

PLASTICS IN THE ANTARCTIC ENVIRONMENT: ARE WE LOOKING ONLY AT THE TIP OF THE ICEBERG?

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ABSTRACT

We synthesise the available literature on marine debris and its impacts in the sub-Antarctic islands, the Antarctic Peninsula and on the coasts of Antarctica. A total of 98 documents covering reports from 1982 to 2010 were included, and of these 95% had their full contents accessed. Seventy documents were obtained online as scientific abstracts from the Commission on the Conservation of Antarctic Marine Living Resources (CCAMLR). The occurrence of marine debris in the Antarctic environment, fur seal entanglement in marine debris, interactions between seabirds and marine debris and long range transport of benthos on floating plastics were the main issues identified. Fishing operations in the Southern Ocean were identified as the major source of marine debris, but depending on the type of debris reported, plastics from lower latitudes may also cross the Polar Front (PF). Possible links between Antarctic and South America, the closest intercontinental connection, in relation to plastic marine debris pollution are highlighted. As reported at lower latitudes, plastic pollution is an important problem now challenging the Antarctic environment. However, further specific and detailed studies are vital, since our current level of knowledge probably exposes only a small part of the full problem - the tip of iceberg.

Keywords: Exotic species; *A. gazella*; Procellariiformes; nylon fishing lines; plastic fragments.

RESUMO

PLÁSTICOS NO ECOSISTEMA ANTÁRTICO: SERÁ QUE ESTAMOS VENDENDO SOMENTE A PONTA DO ICEBERG? A literatura científica relacionada à presença e aos impactos do lixo marinho em Ilhas Sub-Antárticas, na Península Antártica e na costa do continente Antártico foi organizada e interpretada neste trabalho. Um total de 98 documentos, publicados entre 1982 e 2010, foi encontrado e 95% tiveram seu conteúdo acessado integralmente. Setenta documentos são resumos científicos da Comissão para a Conservação dos Recursos Marinhos na Antártica (CCAMLR, em inglês) disponíveis para consulta na internet. A ocorrência de lixo marinho no ecossistema Antártico (principalmente praias arenosas), o enredamento de lobos marinhos em itens do lixo, interações (ingestão, enredamento e ocorrência de lixo em áreas de nidificação) entre aves marinhas e o lixo, e o transporte de organismos bentônicos em plásticos flutuantes foram os assuntos mais abordados nos documentos analisados. Operações de pesca no Oceano Atlântico Sul foram identificadas como a maior fonte de lixo para o ambiente, mas plásticos originados em menores latitudes também foram identificados, indicando transporte através da Frente Polar (PF, em inglês). Possíveis links entre a Antártica

e a América do Sul, a mais próxima conexão intercontinental, em relação à poluição por plásticos também estão destacados e discutidos neste trabalho. Como reportado para menores gradientes latitudinais, a poluição por plásticos é um problema relevante para o ecossistema Antártico. Entretanto, estudos mais específicos e detalhados são necessários já que o conhecimento atual representa, provavelmente, só uma pequena parte do verdadeiro problema. Em relação a este tipo de poluição nos ambientes marinhos e costeiros do ecossistema Antártico, nós estamos possivelmente vendo somente a ponta do iceberg.

Palavras-chave: Espécies exóticas; *A. gazella*; Procellariiformes; linhas de nylon; fragmentos plásticos.

RESUMEN

PLÁSTICOS EN EL ECOSISTEMA ANTÁRTICO: ¿SERÁ QUE ESTAMOS VIENDO SOLAMENTE LA PUNTA DEL ICEBERG? En este trabajo fue organizada y interpretada la literatura científica relacionada con la presencia y los impactos de basura marina en islas sub-antárticas, en la Península Antártica y en la costa del continente Antártico. Fueron encontrados un total de 98 documentos, publicados entre 1982 e 2010, de los cuales se tuvo acceso a la totalidad del documento en el 95% de los casos. Setenta documentos son resúmenes científicos de la Comisión para la Conservación de los Recursos Marinos en la Antártica (CCAMLR, en inglés) disponibles para consulta en internet. La ocurrencia de basura marina en el ecosistema Antártico (principalmente en playas arenosas), el enredamiento de lobos marinos en diferentes ítems de basura, interacciones (ingestión, enredamiento y ocurrencia de basura en áreas de nidificación) entre aves marinas y la basura, y el transporte de organismos bentónicos en plásticos flotantes fueron los asuntos más abordados en los documentos analizados. Operaciones de pesca en el Océano Atlántico Sur fueron identificadas como la mayor fuente de basura para el ambiente, pero plásticos originados en menores latitudes también fueron identificados, indicando transporte a través del Frente Polar (PF, en inglés). También se abordan y se discuten en este trabajo, posibles links entre la Antártica y América del Sur, la conexión más próxima intercontinental, en relación a la contaminación por plásticos. Como es reportado para gradientes latitudinales menores, la contaminación por plásticos es un problema relevante para el ecosistema Antártico. Sin embargo, estudios más específicos y detallados son necesarios ya que el conocimiento actual representa, probablemente, solo una pequeña parte del verdadero problema. En relación a este tipo de contaminación en los ambientes marinos y costeros del ecosistema Antártico, posiblemente estamos viendo solo la punta del iceberg.

Palabras clave: Especies exóticas; *A. gazella*; Procellariiformes; hilos de nylon; fragmentos plásticos.

INTRODUCTION

Plastics were first engineered about 150 years ago, but their types and uses proliferated until fast and easy mass production methods were developed in the Twentieth Century. This transformed manufacturing economically and geographically, allowing most components to be made synthetically. However, hand in hand with the facilities and benefits produced by plastics (e.g. plastic additives, other polymers and synthesized compounds), several environmental problems quickly emerged, with discarded plastics reaching the most remote areas of the planet such as the seabed, remote islands and both polar environments (Moore 2008, Barnes *et al.* 2009).

Plastic has become so cheap and ubiquitous in our daily activities that it is seen as disposable, even

after single use. However it is slow to break down so it can rapidly accumulate in the environment as debris, building a significant environmental challenge for the future. The term 'marine debris' includes any solid material discarded or deposited in the marine environment, but is most obviously and predominantly represented by plastic and other synthetic debris. A scientific literature has grown over the last 40 years documenting the global scale of this problem (Ivar do Sul & Costa 2007, Moore 2008, Barnes *et al.* 2009).

The main sources of debris include both land-based (e.g. tourism activities on coastlines, rivers and sewage runoff) and marine-based sources (e.g. fishing, marine traffic, offshore platforms). Scientists, conservationists and others have recorded patterns in time and space of marine debris on beaches (and other coastal habitats), the ocean surface and ocean

floor by different methods, though these are still to be standardized by the international community. To date the methods applied have varied in objectives, available technological facilities, size and characteristics of marine debris targeted and environments studied. One key area of scientific interest has been the influence of plastic on marine biota. Ingestion and entanglement are commonly reported for vertebrates, but plastics also act as potential vectors to transport various life stages of fouling or rafting species (Barnes 2002, Moore 2008).

Plastic pollution is now disseminated across the surface of our planet, and even the most remote islands and beaches in Antarctica, some never previously visited by humans, have accumulated plastic pollution (Convey *et al.* 2002). In spite of oceanographic, climate and anthropogenic barriers, the sub-Antarctic islands, the Antarctic Peninsula and the coast of the continent of Antarctica are contaminated to varying levels by marine debris. The Southern Ocean has been isolated by the jets of the Antarctic Circumpolar Current, mainly the Polar Front (PF), for at least 25 million years, though this has some porosity through eddies and PF migration (Clarke *et al.* 2005, Barnes *et al.* 2006). Progressive cooling led to the development of massive ice caps over East and West Antarctica, the Antarctic Peninsula and Greenland. Most Antarctic coastline terminates in glaciers, ice sheets and ice shelves, and a distinctive biota has evolved south of the PF that is rich and strongly endemic (Clarke & Johnston 2003).

