidents. Typically 40-80% of mega- and macro-marine debris items are plastic, much of it packaging, carrier bags, footwear, cigarette lighters and other domestic items (Derraik 2002; Barnes 2005). A recent study by Ivar do Sul & Costa (2007) across Central and South America also found marine debris dominated by land-based plastic (though sometimes fishery gear can be abundant along continental shores as well). At more remote islands, fishing related sources of debris are often more prevalent. Following establishment of ‘long term’ monitoring surveys of stranded debris in the 1990s, there are now sufficient data to explore seasonal, annual and longer-term patterns (see e.g. Morishige *et al*. 2007).

Most waste plastics, including the large proportion used in single-use applications such as packaging, are disposed of in landfill sites. However plastic persists in landfill sites and if not properly buried may later surface to become ‘debris’. Durability of plastic ensures that wherever it is, it does not ‘go-away’; that is by placing plastics in landfill we may simply be storing a problem for the future. Although accumulation of plastics on land is important, little information is available on the amounts, rates, fate or impacts whereas there has been a major effort to quantify impacts on shorelines and at sea. In this paper, we examine waste generation and disposal, together with the abundance, composition and fragmentation of plastic. We then consider temporal and spatial trends in accumulation of plastics on strandlines, the sea surface and at depth on the sea-bed. We assess published data and present new surveys and observations of spatial and temporal patterns to evaluate whether persistent marine debris, such as plastics, are still increasing and whether it varies geographically?

2. ANTHROPOGENIC WASTE AND PLASTIC ACCUMULATION IN LANDFILL

Plastics are present in most waste and before trends in accumulation of plastic can be explained it is important to first consider waste generation and disposal. Global production of plastics is estimated at 225 m.t.year^{-1} (APME 2006). Waste composition data are useful to identify the relative quantity and types of plastic. As discussed in the contribution by Takada *et al*. (this volume), different plastics and resins have widely varying properties with respect to contaminant sorption and desorption.

(a) ***waste generation***

Waste is typically categorized based on its point of generation. Categories include municipal, commercial, industrial, agricultural, and construction and demolition (C&D). However, there is ambiguity within these categories. For example, in the U.S., municipal solid waste (MSW) includes that generated in residential, commercial and institutional (e.g. schools, government offices) sectors, while in other countries MSW may include anything from residential waste only to all waste managed in the municipal system (e.g. C&D, non-hazardous industrial). This complexity is exacerbated by the fact that some municipal systems manage residual materials from the treatment of water and wastewater. This relatively heavy waste will distort the composition of dry wastes such as plastics.

Considering these multiple categories, it is difficult to compare waste composition between countries. Waste is typically classified by the agency in need of the information and surveys are typically designed with specific goals. For example, a waste sort conducted to support planning of a recycling programme would identify commonly recycled plastics including pigmented and translucent high density polyethylene (HDPE) containers, clear and pigmented polyethylene terephthalate (PET), and classify the remaining plastics as “other.” These categories are useful in this (recycling) context but are less complete for a study of plastics in the environment. Another confounding issue is that the types of plastics present vary between municipal, agricultural and C&D waste. Municipal waste is dominated by containers (e.g. drink bottles) and films (e.g. carrier bags, packaging sheets), agricultural waste may contain large quantities of a single film, and C&D waste may contain polyvinyl chloride (PVC) pipe and large plastic containers. Thus, a municipal stream that contains 10% (by mass) plastics is not equivalent to a C&D stream containing the same percentage.

Waste composition may also be presented on either an “as generated” or “as discarded” basis. The former includes all the waste generated in a particular sector, prior to separation for recycling, composting, or other treatment. In contrast, “as discarded” indicates the waste remaining for disposal after the aforementioned separation. In areas with significant recycling programmes, the difference between waste generation and waste disposal could be 20 to 40%, and waste composition will change as recyclables are removed. If properly managed at the end of its useful life, plastic waste may be recycled, burned in combustion facilities to generate energy, or buried in landfill. In each of these alternatives, the waste should be destroyed or contained, so that plastic is not released to the environment. The major release of plastics to the environment is the result of inappropriate waste management and improper human behaviour e.g. littering (deliberately abandoning waste away from collection points). For example, plastic films can be released to the environment when not transported properly, and as a result of wind blown litter at the point of burial in a landfill. Well-operated landfills include a daily cover over the waste consisting of soil or a synthetic material, and fences surrounding the landfill to contain wind blown debris.

(b) ***Plastics production and recycling***

Annual global consumption of the major plastic resins is considerable (see Andrady & Neal, this volume). Films (e.g. carrier bags, plastic sheets) are easiest to escape containment as wind-blown debris and are likely the major component of terrestrial plastic litter but plastic litter also includes discarded fishing equipment, food and beverage packaging, and many other items that are present in the marine environment (Koutsodendris *et al*., 2008). Films are dominated by LDPE/LLDPE. We present information on plastics in MSW in the U.S. and their management (Table 1). The quantities recovered (i.e. for recycling) as a fraction of total discards shows that recycling rates are relatively low. In the U.S., plastic recycling is largely limited to drink containers though local authorities continue to expand the types of plastics collected for recycling. In general, citizen participation rather than industrial capacity limits the quantities of plastics recycled. Efforts to provide incentives for recycling can increase the fraction recycled (Loughlin & Barlaz 2006).

In the US durable goods, products that last on average for more than three years and include items such as furniture and appliances, were the most important use for new plastics (Figure 1). Non-durable goods, products that are consumed in less than three years such as trash bags and eating utensils were the next biggest use category. In Europe, data on various packaging applications are typically combined rather than considered separately and hence disposable packaging represents the principal use of plastics (37%, Plastics Europe, 2008).

(c) ***The fraction of plastic in household waste***

Plastics in the waste from various countries is estimated at about 10% (of mass). Such estimates can only be used as an indication of plastics composition for several reasons. First, the data are not all from the same year. Second, where possible, data are on an "as discarded" basis to reflect the composition of waste after diversion for recycling. However, it is not always clear whether the data were reported "as generated" or "as discarded." Third, the waste components included in national surveys vary within and between countries. For example, the U.S. data are for wastes defined as MSW. Finally, country-specific data compiled for Europe (Eurostat 2007) are self-reported at the national level and are unlikely to have been generated using a consistent methodology. In the U.S., plastics are estimated to comprise 11.8 and 16.3% of MSW as generated and as discarded mass, respectively. The composition of discarded plastics is given in Table 1 (U.S. EPA 2006). In Europe, plastics are estimated to comprise 7% of waste mass as generated. Similarly, plastics were estimated to represent 5.8, 7.3, 8 to 10, and 10% of waste mass in Singapore, Australia, the UK, and Finland, respectively (Barlaz 2006; Burnley 2007; Sokka *et al*. 2007). Finally, plastics were estimated to comprise 4 and 13% of waste in regions of China that use coal and natural gas, respectively, and the country-wide average for urban areas is projected to be 14% plastics in 2030 (World Bank 2005). Despite the uncertainty, estimates from around the world are reasonably consistent in estimating plastics to comprise about 10% of municipal waste mass. In contrast, plastics comprise 50-80% of the waste stranded on beaches, floating on the ocean surface and on the seabed (Gregory & Ryan 1997; Derraik 2002; Barnes 2005; Morishige *et al*. 2007).

