Deep-Sea Research Part I (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Deep–Sea Research I

journal homepage: www.elsevier.com/locate/dsri

Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory

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ARTICLE INFO

Keywords:
Marine litter
Plastic
Arctic
Deep sea
Observatory
Photo/video system
Image analysis
Time series
Litter-Megafaunal encounters

ABSTRACT

The increased global production of plastics has been mirrored by greater accumulations of plastic litter in marine environments worldwide. Global plastic litter estimates based on field observations account only for 1% of the total volumes of plastic assumed to enter the marine ecosystem from land, raising again the question ‘Where is all the plastic? ’. Scant information exists on temporal trends on litter transport and litter accumulation on the deep seafloor. Here, we present the results of photographic time-series surveys indicating a strong increase in marine litter over the period of 2002–2014 at two stations of the HAUSGARTEN observatory in the Arctic (2500 m depth).

Plastic accounted for the highest proportion (47%) of litter recorded at HAUSGARTEN for the whole study period. When the most southern station was considered separately, the proportion of plastic items was even higher (65%). Increasing quantities of small plastics raise concerns about fragmentation and future microplastic contamination. Analysis of litter types and sizes indicate temporal and spatial differences in the transport pathways to the deep sea for different categories of litter. Litter densities were positively correlated with the counts of ship entering harbour at Longyearbyen, the number of active fishing vessels and extent of summer sea ice. Sea ice may act as a transport vehicle for entrained litter, being released during periods of melting. The receding sea ice coverage associated with global change has opened hitherto largely inaccessible environments to humans and the impacts of tourism, industrial activities including shipping and fisheries, all of which are potential sources of marine litter.

1. Introduction

Accumulations of marine litter on beaches or coastal areas as well as deleterious effects on marine mammals, turtles, birds and, to some extent, also on fish have attracted wide public attention as they can be directly observed by stakeholders. Marine litter has been recorded from everywhere on Earth including Antarctica and the Arctic (Galgani et al., 2015), proving that even the Polar Regions, some of the remotest areas of our planet, are not immune to litter pollution. During the last decade, the number of marine litter studies has increased drastically (Ryan, 2015), in part due to the discovery of the six so called ‘garbage patches’ and increasing quantities of microplastics (Thompson et al., 2004). 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), with plastic being the most common material observed due to its durability, wide usage and high disposal rates (Andrady, 2015). Latest figures indicate that the global plastic production has increased to 322 million t a^{-1} in 2015 (PlasticsEurope, 2015). The spatial variability of marine litter is high, depending on population levels, coastal usage, hydrodynamics, riverine drainage and shipping traffic (Galgani et al., 2015). The large discrepancy between global estimates of plastic litter inputs from land (Jambeck et al., 2015) and global plastic litter figures derived from field studies (Cozar et al., 2014; Eriksen et al., 2014; van Sebille et al., 2015) suggests the presence of hidden sinks of plastic in the oceans. Fragmentation into microplastics of larger fragments could be one explanation for ‘missing‘ marine litter (van Sebille et al., 2015). Still, recent research suggests that litter is widely spread in the deep sea (Pham et al., 2014). As with microplastics, the deep-sea realm is difficult to observe, which may render this remote ecosystem another potential sink for the’missing‘ amounts of litter.

More than 60% of the Earth's surface is covered with oceans deeper

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http://dx.doi.org/10.1016/j.dsr.2016.12.011
Received 17 June 2016; Received in revised form 30 November 2016; Accepted 10 December 2016
0967-0637/

Please cite this article as: Tekman, M.B., Deep-Sea Research Part I (2016), http://dx.doi.org/10.1016/j.dsr.2016.12.011

than 2000 m (Smith et al., 2009). Technical issues caused by extreme hydrostatic pressure as well as the causticity of the oceans (Smith et al., 2009) prevented direct observations of the deep seafloor until the late 1970 s, prior to which the deep seafloor was often portrayed as a huge near lifeless desert, making it appear as a suitable place onto which to dump waste (Ramirez-Llodra et al., 2011). Even though large scale waste disposal at sea was banned in 1972 (London Convention), the problem persists. The deep seafloor has not only already accumulated litter from the period preceding this ban but has also continued to receive waste from illegal dumping, coastal waste, riverine discharge, loss of fishing gear and maritime accidents (Ramirez-Llodra et al., 2011). The deep sea has therefore likely become one of the largest regions of marine litter accumulation (Pham et al., 2014). Even though technological progress has eased access to the deep ocean floor and there is a growing attention paid to the ecosystem as a result of rekindled mineral exploration interests, it remains the least explored ecosystem on Earth. A number of recent studies have reported considerable amounts of litter from the deep seafloor (Bergmann and Klages, 2012; Mordecai et al., 2011; Pham et al., 2014; Ramirez-Llodra et al., 2013; Schlining et al., 2013; Tubau et al., 2015). Litter densities on the deep seafloor vary greatly depending on topography (Pham et al., 2014) and hydrodynamic conditions (Tubau et al., 2015), nearby coastal usage related with population densities (Mordecai et al., 2011), changing environmental conditions or catastrophic events (Goto and Shibata, 2015) and riverine inputs (Rech et al., 2014).

