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Increase of litter at the Arctic deep-sea observatory HAUSGARTEN

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ABSTRACT

Although recent research has shown that marine litter has made it even to the remotest parts of our planet, little information is available about temporal trends on the deep ocean floor. To quantify litter on the deep seafloor over time, we analysed images from the HAUSGARTEN observatory (79°N) taken in 2002, 2004, 2007, 2008 and 2011 (2500 m depth). Our results indicate that litter increased from 3635 to 7710 items km^{-2} between 2002 and 2011 and reached densities similar to those reported from a canyon near the Portuguese capital Lisboa. Plastic constituted the majority of litter (59%) followed by a black fabric (11%) and cardboard/paper (7%). Sixty-seven percent of the litter was entangled or colonised by invertebrates such as sponges (41%) or sea anemones (15%). The changes in litter could be an indirect consequence of the receding sea ice, which opens the Arctic Ocean to the impacts of man's activities.

1. Introduction

Although the deep sea covers ~60% of our planet's surface the deep ocean floor remains the least explored ecosystem on Earth (Smith et al., 2009). Still less is known of deep-sea ecosystems from remote polar regions such as the Arctic. Despite our scarce knowledge, exploitation of its resources is already underway in terms of hydrocarbon exploration, fisheries, shipping and tourism as the sea ice is receding. Although the disposal of solid waste at sea was prohibited in 1988 (Annexe V, MARPOL Convention) more and more reports indicate that even the most secluded environments such as polar regions and the deep ocean floor are no longer exempt from contamination with litter (Barnes, 2002; Galgani et al., 2000). The annual global production of plastic products is estimated at 230 million tons (Weisman, 2007). Because of their chemical composition plastics are durable and degrade very slowly. Since the 1950s one billion tons of plastic have been discarded, which may persist for hundreds of years (O'Brine and Thompson, 2010). In fact, recent studies suggest that the 1982 figure of 8 million litter items entering the oceans every day may need to be multiplied several fold (Barnes, 2005). Marine litter is defined as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment" (UNEP, 2009).

Plastic accounts for the large majority of marine litter (Laist, 1987; Spengler and Costa, 2008), which is hardly surprising given an annual global production of 230 million tons in 2009 (Cole et al., 2011), of which >10% end up in the oceans (Thompson, 2006). Plastics are non-biodegradable but can mechanically be broken down into secondary micro-plastics (Cole et al., 2011). Recently, exposure to ever increasing quantities of micro-plastics was identified as a problem of major environmental concern (Cole et al., 2011; Thompson et al., 2004). Micro-plastics are considered vectors for adsorbed pollutants such as endocrine disrupting chemicals, phthalates, polyaromatic hydrocarbons, organochlorine pesticides and polychlorinated biphenyls (Cole et al., 2011; Zarfl and Matthies, 2010). Through ingestion, they reach the tissues of suspension and deposit feeders (Graham and Thompson, 2009) and other biota (Thompson et al., 2004), accumulate through the food web and may enter the human food chain (Murray and Cowie, 2011). Alarmingly, micro-plastics were also found in most sediment samples from UK waters and increased from the 1960s to the 1990s in plankton samples taken between Scotland and Iceland (Thompson et al., 2004).

Macro-litter is not a mere aesthetic problem. In the oceans, it affects marine life in different ways. Most obviously, it causes entanglement, suffocation and disrupts ingestion/food uptake in birds, fish, mammals, turtles and fish (Derraik, 2002). Such deleterious effects have been documented in >267 marine species in the late 1980s (Laist, 1987) and this figure has probably risen since. In addition to suffocation, fisheries-related litter may increase mortality by ghost fishing (Laist, 1987). Plastic bags may smother and damage organisms from soft and hard substrata (Parker, 1990). Litter on the seafloor can cause anoxia to the underlying sediments, which alters biogeochemistry and benthic community structure (Goldberg, 1994). Furthermore, litter may provide substrata for the attachment of sessile biota in sedimentary environments and increase local diversity (Mordecai et al., 2011; Moret-Ferguson et al., 2010; Pace et al., 2007) although this replaces existing species and leads to non-natural alterations of faunal community composition. Attachment to or entanglement

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in floating debris, opens new routes of transportation, 'rafting' (Barnes, 2002; Barnes and Milner, 2005; Issacs et al., 2000) and may enable alien invasion (Gregory, 2009), especially in polar regions during an era of rapid environmental transition due to global warming (Barnes, 2002, 2005; Barnes et al., 2010). Long-distance transport may be enhanced by storms/strong winds (Kukulka et al., 2012), projected to become more frequent as a result of climate forcing (IPCC, 2007).

Since plastic litter is light and durable it can travel long distances in the marine realm distributing its pollutants to hitherto unspoiled remote ecosystems (Barnes et al., 2010; Zarfl and Matthies, 2010). As plastics are colonised or loaded with sediments they sink to the seafloor (Thompson, 2006; Ye and Andrady, 1991). However, recent models indicate that wind stress significantly enhances the vertical mixing of buoyant micro-plastic litter into the water column and that, depending on wind speed, surface observations may underestimate the total amount of buoyant plastic distributed in the upper water column by a factor of up to 27 (Kukulka et al., 2012). In the sediments, plastic litter can persist for centuries (Derraik, 2002). In polar deep-sea sediments degradation rates may be even lower due to the absence of sunlight, low ambient temperatures and low energy input.