3. TEMPORAL AND SPATIAL TRENDS IN ACCUMULATION

(a) *Ocean surface and beaches*

Many plastics are buoyant (46% US EPA 2006) and remain so until they become waterlogged or amass too much epibiota to float. Plastic items are commonly found at the sea surface or washed up on the shoreline. Mass production of plastics began in the 1950s, so less than a century ago we estimate the amount of anthropogenic debris at sea would have been three to four orders of magnitude lower and restricted to much more degradable items. Some of the earliest accounts of plastic debris in the marine environment are of fragments and pellets ingested by seabirds in the 1960's (e.g. Kenyon & Kridler 1969, Harper & Fowler 1987), but now plastic mega- and macro-debris is routinely observed from boats everywhere on the planet. There has been a rapid and substantial increase in anthropogenic debris on the ocean surface and beaches over recent decades (e.g. Dixon & Dixon 1981, Derraik 2002, Barnes 2005), but of more pertinence now are the current spatial trends. Surveys of anthropogenic debris and clean-up operations have generally focussed on the larger items along strandlines, and there is a wide geographic variability in the type of data available to examine potential trends. However in the last three of decades it has become apparent that the raw material for making plastics, tiny pellets, and microplastics have become more numerous (as marine debris) and, like larger pieces, these can travel considerable distances. Volunteer observations and collections in a growing number of nations are aiding our understanding of the scale and pattern of distribution of macro- and megaplastics in the marine environment but specialist examination is generally needed to investigate accumulation of microplastic, e.g., in sediments (see Thompson *et al*. 2005). Beaches are the most easily accessible areas for studying marine debris (although such studies have some confounding factors), yet despite the establishment of many study sites, irregularity of sampling, differing protocol and observers have led to very few data sets spanning more than a decade (see Barnes & Milner 2005).

The distribution of plastic debris is very patchy at sea for a variety of reasons, including local wind and current conditions, coastline geography and the points of entry into the system such as urban areas and trade routes. For example, stranding of macro- and megaplastics is between one and two orders of magnitude less per length of coastline on remote shores and at large spatial scales abundance correlates very strongly (Pearson's correlation = 0.971, $P<0.001$) with human population (per 10 degree latitude, see Barnes 2005). Enclosed seas and semi-enclosed seas such as the Caribbean (Coe *et al*. 1997), typically have high densities of plastic debris but also considerable variability. High densities and variability can also be a feature of open ocean coastlines e.g., Brasil (Santos *et al*. 2005) and Hawaii (Dameron *et al*. 2007). One of the key sources of interannual variability seems to be changes in oceanic circulation driven by El Niňo events (Matsumura & Nasu 1997; Morishige *et al*. 2007). Typically about 2000 and 500 items of anthropogenic debris strand on north and south Atlantic Ocean shores (respectively) per linear km per year of which more than half is plastic (scaled up from surveys of items >1cm in size along 200 m long beach sections, see Barnes & Milner 2005). More than six times as much plastic strands in the Mediterranean Sea and less than six times as much strands in the Southern Ocean shores (see Barnes & Milner 2005, Table 2). Despite considerable variability in observation and accumulation rates of plastic debris, some temporal trends do emerge. Studies initiated in the 1980s and 1990s indicated that the rate of plastic stranding from oceanic sources showed a sustained and considerable increase over time (e.g., Ryan & Moloney 1993; Ribic *et al*. 1997; Torres & Jorquera 1999). Similarly the occurrence of macro-plastics associated with wildlife (e.g., in bird nests and stomachs, entangling seals, strangling a wide variety of vertebrates or even used by hermit crabs instead of shells, see Barnes 2005) also drastically increased. For example, between 1992 and 2005 the frequency of plastic garbage items in Kittiwake nests increased from 39.3% to 57.2% in Northwest Denmark (Hartwig *et al*. 2007). Monitoring of strandings and effects on megafauna (such as birds) has now commenced on at least a few remote island shores in every ocean and these, with negligible local sources of plastics, have revealed the scale at which anthropogenic debris is accumulating.

Barnes (2005) found high levels but no consistent temporal trends in the abundance of anthropogenic debris on northern hemisphere shores compared to much lower levels but increased densities through the 1980s, 1990s and early 2000s were reported in the Southern hemisphere. The highest increases were at high southern latitudes (see Barnes 2005). However new data (reported here) show that patterns of stranding on islands is no longer clearly increasing and may be stabilising, though often with a ‘noisy’ signal of annual variability (Figure 2, see also Ryan *et al.* this volume). A similar lack of clear temporal trend in stranding densities of plastics is apparent in data collected intermittently at Ascension I., in the tropical Atlantic Ocean, and in the Falkland Is., south Atlantic Ocean (Barnes unpublished data). About 27% of macro-debris items stranding at Ascension I. was fishery related, similar to remote Tern I. in the Hawaiian Is. (Morishige *et al*. 2007). This is much less than on shores adjacent to important fisheries e.g. in Brazil (Oigman-Pszczol & Creed 2007) or even sub-Antarctic Bird I. (Walker *et al*. 1997). Bird I. and Signy I. in the Southern Ocean (Figure 2) have stranding densities of plastics an order of magnitude lower than remote localities at low latitudes, which in turn have at least an order of magnitude fewer plastics per km than urban sites. Further south in the Southern Ocean, debris washes ashore much more rarely at Adelaide Island (west Antarctic Peninsula). The relatively consistent level of abundance for macro and mega-debris at sea at high southern latitudes is supported by recent resurveys around the Drake Passage, Scotia arc and northern Antarctic Peninsula (Figure 3). Fifteen years after the first (see Barnes & Milner 2005), the most recent survey of this area took place early in 2008 and will involve the first marine debris surveys of the south Bellingshausen and Amundsen seas. Visual surveys such as these are weaker as a source of data than surface towed trawls but much more common and thus arguably comparable with data collected elsewhere, despite being semi quantitative. Gregory *et al*. (1984) reported similarly low (on a global scale) levels of floating anthropogenic debris in the Ross Sea (Pacific sector) of the Southern Ocean. Observers from the University of Essex in conjunction with Greenpeace are currently undertaking repeat survey of plastics at sea in this area. As on surrounding strandlines, the North Atlantic and Pacific oceans have high densities of floating plastic debris, especially at 20-40º N within a few hundred km of the coast and in the gyre centres, e.g. between the tropical and subarctic waters (see Matsumura & Nasu 1997). A recent (2005) survey of the subtropical convergence zone in this area showed plastic debris to be concentrating there remotely using satellite imagery (Pichel *et al*. 2007).