Despite the current lack of standardisation of quantification methods, it is essential to increase our knowledge base on the distribution of litter on the deep seafloor in order to be able to identify any hidden sinks and to quantify the true extent of litter in our oceans. Unfortunately, most studies report litter densities from a particular point in time, or over a rather limited time-period, which precludes the observation of any long-term trends, which are needed to assess the compliance and efficiency of regulations. Sinking rates of buoyant litter items are largely unknown, so there is potential for a delay in the arrival of such material to the seafloor. Systematic long-term observations of litter over time, analysed in the context of anthropogenic activities, the efficiency of legislation and environmental changes, will enable us to identify more accurately the possible sources, transport pathways and transport mechanisms of marine litter.

One of the few longer-term studies available (Bergmann and Klages, 2012) showed that marine litter densities had increased between 2002 and 2011 at one station of the LTER observatory HAUSGARTEN (Arctic). Here, we extend the study to include new data from a station even further to the north and from HAUSGARTEN central station after 2011 to gauge if litter densities continued to increase. This enabled us to quantify temporal and spatial variability between two stations from the latitudinal HAUSGARTEN gradient. Analysis of seafloor photographs taken between 2002 and 2014 produced data on counts, types and sizes of marine litter. In addition, we assess encounters between megafauna and litter to evaluate ecological impacts on benthic biota to fill another important knowledge gap on how such waste products may be interacted with by the marine benthic communities.

2. Material and methods

2.1. Study site

In 1999, the Alfred Wegener Institute established the LTER (long-term ecological research) observatory HAUSGARTEN (Soltwedel et al., 2016). It is located in the eastern Fram Strait and comprises currently 21 stations along a bathymetric gradient and a latitudinal gradient. These stations are sampled annually to assess temporal variability in faunal, bacterial, biogeochemical and geological properties as well as on hydrography and sedimentation patterns that may be affected by global change. Here, we focus on two stations of the latitudinal gradient at ca. 2500 m depth: the central station HG IV and N3, located 60 km to the north (Fig. 1).