The Antarctic environment is considered a last frontier since this is the last major marine environment for which no exotic (non-indigenous) marine animals and only a single marine alga are yet known to have established (Frenot *et al.* 2005). Besides research, coastal tourism, and sparse temporary human populations, human access is limited to industrial fisheries, such as longline fishing operations (there are no trade routes) regulated by international protocols.

The Antarctic Treaty was originally signed in 1959 with the objective of recognizing the importance of the Antarctic environment (south of 60°S), in order for it to be used exclusively for peaceful purposes (military activity, nuclear tests and the disposal of radioactive waste are permanently prohibited) and scientific investigations (with cooperation among all

countries), for an undetermined period of time (see Hughes & Convey 2010 for recent discussion).

Most recently, in 1991, the Protocol on Environmental Protection to the Antarctic Treaty, the 'Madrid Protocol', was created with the objectives of preventing the contamination of the Antarctic environment and to guarantee its preservation. Each Antarctic Treaty Signatory Party which conducts activities in Antarctica must plan their actions with the aim of minimising adverse impacts on the Antarctic environment, and its dependent and associated ecosystems (Hughes & Convey 2010). Annexes III and IV of the Protocol relate to waste (both solid and liquid) disposal and management in the Antarctic Treaty area. They require that countries reduce waste production, disposing of it *in situ* only under exceptional conditions, and export or burn such garbage in incinerators. The disposal on land of batteries, hazardous waste and different kinds of plastics, for example, is prohibited. In addition, the disposal of all plastics into the sea, including synthetic ropes, fishing nets, packaging bands and plastic bags is also prohibited under the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78). The MARPOL Convention regulates the disposal of plastics (permanently prohibited anywhere in the oceans) and other waste into the sea.

Under the Antarctic Treaty, the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) came into force in 1982, aiming at the conservation of marine life. Amongst others, Conservation Measure 63/XV, in force since the 1995/96 austral summer, prohibited the use and disposal of plastic packaging bands which are used to secure bait boxes on fishing vessels, requiring that they shall be cut into 30cm sections and not left as loops, in order to avoid entanglement of seals and other marine vertebrates. Some national operators have reported and collected any marine debris, including plastics, found adjacent to their operations to CCAMLR since the 1990s.

Sightings of marine debris and its impacts around Antarctica were first recorded by observers engaged in other studies with different objectives, although these studies can give important early information related to the presence (and impacts) of marine debris in this environment. Nowadays, studies are often

specifically designed for plastic debris monitoring, recognizing the clear risk of plastics to the Antarctic environment (Barnes *et al.* 2010).

The objectives of the current study are to provide an up to date review of marine debris studies in the Antarctic environment, with particular attention on possible links between Antarctic and South America – geographically the closest intercontinental connection with Antarctica - in relation to plastic marine debris pollution.

MATERIALS AND METHODS

The scientific literature was searched through conventional academic facilities, particularly “Science Direct”, “Web of Science”, the Brazilian Education Ministry (www.capes.gov.br) and the

Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) databases (<http://www.ccamlr.org>). First priority was given to widely available articles published in international journals, primarily in English. We then considered articles published in regional journals, books and official documents concerning marine debris problems in the Antarctic environment.

This literature review aimed to collect and link all available articles relating to marine debris and its potential impacts in the Antarctic environment. Investigations were concentrated in the Antarctic Treaty area (south of 60°S) (Figure 1), but accessible works referring to the Southern Ocean and surrounding southernmost regions of other oceans (latitudes greater than ~45°S) were also examined.

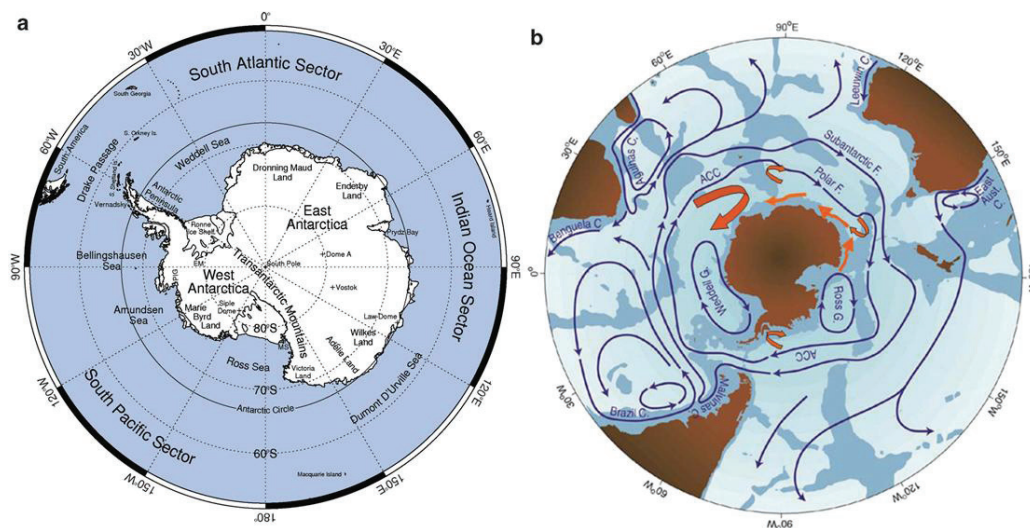


Figure 1. a. The Antarctic environment and its sub-Antarctic Islands. See the Drake Passage (~800km) connecting South America and the Antarctic Peninsula. Abbreviations: EM=Ellsworth Mountains, MS=McMurdo Sound, PIG=Pine Island Glacier. b. Schematic map of major ocean currents south of 20°S (F=Front, C=Current, G=Gyre), showing: i) the Polar Front and sub-Antarctic Front, which are the major fronts of the Antarctic Circumpolar Current, ii) Other regional currents, iii) the Weddell and Ross Sea gyres, and iv) depths shallower than 3500m shaded. In orange are shown a) the cyclonic circulation west of the Kerguelen Plateau, b) the Australian-Antarctic Gyre (south of Australia), c) the slope current, and d) the cyclonic circulation in the Bellingshausen Sea, as suggested by recent modelling studies and observations. Source: Convey *et al.* (2009), p.542.

Results of the literature search were classified according to the main focus of work: (1) the occurrence of marine debris in coastal and marine habitats in the Antarctic environment; (2) the occurrence of one specific type of interaction between marine debris and the biota; (3) multiple interactions between marine debris and the biota; and (4) a specific type of interaction between marine debris and the biota – long range transport on floating plastics. Data were

also analyzed by time of publication, location in Antarctica and document source.

STUDY AREA

The Antarctic environment was first visited and exploited in the Eighteenth Century by British and American fisherman concentrated around the South Georgia archipelago (Trathan & Reid 2009).

Nowadays, after the whaling era, the continent and the nearby islands are inhabited by researchers (and support staff) in more than 60 research stations permanently maintained by 30 countries. Numbers of staff involved in these operations within the Antarctic Treaty area rise to 4-5,000 in the summer months, with about 1,000 being present overwinter (Tin *et al.* 2009).

