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Floating marine debris in coastal waters of the SE-Pacific (Chile)

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Abstract

Herein we report on the abundance and composition of floating marine debris (FMD) in coastal waters of the SE-Pacific (off the Chilean coast) during the austral summer 2002. The observed FMD consisted mainly of plastic material (86.9%). Densities of FMD were highest between 20°S and 40°S, corresponding to the main concentrations of human population and activities. Low densities of FMD were found in the south between 40°S and 50°S (<1 item km^{-2}). Generally, the highest densities were recorded in nearshore waters of major port cities (>20 items km^{-2}), but occasionally high concentrations of debris were also found 50 km offshore. Densities of FMD in coastal waters of the SE-Pacific are of similar magnitudes as those found in coastal waters or inland seas of highly populated regions in the northern hemisphere, indicating the need for improved regulation and legislation in the countries of the SE-Pacific.

Keywords: Debris; Plastics; Plastic bags; Sewage; Latitudinal; Humboldt current; Chile

1. Introduction

Solid marine debris deposited in the sea consists mainly of two types: particles that immediately sink to the seafloor and debris with a high capacity to float for extended periods (weeks to several months). Floating marine debris (FMD) is commonly transported by currents and wind before it finally is cast ashore or loses floatability and sinks. Among the ecological impacts most frequently documented are entanglement and ingestion by marine vertebrates (Laist, 1997), in particular birds (Blight and Burger, 1997), sea turtles (Carr, 1987), and mammals (Hanni and Pyle, 2000). Another important ecological impact caused by FMD may be long-distance dispersal of marine invertebrates (Minchin, 1996; Barnes, 2002). Many sessile species settle and grow on FMD (Winston et al., 1997). Sessile organisms with short-lived larval stages are generally thought to have very limited dispersal capacity (Mileikovsky, 1971), but adults that live on marine debris with a high floating potential, for example some bryozoans on plastic containers (Barnes and Sanderson, 2000), may be transported over large distances.

Many studies that refer to the potential ecological impact of FMD are based on samples of debris on the shore (e.g. Gregory and Ryan, 1997; Walker et al., 1997; Barnes, 2002). While shore-based studies may provide some first approximation to the composition and abundance of marine debris in adjacent seas, they nevertheless represent only the fraction of marine debris that has been cast ashore. Furthermore, once on the beach, debris may become buried, resulting in underestimation of the total amount of items reaching the shore (Williams and Tudor, 2001). Permanence of marine debris on shores may also vary depending on its weight and size: for example, styrofoam, plastic bottles, and bags cast ashore may be blown away from the flotsam (e.g. Garrity and Levings, 1993), and consequently this fraction of FMD may also be underrepresented in shore-based surveys focusing on the flotsam. Distribution and composition of marine debris floating at sea may depend largely on local current regimes and may not necessarily coincide with that found on shores. A sound understanding of the dynamics of FMD can only be obtained by surveys at sea.

The composition, abundance, distribution and ecological impacts of FMD have been studied thoroughly in the northern hemisphere (McCoy, 1988; Lecke-Mitchell and Mullin, 1992; Matsumura and Nasu, 1997; Coe and Rogers, 1997). Apart from some shore-based

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(Gregory and Ryan, 1997) or trawl-based surveys (Jones, 1995) or qualitative reports (Bourne and Clarke, 1984), little information about abundance, composition and distribution of FMD is available for the southern hemisphere. Since the major ecological impacts caused by FMD occur while it is afloat (e.g. Walker et al., 1997), we examined the composition and abundance of FMD at sea. We compare our results from coastal waters of the SE-Pacific with data from the northern hemisphere, and address aspects that should be pursued in the future. Finally, we utilize our data to infer about the origin of FMD in the SE-Pacific and identify potential threats and possible measures to mitigate these threats.