Despite these implications, little is known about the distribution of litter on the ocean floor as most studies refer to reports of litter floating on the water surface, coastal areas and beached litter (Barnes and Milner, 2005; Thompson et al., 2004). Several studies highlighted a problem with litter pollution in the Mediterranean, e.g. (Galgani et al., 1995a; Galgani et al., 1996; Galil et al., 1995; Katsanevakis and Katsarou, 2004; Stefatos et al., 1999) and other European coasts (Galgani et al., 1995b; Galgani et al., 2000). More studies on litter emerged from the US (June, 1990; Keller et al., 2010; Moore and Allen, 2000; Moret-Ferguson et al., 2010; Watters et al., 2010; Ye and Andrady, 1991) and elsewhere (Lee et al., 2006). Litter was also recorded from remote localities off Antarctica (Barnes, 2005; Barnes et al., 2010), the Arctic (Day and Shaw, 1987; Feder et al., 1978; Fowler, 1987; Hess et al., 1999; Jewett, 1976; June, 1990; Mallory, 2008; Provencher et al., 2010; Shaw, 1977; Zarfl and Matthies, 2010) and the deep seafloor (Galgani and Andral, 1998; Galgani and Lecornu, 2004; Keller et al., 2010; Mordecai et al., 2011; Pace et al., 2007; Ramirez-Llodra et al., in press; Wei et al., 2012).

Despite an increase in the number of papers on marine debris in recent years, most of these studies deal with litter from specific areas or map its distribution. While such information is crucial to estimate the scope and spread of the problem, information about the amount of oceanic macro-litter over time is scarce (but see (Galgani et al., 2000; Hess et al., 1999; Watters et al., 2010; Wei et al., 2012). Here we analyse photographs taken at a set camera transect at the HAUSGARTEN observatory in 2002, 2004, 2007, 2008 and 2011 to assess if the quality and quantity of litter in the deep Arctic sea has changed over the past decade.

2. Materials and methods

In 1999, the AWI established the deep-sea observatory HAUSGARTEN in the eastern Fram Strait west of Svalbard (Soltwedel et al., 2005). HAUSGARTEN comprises nine stations along a bathymetric gradient which is crossed by a latitudinal transect of currently eight stations at the central HAUSGARTEN station (Fig. 1). It serves as an experimental arena and harbours longer-term experiments and instrumentation. In 2002, a camera track at 2500 m water depth was also established at this station and revisited in 2004, 2007 and 2011 (Bergmann et al., 2011a). In 2008, the camera had to be towed along a different track nearby due to strong water currents (Fig. 1).

Images were taken at set 30-s or 50-s intervals by a towed camera system (Ocean Floor Observation System, OFOS) during expeditions (ARK XVIII/1, ARK XX/1, ARK XXII/1, ARK XXIII/2, ARK XXVI/2) of the German research icebreaker "Polarstern". The OFOS set up used from 2002 to 2007 is described in Bergmann et al. (2011a). The OFOS used in 2011 (Fig. 1) comprised a Canon camera (EOS-1Ds Mark III, modified for underwater applications by Isitec, Germany), a Kongsberg strobe (OE11-242), four DeepSea Power & Light LED lights (LED Multi-Sealite), telemetry (LRT-400 Fiber, Isitec) and three red laser pointers (Oktopus, Germany) at a distance of 50 cm to each other. The OFOS was towed for 4 h at ~0.5 knots and a target altitude of 1.5 m, which varied as the winch operator had to adapt to varying bottom topography and sea state. The camera footprint encompassed 3–4 m^2. The start and end positions of the OFOS transect (from GPS fixes) and water depths along transects (from echo soundings) were taken from the ship's data acquisition and management system, or in 2011, by the OFOS' telemetry.

All images were uploaded onto the BIIGLE (Bio-Image Indexing and Graphical Labelling Environment) database (Bergmann et al., 2011b). For the quantification of anthropogenic debris in the deep Arctic sea, we scanned all images available for litter. Any shape which could be identified with more than 90% certainty as human waste was labelled with 'litter' and recorded. The laser points were automatically detected and from this the machine generated area calculations for each image (Bergmann et al., 2011b). Areas could not be calculated in 2008 as the laser pointers did not function. Unsuitable images (too dark, too high altitude, extensive sediment clouds) were omitted and excluded from the calculation of total areas covered. An area of 1926, 2471, 2747 and 1427 m^2 was analysed in 2002, 2004, 2007 and 2011, respectively. Based on area calculations we converted litter numbers to densities (m^{-2}). Although we acknowledge that the distribution of litter is highly variable in space we converted this to km^{-2} to enable a comparison with published figures on litter from elsewhere. We calculated litter densities (m^{-2}) for each image and used a Kruskall–Wallis test (Minitab 14) to test for differences in litter densities between years.