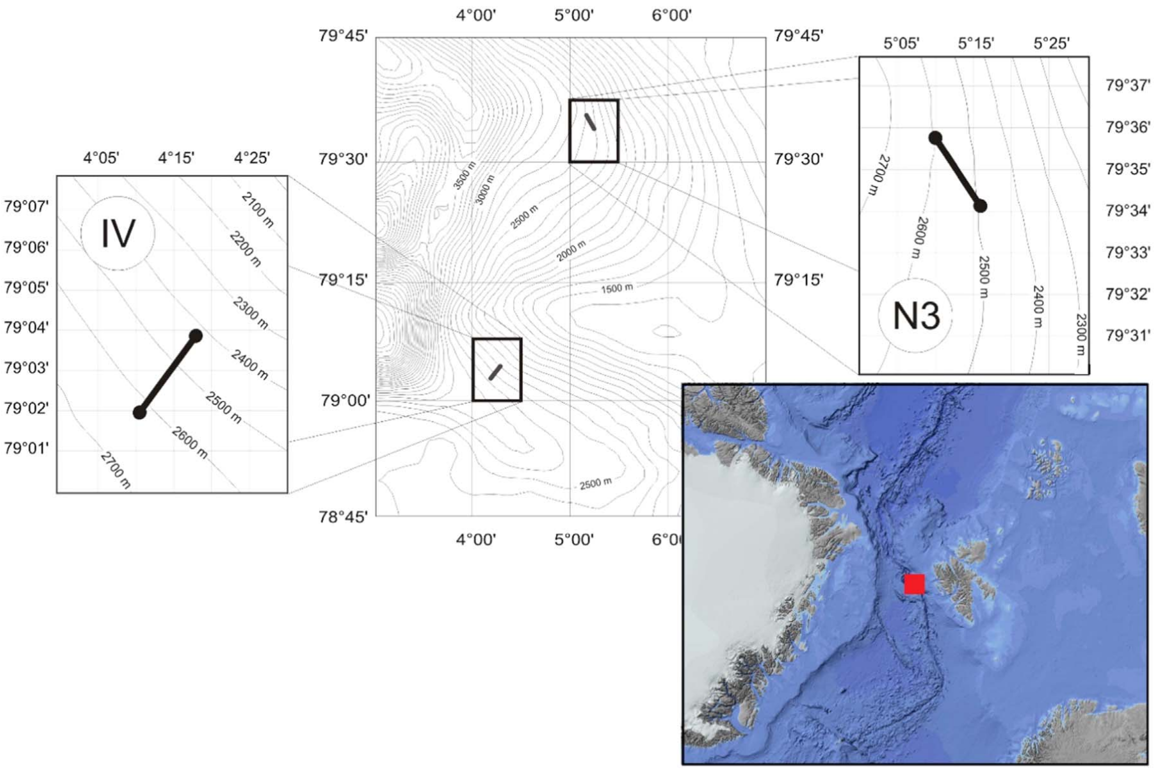

Fig. 1. Positions of Ocean Floor Observation System transects at the LTER observatory HAUSGARTEN (red point indicates HAUSGARTEN observatory) (map courtesy of T. Soltwedel, AWI, produced in CorelDraw version 16, PanMAP version 0.9.6, ArcMap 10.3.1).

2.2. Photographic surveys

Photographic surveys were undertaken by a towed camera system (Ocean Floor Observation System, OFOS)(Bergmann and Klages, 2012) during expeditions in 2002 (ARK XVIII/1), 2004 (ARK XX/1), 2007 (ARK XXII/1), 2011 (ARK-XXVI/2), 2012 (ARK-XXVII/2), 2014 (ARK-XXVIII/2) of the German research ice-breaker RV *Polarstern* and RV *MS Merian* expedition in 2013 (MSM29) to the HAUSGARTEN observatory. Images were taken along the same track at HG IV in 2012 and 2014 and at N3 in 2004, 2007, 2011, 2012, 2013 and 2014 and analysed for litter. Published data (Bergmann and Klages, 2012) from earlier HG IV transects (2002, 2004, 2007, 2011) were included in our data analysis.

Information regarding research cruises and OFOS, camera and lighting configurations for each sampling were detailed in Bergmann and Klages, 2012; Bergmann et al., 2011; Meyer et al., 2013 for 2002–2012. The camera setup of the OFOS changed in 2014 to Canon EOS 5D Mark III (modified for underwater applications by Isitec, Germany). The OFOS lighting set-up in 2013 and 2014 comprised two Sea & Sea YS-250PRO strobes (modified by Isitec for underwater applications) and four Multi-Sealite LED Lights. Three stable laser pointers (Oktopus, Germany) produced three laser points at 50 cm distance to each other and were used as reference points for area calculations. To allow for the strobe illumination to recharge and to avoid overlap between successive images, a timer was used to take a photograph every 30 s'. Additionally, manually triggered images were taken if an object of particular interest occurred in the field of view. The OFOS was controlled by the winch operator and towed for ~4 h at ~0.5–0.7 knots and a target distance to the seafloor of 1,5 m although there was variation due to swell and variability in bottom topography.

2.3. Image analysis and litter identification

Images were analysed for litter using BIIGLE (Bio-Image Indexing and Graphical Labelling Environment) (Ontrup et al., 2009). In total, 5018 images were analysed for litter, 3635 of which were taken at N3 (2004, 2007, 2011, 2012, 2013, 2014) and 1,383 images at HG IV (2012, 2014). All analyses were done in a shaded room, with the same 20” computer monitor connected to a PC to avoid variation resulting from the resolution or brightness characteristics of differing monitors. A zoom of 120% was used and images were labeled temporarily by five parallel lines during analysis to ensure not to miss any part of the images. Firstly, all images were analysed and items which could easily be identified as litter were labeled. Moreover, any object or shape in the image which could not with certainty be evaluated as biological or environmental was labeled as possible litter item. After completing the first assessment of all images, these images with possible litter items were evaluated several times by the authors until the final decision was reached if the object should or should not be identified as litter. In cases of final uncertainty, the item was not considered as litter.