2. Materials and methods

The coastal SE-Pacific is characterized by the northward flowing Humboldt Current and the southward flowing Peru Counter Current. These alongshore currents may show intra- and inter-annual variability in intensity and width, but in general remain within 50–150 km of the coast (Strub et al., 1998). Upwelling may be intense and consistent in some parts of the study area, but typically is infrequent along the Chilean coast of the SE-Pacific (Strub et al., 1998). During austral summer, onshore winds are common and may be locally intense (Poulin et al., 2002). Water temperatures at the sea surface range in summer between 22 °C at about 18°S and 10 °C at about 50°S (own unpublished data).

During the austral summer (January–March) 2002, we carried out nine surveys of FMD between 18°S and 50°S. The study site near Antofagasta was subdivided in two areas since it comprises two systems (Bahía de Antofagasta, Bahía de Mejillones) that substantially differ in their oceanographic conditions. Surveys were conducted from dawn to dusk, navigating from the coast to the west up to a distance of ~50 km from the coast, turning south for ~15 km before returning directly to the coast (see also Fig. 1). For the surveys we utilized medium-sized (~15 m long) fishing boats or research vessels with deck heights of ~1 m above the water line and velocities of 4–10 knots. During navigation a team of three skilled observers surveyed both sides of the vessel: two observers continuously focused on the port or starboard side of the vessel reporting any observed item to the third person who immediately recorded position, type, size, number and distance of each item. Herein we distinguished five categories of FMD: plastic bags, plastic lines, other plastics, manufactured wood and other debris. Sizes of items were estimated based on that of known items (e.g. plastic bottles or plastic bags). The perpendicular distance of each item to the transect line was estimated using known distances (e.g. width, height or length of vessel) for items within ~20 m distance from the vessel. For items farther away than 20 m we utilized a calibrated scale that allowed us to estimate the distance of the item from the horizon–using the eye height of the observer above the water line and the distance of the horizon we calculated the distance of the item from the vessel (see also Matsumura and Nasu, 1997 for more detailed description of the method).

In order to estimate total density of FMD, we used the strip transect method (see Seber, 1982), based on the number of items seen, the perpendicular distance to the transect for each item, and the transect length. Density (D = items km^{-2}) of FMD was calculated using the following equation:

$$D = n/(2 \times (w/1000) \times L)$$

where n is the number of debris observed, w the maximum distance perpendicular to the transect, and L the total length (in km) of the transect. Since a preliminary examination of the data set showed that the number of observed items decreased substantially at distances >15 m from the vessel, we herein used a conservative measure and only considered a transect width w of 10 m on either side of the vessel. Applying this conservative measure we ensured that the abundance of floating items is not underestimated due to overlooked items.

3. Results

During the surveys, a large variety of FMD was registered, but plastic items were most abundant and ubiquitous (86% of the total number), regardless of the sites and the distance from the shore (Table 1). Plastic bags by far outnumbered other items (47.6%) followed by other plastics (34.7%). Plastic lines or other fishing-related debris only made up 3.6% of FMD. Other items comprised cardboard, paper, melon skin, diapers, ice-cream boxes, hygiene towels and other typical household garbage. Most items were smaller than 50 cm in diameter or length.

FMD was found on all transects (Fig. 1). Highest densities of FMD were found in the northern part of the study area between 20°S and 40°S (>10 items km^{-2}), whereas densities in the less populated regions in S-Chile (> 40°S) were comparatively low (<1 item km^{-2}) (Fig. 2).

FMD often occurred in concentrated patches in the coastal but also in the offshore region (Fig. 1). In general highest concentrations were found in coastal waters, especially near major port cities (>20 items km^{-2}), but in some regions the highest densities were found in offshore waters (Fig. 2, Table 1).