To quantify the amount of litter, the length (longest dimension) of each item was measured and grouped into small (<10 cm), medium (10–50 cm) and large (>50 cm) size categories (Mordecai et al., 2011). The origin/material of each item was identified although this was not always possible because of low resolution, burial, small size or advanced state of degradation. All epibenthic megafaunal organisms entangled with or attached to litter were recorded to investigate possible interactions.

3. Results

A total of 2878 images or an area of 8570 km^2 (excl. 741 images from 2008) was analysed (Table 1). Twenty-seven items of litter were recorded and 24 images showed litter. Further items ($n = 8$) may also be litter but were not counted because the certainty was <90%.

3.1. Temporal changes in litter

Litter densities increased from 3635 to 7710 km^{-2} between 2002 and 2011. A Kruskal–Wallis test indicated significant differences in the litter densities from different years (adjusted for ties, $H = 8.60$, $df = 3$, $p = 0.035$). The strongest increase by more than an order of magnitude occurred between 2007 and 2011 (Fig. 2). No litter density data are available for 2008, as the laser pointers did not function, which precluded area calculations. Similarly, the number of images with litter increased from 1.08% to 2.08% over the whole study period (Fig. 2). Between 2002 and 2008 the number of images with litter decreased followed by a period of strong increase from 0.54% in 2008 to 2.87% in 2011 (Fig. 2).

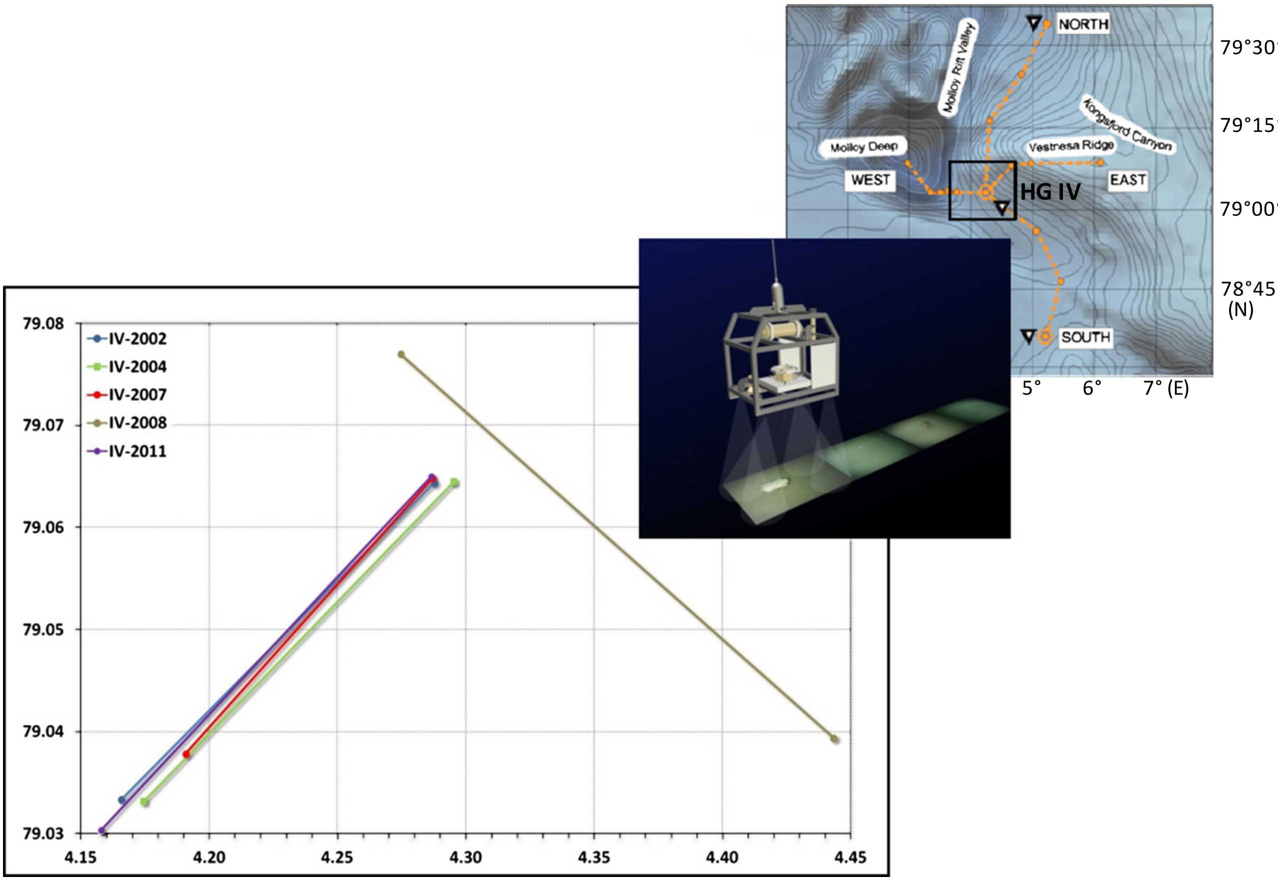

Fig. 1. Sketch of the Ocean Floor Observation System (OFOS) and map of the study area and camera transects.

Table 1
Litter densities, types and sizes and interactions between litter and megafauna recorded from seafloor photographs taken at the HAUSGARTEN observatory between 2002 and 2011.