Fishing operations in the Southern Ocean commenced in the 1960s around South Georgia. A decade later, the former Soviet Union caught almost 400,000 tonnes of *Notothenia rossii* by bottom trawling (Kock 2001). In the second half of the 1970s, this fishing method expanded to more southerly grounds (Kock 2001). In 1984, the CCAMLR started to regulate fishing in the Southern Ocean, but few inspections were conducted until recently. In the 1990s, stocks of *N. rossii* had been recognizably depleted, and fishery effort switched to longlining for *Dissostichus eleginoides*. This is a lucrative fishery and each season almost 12,000 tonnes were caught (Kock 2001). However this fishery had a marked impact on seabird mortality. As a result many initiatives have been taken to minimise seabird bycatch.

Tourism activity started in the second half of the Twentieth Century with a Chilean commercial flight over the continent (Frenot *et al.* 2005). Since then, tourism around the Scotia arc and the Antarctic Peninsula has increased dramatically, doubling during the last decade (Frenot *et al.* 2005). Tourists depart predominantly from South America, visiting the Antarctic Peninsula and Scotia arc archipelagos (see Tin *et al.* 2009, Lynch *et al.* 2010), but also from New Zealand and Australia where sub-Antarctic islands and the Ross Sea are visited. While science and other governmental activities, fisheries and tourism all represent potential sources of debris within the Southern Ocean itself, the porosity of the PF means that there are also many external sources.

LITERATURE ACCESSED

A total of 98 documents, covering almost three decades of investigations were examined in the preparation of this review. Of these, 70 works (71%) were scientific abstracts from the CCAMLR, a result largely of efforts made by the British Antarctic

Survey (BAS) to monitor marine debris and its consequences to the Antarctic environment during recent decades. The other studies were published in eleven international journals (18 papers), six regional journals (6 papers), two conference proceedings and one book chapter. Ninety-three full texts were readily available and assessed. One of the 98 works was in Spanish and one was in Portuguese, and the others were in English.

The studies in the literature were carried out inside the PF at Bird Island, South Georgia Islands (46), Signy Island, South Orkney Islands (21), Livingston Island, South Shetland Islands (7), and King George Island (South Shetland Islands), the South Sandwich Islands, the Ross Sea and adjacent areas, Adelaide Island, Bouvetøya and the Scotia arc generally (1 each). Outside the PF studies were examined from Marion Island (6), Heard and Macquarie Islands (2) and the Falkland Islands (1). In addition, nine studies covered the Southern Ocean and/or more than one sub-Antarctic island (Figure 1).

Four studies were published in the 1980s. During the 1990s the number of works increased considerably (37 studies). The majority (56 studies) was published in the last decade (2000-2009), and the most recent was in 2010. The most recent studies relate to the increasing occurrence of plastics inside and outside the PF, and also to more sightings and recording of those plastics. Greater amounts of virgin pellets and manufactured plastics are produced and discarded at lower latitudes, reaching the Antarctic environment by ocean currents and winds and/or entering on board fishing, research and tourism vessels.

THE OCCURRENCE OF MARINE DEBRIS IN COASTAL AND MARINE HABITATS IN THE ANTARCTIC ENVIRONMENT

In the early 1980s, the New Zealand sector of the Southern Ocean and the Ross Sea were sampled with a neuston net aiming at the quantification and qualification of floating plastic debris (Gregory *et al.* 1984, Santos *et al.* 2004). Few plastics were collected and the most common type of item was highly weathered polystyrene foam. Samples obtained from the Ross Dependency shore also revealed minor

amounts of marine debris, with only lumber being systemically identified along the whole shore (Gregory *et al.* 1984).

At Heard and Macquarie Islands, fishing-related debris, plastics and other types of marine debris were also sampled between 1986 and 1989 (Slip & Burton 1991). Lowest values of sampled marine debris were 13 items/km and 90 items/km at Heard (53°S, 73°E) and Macquarie Islands (54°S, 158°E), respectively. Plastics were the main type of material sampled on both islands. This study showed that fishing-related debris was most common at Heard Island (40% of the total) when compared with Macquarie Island (29%). To date, this study represents the only systematic monitoring of marine debris at these islands, although direct impacts on the marine biota have also been reported (Auman *et al.* 2004).

The scenario of plastic marine debris contamination in Antarctic, along with the rise of this type of marine pollution at lower latitudes and recognition of its potential impacts, stimulated the CCAMLR Parties to initiate marine debris monitoring programmes and to encourage the effective implementation of the Annex V of the MARPOL 73/78. The BAS started a systematic

study at Bird Island, South Georgia, and Signy Island, South Orkney Islands in 1990.

On Main Bay (290 m long), Bird Island (54°S, 38°W), beach debris was monitored monthly from April to September during the austral winter. In the summer, the sampling procedure occurred only at the end of March because of the high breeding density of *Arctocephalus gazella* on the beach. Marine debris was counted and classified by material and/or source (Walker *et al.* 1997). A total of 5,716 items (317.5 ± 204.1 per year) were sampled between 1990 and 2007 (Rodwell 1990, Walker *et al.* 1997, Taylor & Croxall 1997, Staniland 1999, Aspey 2000, Jessopp 2001a, Tanton & Jessopp 2002, Le Bouard & Taylor 2007, Green & Warren 2003, Green & Robinson 2005, Taylor & Robinson 2006, Le Bouard 2008) (Figure 2). Total amounts represented a minimum of 0.2 items/m in 1990-1991 and a maximum of 2.8 items/m in 1996. During the first five monitored years, the number of items collected in the winter season was greater than during the summer (Walker *et al.* 1997). This pattern changed through the decade, since in 1996 the majority of items were sampled in March (Figure 2), which also occurred during the following years. Additionally, from 1996 to 2007, 73% of the total sampled marine debris was collected during the austral summer season.

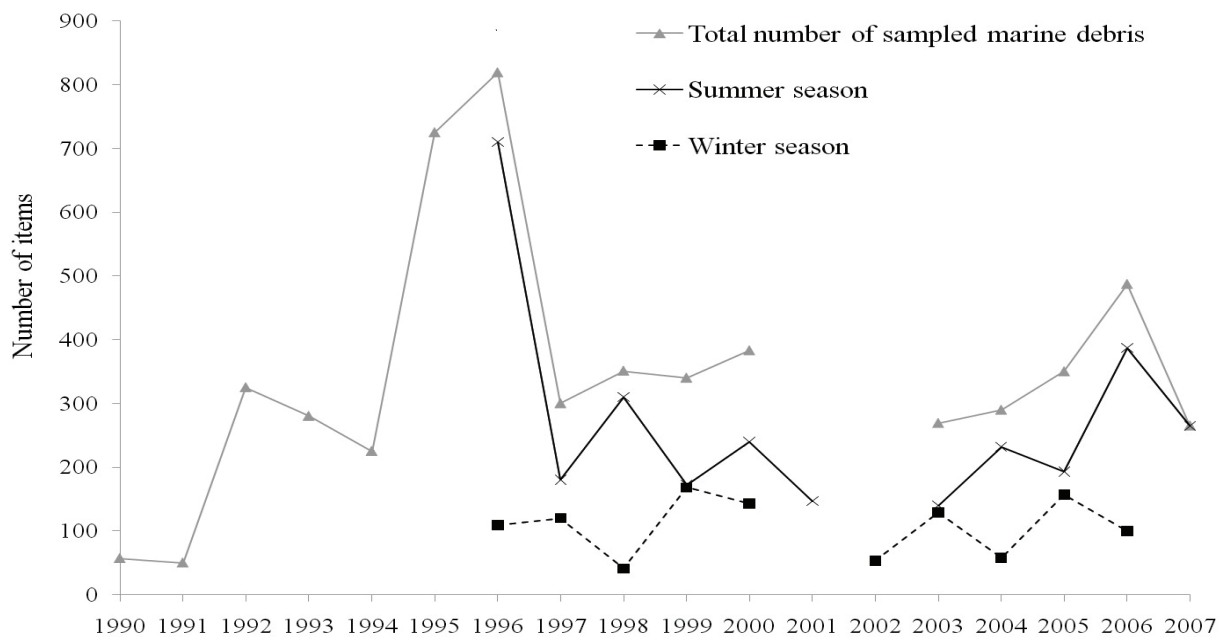


Figure 2. Marine debris sampled at Bird Island, South Georgia, from 1990 to 2007. The 2001 winter season and the 2002 summer season were not monitored. From 1996 to 2007, the total amount of sampled marine debris was the sum of winter and summer sampled items. Data derived from Rodwell (1990), Walker *et al.* (1997), Taylor & Croxall (1997), Staniland (1999), Aspey (2000), Jessopp (2001a), Tanton & Jessopp (2002), Le Bouard & Taylor (2007), Green & Warren (2003), Green & Robinson (2005), Taylor & Robinson (2006) and Le Bouard (2008).