We know much less about the use by and distribution of organisms that hitch-hike on plastics and other anthropogenic debris than about the debris itself. Macro- and megaplastics have the potential to carry a wide range of species and support the growth of many to reproductive viability. The high abundance, lengthy durability and travel of plastics to even the most remote coasts, makes them a major potential vector for the dispersal of organisms (see Gregory this volume). New data from surveys of marine debris stranding in the Seychelles in 2005 and 2006 showed that on some beaches more than 60% of items carried fouling organisms, the highest reported anywhere (D. Barnes unpublished data). This is of significance because the prevailing currents travel from N. Australia and S. Indonesia during summer (South Equatorial) and from Somalia, India and N. Indonesia during winter (Indian Monsoon) could potentially transport a very wide range of species to less biodiverse, mid-ocean islands. Recent surveys of marine debris at Ascension I. (reported here for the first time) found 38, 40 and 41% of debris colonised by fauna in 2002, 2003 and 2005 respectively. Much of this had probably also travelled considerable distances given the prevailing currents come from the cape of South Africa. The likely response of many species to rapid regional warming is to move pole-ward to stay within their normal thermal envelope but in previous phases of warming (interglacial periods) there were few vectors to travel on. Now plastic debris, ship hulls and other vectors make transport more rapid and frequent and unprecedented warming at high latitudes also means that establishment success of potential invaders is likely to be higher.

(b) ***Seabeds from shallows to abyss***

As at the surface, both in the open ocean and on strandlines it is clear that the abundance and distribution of anthropogenic debris shows considerable spatial variability. The geographical distribution of plastic debris is strongly influenced by hydrodynamics, geomorphology and human factors. Moreover, there is notable temporal, particularly seasonal, variation with a tendency for accumulation and concentration along coastal and particular geographic areas.

Under the weight of fouling by a wide variety of bacteria, algae, animals and accumulated sediment, plastics can sink to the seabed (RCT unpublished data). Change in the nature, presence or abundance of anthropogenic debris on the sea floor is much less widely investigated than surface patterns. Studies that investigate seabed debris typically focus on continental shelves and research into the deeper seabed, which forms about half the planet's surface, is restricted by sampling difficulties and cost. Patterns in even the shallow subtidal can differ substantially from the adjacent strandlines. Oigman-Pszczol & Creed (2007) found plastic to constitute a much greater proportion of debris on the nearshore Brazilian seabed than on the shore. While sonar does not enable discrimination of different types of debris, trawling (e.g. using Agassiz) is probably the most adequate method to date, particularly when mesh size and opening width can be manipulated (Goldberg 1994, 1995; Galgani & Andral 1998). Such nets are only semi-quantitative and because of their design for collecting epibenthos, probably underestimate the quantities of debris present. Therefore pole trawling, with a constant mouth width, which works deeper in sediments, is considered the best approach. This is also the only trawling method with off-shelf data from submersibles. General strategies to investigate sea-bed debris are similar to methodology for benthic ecology and place more emphasis on the abundance and nature (e.g. bags, bottles, pieces of plastics) of items rather than their mass. Interpretation of trends is made difficult because the ageing of plastics at depth is not well researched and the fall of plastics to the sea-bed began long before specific scientific investigations started in the 1990s. Plastics have been found on the seabed of all seas and oceans across the planet but macro-debris is still very rare in the Southern Ocean, particularly in deep water. For example a recent series of 32 Agassiz trawls and 29 Epibenthic sledge tows (at 200-1500 m depth, BAS unpublished data) around the most (human) visited area, the northern Antarctic Peninsula and Scotia arc, found just one plastic piece and one metal shot. Large-scale evaluations of sea-bed debris distribution and densities anywhere are scarce (but see Galgani *et al*. 2000; Lee *et al*. 2006; Koutsodendris *et al*. 2008). However, there are a large number of smaller scale studies that have investigated anthropogenic debris in coastal areas such as bays, estuaries and sounds (see table 2 and references therein).

The abundance of plastic debris is very dependent upon location with values ranging from 0-7290 items per hectare (Ha) (although an extreme find of 10110 anthropogenic items per Ha was found in 1998 at one position, 43º42.84'N, 7º22.98'E using a pole trawl). Assessments of abundance clearly demonstrate the domination of this debris by plastics, as at more than half the study sites plastics constituted >50% of debris (Table 2). Of the areas investigated to date, Mediterranean sites tend to show the greatest densities due to the combination of a densely populated coastline and shipping in coastal waters, and a lack of dispersion of plastics by little tidal flow or water circulation. In general, bottom debris tends to become trapped in areas of low circulation and high sediment accumulation in contrast to floating debris, which accumulates in frontal areas. Debris that reaches the sea-bed may already have been transported considerable distance, only sinking when weighed down by fouling. The consequence is an accumulation of plastics debris in bays rather than the open sea (Hess *et al*. 1999; Stefatos *et al*. 1999). Some accumulation zones in the Atlantic and the Mediterranean Seas have very high debris densities despite being far from coasts. These densities relate to the consequence of large-scale residual ocean circulation patterns. There are higher densities in particular areas such as around rocks and wrecks or in depressions or channels (Galgani *et al*. 1996). In the North Sea (Figure 4), accumulation of plastics 320 km offshore from Denmark

(Galgani *et al*. 2000) is a consequence of several factors. These include the eddying circulation in the central north sea (Delhez & Martin 1992) and long-term circulation of water from the gulf stream transporting plastics northwards (Breton & Salomon 1995) and to the convergence zone of seabed sediment movements, due to local decreases of turbidity and turbulence (Tappin *et al*. 1997).

Large rivers are responsible for substantial inputs of debris to the sea bed (Williams & Simmons 1997). They can transport waste out to sea because of their high flow rate and the strength of bottom currents. In smaller rivers the displacement is slight, and waste can be found in zones adjacent to or in the estuaries and is often coincident with fronts (Acha *et al*. 2003). Patterns of debris transport should therefore be linked to river flow strength and may follow similar patterns to deposition of sediment load (often depositing only small amounts of material immediately along the coast).

Deep submarine extensions of coastal rivers also influence the distribution of sea bed debris. In some areas local water movements transport plastics away from the coast to accumulate in zones of high sedimentation. In these conditions, the distal deltas of rivers can fan out in deeper waters, creating areas of high accumulation (Galgani *et al*. 1996). Continental shelves often have lower concentrations of debris since most of the anthropogenic debris in the outer shelf originates from coasts to shelves that are washed offshore by currents associated with river plumes. Data from the shelf areas off the River Rhone (Galgani *et al*. 1995b) and California (Moore & Allen 2000) show circulation can be strongly, locally influenced by storm water events. The accumulation of plastics in coastal canyons may also be related to strong currents occurring in the upper part of canyons, which decrease rapidly in deeper areas resulting from increased confinement. Accordingly, debris distribution seems to be more temporally stable. An inevitable effect of this is the presence of greater amounts of debris in deeper shelf waters than in coastal waters (Galgani *et al*. 1996, 2000).

A wide variety of human activities contribute to these patterns of sea-bed debris distribution, including proximity to fishing activities, urban development and tourism. Also with plastic as a main component, debris from the fishing industry is prevalent in fishing areas (Kanehiro *et al*.1995; Galgani *et al*. 2000). This type of material accounts for a high percentage of debris, for example up to 72 % in eastern China Sea (Lee *et al*. 2006) and 65% in the Celtic sea (Galgani *et al*. 2000). Of sea-bed marine debris in California fishing gear also occupied more space than plastic, metal, and miscellaneous debris (Moore & Allen 2000).