The three laser points present in each image were detected by a computer algorithm (Schoening et al., 2015) and used to calculate the area covered by the image. As the distance to the seafloor of the camera varied with bottom topography and sea swell, the area of each image varied from between 0.63 and 14.70 m^2. Images of poor quality were excluded from the analysis, as were those overlapping the previous imaged area. The longest dimension of each item was measured using the BIIGLE measurement tool and grouped into small (< 10 cm), medium (10–50 cm) and large (> 50 cm) size categories (Bergmann and Klages, 2012). The material comprising each item was categorised as plastic (including Polystyrene and rubber), glass, rope, timber, paper/cardboard, fabric, metal or pottery. Rope, being most likely of ship origin, was set aside as a separate category and was not categorized according to its material because even though synthetic materials are nowadays primarily being used, lost ropes may also be made from natural fibres, a distinction which could not be deduced from the images alone. Encounters with epi-benthic megafauna were noted. Fragments of the hexactinelid sponge *Caulophacus*, which were covered with sediments and were probably dead remains, were termed *Caulophacus* debris. Fauna-litter interactions were categorised as contact (i.e. entangled/entrapped/coverage/touching), colonisation and other (i.e. shrimp on litter item).

2.4. Litter density data analysis

The data from Bergmann and Klages (2012) were included in our analysis (2134 images, 8570 m^2) to compare spatial and temporal changes of litter at N3 and HG IV between 2002 and 2014 as a whole. However, the results from 2008 at HG IV were excluded since the laser points did not work in 2008, preventing area calculations. Data were grouped into transects/years to assess differences in mean litter densities between N3 and HG IV transects for every sampling year and between sampling years at HAUSGARTEN (N3 and HG IV combined). Each image was treated as a sample for statistical analysis. The areas of the images varied, litter count of each image was converted to litter density in items x km^{-2} by the formula n_i x A_i^{-1}, where n_i is the litter count per image and A_i is the area of the image in km^2. The same dataset obtained after this conversion was used in mean, standard error calculations and statistical tests. Mean annual litter density (ALD) was calculated as (∑ litter density)/N, where (∑ litter density) is the sum of litter densities and N is the total number of the images per transect/year, depending on the analysis in question. Standard errors were obtained based on litter density of each image using standard routines. Similarly, litter types/sizes grouped into categories, litter densities of the images within a category were summed up and divided by total number of the images per transect/year (N) to calculate ALD of each category. Litter count per km^2 was computed by dividing the total count of litter items by the total area in km^2 of the transect/year to allow a comparison with published data relying on this method. Megafaunal interactions were used as the number of interactions without any transformation as the data were considered as an indication of the interaction, not the species itself, and species density data were not available for all transects for such a calculation. Spatial differences in megafauna interactions were analysed by calculating percentages of the distribution.

All outputs were computed using R Studio (version 0.99.480) and R (version 3.0.3) based on ALD of every station and HAUSGARTEN. ALD of litter type and size categories per transect/year were plotted to illustrate trends in litter density. In addition, ALD of plastic litter items per transect/year were plotted according to size categories to illustrate spatial and temporal changes in plastic litter item size.

The dataset was characterised by a high number of zero values as only 82 out of 7058 images showed litter. Non-parametric tests were initially applied as the data were not normally distributed (Kolmogorov-Smirnov test, $p < 0.05$). PRIMER 6.1.16 and PERMANOVA 1.0.6 using Bray Curtis similarity of litter density with 4th-root transformation was used for the analysis since PERMANOVA does not require a normal distribution in data and is insensitive to high zero counts (Anderson and Walsh, 2013). A one-way PERMANOVA was conducted to compare litter densities, size and type categories between and within stations for all transects. When a significant difference was found between stations or within a station, a pair-wise PERMANOVA was applied to compare transects.

2.5. Maritime information, sea ice extent and drift trajectories

Data for ship calls, provided by the Harbour Master of Longyearbyen (Svalbard) were analysed for temporal trends and correlations with litter density at N3, HG IV and HAUSGARTEN total. Ship calls included tourism (cruise vessels, day-tour boats, private yachts), cargo, research, fishing, navy/coastguard and Governors vessel categories between 2002 and 2014 and were plotted. The fishing category was removed from the data to eliminate overlap with the fisheries data obtained from the Norwegian Directorate of Fisheries from coastguard patrols. Fishing vessel inspection data from west Svalbard were plotted by country of origin. Since litter density data are not normally distributed, Spearman's rank correlation was used to test for a correlation with ship calls at Longyearbyen and fishing vessel sightings made during coast guard patrols.