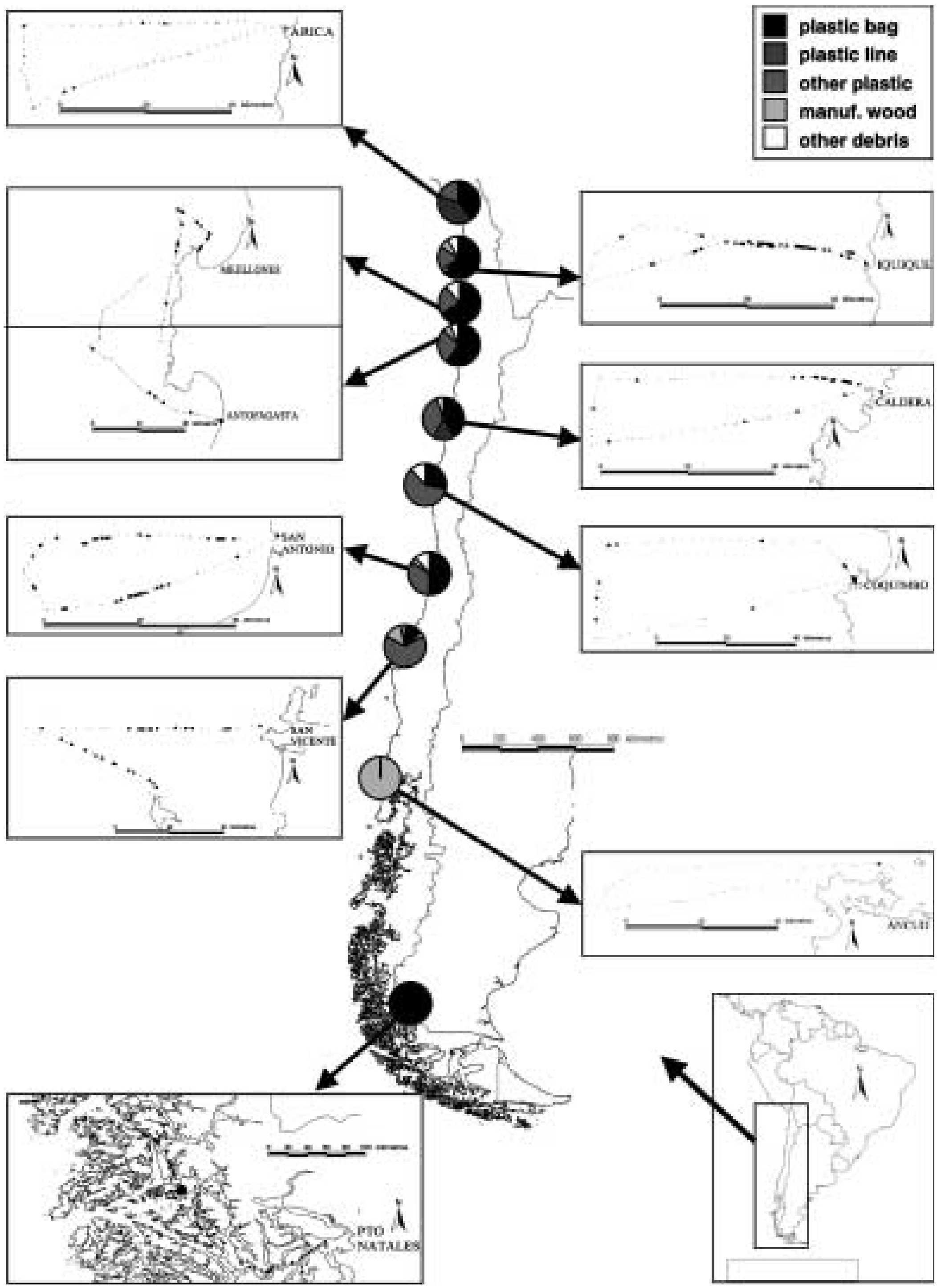

Fig. 1. Location of observed FMD in the surveys conducted along the coastal waters of the SE-Pacific off the Chilean coast; large dots represent one item, dotted line represents the transect line; pie-charts represent composition of FMD at each study site; for further details, see text.