Investigations using submersibles at depths beyond the continental shelf usually consider the number of items per linear km because of variability in transect width. They have revealed substantial quantities of debris (Fig 5). Besides the high densities found in coastal canyons (up to 112 items km^{-1} and 70 % plastics), plastics and other anthropogenic debris were found widely dispersed at slope and abyssal depths (Galgani *et al*. 2000). Deployment of a Remotely Operated Vehicle submarine in the Fram Strait (Arctic) (Galgani & Lecornu 2004) revealed 0.2-0.9 pieces of plastic per linear km at Hausgarten (2500 m). On dives between 5500 and 6770 m, 15 items of debris were observed, of which 13 were plastic, probably carried there by the Norwegian current in the North Atlantic. At such latitude and bathymetry there is negligible human activity, suggesting long distance transport of debris. Even more than on the sea surface or strandlines of remote locations, such as in the Southern Ocean, accumulation trends in the deep sea are of special concern. Most polymers are highly persistent in the marine environment and only degrade slowly via photocatalysis when exposed to ultra-violet radiation (Andrady 2003). Estimates for the longevity of plastics are variable but are believed to be in the range of hundreds or even thousands of years depending on the physical and chemical properties of the polymer, but this is likely to be greatly increased at depth where oxygen concentrations are low and light is absent. We know little about trends in accumulation of debris in the deep sea as studies are rare but the data we have indicate considerable variability. For example in some areas, such as the bay of Tokyo, debris densities decreased from 1996 to 2003 (Kanehiro *et al*. 1995; Kuriyama *et al*. 2003). In contrast, abundance remained stable in the gulf of Lion, France during a similar period (Fig 6). Furthermore in some areas around Greece the abundance of debris at depth has increased over the last 8 years (Stefatos *et al*. 1999; Koutsodendris *et al*. 2008). Interpretation of temporal trends is also complicated by annual variations in debris transport, such as seasonal changes in flow rate of rivers. Other seasonal factors include variation in the position of water fronts, the intensity of currents, swell, winds and upwelling which influence both the distribution and densities. Nevertheless if we extrapolate from existing data, it would appear that in the Mediterranean Sea as a whole there are about 3 x 10^9 debris items (floating or sunk) of which 70-80% are plastic. New initiatives to minimise littering and to reduce, re-use and recycle plastic should ultimately reduce plastic input into the at sea, although usage is still very high. However, fragmentation of macro- and megaplastics to microplastic pieces will also contribute to future trends in the abundance of visible plastics.

4. FRAGMENTATION OF PLASTICS IN THE ENVIRONMENT

The longevity of plastics is a matter for some debate, and estimates range from hundreds to thousands of years. It is considered that (with the exception of materials that have been incinerated) all of the conventional plastic that has ever been introduced into the environment still remains to date unmineralised either as whole items or as fragments (Thompson *et al*. 2005). However, since we have only been mass-producing conventional plastics for around 60 years it is too early to say exactly how long these materials will persist. Despite the durability of these polymers, plastic items are fragmenting in the environment as a consequence of prolonged exposure to ultraviolet light and physical abrasion (Colton *et al*. 1974; Gregory 1978; Andrady 2003; Thompson *et al*. 2004). This is particularly evident on shorelines where photo-degradation and abrasion through wave action makes plastic items brittle increasing their fragmentation.

Some of the first evidence of accumulation of plastic fragments in the environment came indirectly from examination of the gut contents of sea birds in the 1960's (e.g. Kenyon & Kridler 1969). Later, in the early 1970's, small fragments of plastic were observed in seawater collected with plankton samples from the North Sea (Buchanan 1971) and were subsequently reported on much broader scales in the north-western Atlantic (Colton *et al*. 1974). There have since been numerous reports of fragments in the oceans, on the seabed and on shorelines worldwide (Figure 7) and there is clear evidence that the abundance of these fragments is increasing (Figure 8). The UK Marine Conservation Society, which organises annual voluntary beach cleaning on shores all around the UK, reports a 30% increase in the abundance of large fragments (1-50cm in size) and a 20% increase in the abundance of smaller fragments (<1cm) between 1998 and 2006 (MCS 2007). On shorelines close to Plymouth one of us (RCT) recently recorded strandline material with more than 10% (10.89 ± 0.67, mean ± standard deviation) by weight of plastic fragments and pieces (including some plastic spherules, the raw materials for manufacture). In 2004, Thompson *et al*. (2004) reported on the abundance of even smaller fragments of plastic, some just 20µm, in diameter, which had accumulated on shorelines around the UK. Using plankton samples archived by the Sir Alistair Hardy Foundation for Ocean Science it was evident that the abundance of this microscopic debris had increased significantly in recent years (Figure 8). Similar fragments have since been identified from shorelines worldwide (Figure 7) and in terms of numerical abundance microplastic can constitute over 80% of intertidal plastic debris at some locations (Browne *et al*. 2007).

Fragments of plastic can be identified using Fourier Transform Infrared (FT-IR) Spectroscopy to match spectra obtained from unknown debris items to those of known polymers. Using this approach a range of common polymers including polypropylene, polyethylene and polyester have been identified as fragments and microscopic fragments. These materials have a wide range of domestic and industrial uses from rope and packaging to clothing and it seems likely that the fragments are forming from the breakdown of a wide range of everyday plastic products (Thompson *et al*. 2004). In addition to this 'natural' deterioration, it has been suggested that plastic items are also deliberately being shredded on board some ships in order that plastic waste can be concealed in food waste discharged at sea (van Franeker *et al*. 2005). The abundance of small items of plastic is further increased by the use plastic particles as scrubbers and abrasives in commercial cleaning applications (Gregory 1996) and by spillage of pre-production plastic pellets (~ 5mm in diameter) and powders such as those used for rotomoulding (~ 300µm in diameter) (e.g. Carpenter *et al*. 1972; Colton *et al*. 1974; Gregory 1978). Hence it is apparent that small items of plastic are entering the environment directly and that larger items of debris are fragmenting.

The accumulation of plastic fragments is of particular concern because they are difficult to remove from the environment and because they have the potential to be ingested by a much wider range of organisms than larger items of debris. Marine mammals, turtles and numerous other organisms are known to ingest large items of plastic including bags and bottles (Laist 1997; Derraik 2002). Smaller fragments can be ingested by birds, fish and even invertebrates (Thompson *et al*. 2004; Van Franeker *et al*. 2005). Upon ingestion it is possible that these small fragments may present a physical hazard in a similar way to larger items of debris by clogging feeding appendages or the digestive system (Laist 1997; Derraik 2002). Microscopic fragments are also be taken up from the gut into other body tissues (Browne *et al*. 2008). In addition to concerns about the physical hazards presented by this debris it has also been suggested that plastics could transfer harmful chemicals to living organisms (e.g. Oehlmann *et al.*, Talsness *et al*. and Kock *et al*. all in this volume). A range of chemicals are used as additives in the manufacture of plastics. These increase the functionality of the plastics, but some such as phthalate plasticisers and brominated flame retardants are potentially harmful and have been associated with carcinogenic and endocrine disrupting effects (see Takada *et al*. this volume). In seawater, plastics are also known to sorb and concentrate contaminants, which have arisen in the environment from other sources. These contaminants include persistent organic "pollutants" such as PCBs DDE, nonylphenol and phenanthrene can become several orders of magnitude more concentrated on the surface of plastic debris than in the surrounding seawater (Mato *et al*. 2001). It has been widely suggested that these sorbed contaminants and the chemicals additives that are used in manufacture could subsequently be released if the plastics are ingested (see Takada *et al.* this volume). Small and microscopic plastic fragments present a likely route for the transfer of these chemicals because they have a much greater surface area to volume ratio than larger items of debris from which they have originated and because of their size they are available to a wide range of organisms, including deposit feeders like the lug worm, *Arenicola* *marina*, that feed by stripping organic matter from particulates (Mayer *et al*. 1997; Voparil *et al*. 2004). Recent in-vitro modelling studies predict that even very small quantities of microplastic have the potential to significantly increase the transport of phenanthrene to *A. marina* (Teuten *et al*. 2007) and work in this volume has examined uptake of contaminants from plastics by birds (Takada *et al* this volume).