	2002	2004	2007	2008	2011	Total	%
No. of images analysed	647	660	451	741	383	2882	
Area photographed (m^2)	1926	2471	2747	n.a.	1427	8570	
No. of litter items recorded	7	3	2	4	11	27	
Litter items km^{-2}	3635	1214	728	n.a.	7710	13,287	
Litter type							
Plastic	4	2	2	4	4	16	59.26
Paper/cardboard	1	1				2	7.41
Black material	1				2	3	11.11
Metal	1					1	3.70
Pottery					1	1	3.70
Rope					1	1	3.70
Polystyrene					1	1	3.70
Glass					1	1	3.70
Rubber					1	1	3.70
Litter size							
Small	1	1	1	2	3	8	29.63
Medium	6	2	1	2	7	18	66.67
Large	0	0	0	0	1	1	3.70
Megafauna interaction							
No visible biota	4		1	1	3	9	33.3
Cladorhiza gelida		2	1	3	5	11	40.7
Caulophacus fragments	1				1	2	7.4
Actinian	1	1			2	4	14.8
Hydrozoa					1	1	3.7
Bathycrinus carpenterii	1				1	2	7.4

3.2. Type and size of litter

The majority of items that could be identified with certainty appeared to be plastic (Fig. 3), mostly fragments of plastic bags. Three images showed a flat black object, which resembled roofing/tar paper and was termed ‘black material’ (Fig. 4I). Cardboard/paper packaging was recorded from two images in 2002 and 2004 (Table 1 and Fig. 4B). Plastic was the predominant type of litter

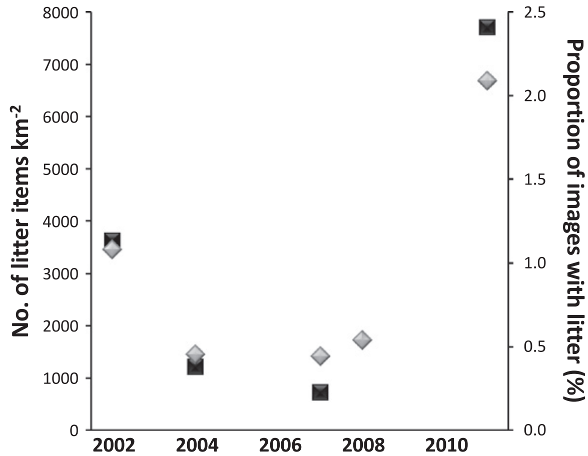

Fig. 2. Abundance of litter items at HAUSGARTEN central station (2500 m depth) between 2002 and 2011. Black symbols represent mean litter densities (number km^{-2}); grey symbols represent the proportion of images showing litter every year.

in all years (Fig. 3). Litter 'diversity' was higher in years with higher litter abundance (2002 and 2011). Fig. 4 illustrates some of the litter types recorded.

When grouping litter into size categories, the majority of items were of medium size (67%), followed by small (30%) and large items (3%) (Table 1).

3.3. Interactions between litter and megafauna

Sixty-seven percent of the litter items recorded were in some way 'associated' with megafaunal organisms. As it was often difficult to differentiate if the litter was entangled with biota or colonised we counted both as 'interaction'. The highest proportion of litter appeared to be entangled with the sponge *Cladorhiza gelida*, followed by sea anemones, probably *Bathyphellia margaritacea* and *Amphianthus* sp., which colonised 15% of the litter items (Table 1). The sea lily *Bathycrinus carpenterii* settled on cardboard packaging and a bottle, which was also colonised by hydroids. A few litter items were entrapped with dead fragments of the sponge *Caulophacus arcticus*.

In 2002, more than half of the litter items recorded was free of megafauna. Over time, the proportion of litter 'associated' with megafauna increased as did the proportion of litter entangled with the sponge *C. gelida* (Table 1). Fig. 4 illustrates some of the interactions observed between litter and megafauna.

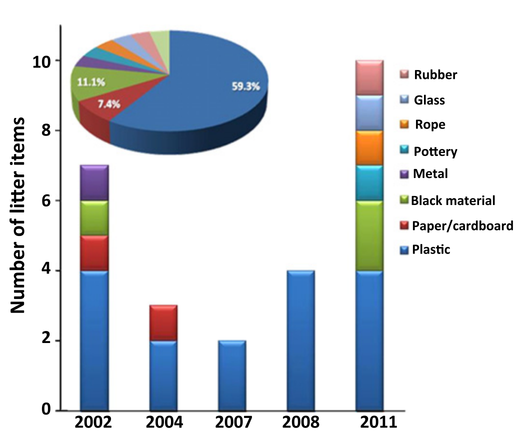

Fig. 3. Types of litter recorded from seafloor photographs taken between 2002 and 2011.