The composition of materials revealed much about their sources at this location. The most common item sampled from 1992 to 2001 was nylon fishing line (Figure 3), which represented more than 50% of the total number of items. Walker *et al.* (1997) related the occurrence of nylon lines directly to longline fishing around South Georgia. Other fishing-related debris, such as plastic packaging bands, and items with multiple origins (miscellaneous) occurred in small amounts. However, this scenario changed in

2003, when the percentage of nylon lines declined to zero (2004-2007). Concomitantly, the frequency of miscellaneous items increased to 80%+ of total amounts (Figure 3), indicating that fishing vessels are making successful efforts to comply with the correct waste disposal procedures for both domestic and fishing-related waste (Green & Warren 2003). Additionally, 67 marine debris items, mainly plastic packaging bands and synthetic ropes were sampled at Husvik Beach, South Georgia (Convey *et al.* 2002).

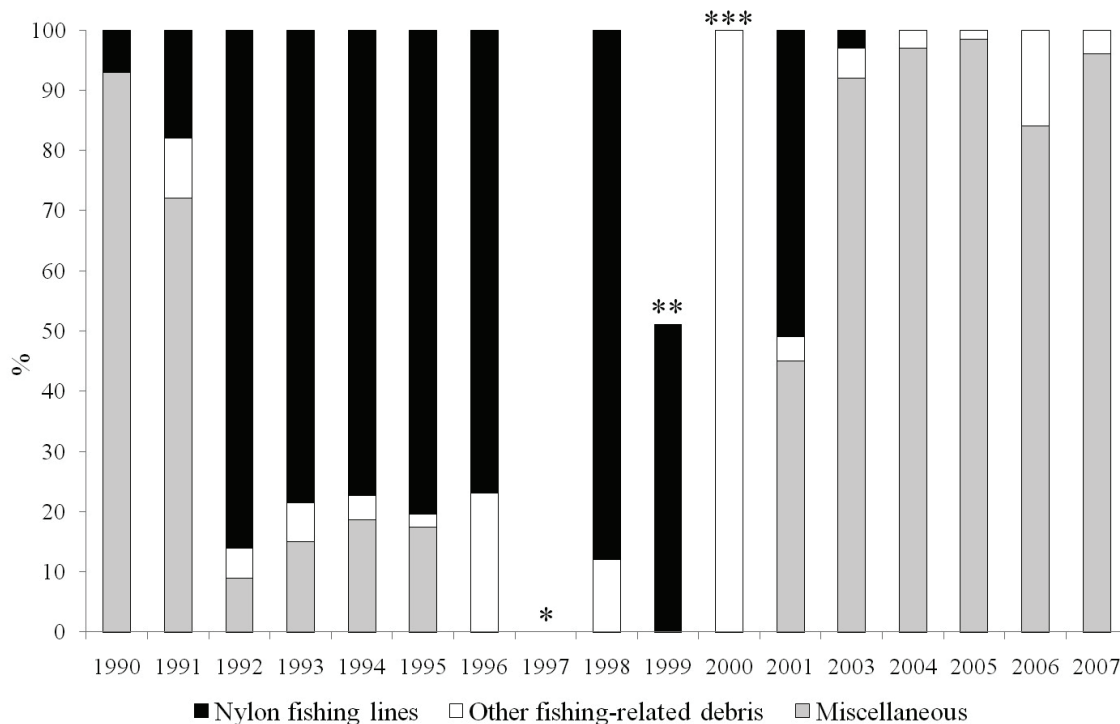


Figure 3. Percentage of nylon fishing line, other fishing-related debris and miscellaneous items sampled at Bird Island, South Georgia, from 1990 to 2007. *In 1997, the relative frequency of these items was not reported. **In 1999, only nylon fishing line contribution was recorded. ***In 2000, the 'other fishing-related debris category' included sampled nylon fishing lines. Data derived from Walker *et al.* (1997), Staniland (1999), Aspey (2000), Jessopp (2001a), Tanton & Jessopp (2002), Green & Warren (2003), Green & Robinson (2005), Taylor & Robinson (2006) and Le Bouard & Taylor (2007).

At Signy Island (60°S, 45°W), marine debris was collected from Cummings Cove, Foca Cove and Starfish Cove beaches (Lynnes & Shears 1997) from 1990 to 2008, always during the austral summer season (Shears *et al.* 1993, Lynnes & Shears 1997, 1999, 2000, Lynnes 2001a, Dunn 2002a, 2003a, 2006a, 2007a, Taylor 2005, Dunn & Waluda 2008). Marine debris was counted, measured and classified by material, weight and size. A total of 476 marine debris items (47.6±18.6 per year), weighing 134.9 kg (13.49±9.2 kg) were collected between 1997 and 2008 (Figure 4). Plastic was the main material

observed, representing between 38 (2000) and 80% (2007) of the total amounts. Packaging bands (all cut) were sampled throughout the study. Fishing-related items seemed to follow the same pattern (Dunn 2002a, Dunn & Waluda 2008). The occurrence of fragmented polystyrene foam, small enough to be ingested by seals and seabirds, was highlighted by Lynnes & Shears (1999, 2000). Wood and metal were also found. Very low amounts (6-7% of items) originated from the neighboring research station or previous whaling station activities at the same location.

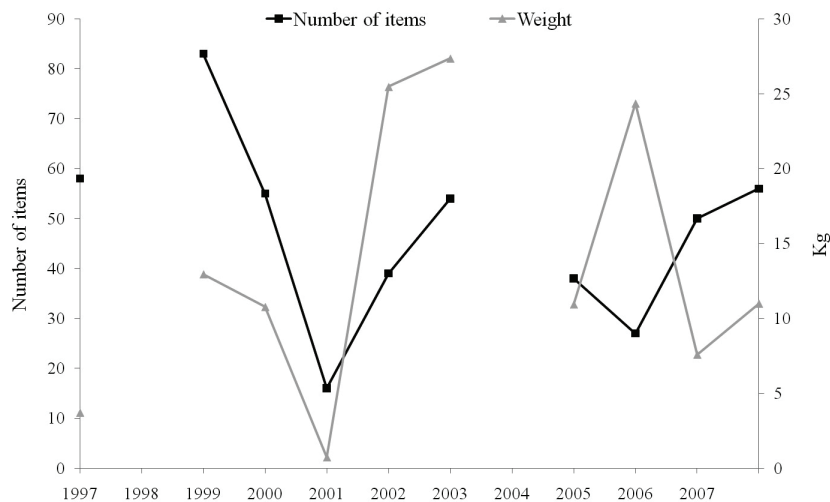


Figure 4. Numbers of items and weight of marine debris sampled at Signy Island, South Orkney Islands, from 1997 to 2008. 1998 and 2004 were not monitored. Data derived from Lynnes & Shears (1997, 1999, 2000), Lynnes (2001a), Dunn (2002a, 2003a, 2006a, 2007a), Taylor (2005) and Dunn & Waluda (2008).