Sea-ice extent data was provided by the Centre for Satellite Exploitation and Research (CERSAT) at the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), France (Ezraty et al., 2007). Ice extent was calculated based on the ARTIST Sea Ice (ASI) algorithm developed at the University of Bremen, Germany (Spreen et al., 2008). Sea-ice extent data from HAUSGARTEN (78.3N–80.3N, 1.7E–7.7E) was extracted. Mean values for summer months (May–September) between the study period 2002–2014 were used for Spearman's rank correlation analysis with ALD's at N3, HG IV and HAUSGARTEN total. All analyses and figures were done using R Studio (version 0.99.480) and R (version 3.0.3).

An approximation for potential source areas of sea ice passing over the HAUSGARTEN site can be obtained by tracking sea ice backward in time using a combination of low-resolution ice drift information and concentration obtained from the National Snow and Ice Data Centre (NSIDC) https://nsidc.org/ and CERSAT (Krumpen et al., 2015). Here, the tracking of ice parcels was limited to the summer months (May – September, between 2002 and 2014), when ice coverage was high enough and information on ice drift was available. Sea-ice drift trajectories and corresponding plots were produced by IDL 8.4.1 from Exelis Visual Information Solutions.

3. Results

3.1. Spatial and temporal changes in litter density

A total area of 28,161 m^2 showed 89 litter items in 82 of 7058 images from HAUSGARTEN total (central HG IV and northern N3 stations combined) taken between 2002 and 2014 (Table 1).

Varying distances of OFOS to the seafloor during surveys resulted in image areas with a mean value of 3.99 m^2 (0.63–14.70 m^2). Litter items were ubiquitously distributed along the transects. Mean annual litter density (ALD) ranged between 660 (± 337 SEM) and 6566 (± 1422 SEM) items km^{-2}, but the two stations did not show significant spatial differences in ALD (PERMANOVA: Pseudo-F=0.67, p=0.4). However, there were significant temporal differences at HAUSGARTEN, the northern station N3 and the central station HG IV (PERMANOVA: Pseudo-F=4.66, p=0.002; Pseudo-F=4.39, p=0.002 and Pseudo-F=2.19, p=0.049, respectively), indicating an increase in litter over time (Fig. 2). At N3, ALD increased 23-fold within the timeframe of a decade (2004–2014), with a particularly strong increase in 2012 (Fig. 2b). Even though significant difference was found at HG IV between years, it did not show a clearly increasing trend in observed densities (Fig. 2c).

3.2. Litter size and type

Small litter items constituted 57% of the litter at HAUSGARTEN total, followed by medium-sized (40%) and large items (4%). Eighty percent of the litter at N3 was small-sized with a strong temporal increase from zero to 100% between 2004 and 2014 (see Supplementary Table S1 online). Conversely, medium-sized litter was the most abundant category at HG IV (57%). PERMANOVA indicated significant differences in the size of plastic litter items between years at N3 (Pseudo-F=4.69, p=0.001) but not at HG IV (Pseudo-F=1.88, p=0.055). If the data of the two stations were pooled, a comparison of ALD of size groups at HAUSGARTEN total indicated significant difference between years (PERMANOVA: Pseudo-F=4.26, p=0.002), but not between stations (PERMANOVA: Pseudo-F=2.54, p=0.071).

Plastic was the dominant litter type accounting for 47% at HAUSGARTEN total, followed by glass (26%), rope (11%), metal (7%), fabric (6%), paper/cardboard, pottery and timber (4%) (Fig. 3). Annual plastic counts ranged between two and 15 items (see Supplementary Table S2 online), reaching a maximum ALD of 4060 items km^{-2} in 2014 (Fig. 3).

The comparison of ALD for the different litter types showed significant differences between stations and years at HAUSGARTEN total (PERMANOVA: Pseudo-F=3.43, p=0.035 and Pseudo-F=3.70, p=0.001, respectively). Glass items, which dominated at N3 (56%), started to appear in 2012 and increased thereafter (Fig. 3e). By contrast, a higher proportion of plastic characterised images from HG IV (60%), followed by rope (16%) and fabric (7%). The contribution of litter types of N3 and HG IV to the overall HAUSGARTEN were different, 31 of the 42 plastic litter items at HAUSGARTEN were observed at HG IV (see Supplementary Table S2 online).

Table 1
Summary of area covered, image count, litter count, litter count per km^2, mean and standard error of litter densities at HG IV, N3 and HAUSGARTEN Total (TOTAL) between 2002 and 2014.