4. Discussion

The amount of litter recorded during this study was less than observed elsewhere. For example, Galgani et al. (2000) reported densities as high as 101,000 items km^{-2} from European waters and Watters et al. (2010) found densities of up to 76,000 items km^{-2} off California. However, it was more than expected given the remote and presumably secluded nature of both polar and deep-sea environments. In fact, the densities recorded in 2011 (7710 items km^{-2}) are comparable to those observed in the deep northern Gulf of Mexico (Wei et al., 2012) and even higher than quantities reported from canyons close to Lisboa (6600 items km^{-2}), which were classified as moderately high and attributed to the proximity to the heavily populated and industrialised Portuguese capital (Mordecai et al., 2011). An earlier litter survey at HAUSGARTEN conducted by the remotely operated vehicle *Victor 6000* reported quantities of up to 0.52 km^{-1} in 1999 and up to 0.86 items km^{-1} in 2003 and concluded that they were in the same range as those reported from the Celtic Sea and the Bays of Seine and Biscay (Galgani and Lecornu, 2004). Although these figures suggest lower incidents of litter compared with ours, unfortunately they are not strictly comparable as the authors used transect length and not area coverage and analysed video footage instead of still photographs.

As we aimed to visit the same transect position during each campaign, we cannot discount entirely that we have recorded the same litter items repeatedly. If this was the case, however, it was not obvious for us to notice. Furthermore, given the long persistence of plastic litter, it could be argued that time-series records of plastic in the marine environment should be expressed as cumulative densities. So, how come the litter densities in 2004 and 2007 were lower? This may be due to spatial variability in the distribution of litter. Although we aimed for the same transect positions, it is technically very difficult to hit exactly the same ground with an instrument deployed at a wire length of 2.5 km. The decrease in litter may also be a result of burial by sediments and overgrowth.

To our knowledge this is one of the few long-term reports of litter on the (deep) seafloor. Although Galgani et al. (2000) provided litter data from 1992 to 1998 the results were interpreted primarily in terms of seasonal rather than interannual variation. When plotting the mean of their seasonal litter estimates from the Bay of Biscay and Gironde estuary, it turns out that there was a strong increase in 1993 at both locations, followed by a steady decrease until 1998 (Galgani et al., 2000) but this peak is not discussed. Similarly Watters et al. (2010) reported a significant increase in litter at some of their shelf locations off California between 1993 and 2007 but this not discussed in detail and it is unclear if the same survey tracks were revisited.

Although litter counts from the Kodiak Islands (Alaska) from 1994 to 1996 indicated a ~30% increase of inputs in 1995 the authors negated the need for annual litter monitoring schemes at the then low fishing levels (Hess et al., 1999). The increase in litter recorded in this study highlights the need for time-series litter monitoring schemes. The majority of litter recorded was plastic. If our data were presented as cumulative litter density, which would not be unreasonable given the centuries-long persistence of plastic (O'Brine and Thompson, 2010) the numbers would be even more alarming.

4.1. Possible sources of litter at HAUSGARTEN

The prime sources of marine debris comprise fisheries, ships, pleasure crafts, aquaculture, and terrestrial sources originating from urban populations and industry (Keller et al., 2010). Unfortunately, it is difficult to ascertain the exact source of litter from images as – unlike physical samples from trawls – it precludes

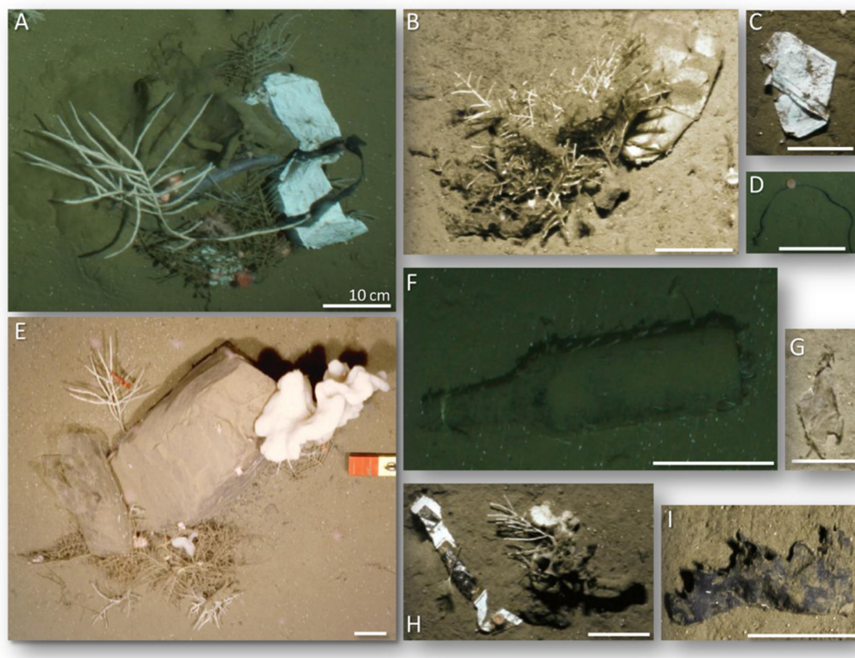

Fig. 4. Examples of types of litter and of interactions between litter and megafauna recorded from seafloor photographs: (A) polystyrene, fragment of plastic bag and black material entangled with *Cladorhiza gelida* and *Caulophacus* fragments, rubber band with actinian; (B) cardboard/paper packaging entrapped with *C. gelida*; (C) sanitary towel; (D) rope colonised by actinian (cf. *Amphianthus*); (E) plastic bag entrapped with *Cladorhiza gelida* and dropstone; (F) beer bottle colonised by hydroids and *Bathycrinus carpenterii*; (G) fragment of plastic bag; (H) tinfoil packaging colonised by actinian; and (I) black material resembling roof paper.