Studies have also been reported from the South Sandwich Islands, Marion Island and the South Shetland Archipelago (Convey & Morton 1997, Torres *et al.* 1997, 1999, 2001, Nel & Hurford 1998a, Jones & Nel 1999, Convey *et al.* 2002, Aguilar & Torres 2005). At the South Sandwich Islands (57°S, 26°W) beach debris was sampled on Candlemas Island (1km length) in January and February 1997 and at Saunders Island also in January 1997. At Saunders Island, 58 items were sampled and the main identified material was weathered driftwood. Fishing-related debris was relatively scarce compared with other sites (Convey *et al.* 2002). Eight and 26 items were sampled at Candlemas Island in January and February, respectively (Convey & Morton 1997, Convey *et al.* 2002). These items were mainly plastic and polystyrene; neither packaging bands nor fishing lines were reported, in contrast to results for Bird Island (Walker *et al.* 1997). This highlights significant contamination rates despite the extremely remote location of these islands.

At Marion Island (46°S, 37°E), the increased accumulation of marine debris was considered related to illegal fishing (Nel & Hurford 1998a, Jones & Nel 1999). Polystyrene pieces, plastic bottles and fishing-related items were the most commonly sampled. In 1999, the number of polystyrene items had decreased but the proportion of other plastic debris increased (Jones & Nel 1999).

At the South Shetland archipelago (62°S, 58°W), studies have been carried out at Livingston (Torres & Gajardo 1985, Torres & Jorquera 1996, Torres *et al.* 1997, 1999, 2001, Aguilar & Torres 2005) and King George Islands (Sander *et al.* 2009). At least 5,000 marine debris items were sampled at Livingston Island between 1997 and 2005 (Figure 5). Plastics were always the main type of material and represented 95-98% of the total amounts (Torres *et al.* 2001, Aguilar & Torres 2005). Besides the occurrence of fishing-related debris (packaging bands, ropes), these studies highlighted the presence of expanded polystyrene from electronic equipment presumably lost during re-supply operations (Torres *et al.* 1997). Signs of burned plastics were also reported (Torres *et al.* 1997), evidencing the presence of incinerators on board some ships. Other materials sampled included metal, glass and paper.

At King George Island there are at least eight research stations, including the Brazilian Station “Comandante Ferraz”, as well as tourism activities during austral summer seasons (Santos *et al.* 2004). There, a total of 186 items were sampled between 2003 and 2005 (Sander *et al.* 2009). Wood was the most common item (49%), followed by metal (18%) and plastic (16%). Cigarette butts were also collected near the scientific stations. The weathered wood was attributed to historical expeditions (abandoned structures and boats) (Sander *et al.* 2009).

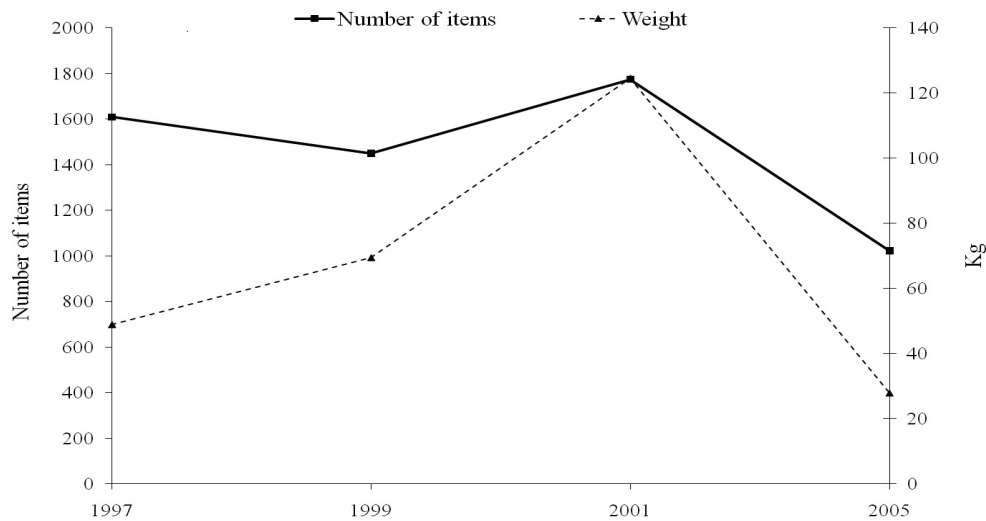


Figure 5. Numbers of items and weight of marine debris sampled at Livingston Island, South Shetlands Archipelago, in 1997, 1999, 2001 and 2005. Data from Torres *et al.* (1997, 1999, 2001) and Aguilar & Torres (2005).

North of the PF at Volunteer Beach (51°S, 59°W), on the north-eastern coast of the Falkland Islands, 892 marine debris items weighing 209 kg were collected in a six-month survey in 2001/02 (Otley & Ingham 2003). Plastic was the most common material (74%) followed by cotton and glass. Fishing-related debris dominated items (42%), as at other fishing grounds (Walker *et al.* 1997, Otley & Ingham 2003). The most frequently sampled items were clothes, ropes, polystyrene packing sheet, plastic packing bands and plastic fragments.

A 2001-2002 global transect of spot surveys of debris loadings of island shores along the Atlantic, from Arctic latitudes to the western Antarctic Peninsula, showed that the Southern Ocean islands examined (Trump, Adelaide, Wienke and King George Is.) were lowest – with 0-0.18 items per m of coast (Barnes & Milner 2005). Surveys made at sea have rarely been conducted around Antarctica, and most of these have consisted of brief daily observations of plastics around the Scotia and East Bellingshausen seas, recording < 5 items per km² south of the PF (Barnes & Milner 2005).

More recently, plastics have been observed at the highest southern latitudes and in the most remote areas of the Southern Ocean, such as the Amundsen Sea (Barnes *et al.* 2010). On board researchers from BAS and Greenpeace observed 51 (41% plastics) and

69 marine debris items (43% plastics) in different parts of the Atlantic, Pacific and Indian sectors of the Southern Ocean. Plastic bags, cups, fishing buoys and packaging bands were amongst the identified items. The most southerly sampled item was a plastic packaging band, seen at 72.6°S, 107.3°W. However, BAS scientists on board HMS *Endurance* in February 2008 reported 3 items (two fishing buoys and a metal oil drum) even further south, at 73°S, 76°W near the Ronne Entrance south of Alexander Island (P. Convey, pers. obs., Barnes *et al.* 2010).

SPECIFIC INTERACTION BETWEEN MARINE DEBRIS AND THE BIOTA – ENTANGLEMENT

In the early 1980s, neck collars started to be observed on fur seals *Arctocephalus gazella* at Bird Island, South Georgia (Bonner & McCann 1982). Collars were formed of marine debris such as nylon ropes, packaging plastic bands and rubber rings, and occasionally other types of items. Polypropylene ropes had circle shapes fastened with fishing knots, clearly related to fishery activities in the Southern Ocean. Other identified items were also related to fishing operations probably concentrated around the South Georgia area (Arnould & Croxall 1995). Year on year sightings and records of entangled fur seals confirm that this is a persistent problem at South

Georgia (Croxall *et al.* 1990, Arnould 1992) and other locations. Numbers of entangled animals were similar to those reported in the northern Pacific region, where significant population declines have already been observed (Arnould & Croxall 1995).