Year	Station	Area Photographed (m^2)	Image Count	Litter Count	Litter Count km^{-2}	Mean Litter Density ± Standard Error (Items km^{-2})
2002	**HG IV**	1926	648	7	3635	3523 ± 1354
	TOTAL	1926	648	7	3635	3523 ± 1354
2004	**N3**	2561	749	1	390	346 ± 346
	HG IV	2471	658	3	1214	1018 ± 603
	TOTAL	5032	1407	4	795	660 ± 337
2007	**N3**	3570	750	4	1121	1049 ± 546
	HG IV	2747	449	2	728	577 ± 419
	TOTAL	6316	1199	6	950	873 ± 376
2011	**N3**	1195	302	2	1674	1642 ± 1168
	HG IV	1427	379	11	7710	7785 ± 3710
	TOTAL	2622	681	13	4959	5061 ± 2130
2012	**N3**	3637	759	10	2750	4284 ± 1739
	HG IV	2661	812	14	5260	5459 ± 1495
	TOTAL	6298	1571	24	3811	4891 ± 1141
2013	**N3**	2020	536	10	4950	4731 ± 1642
	TOTAL	2020	536	10	4950	4731 ± 1642
2014	**N3**	1819	452	14	7699	8082 ± 2372
	HG IV	2129	564	11	5166	5351 ± 1716
	TOTAL	3948	1016	25	6333	6566 ± 1422
2002-2014	**N3**	14,801	3548	41	2770	3096 ± 567
	HG IV	13,361	3510	48	3593	3878 ± 660
	TOTAL	28,161	7058	89	3160	3485 ± 435

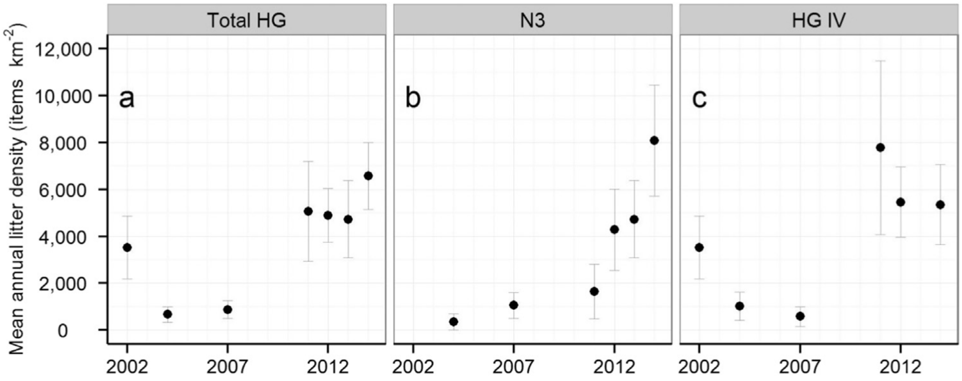

Fig. 2. Mean annual litter densities (items km^{-2}) grouped by station. Total HG represents mean annual litter densities for the two HAUSGARTEN stations combined. Error bars represent standard error of the mean.

Plastic litter items were grouped separately according to their size, as this is important in the context of fragmentation into microplastics (Fig. 4). The majority of plastic items at N3 were small (Fig. 4d), whereas medium-sized plastic items dominated at HG IV (Fig. 4h).

3.3. Encounters of megafauna with anthropogenic litter

Fifty of the 89 litter items observed were in some way interacting with megafauna (biota > 1.5 cm) including hydrozoans, the sponges *Cladorhiza gelida,* cf. Pachastrellidae, *Caulophacus arcticus* and *Caulophacus* debris, the stalked sea lily *Bathycrinus carpenterii*, the sea anemone cf. *Bathyphellia margaritacea* and Hormathiidae as well as shrimps (*Bythocaris* spp.) (Figs. 5, 6). A total of 60 encounters of fauna with marine litter were observed (see Supplementary Table S3 online). In some images, multiple encounters with different organisms were observed. Eighty percent of all interactions were identified as “contact” (see methods section), of which 63% where with suspension feeders (*C. gelida, C. arcticus, B. carpenterii*). Forty-one of the 60 encounters were with plastic litter. There was a clear distinction between the two stations with regard to megafaunal encounters. The number of litter items ‘associated’ with megafauna was higher at HG IV compared with N3 (35 and 15, respectively), as well as the number of all types of interactions (45 and 15, respectively).