4. Discussion

4.1. Abundance and composition of floating marine debris

FMD is ubiquitous throughout the world's oceans (e.g. Coe and Rogers, 1997), and even remote shores distant from major sources receive their share of marine debris (e.g. Torres et al., 1997). Herein, we found comparatively high densities of FMD in coastal waters of the SE-Pacific. Densities found at some of our study sites did not differ substantially from densities reported for other regions of the world (Table 2). For example,

Table 1
Densities of FMD in different regions of the coastal waters of the SE-Pacific off Chile

Site		Plastic bag n (%)	Plastic line n (%)	Other plastics n (%)	Wood n (%)	Other FMD n (%)	Total n
Arica	Nearshore	0	0	0	0	0	0
18°28′S, 70°19′W	Offshore	2 (40,0)	2 (40,0)	1 (20,0)	0	0	5
Iquique	Nearshore	4 (28,6)	0	7 (50,0)	1 (7,1)	2 (14,3)	14
20°13′S, 70°09′W	Offshore	38 (70,4)	2 (3,7)	6 (11,1)	4 (7,4)	4 (7,4)	54
Mejillones	Nearshore	10 (66,7)	0	3 (20,0)	0	2 (13,3)	15
23°02′S, 70°30′W	Offshore	2 (66,7)	0	1 (33,3)	0	0	3
Antofagasta	Nearshore	8 (57,1)	0	4 (28,6)	1 (7,1)	1 (7,1)	14
23°38′S, 70°24′W	Offshore	1 (100)	0	0	0	0	1
Caldera	Nearshore	7 (53,8)	2 (15,4)	4 (30,8)	0	0	13
27°04′S, 70°49′W	Offshore	1 (16,7)	1 (16,7)	3 (50,0)	0	1 (16,7)	6
Coquimbo	Nearshore	5 (27,8)	0	11 (61,1)	0	2 (11,1)	18
29°58′S, 71°21′W	Offshore	2 (28,6)	0	4 (57,1)	0	1 (14,3)	7
San Antonio	Nearshore	2 (50,0)	0	1 (25,0)	1 (25,0)	0	4
33°35′S, 71°37′W	Offshore	20 (50,0)	0	14 (35,0)	1 (2,5)	5 (12,5)	40
San Vicente	Nearshore	2 (28,6)	0	3 (42,9)	2 (28,6)	0	7
36°44′S, 73°08′W	Offshore	2 (9,1)	1 (4,5)	16 (72,7)	2 (9,1)	1 (4,5)	22
Ancud	Nearshore	0	0	0	1 (100,0)	0	1
41°51′S, 73°50′W	Offshore	0	0	0	0	0	0
Pto Natales	Nearshore	1 (100)	0	0	0	0	1
51°44′S, 72°30′W	Offshore	0	0	0	0	0	0
Total	Nearshore	39 (44,8)	2 (2,3)	33 (37,9)	6 (6,9)	7 (8,0)	87
	Offshore	68 (49,3)	6 (4,3)	45 (32,6)	7 (5,1)	12 (8,7)	138
Total		107 (47,6)	8 (3,6)	78 (34,7)	13 (5,8)	19 (8,4)	225

studies carried out in coastal waters of California, the Pacific coast of Mexico, and the North Sea revealed densities similar to those from the SE-Pacific (Table 2). However, these densities remain far below those reported more than two decades ago for the Mediterranean Sea (Morris, 1980) or more recently for a bay in Indonesia (Uneputty and Evans, 1997). Since environmental awareness and legislation in Europe and in N-America have substantially improved during the past two decades, we hope that densities reported for the mid-1970s from the Mediterranean probably represent peaks that have diminished since then. While in some areas of the world the quantities of marine debris apparently show a decreasing trend during the past two decades (Ribic et al., 1997), other authors reported increases (Walker et al., 1997). Since our study represents the first quantitative survey of FMD in coastal waters of the SE-Pacific, no temporal comparisons can be made. Regardless of potential temporal trends, it becomes evident that densities of FMD in coastal waters of the SE-Pacific are among the highest recently reported for the world's oceans (Table 2).

4.2. Possible sources and sinks of floating marine debris

The major proportion of FMD typically consists of plastic items. For example in the N-Pacific, plastic items made up more than 80% of all FMD (Matsumura and Nasu, 1997), and also in the North Sea plastic items dominated among FMD (Dixon and Dixon, 1983). The percentage of plastic items found in coastal waters of the SE-Pacific (86.6%) is not different from this trend.