Worried about the entanglement problem, the BAS, encouraged by the CCAMLR, started annual monitoring of fur seals at Bird Island in the summer of 1989. Twice a year (during the pup-rearing summer – November to March – and winter – April to October), the number, sex and age-classes of entangled animals were recorded, as well as type of entangling material and severity of entanglement injuries.

From 1989 to 2008, approximately 806 and 316 *A. gazella* were entangled at Bird Island during the

summer and winter seasons, respectively (Figure 6). Juvenile males were the most frequently entangled and this was mainly in winter (Arnould 1992, Arnould & Croxall 1993, Croxall *et al.* 1994, Walker & Taylor 1996, Taylor 1997, Staniland 1998, Aspey & Staniland 1999, Jessopp & Aspey 2000, Jessopp 2001b, Warren 2002, 2003, Robinson 2005, Malone 2006, 2007, Edwards 2008), when they dominated the population seen ashore. During the first five monitored years they frequently represented more than 60-70% of entangled individuals (Arnould & Croxall 1995). However, to that date, rates of entanglement probably had negligible effects on the reproductive rate of the South Georgia population (Arnould & Croxall 1995).

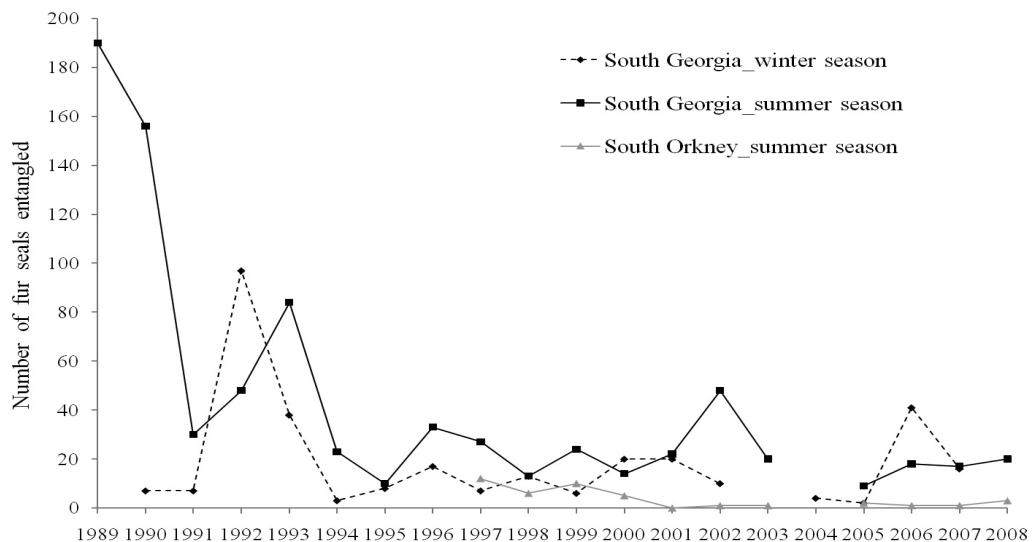


Figure 6. Numbers of entangled fur seals *A. gazella* observed at Bird Island, South Georgia, during the winter and summer seasons (1989-2008), and at Signy Island, South Orkney Islands, during the summer season (1997-2008). The 2003 winter season was not monitored at Bird Island and the 2004 summer season was not monitored at Bird and Signy Islands. Data from Arnould (1992), Arnould & Croxall (1993), Croxall *et al.* (1994), Walker & Taylor (1996), Taylor (1997), Staniland (1998), Aspey & Staniland (1999), Jessopp & Aspey (2000), Jessopp (2001b), Warren (2002, 2003), Robinson (2005), Malone (2006, 2007) and Edwards (2008).

The prevalence of polypropylene ropes fastened with knots, among other types of items clearly from fishing activities (Bonner & McCann 1982), motivated the CCAMLR to prohibit the accidental or deliberate disposal of collar ropes and plastic packaging bands in the Antarctic Treaty Area in the 1995/96 summer season. A number of reports highlighted the increased prevalence of fishing debris on fur seals, illustrating the lack of inspection on illegal fishing vessel operations in the area (especially around South Georgia). The most common items were nylon net fragments and plastic packaging bands (Arnould &

Croxall 1995), responsible for approximately 80% of the entangling debris.

From 1997 to 2008 (Figure 6), 42 juvenile male *A. gazella* were observed entangled in marine debris at Signy Island, South Orkney Islands (Lynnes 1998, 1999, 2000, 2001b, Dunn 2002b, 2003b, 2006b, 2007b, Taylor 2005, Dunn & Waluda 2008). More severe and very severe injuries were reported when compared with the results from Bird Island. The authors suggested that the majority of fur seals observed entangled at Signy Island had become entangled in other areas, such as around South

Georgia, where fishing activities were higher (Lynnes 1999). At Livingston Island, the BAS also reported the entanglement of 20 *A. gazella* in packaging bands and fishing related debris over a decade, from 1988 to 1997 (Hucke-Gaete *et al.* 1997). A single live fur seal was also observed entangled at the South Sandwich Islands (Convey *et al.* 2002).

Packaging bands, nylon net fragments and ropes were also the main types of entangling materials reported at Marion Island and Bouvetøya (Hofmeyr *et al.* 2002, 2006). At Marion Island, 108 pinnipeds were recorded entangled over ten years (1991-2001). The majority were *A. tropicalis* (82%), followed by *A. gazella* (13%) and *Mirounga leonina* (5%). Hooks from the longline industry were also identified on seals (Hofmeyr *et al.* 2002). At Bouvetøya (54°S, 3°E), at least 106 *A. gazella* were observed entangled in marine debris during the summer seasons of 1997, 1999, 2001 and 2002. The number of entangled seals sighted per day significantly decreased over the period of the study (Hofmeyr *et al.* 2006). Once more, high prevalence of fishing debris (fishing nets, packaging bands and ropes) was reported. These authors suggested that the death of one individual was due to entanglement although more generally the form and severity of injuries seen on entangled animals suggests that death will be a frequent consequence.

Plastics entangle fur seals, restricting or decreasing efficiency of movement or resulting in injuries (Hofmeyr *et al.* 2002, 2006). Death may result from drowning, strangulation, the severing of arteries or organs, infection, an inability to evade predators or starvation due to an impaired ability to catch prey (Hofmeyr *et al.* 2002). Even if removed, plastic collar rings can cause suffering (open wounds), which may also result in infections (Hofmeyr *et al.* 2002).

MULTIPLE INTERACTIONS BETWEEN MARINE DEBRIS AND THE BIOTA – INGESTION, ENTANGLEMENT AND THE OCCURENCE OF MARINE DEBRIS ON NESTING AREAS

Part of the available literature concerning impacts on seabirds in the Antarctic focuses on interactions between seabirds and longline fishing operations, which are a key element responsible for population declines, especially in albatrosses (Huin & Croxall

1996). In 1988 plastics were identified in the stomach contents of *Oceanites oceanicus* and *Daption capense* breeding on the Antarctic continent (van Franeker & Bell 1988). These authors suggested that items were ingested outside Antarctica, since the Southern Ocean surface was considered free from plastics at this time (but see Gregory *et al.* 1984). Still in the 1980s, plastics were incidentally identified in the stomach contents of Procellariiformes, Charadriiformes and Sphenisciformes inside the PF, in the Weddell, Ross and Scotia Seas (Ainley *et al.* 1990). Eight (36%) of the 23 studied species had ingested plastic debris. All contaminated seabirds were petrels; other Procellariiformes with well developed gizzards, and those which regularly regurgitate indigestible matter, were not found to have ingested plastics.