close examination. Inspection of the objects photographed at HAUSGARTEN did not allow us to draw firm conclusions as to any particular source of litter. Samples from elsewhere, for example, contained great proportions of ship paint, fishing gear or clinker such that the samples could easily be attributed to fisheries or shipping (Galil et al., 1995; Mordecai et al., 2011; Ramirez-Llodra et al., in press). Of anecdotal character was our (ROV-based) sighting of a bag of crisps at the HAUSGARTEN observatory imprinted "*Made in Hong Kong*".

Barnes (2005) found that litter accumulation rates were very closely correlated with human population levels for each 10° of latitude from the equator to near the poles. Data from deep submarine canyons off the west coast of Portugal suggest that the majority of marine litter recorded was from terrestrial sources (Mordecai et al., 2011). Waste input from urban areas and tourism also affected the abundance and distribution of litter along European coasts (Galgani et al., 2000). However, although there was an increase in Svalbard's population and tourism during the study period, both decreased after 2007 and 2008, after which the highest increase in litter occurred (Fig. 5A). Therefore, a rise due to increased terrestrial input seems unlikely, especially as the study area is located some 150 km off the coast of Svalbard.

Other studies identified maritime traffic, e.g. shipping, as a major source of waste (Shaw, 1977; Shaw and Mapes, 1979; Vauk and Schrey, 1987). While there was a general increase in ship arrivals in Svalbard at Longyearbyen between 2002 and 2010 the strongest rise was after 2005 and remained at a relatively constant level thereafter (Fig. 5B). However, when considering the number of ship arrivals from different sectors (cruise vessels, costal cruises, day tour boats, private yachts, cargo, science vessels, fishing vessels, navy/coastguard, Governors vessels) research vessel and private yacht arrivals increased more than two- and almost threefold, respectively, after 2007 (Fig. 5B). Since most research vessels follow strict waste disposal rules, we consider these an unlikely cause of waste although accidental inputs cannot be entirely discounted. In US waters, recreational fishing and pleasure craft accounted for up to 50% of all refuse disposed (UNESCO, 1994). Marine vessel and fishing activity was also identified as the primary source of anthropogenic debris from the California Bight (Moore and Allen, 2000). It should be noted, that ship arrival data are probably unsuitable indicators of fishing traffic as only few fishing vessels call at Longyearbyen (T.E. Haug, pers. comm.).

It is difficult to obtain data for fishing activities because HAUSGARTEN is located outside the 12-nm zone, beyond the jurisdiction of Svalbard. Automatic Identification System (AIS) data from the Norwegian satellite AISSAT-1 covering all ship types are only available since June 2011. Vessel monitoring systems for fishing vessels commenced in 2000. But because of differences regarding the status of the Fisheries Protection Zone around Svalbard some countries, including Russia, do not forward position reports outside the 12-mile zone. However, the AIS data from 2011 show that 94 of 178 vessels operating west of Svalbard were Russian (P. Finne, Norwegian Directorate of Fisheries, unpublished data). Fishing boat sightings made by coastguard patrols indicate a strong increase in Russian fishing vessels operating west of Svalbard (Fig. 5C). Sightings quadrupled and doubled in 2010 and 2011, respectively. Catch statistics from within the 12-nm zone showed that the catches of fish (namely cod, haddock) increased strongly after 2008 (Norwegian Directorate of Fisheries,2011). Evidence from local beach clean-ups suggests that the majority of washed-up litter originates from fisheries (T.E. Haug, pers. comm.). Elsewhere, areas of high fishing intensity were characterised by increased quantities of litter (Feder et al., 1978; Hess et al., 1999; Jewett, 1976; Pruter, 1987).

However, it is also possible that the litter observed on the deep seafloor of HAUSGARTEN entered the sea far away, for example in the NE Atlantic, and was transported north as flotsam with the North Atlantic drift and the West Spitsbergen Current. Strong winds may further enhance both the horizontal and vertical mixing of plastic litter in the sea (Kukulka et al., 2012). Litter stranded on a remote island in the south Atlantic was supposed to have travelled