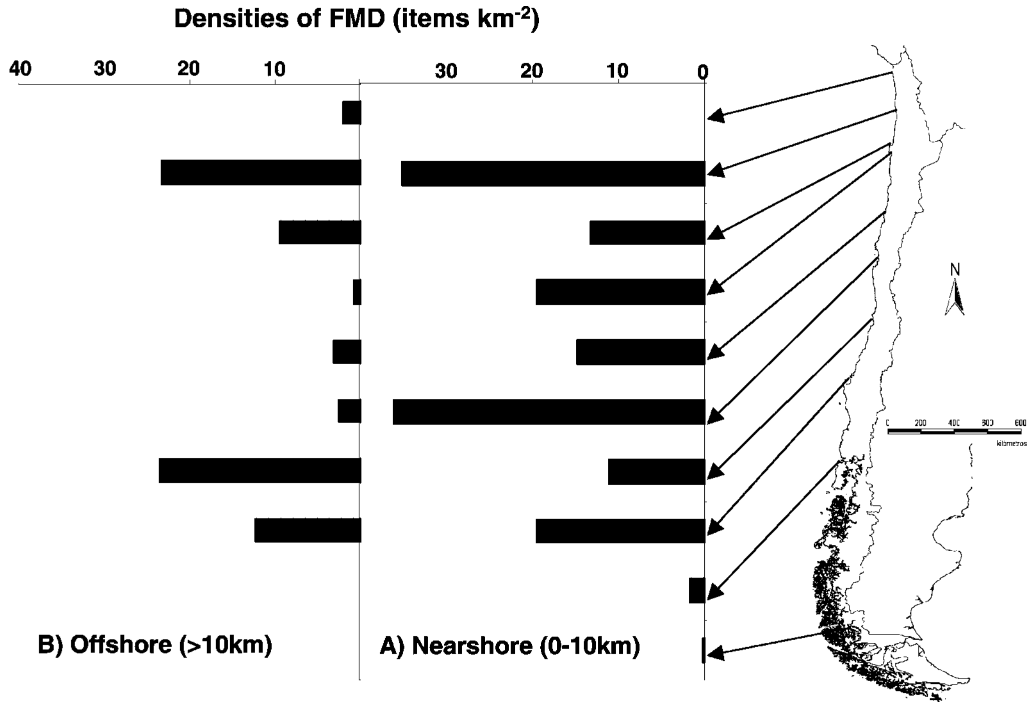

Fig. 2. Densities of FMD in (A) nearshore, and (B) offshore waters of the SE-Pacific off the Chilean coast; for details see text.

Table 2
Densities of FMD in different regions of the world's oceans

Region	Density (items km^{-2})	Type	Method	Reference
N-Pacific (subarctic)	0.15	P	VSS	Dahlberg and Day (1985)
NE-Pacific (>40°N, coastal)	1.0	P	VSS	Matsumura and Nasu (1997)
NW-Pacific (>40°N, coastal)	0.2	P	VSS	Matsumura and Nasu (1997)
N-Pacific (subtropical)	3.15	P	VSS	Dahlberg and Day (1985)
NE-Pacific (20°N–40°N, coastal)	1.0	P	VSS	Matsumura and Nasu (1997)
NW-Pacific (20°N–40°N, coastal)	0.8	P	VSS	Matsumura and Nasu (1997)
NE-Pacific (<20°N, coastal)	1.8	P	VSS	Matsumura and Nasu (1997)
NW-Pacific (<20°N, coastal)	0.25	P	VSS	Matsumura and Nasu (1997)
N-Pacific (central)	2.20	P	VSS	Venrick et al. (1973)
N-Pacific (central)	0.01	P	VSS	Matsumura and Nasu (1997)
Indonesia	>4000	P	VSS	Uneputty and Evans (1997)
S-Pacific (subantarctic)	1–2	P	VSS	Gregory (1990) (cited in Gregory and Ryan, 1997)
S-Pacific (<40°S)	<20	P	VSS	Gregory (1990) (cited in Gregory and Ryan, 1997)
S-Pacific (20°S–40°S, costal)	1–36	P	VSS	This study
S-Pacific (>40°S, coastal)	<1	P	VSS	This study
S-Atlantic (~30°S, <10 km)	19.6	P	VAS	Ryan (1988, 1990) (cited in Gregory and Ryan, 1997)
S-Atlantic (~30°S, 50 km)	1.6	P	VAS	Ryan (1988, 1990) (cited in Gregory and Ryan, 1997)
North Sea	1 to >3	P	VSS	Dixon and Dixon (1983)
Mediterranean	~1200	P	VSS	Morris (1980)
Gulf of Mexico	0.2–0.8	P_l	VAS	Lecke-Mitchell and Mullin (1992)
Gulf of Mexico	0.8–2.4	P	VAS	Lecke-Mitchell and Mullin (1997)