At the beginning of the 1990s, the BAS, motivated by the CCAMLR, attempted to monitor interactions (ingestion of plastics, entanglement on fishing gear and occurrence of marine debris on nests and nesting areas) between seabirds and marine debris at Bird Island, South Georgia (Huin & Croxall 1994, Humpidge & Croxall 1996, Humpidge 1997, Hill 1998, 1999, Roberts 2000, 2001, Phalan 2002, 2003, Auman *et al.* 2004, Forster 2005, Snape 2006, 2007, Fox 2008).

The wandering albatross *Diomedea exulans* was the main species associated with marine debris and fishing gear, as well as reported to have ingested plastics (Cooper 1995, Huin & Croxall 1996). During one single year, individuals of this species at Bird Island may have ingested at least 630 fishing hooks (Phalan 2003) observed on regurgitation. Hooks were identified as those typically used in the demersal longline fishery for the Patagonia toothfish *D. eleginoides* around South Georgia and the Falkland Islands (Phalan 2003). Other identified items included squid jigs, nylon lines and ropes (associated with hooks), frequently observed impaled in seabirds; plastic bags, plastic fragments and even human food were also commonly observed on nests. Most of these items can be directly associated with fishery activities. Cigarette butts and gloves, with multiple potential sources, were also regurgitated by *D. exulans* at Bird Island (Huin & Croxall 1996). Other species were also identified in association with marine debris, such as *Thalassarche chrysostoma*, *T. melanophrys*,

Procellaria aequinoctialis, *Macronectes giganteus*, *M. halli*, *Pachyptila desolata* and *Stercorarius antarctica*.

At Marion Island, rope nooses were the most common single item identified in association with seabirds (Nel & Hurford 1998b, Nel & Jones 1999, Nel & Nel 1999), followed by hooks. *D. exulans* was again the main species associated with marine debris and fishing gear (both on nests and entangled), while *Chionis minor* was the main species identified as having ingested plastic debris, besides other identified species (Nel & Nel 1999).

At Heard Island two *P. desolata* were found to have ingested plastic fragments (Auman *et al.* 2004). As these seabirds are surface seizers, it was not surprising to the authors that they had ingested plastics. However, the contamination of seabirds was not considered an important problem at Heard Island.

Ingested plastics obstruct the passage of food and/or cause injuries in the upper gastrointestinal tract, which may lead to infections. Greater amounts can reduce feeding stimulus and death may result from starvation. Ingested debris are also regurgitated to chicks, when potential damaging consequences are magnified. Organic pollutants absorbed and adsorbed on plastics can be released into the digestive tracts, contaminating both adults and chicks. When entangled, seabirds are unable to fly, feed or evade predators. Entangled debris were also commonly related to fishery activities, such as nylon lines and synthetic ropes. Plastics use has also been observed in nests building, increasing the possibility of interactions between marine debris and seabirds. Besides fishing-related items, human food, plastic bags and plastic fragments were also observed.

A SPECIFIC TYPE OF INTERACTION BETWEEN MARINE DEBRIS AND THE BIOTA – LONG RANGE TRANSPORT ON FLOATING PLASTICS

Scientific works concerning fouling of marine debris and potential dispersion of exotic species in the Southern Ocean have only recently (last decade) been reported in the literature (Barnes & Sanderson 2000, Barnes 2002, Barnes & Fraser 2003, Barnes *et al.* 2004, 2006, Lewis *et al.* 2005, Barnes & Milner 2005). The potential for introduction of exotic

species on floating plastic debris is ecologically more significant to the Southern Ocean (Barnes 2002). Seas around the Antarctic continent have been isolated by the Antarctic Circumpolar Current for at least 25 million years (Barnes *et al.* 2006), and it has remained a last frontier, since to date no exotic marine animal species have yet been identified (Barnes & Fraser 2003, Barnes *et al.* 2004, Barnes & Milner 2005).

However, marine debris (driftwood and fishing-related debris) does cross the PFZ in both directions (see Convey *et al.* 2002 and Barnes *et al.* 2004) indicating that it is a viable route for organisms to raft. In addition, it has been estimated that plastics have doubled organisms' opportunities for dispersal at sub-polar latitudes (Barnes 2002), providing a real potential vector for the introduction of new species. However, fouling on vessel hulls may potentially create more opportunists for the transport of biological communities over long distances and across substantial biogeographical barriers (Lewis *et al.* 2005).

In 2003, a plastic packaging band was sampled at Adelaide Island (68° S), Antarctic Peninsula (Barnes & Fraser 2003) which showed that benthos were rafting on synthetic debris in the Southern Ocean. On this plastic were organisms from five phyla: Bryozoa, Porifera, Annelida, Cnidaria and Mollusca. The gastropod (Mollusca) and five bryozoans were endemic to the Southern Ocean. However, some bryozoans were at least 1 year old and were reproductively active, demonstrating that such debris colonists can survive through the southern polar winter and can potentially colonize new areas wherever they drift to (Barnes & Fraser 2003).

Studying floating marine debris in the Atlantic Ocean (79° N to 68° S), Barnes & Milner (2005) found that none of the Southern Ocean marine debris sampled carried colonists. However, across the latitudes studied, the highest frequencies of such colonists were found with the highest abundance of marine debris. If current quantities of debris found in the Southern Ocean increase, this scenario may change in the near future (Barnes & Milner 2005). Further, warming is predicted to take place in the Southern Ocean, and has been reported particularly west of the Antarctic Peninsula (Convey *et al.* 2009, Turner *et al.* 2009), and the PF may not continue to act

as an efficient shield (Barnes & Milner 2005, Barnes *et al.* 2006) to the transport, establishment and spread of new species (Barnes *et al.* 2004).

DISCUSSION

The accessible literature was classified according to their main subject: (1) the occurrence of marine debris on coastal and marine habitats in the Antarctic environment (40 studies); (2) the occurrence of entanglement between marine debris and pinnipeds (31 studies); (3) Multiple interactions (ingestion, entanglement and occurrence of marine debris on nesting areas) between seabirds and marine debris (21 studies); and (4) long range transport on floating plastics (7 studies).

These studies all confirm the prevalence of plastics on beaches in Antarctica and the sub-Antarctic islands, as well as floating in the Southern Ocean. Almost anywhere in the Southern Ocean, identified sources included fishing activities, governmental research and tourism. Regulated and illegal fisheries provided by far the greatest source. Plastic packaging bands, nylon lines, ropes and net fragments are among the most sampled items which can be directly related to regional fishing operations. Polystyrene and foam (as well as metal, glass, paper and cloth) were also identified, but these can have multiple sources. Highly weathered driftwood was mainly related to abandoned research infrastructure and boats, and historical industries and exploration (Sander *et al.* 2009). Greater amounts of marine debris are usually reported in the austral summer season, including more surveys and easier observation but more importantly more ships and fishing operations being present (Walker *et al.* 1997), as well as the lower accessibility of the more southern beaches through ice accumulation in winter (Convey *et al.* 2002).

At Bird Island, no significant differences in marine debris contamination on beaches were seen between the 1990s and the 2000s decades despite the development of international protocols and Commissions, CCAMLR actions (such as scientific monitoring and prohibition measures) and the civil society initiatives. Over the period the consequences of marine debris on coastal and marine environments and biota have been frequently highlighted in both scientific and public arenas, stimulating action in

response over the last decade. However spatial and temporal trends and/or the establishment of significant changes for better scenarios are limited since different methods were applied to sample and classify marine debris even in the Antarctic environment.