Given current levels of production and the quantities of plastic that are already present in the environment it seems inevitable that the abundance of plastic fragments will continue to increase for the foreseeable future. More work is therefore needed to model the environmental consequences of this debris and to produce environmental risk assessment models to predict the transport of a range of contaminants by fragments of common polymers (Thompson *et al*. 2005; Thompson 2006; Teuten *et al*. 2007).

5. SUMMARY AND CONCLUSIONS

Less than 60 years ago, the mass production of plastics started and now most items that people use, virtually anywhere on the planet are partly or wholly made of this inexpensive, durable material. Plastics have transformed the surface of the planet far beyond areas of human population density – fragments of all sizes are ubiquitous in soils to lake beds, from remote Antarctic island shores to tropical sea-beds. Plastics turn up in bird nests, are worn by hermit crabs instead of shells and are present in turtle stomachs. Human populations generate considerable amounts of waste and the quantities are increasing as standards of living and population also increase. Although quantities vary between countries, about 10% of solid waste is plastic. Up to 80% or sometimes more of the waste that accumulates on land, shorelines, the ocean surface or seabed is plastic. The most common items are plastic films, such as carrier bags, which are easily wind blown as well as discarded fishing equipment and food and beverage packaging. Strandline surveys (beach cleaning operations) are now organised in many countries and provide information about temporal and spatial trends. However, these surveys typically only provide data on coarse trends and larger items. There is considerable variation in methodology between regions and between investigators and more valuable and comparable data could be obtained by standardising monitoring approaches (Ryan *et al.* this volume). Accumulation rates vary widely with many factors such as proximity of urban settlements, shore use, prevailing wind and ocean currents, and region. There were dramatic increases in quantities of mega and macro-plastic debris in the northern hemisphere up to the 1990s. Quantities of debris in the oceans appear to have stabilised in the oceans over the last decade but have increased on shorelines. However this could indicate quantities of debris entering the sea are declining, but the material already in the sea is progressively being deposited on the shore or sinking to the deep. . Accumulation rates are much lower in the southern hemisphere but are still increasing significantly, although repeat surveys on remote Antarctic islands and ocean areas suggest stabilisation over the last decade. Fouled by organisms and sediment, plastics can sink and form an even higher proportion of human waste reaching the seabed and quantities in excess of tens of thousands of items per km^2 have been reported. As on beaches and the ocean surface, enclosed seas such as the Mediterranean have the highest densities, but investigations in deeper waters have shown high accumulation rates can stretch far (hundreds of km) from the coast, particularly adjacent to large river mouths or in canyons. As on surface environments, trends of debris accumulation on the seabed increase at some locations, but are stable or decreasing at other sites. Quantities of debris in the oceans appear to have stabilised in the oceans over the last decade but have increased on shorelines. The problem of plastic fragments has taken on increased importance in the last few decades. From the first reports in the 1970s, it was only a few years before the widespread finding of plastic including reports of microscopic fragments (20µm in diameter). The abundance of microscopic fragments was greater in the 1980s and 1990s was than in previous decades. It has also been suggested that plastic waste is deliberately being shredded into fragments to conceal and discarded at sea. Plastics of all sizes are now reaching the most remote and deepest parts of the planet and although we have much better knowledge of their sources, quantities, and distribution, we still understand little about their longevity, and affects on organisms. Further, we have made little progress in reducing the release of plastic to the environment. Temporal trends of macroplastics on remote islands suggest regulations to reduce dumping at sea have been successful to some extent. However our sustained demand for plastic means that contamination of the environment by microplastic pieces seems set to increase. In addition, future sampling may reveal increasing quantities of debris in the planet's least known habitat, the deep sea.

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Figure and table legends

Figure 1 Production of Plastic Products in the U.S. in 2005 (adopted from US EPA, 2006)

Figure 2 Annual accumulation of marine debris on shores of selected islands with year. Data for Bird I. and Signy I. are from Walker *et al*. (1997), Convey *et al*. (2002) and CCAMLR. Data for Tern I. are from Morishige *et al*.(2007) and for the UK from Beachwatch 2006 (MCS 2007).

Figure 3 Densities of marine debris at sea in the South-West Atlantic and Atlantic sector of the Southern Ocean by 10 degree latitude and longitude areas. Shades of light to dark blue code for densities 0-1, 2-10, 11-100, 101-1000 and 1001+ items per km^2 respectively. The survey years are April 1993 (a), April 2002 (b) and April 2006 (c). Data from Barnes & Milner (2005) and present study.

Comment [r1]: Will need to modify if published in Black & White

Figure 4 Plastic debris on the sea-bed from the southern North Sea (North Atlantic) in 1999. Plastics were counted after 30 minutes trawl time (16 m mouth, 20 mm mesh) at 64 stations (●) on the continental shelf. Results are given as items per Ha (10,000 m^2).

Figure 5 Accumulation of debris in deep sea environments. Submersible observations in Mediterranean canyons (A & B: plastic bottles at 1000 m depth at two different locations in the Marseille canyon, 43°03”.00N 05°00”.00 E) and above the polar circle, under ice floe (C & D: individual plastic bags, 2200-2600 m depth at Hausgarten, Fram strait, 79°03”.80 N 04°11”.60 E).

Figure 6 Plastic debris on the sea floor from the Gulf of Lion (Mediterranean Sea , France) between 1994 and 2004. Plastics were counted after 60 minutes trawl time (net = 16 m mouth, 10 mm mesh) at 65 stations (●) located on the continental shelf and adjacent canyons (down to 800m) from the gulf. Results are given as items per Ha (10,000 m^2).

Figure 7 Reports of plastic fragments in the marine environment presented in chronological order: 1, Harper & Fowler (1987) report on plastic (mainly pre-production pellets) ingested by seabirds since 1960; 2, (Kenyon & Kridler 1969) plastic fragments found in body cavity of dead laysan Albatrosses during 1966 survey; 3, (Buchanan 1971) synthetic fibres in medium plankton net hauls (size not specified); 4, (Carpenter *et al*. 1972) polystyrene spherules (average 500 µm) in coastal waters; 5, (Colton *et al*. 1974) particles, spheres and discs (1-5mm) in surface waters; 6, (Gregory 1978) resin pellets (~5mm) on shoreline; 7 (Ryan and Moloney 1990) temporal trends in abundance and composition of plastic on beaches 1984 to 1989; 8, (van Franeker & Bell 1988) plastic particles (~ 3mm) in gut of Storm Petrels; 9, (Shaw & Day 1994) fragments (≥ 500µm) at sea surface; 10, (Habib *et al*. 1996) Microplastic fibres (≥ 20µm) in sewage sludge; 11, (Galgani *et al*. 2000) Fragments in deep sea (size not specified); 12, (Moore *et al*. 2001a) fragments (≥ 350µm) at sea surface; 13, (Moore *et al*. 2001b) fragments and resin pellets on shoreline (size not specified); 14, (Eriksson & Burton 2003) fragments (≥1mm) in scats of fur seals; 15, (Kusui & Noda 2003) fragments (≥1mm) on beaches; 16, (Thompson *et al*. 2004) Microplastics (≥ 20µm) in surface waters and on beaches; 17, (Endo *et al*. 2005) resin pellets (~5mm) on beaches; 18, (Reddy *et al*. 2006) microplastics (≥10µm) on shorelines near ship breaking yards; 19, (Ng & Obbard 2006) Microplastics in surface waters and sediments (≥1.6µm). Red squares show distribution of microplastics (≥ 20µm) in intertidal sediments (Thompson et al unpublished data). White dots show mega and macroplastic strandline surveys (Barnes 2002, 2005).