P, plastic items; P_l, large (>23 cm) plastic items; VSS, visual ship-based surveys; VAS, visual aerial surveys.

Plastic items have a high floatability, probably being the main reason for their proportional dominance among marine debris.

Composition and specific characteristics of marine debris permit to infer about its sources. For example, markings on debris have been used to identify countries of origin (Garrity and Levings, 1993; Ribic et al., 1997). Similarly, the general composition of debris (e.g. Moore and Allen, 2000; Nagelkerken et al., 2001) or seasonal dynamics (e.g. Galgani et al., 1995) permit to draw conclusions on possible sources of marine debris. In coastal waters of the SE-Pacific plastic bags were by far the most abundant items. Galgani et al. (1995) reported high abundances of plastic bags in dredge samples from the continental shelf along the French and Spanish Atlantic coast. They suggested that the high proportion of plastic bags and their high abundance during the tourist season hints towards shipping (commercial and pleasure boats) as a potential source. In the coastal waters of the SE-Pacific pleasure boating is relatively infrequent (personal observations), but commercial shipping is common. The higher concentration of plastic bags near major port cities reported herein supports the conclusion that a large part of the plastic debris in the SE-Pacific may originate from commercial shipping activities. Land-based sources such as beach litter or untreated sewage waters (Williams et al., 1993) may also be responsible for part of the plastic debris. These latter authors found that 24% of marine debris caught in submarine fishing nets originated from sewage systems. Given that most sewage waters in Chile reach the ocean without any treatment either by direct discharge or via rivers (UNEP, 1999), it is not unlikely that the high percentage of plastic bags near cities originates from sewage systems.

Fishing gear occurred in very low abundances among FMD in coastal waters of the SE-Pacific. This differs from shore-based surveys conducted in Australia, Canada and England, which reported that >10% of all debris was fishing debris (Jones, 1995). Presently, it is not clear whether ecological awareness (or poverty) of local fishermen or other factors (negative buoyancy of fishing gear combined with great water depths) contribute to the fact that fishing gear only represents a small fraction of FMD near the Chilean coast. Other items that may be important in some areas of the world, such as tar balls (Day and Shaw, 1987; Morton and Blackmore, 2001), were not found during this study.

Previous studies had indicated that densities of FMD might follow a latitudinal pattern with high densities at low and intermediate latitudes and lower densities at high latitudes (Day and Shaw, 1987; Matsumura and Nasu, 1997). Herein, we found that the densities of FMD were highly variable between 18°S and 40°S, but diminished strongly at higher latitudes. Similar results have been reported for FMD in the N-Pacific, where highest abundances of marine debris were found between 20°N and 40°N, but strongly diminished at higher latitudes (Matsumura and Nasu, 1997). Since human populations and activities are concentrated at mid and low latitudes, it can be expected that FMD also is concentrated in these regions (see also Table 1). A study carried out by Barnes (2002) indicates that the proportion of man-made debris on island shores in the southern hemisphere is higher at high latitudes than at low latitudes. Our study shows that the abundance of FMD strongly decreases towards high latitudes, while natural floating substrata (macroalgae) increase in abundance (unpublished data). Shore-based surveys may not be representative of marine debris floating at sea, since accessible shores may be (a) close to potential sources, such as villages or research stations, or (b) affected by post-deposition processes (burial, decomposition, wind-induced export). These comparisons indicate that a better understanding of the dynamics of FMD can only be obtained by monitoring the distribution and behaviour of these items at sea.