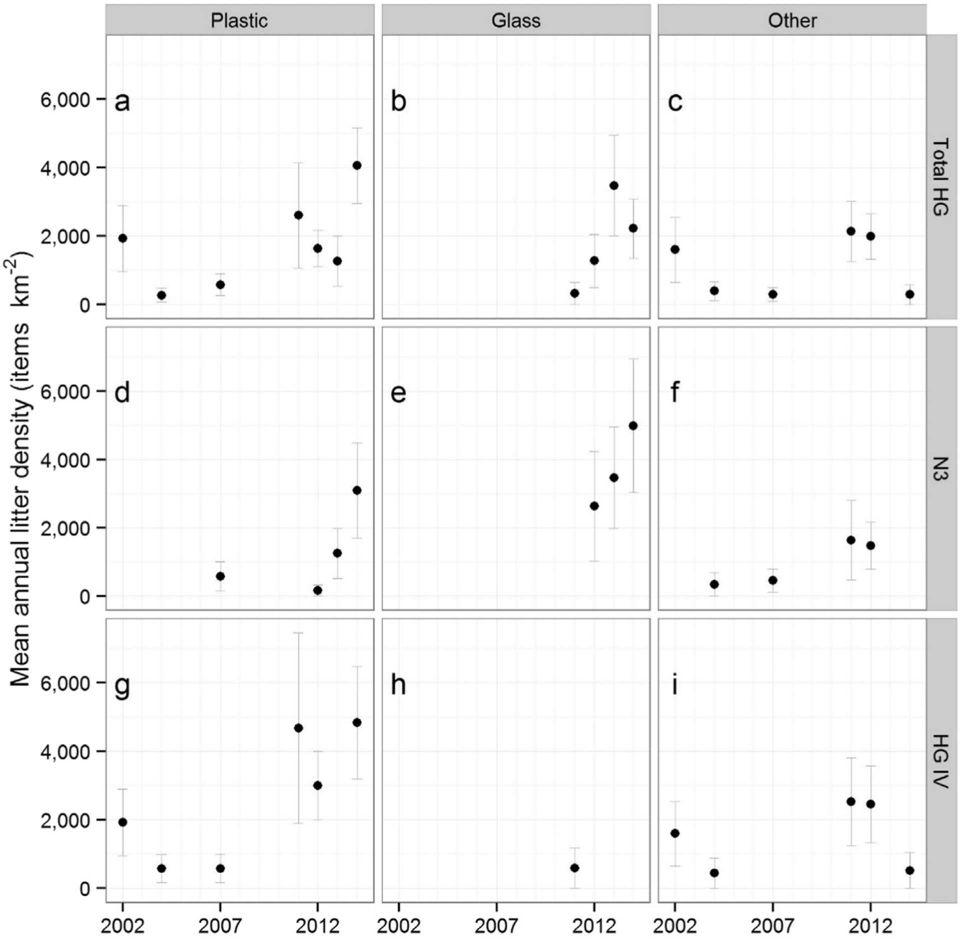

Fig. 3. Mean annual litter densities (items km^{-2}) grouped by station and litter type. Total HG represents mean annual litter densities of the two HAUSGARTEN stations combined. ‘Other’ comprises fabric, metal, paper, pottery, rope, timber. Error bars represent standard error of the mean.