Figure 8 Microscopic plastic in surface waters, collected with Continuous Plankton Recorder, revealed a significant increase in abundance when samples from the 1960s and 1970s were compared with the 1980s and 1990s (* = $F_{3,3} = 14.42$, $P < 0.05$). Global production of plastic overlain for comparison (APME 2006). Adapted from Thompson *et al*. (2004).

Table 1

Plastics Production, Recovery and Disposal in the U.S. in 2005 (thousands of metric tons). This Table was adopted from US EPA (2006). The data originated in reports of The American Plastics Council and includes net imports. Plastic from the construction and agricultural sectors are not included in these quantities.

	Generation of Plastics in MSW	Recovery	Discards
PET	2600	491	2109
HDPE	5355	473	4882
PVC	1491	0	1491
LDPE/LLDPE	5864	173	5691
Polypropylene	3636	9	3627
Polystyrene	2355	0	2355
Other	4982	355	4627
Total	26282	1500	24782

Table 2

Densities and proportion of plastics among benthic marine litter worldwide (per number of items). EA: Eastern Atlantic Ocean; M: Mediterranean Sea; B: Baltic Sea; N: North Sea; NP: Northern Pacific Ocean; WP: Western Pacific Ocean. T: trawling, PT:Pole Trawling.

Region	Sea	Method	Item/Ha	Plastic %	Reference
NA	Bay of Biscay	T	1.42+/- 0.25	62.2	Galgani *et al.* 1995a
M	NW Mediterranean	T	19.35 +/- 6.33	77.1	Galgani *et al.* 1995b
B	Baltic Sea	T	1.26 +/- 0.82	35.7	Galgani *et al.* 2000
NA	North Sea	T	1.56+/- 0.37	48.3	Galgani *et al.* 2000
NA	Channel East	T	1.17.6+/- 0.067	84.6	Galgani *et al.* 2000
NA	Bay of Seine	T	1.72 +/-0.058	89	Galgani *et al.* 2000
NA	Celtic Sea	T	5.28+/- 2.47	29.5 *	Galgani *et al.* 2000
SA	Rio de la Plata	T	0- 15.09	74	Acha *et al.* 2003
M	Greece, 59 sites	T	149	55.5	Katsanevakis & Katsarou 2004
M	Greece, Patras gulf	T	0.89-2.40	79-83	Stefatos *et al.* 1999
M	W & S Greece	T	0.72-4.37	55.9	Koutsodendris *et al.* 2008
M	Gulf of Lion	T	1.43+/-0.19	70.5	Galgani *et al.* 2000
M	East Corsica	T	2.29 +/- 0.72	45.8	Galgani *et al.* 2000
M	Adriatic Sea	T	3.78+/-2.51	69.5	Galgani *et al.* 2000
M	Sicily /Tunisia channel	T	4.01	75	Cannizarro *et al.* 1995
M	Oriental basin	P T	5.85 –161.98	37	Galil *et al.* 1995
NP	Kodiak Island, Alaska	T	0.11-1.47	47-59	Hess *et al.* 1999
NP	Oregon Coast	T	1.49	26*	June 1990
NP	Bering Sea	T	0.075 – 0.51	27=	June 1990
NP	Norton Sound	T	2.49	49 0	June 1990
WP	Tokyo Bay	T	2.70-5.50	40.1-41.6	Kanehiro *et al.* 1995
WP	Tokyo Bay	T	1.85-3.38	48.3-58.9	Kuriyama *et al.* 2003
WP	Eastern China Sea	T		<5	Lee *et al.* 2006
WP	South Sea of Korea	T		<10	Lee *et al.* 2006

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Figure 1

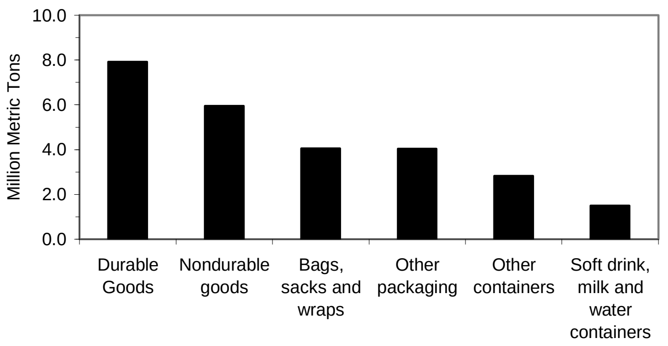

10.0
8.0
6.0
4.0
2.0
0.0
Million Metric Tons
Durable Goods
Nondurable goods
Bags, sacks and wraps
Other packaging
Other containers
Soft drink, milk and water containers