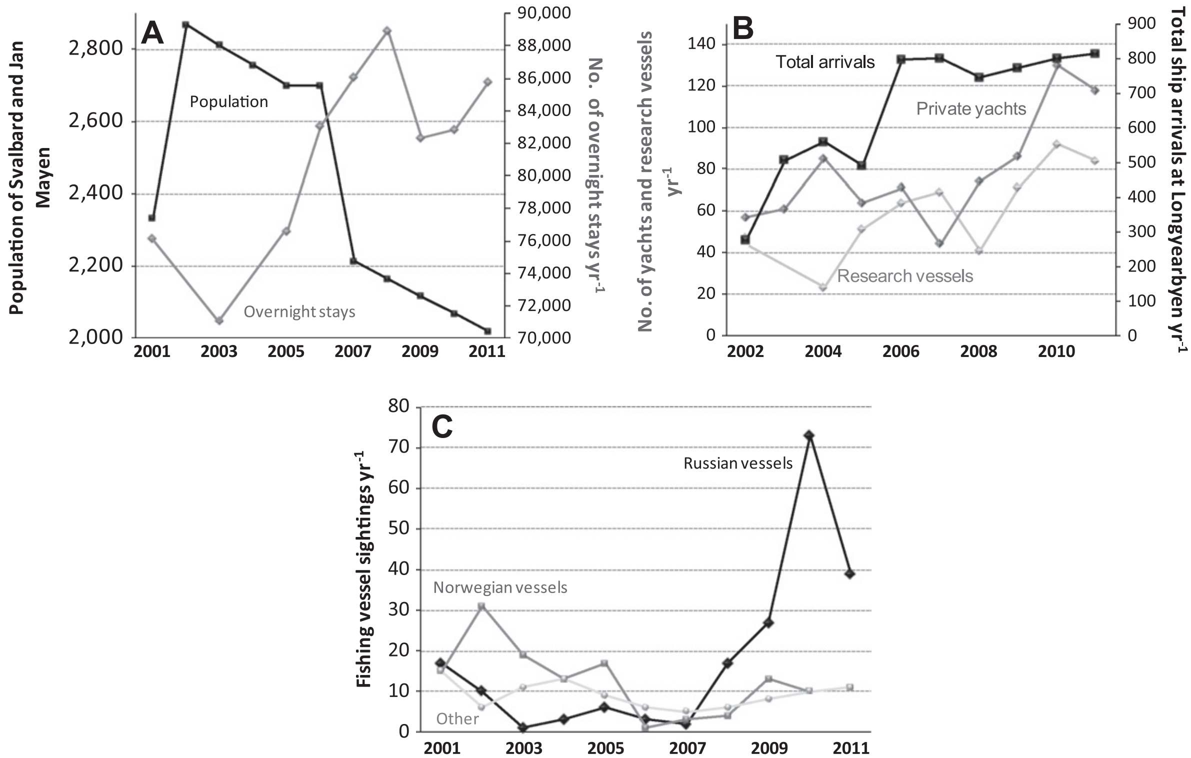

Fig. 5. Possible sources of litter. (A) Development of Svalbard's population and tourist stays between 2001 and 2011 (source: http://www.indexmundi.com/g/g.aspx?c=sv&v=21 and Governor of Svalbard). (B) Annual ship arrivals at Longyearbyen between 2001 and 2011 (*Source*: Harbourmaster of Svalbard). *Note*: most fishing vessels do not call at Longyearbyen. (C) Annual sighting of fishing vessels recorded during patrols by Svalbard's coastguard.

some 3000 miles from South America (Ryan and Moloney, 1993). The high incidence of marine debris at the seafloor of the Gulf of Lyons was attributed primarily to the local hydrodynamic regime (Galgani et al., 1995a). Fahrbach et al. (2001) estimated a northward flowing volume transport average of 9.5 Sverdrup yr^{-1} through the Fram Strait. The estimated plastic flux to the Arctic Ocean ranges from 62,000 to 105,000 tons yr^{-1}, assuming the maximum volume transport of ocean water (Zarfl and Matthies, 2010). Indeed there was an increased influx of Atlantic waters in the 2000s but after a peak in 2007 it decreased (Beszczynska-Möller et al., 2012). However, little is known about the sinking rates of plastics to the deep seafloor. So, low sinking rates of light plastic litter could have delayed the arrival on the deep ocean floor.

Currently, we cannot draw any firm conclusions as to the causes of the marine debris. Circumstantial evidence suggests that increased shipping due to a rise in private yachts and fishing activities may have contributed to litter inputs at HAUSGARTEN but an increased influx of Atlantic waters carrying litter may also play a role. Higher inputs of litter due to increased shipping activities in the Arctic may be an indirect consequence of global warming. First of all, the shrinking sea ice opens hitherto less travelled routes to ships. In particular, the increase in small boats without ice class such as private yachts may be a response to the thinning sea ice (Perovich et al., 2007) observed in recent years. Furthermore, changes in water temperatures may push cod (*Gadus morhua*) populations further north (Drinkwater, 2005; Rindorf and Lewy, 2006) attracting more fishing boats, particularly as there is less sea ice, which would result in higher catches (Norwegian Directorate of Fisheries, 2011). Sea ice acts as a protective shield preventing disposed solids from entering the water column (Barnes and Milner, 2005). Together with a projected increase in strong winds and storms (IPCC, 2007) sea ice shrinkage could indirectly increase the probability of litter entering the Arctic Ocean. As wind stress increases the vertical mixing of plastic into the ocean, the problem is likely to be exacerbated (Kukulka et al., 2012).