Little is known about the possible sinks of FMD from coastal waters of the SE-Pacific. Onshore winds are common in this region and a large proportion of FMD may end up on the shore after variable periods of pelagic drift. Data by Gregory and Ryan (1997) indicate high numbers of marine debris on beaches near Valparaiso (33°S) in the SE-Pacific, but to our knowledge no other data have been reported from this region of the world. With time, FMD may become negatively buoyant and sink to the seafloor. Several studies of marine debris at the seafloor report similar items as those that are commonly found floating at the surface (e.g. plastic bags, bottles and fishing gear—Galgani et al., 1995; Moore and Jones, 2000; Nagelkerken et al., 2001). Two surveys from the French Atlantic coast (Galgani et al., 1995) and from the French Mediterranean coast (Galgani et al., 1996) reported very high proportions of plastic bags from the seafloor. Since shore-based surveys report comparatively low percentages of plastic bags (Gregory and Ryan, 1997; Ribic et al., 1997), these observations could indicate that plastic bags feature relatively limited floating potential and sink to the seafloor before currents carry them to the shore. During our surveys we often observed plastic bags that were fully submerged, sometimes drifting below the water surface at depths of 10–200 cm. If indeed plastic bags have limited floating potential, the large proportion of plastic bags found in our sea-based survey suggests that they can't have been adrift for a long time period, i.e. they probably had been deposited in coastal waters close to the sighting points. The observations of cardboard and organic litter (see results), items with limited floating potential, support this conclusion.

Large quantities of fishing gear have also been reported from sea-floor surveys (Jones, 1995; Donohue et al., 2001), indicating that a large proportion of this material is negatively buoyant and will sink rapidly to the seafloor. No information about marine debris on the seafloor is available from the SE-Pacific, possibly due to the great water depths even a few km offshore.

FMD may also drift over large distances as is indicated by the fact that identifiable items have been found on shores hundreds of km from the source regions (Ebbesmeyer and Ingraham, 1992). In the coastal waters of the SE-Pacific with predominant alongshore currents, items may potentially drift over large distances primarily in longitudinal direction. The fact that low abundances of FMD were found south of 40°S, nevertheless, indicates that the predominant currents along the Chilean coast impede export from areas with high densities of FMD towards high latitudes. Thus, it can be considered likely that most FMD, which probably has its origin in the densely populated region between 18°S and 40°S (see above) will end up on beaches or on the seafloor in this region or north thereof, i.e. in downstream direction of the Humboldt Current.

4.3. Potential threats of floating marine debris in the SE-Pacific

FMD of variable size and composition may dramatically increase the availability of dispersal substrata for some marine invertebrates (e.g. bryozoans, Winston, 1982). Given the fact that some FMD may have very high floating potential and occur in regions with little natural pelagic substrata (e.g. Barnes, 2002), its role as dispersal vector should not be underestimated. Since natural floating substrata (macroalgae) are highly abundant in the SE-Pacific (unpublished data), FMD may be of minor importance as dispersal vector for marine invertebrates in most parts of the study region.

FMD also presents a threat to marine birds and mammals that may ingest or become entangled in marine debris (Hanni and Pyle, 2000; Laist, 1997). Fur seals, Procellariiformes and Pelecaniformes are among those species frequently found entangled in FMD (Fowler, 1987; Laist, 1997). Along the shores of the SE-Pacific, large colonies of these species occur near the sites with high densities of FMD (Murphy, 1936; Aguayo and Maturana, 1973). Seabirds may also concentrate at oceanographic fronts where most FMD accumulates (Bourne and Clarke, 1984). Given the precarious status of several seabird species from the SE-Pacific and the potential ecological risks caused by FMD, possible measures should be taken to reduce the amount of FMD. Since most marine debris found in coastal waters of the SE-Pacific apparently has its origin in shore-based activities, measures need be taken on the regional (and national) level.

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