Figure 2

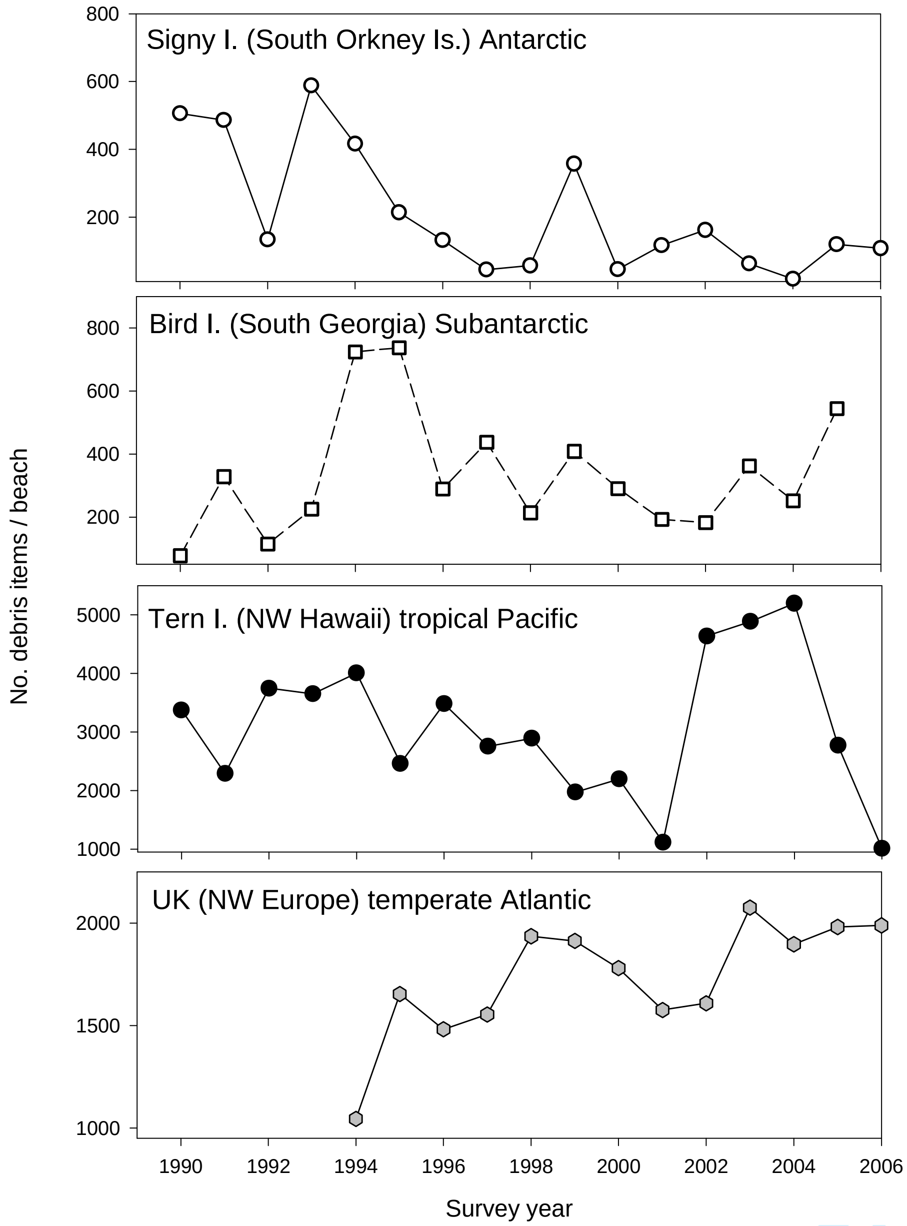

Signy I. (South Orkney Is.) Antarctic
Bird I. (South Georgia) Subantarctic
Tern I. (NW Hawaii) tropical Pacific
UK (NW Europe) temperate Atlantic
No. debris items / beach
Survey year
1990
1992
1994
1996
1998
2000
2002
2004
2006

Figure 3

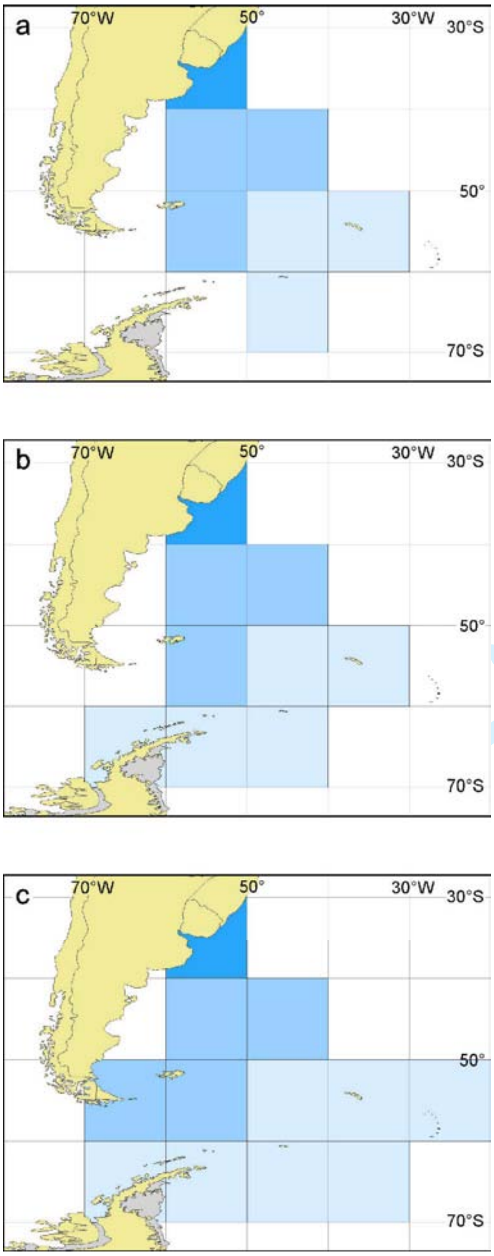
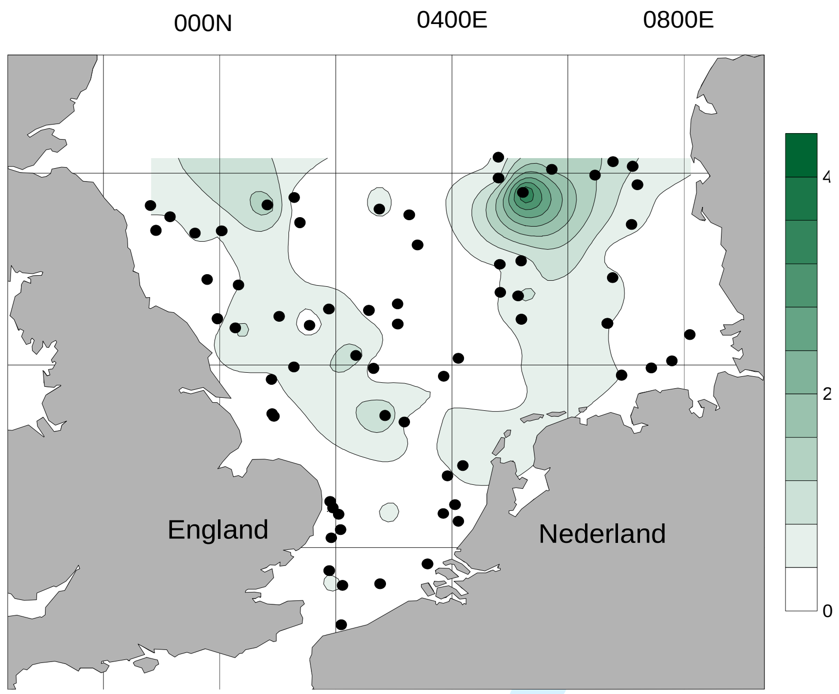

a
70°W
50°
30°W
30°S
50°
70°S
b
70°W
50°
30°W
30°S
50°
70°S
c
70°W
50°
30°W
30°S
50°
70°S

Figure 4



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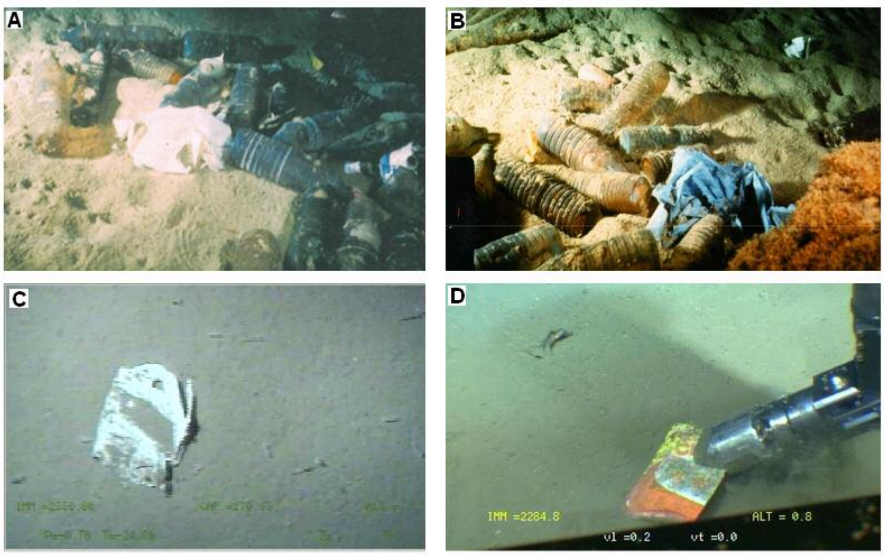