The fur seal *A. gazella* is the main pinniped species vulnerable to entanglement in the Antarctic environment. In spite of conservation measures, significant differences between decades were not reported. True frequencies of entanglement may be much higher since some animals may not visit beaches during monitoring (Arnould & Croxall 1995, Santos *et al.* 2004). At Marion Island the sub-Antarctic fur seal *A. tropicalis* is similarly threatened.

Ingestion, entanglement and occurrence of marine debris on nesting areas had impacts on seabirds in the Antarctic environment for at least three decades. Procellariiformes were in greatest danger within the PF, paralleling reports in others studies around the world. Most ingested items, such as hooks, are directly related to fishing activities in the Southern Ocean. However, gloves, cigarettes butts and plastic fragments with multiple potential sources are also frequently ingested.

Fouling items as potential vectors to the introduction of exotic species into the Antarctic environment is the least studied issue identified in this review. Plastic debris can transport a rich fauna and flora around the globe, reaching the most remote areas, even in the Southern Ocean (Barnes 2002). At lower latitudes the introduction of exotic species through this mechanism is suspected, but the contexts strongly differ. Warmer waters have long had multiple sources of natural debris and rafting, furthermore few if any locations are free from exotic species. In the Antarctic environment new and increased opportunities for aliens to raft in coincide with rapid recent warming and reduced sea ice around West Antarctica which likely increases survival prospects of colonists, putting potentially vulnerable communities and endemic species at risk. The PF, which has acted as an efficient shield to exotic species entrance over many millions of years, may reduce in effectiveness with ocean warming and surface oceanic circulation changes (Frenot *et al.* 2005).

The studies reviewed here are important as baselines for future studies in the Antarctic environment. Since plastic production continues

to accelerate in the current decade, and is not accompanied globally by improved management actions or environmental education, the amounts and impacts of plastics in Antarctica are also expected to increase. Understanding of marine debris impacts is required across a wide range of subjects, such as the occurrence of floating and deposited micro-plastics (<1mm), incidence of virgin plastic pellets, transport of organic pollutants on plastic pieces, impacts of ghost fishing to cetaceans and other groups, and the fragmentation of plastics under severe climate conditions, providing a great challenge and impetus for future research, and the delivery of that research into the industrial, public and political spheres.

CONNECTIVITY BETWEEN ANTARCTIC AND SOUTH AMERICA IN RELATION TO PLASTIC POLLUTION

The Scotia arc mountain chain is mostly subsurface and includes four major archipelagos (South Georgia, South Sandwich, South Orkney and South Shetland) and the Antarctic Peninsula, linking South America (the closest point of Antarctica to another continent, with ~800 km separating Tierra del Fuego from the South Shetland Islands) with west Antarctica (Figure 1). These islands represent ideal localities for the monitoring of floating plastics from lower latitudes which may reach the Antarctic environment.

Plastic bottles and other labeled marine debris manufactured in South America have already been identified both within the Scotia arc (Convey & Morton 1997, Convey *et al.* 2002) and outside the PF at Marion Island (Nel & Hurford 1998a, 1998b). Oceanographic mechanisms (surface ocean currents and wind cells) are responsible for the transport of floating plastics in the tropical Atlantic (Santos *et al.* 2005) as well as in the Southern Ocean. In the South, they may cross the PF pushed by the westerlies from higher (tropical Atlantic) (Ivar do Sul & Costa 2007) to lower (~60°S) atmospheric pressures. Marine debris are then transported by the Antarctic Circumpolar Current, deposited on beaches or exported again to lower latitudes.

Marine debris can also cross the PFZ carried by nektonic animals such as seabirds and seals (Barnes *et al.* 2004). During the austral winter migratory marine biota reach lower latitudes, when seabirds ingest

floating plastics in the open ocean; on nesting areas, plastics can then be regurgitated to chicks. Fur seals can also become entangled on the South American continental shelf or along populated shores. Greater quantities of plastics traveling in the Southern Ocean (Barnes 2002) increase the possibility of transport of colonists to Antarctica. If warmer temperatures are observed in the Drake Passage (Meredith & King 2005, Hughes & Convey 2010), marine invertebrates from South America and adjacent areas will probably reach the PF and the Antarctic continent alive on floating plastics (Barnes & Fraser 2003, Barnes *et al.* 2004, Frenot *et al.* 2005).

Shipping may also be important in transporting aliens but plastic debris is easily colonized, its long transit times to Antarctica are likely to reduce the thermal shock of crossing the PF and plastics can reach any shore (compared to a very restricted number of ship ports) or even sink to deposit benthos directly into suitable habitat. The scale of this problem is still almost entirely unknown, but it is probably the most important problem related to marine debris pollution in the Antarctic environment.

Studies concerning other potential connections (and barriers) between Antarctica and South America in relation to plastic pollution are required to improve preventive measures and the conservation of this important environment by South American countries. These include (a) studies of eddies formed in the PFZ which may facilitate the introduction of fouling biota on floating plastics; b) plastic dispersal by winds during the winter and summer seasons; (c) wind-driven vortical circulation as Langmuir cells (Barstow 1983) and the accumulation of (micro) plastics in the Southern Ocean; (d) unidentified sources of plastics impacting the Scotia arc; and (e) the development of tourism activities and cruises from South America to the Antarctic Peninsula, and how they may influence plastic amounts. Integral to all these fundamental research and management aims is the establishment of robust multi-year monitoring programmes.

FINAL REMARKS

The Antarctic environment is no exception in relation to global marine debris problems despite being furthest from most sources. As observed elsewhere, sources in the Antarctic environment are

both marine- and land-based. Marine-based sources include fishing, and research/tourism vessels traveling in the Southern Ocean, but also global oceanic debris rafting across the PF. Land-based sources are mainly research stations established on the continent and the sub-Antarctic islands.

Fishing operations are important sources of marine debris to Antarctica, contributing not only directly fishing-related debris but also miscellaneous items. However, it is difficult to attribute some types of item, such as unlabeled plastic bottles, since these items can derive from many sources. In the current review, few of the studies examined related the sampled marine debris to research stations or vessels, while the impacts of tourism on plastic debris contamination have yet to be quantified. The establishment of currently non-indigenous biota to the Antarctic environment is an additional predicted consequence of global warming, either as natural colonists or with anthropogenic assistance. The combination of greater vector density (e.g. plastic debris) for transport, with warmer temperatures and reduced sea ice may significantly improved survival and establishment of rafters. The PF position and structure may also change exposing the Southern Ocean and the Antarctic environment to greater threats from non-indigenous species.

The occurrence of plastics in the Antarctic environment is a significant problem that has to be recognized and acted on by all Parties conducting activities in Antarctica, as well as by all populations living at lower latitudes, in order to reduce plastic production and disposal into coastal and marine environments. With correct preventive measures, there is still the opportunity in Antarctica to avoid the drastic consequences that are observed on urbanized beaches in tropical countries or at the North Pacific Gyre (e.g. Moore 2008).

In drafting this review, it has become clear that the majority of available studies are published in the form of internal reports and other types of 'grey literature'. Thus they are not readily available either to the scientific community or to those in the public and policy making arenas. There is therefore an urgent challenge to the science community to bring this important issue to these wider audiences. Even where initiatives have been developed over recent decades aimed at reducing the incidence and impacts of marine and particularly plastic debris, for instance

through the CCAMLR, there appears to have been a very uneven take-up or application of protocols for simply obtaining the baseline data required to monitor the effectiveness of these initiatives across the international Antarctic research community. Even based on the limited data currently available, it seems clear that only the tip of the iceberg has been identified thus far in relation to the problems and impacts of marine debris in the Southern Ocean and on Antarctica. This provides a further and urgent challenge to all the Parties to the Antarctic Treaty.

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