4.2. Effects on local fauna

Although millions of tons of plastic are produced every year, we still know very little about its effects on ecosystems and health. Most reports on the detrimental effects of litter on marine life refer to large biota such as turtles, mammals and sea birds (Derraik, 2002). Keller et al. (2010) reported a significant negative relationship between litter quantities and demersal catch. Litter also outweighed benthic megafauna at some stations in the deep eastern Mediterranean (Ramirez-Llodra et al., in press). As elsewhere, the majority of litter recorded at HAUSGARTEN was plastic (Derraik, 2002). Plastic also constituted the majority of litter items recorded at various HAUSGARTEN stations in an earlier ROV-survey (Galgani and Lecornu, 2004). This is probably a result of the extensive usage of this material but also of its long persistence (O'Brine and Thompson, 2010).

C. gelida was the organism most frequently observed entangled with litter. The emergent *habitus* of this sponge has probably led to entrapment of floating pieces of plastic. In the Florida Keys, lost hook-and-line fishing gear led to tissue abrasion causing partial individual or colony mortality in sponges and it was suggested that such impacts may render organisms more susceptible to predation, competitive overgrowth and disease (Chiappone et al., 2005). Like elsewhere, entrapment may lead to local damage/breakage (Parker, 1990). Apart from these effects we are left to speculate how this would affect the sponge. As plastic often smothers (parts of) sponges, it may reduce particle uptake and therefore, with time, also growth and reproductive output. Furthermore, it could reduce water exchange and thus respiration. Small plastic fragments and/or adsorbed toxins may be taken up by endocytosis. However, little is known to date about the (sublethal) effects of such contaminations. Fragments of another sponge, *C. arcticus*, were also seen entangled with plastic litter. These fragments were probably dead but it is unknown if death has occurred before or after entanglement. Such fragments were frequently recorded throughout

HAUSGARTEN (Schoening et al., 2012), however, not necessarily in combination with litter.

Litter can provide shelter and act as hard substratum such that sessile biota, for example the sea anemones, hydroids and crinoids recorded here, can settle on it. Sea anemones (*Amphianthus* sp.) were also reported from fishing gear from Portuguese canyons as where hydroids and crinoids from a bottle (Mordecai et al., 2011). It could thus be argued that – as with dropstones – the presence of marine litter alters diversity as it increases habitat heterogeneity. However, the originally present species would have to be replaced and it is a matter of debate, which is more 'valuable'. It should be noted that the taxa reported here were also observed on 'natural' hard substrata or sediments (although crinoids and anemones may have settled on invisible pieces of hard substratum buried below the sediment). However, natural hard substrata such as drop stones from the deep nearby Greenland channel harboured a richer megabenthic community (Schulz et al., 2010) compared with the few species reported here.

Interestingly, all biota recorded to be 'associated' with litter were suspension feeders. In addition to provision of hard substratum for settlement, the elevated position may grant better access to food particles carried in the water current. Still, the sub-lethal effects of permanent exposure to the adsorbed toxins are unknown although they are suspected to induce mutagenesis, carcinogenesis and bio-magnification to higher trophic levels (Cole et al., 2011).

Litter on soft-sediment could alter the gas exchange and local biogeochemistry (Goldberg, 1995). Mordecai et al. (2011) reported anoxic sediments underneath a plastic bag. As with drop stones or erect megafauna emergent litter objects may alter the small-scale hydrodynamic regime and drifting plastic could leave behind traces in sediment (Hasemann et al., in press; Hasemann and Soltwedel, 2011; Quéric et al., 2008; Quéric and Soltwedel, 2007). All of these factors can be expected to have an impact on benthic bacteria, meiofauna and macrofauna and therefore affect benthic community structure as a whole. As the life history of many deep-sea organisms is characterised by longevity it can be assumed that they are exposed to the impact of litter contamination for longer than their relatives from shelves or shallow waters.

As described above, plastic litter can travel vast distances (Barnes and Milner, 2005; Ryan and Moloney, 1993) increasing opportunities for organisms' dispersal significantly and doubling the risk of alien invasion (Barnes, 2002). Unfortunately, the method used precluded close examination of litter items, which is necessary to identify invasive species. However, Barnes and Milner (2005) reported that up to 7% of litter stranded at beaches of the Kongsfjord was colonised with organisms such as the exotic invasive barnacle *Elminius modestus* and the "most extreme latitude organism hitchhiker", *Membranipora membranacea* (Bryozoa). Over long, long-distance 'rafting' of biota on plastic flotsam may increase the risk of alien invasion and successful establishment, particularly in areas of currently rapid environmental changes such as the Arctic.

5. Conclusions

The extent of Arctic sea ice cover has changed significantly over the past decade with an all-time summer minimum observed in 2012. The receding sea ice opens hitherto largely inaccessible environments to man and the impacts of man's activities including shipping, fisheries and tourism. Environmental changes, possibly due to global forcing, may have lead to changes in the hydrodynamics and a decrease in sea ice cover, the most effective barrier to pollutants such as plastic litter. Ongoing research at other stations will allow us to determine if there has been an increase at other stations, too and to shed more light on the spread of the problem. The world-wide increase in marine litter even at remote locations such as the Poles and the deep ocean floor highlights the fact that the implementation of the current legislation does not suffice to solve the problem of poor practices of solid waste management. Unless effective action is taken it will only continue to worsen in the years to come (UNEP, 2009). Together with Barnes (2005) we conclude that our surveys have involved the first known glimpse of man to one of the remotest habitats on Earth, "but our miracle material had long since beaten us there".

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