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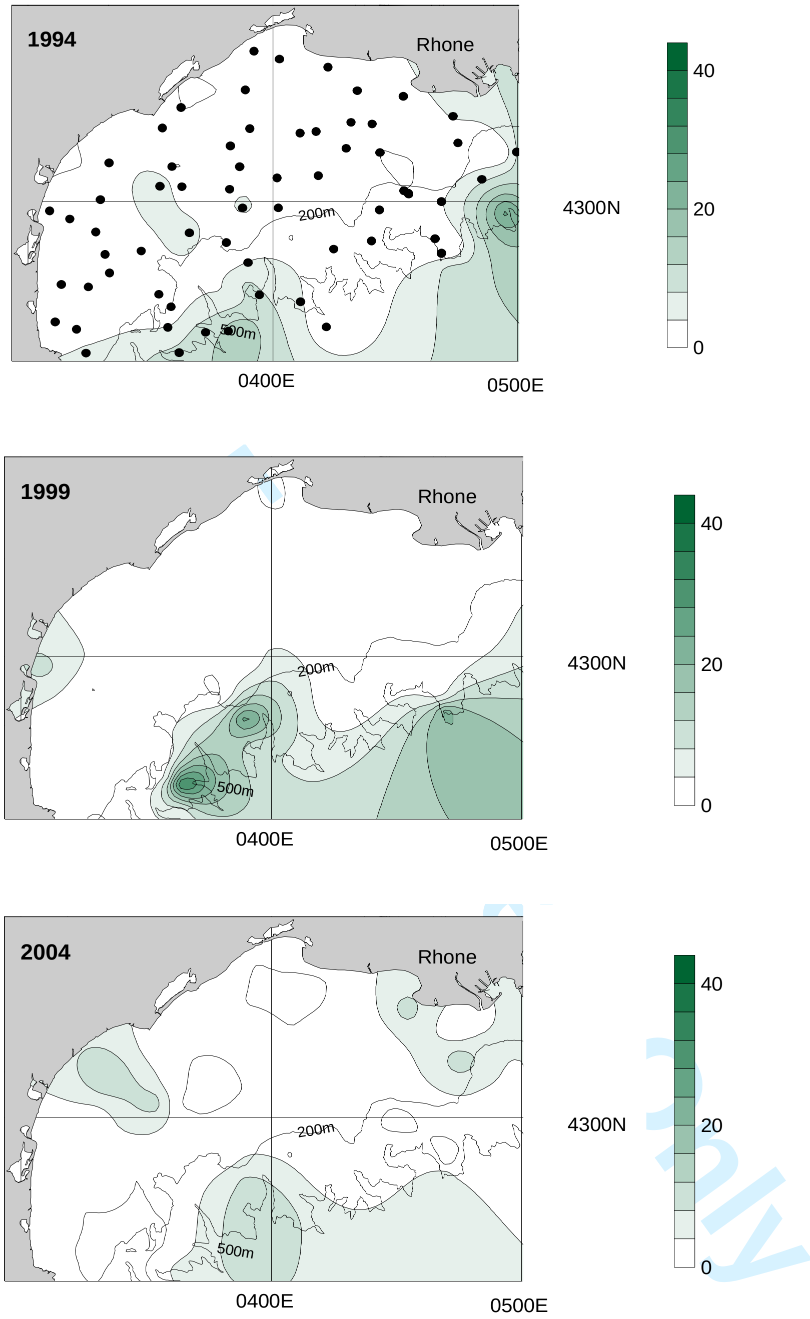
1994
Rhone
200m
500m
4300N
0400E
0500E
40
20
0
1999
Rhone
200m
500m
4300N
0400E
0500E
40
20
0
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500m
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0400E
0500E
40
20
0

Figure 7

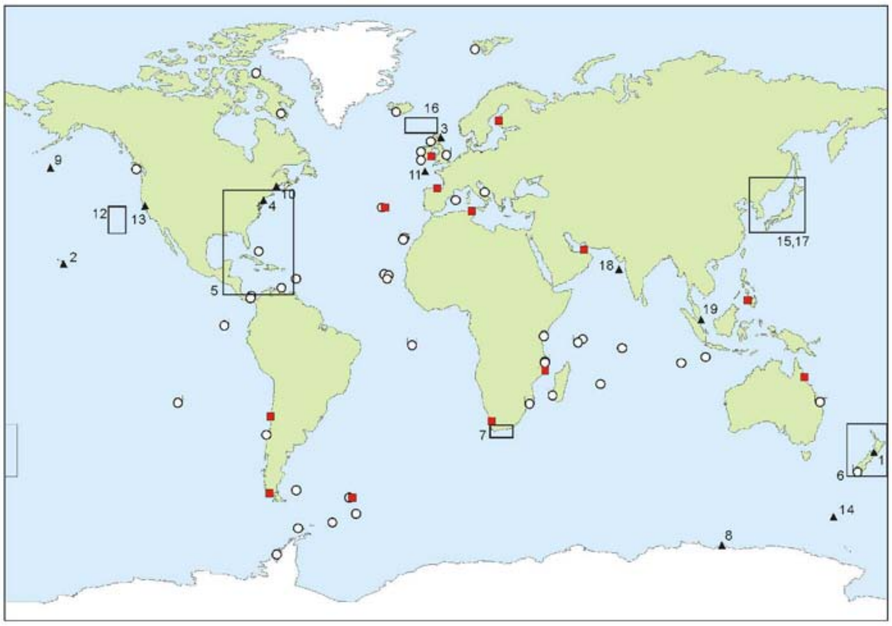
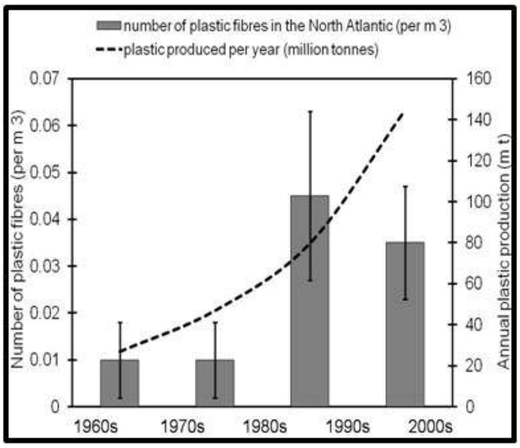


Figure 8


number of plastic fibres in the North Atlantic (per m 3)
plastic produced per year (million tonnes)
Number of plastic fibres (per m 3)
Annual plastic production (m t)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
160
140
120
100
80
60
40
20
0
1960s
1970s
1980s
1990s
2000s