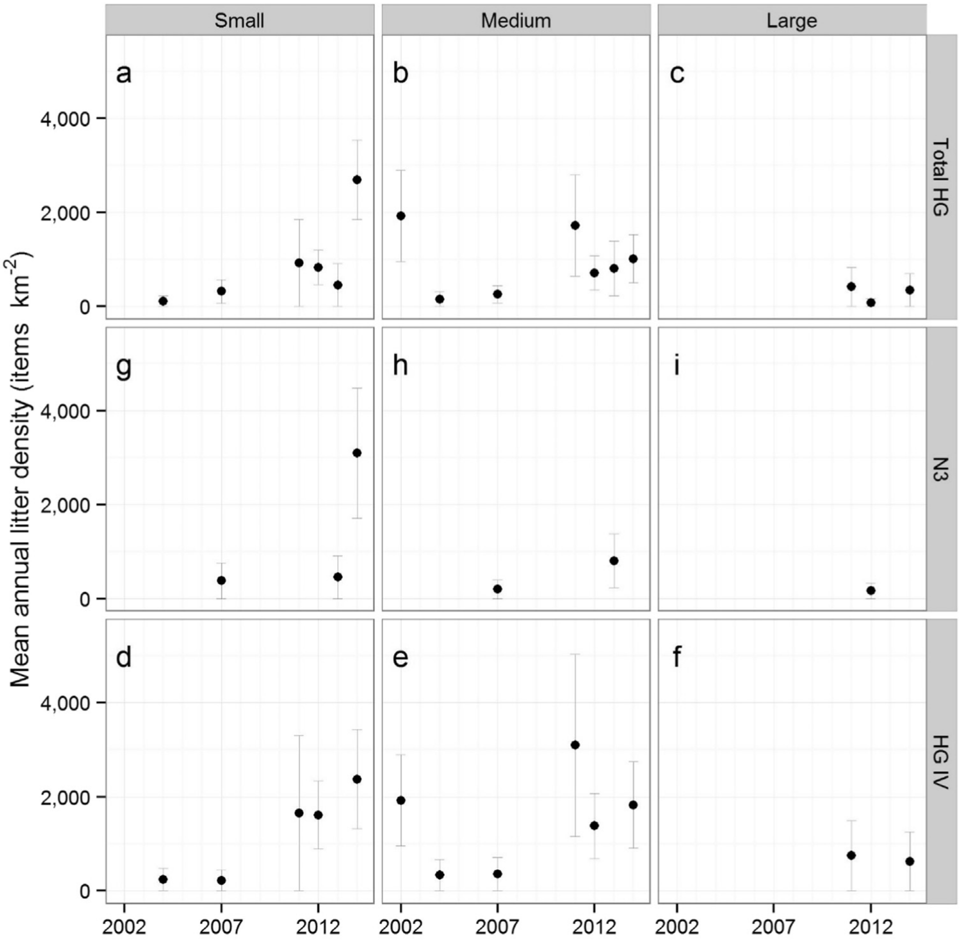

Fig. 4. Mean annual litter densities (items km^{-2}) for plastic, grouped by station and item size. Total HG represents mean annual litter densities of the two HAUSGARTEN stations combined. Error bars represent standard error of the mean.

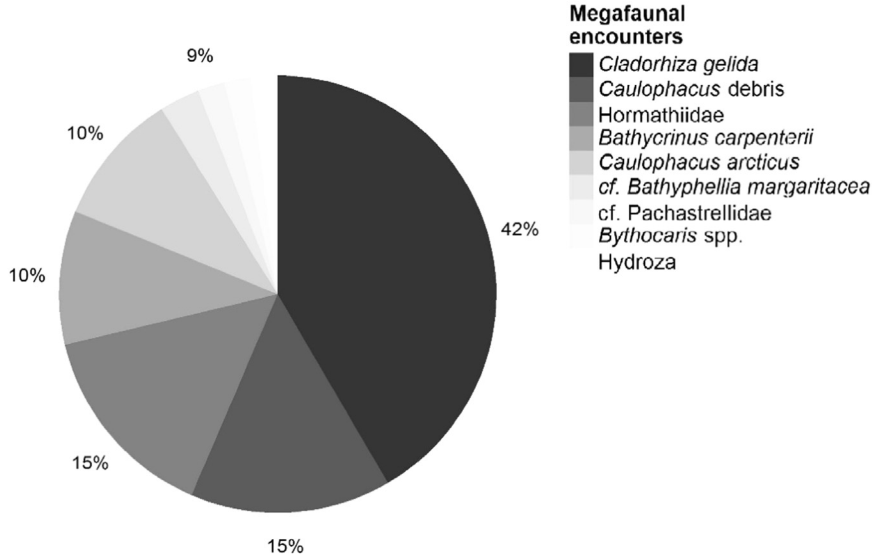

Fig. 5. Proportions of epibenthic megafaunal encounters with litter items.

3.4. Maritime traffic, summer sea-ice extent and trajectories

Analysis of annual maritime data and mean litter density indicate significant positive correlations between litter densities at N3 and total ship counts (harbour ship calls and fishing vessel sighting counts combined: ρ=0.94, p=0.017), total harbour ship calls (ρ=0.94, p=0.017) and tourism vessel harbour calls (ρ=1, p=0.003). Litter densities at HAUSGARTEN total were also positively correlated with total ship counts (ρ=0.89, p=0.012), total harbour ship calls (ρ=0.79, p=0.048), other-category ship harbour calls (ρ=0.89, p=0.012), and the number of docking days of tourism vessels (ρ=0.86, p=0.023). While our figures imply a general increase in maritime traffic in the area over

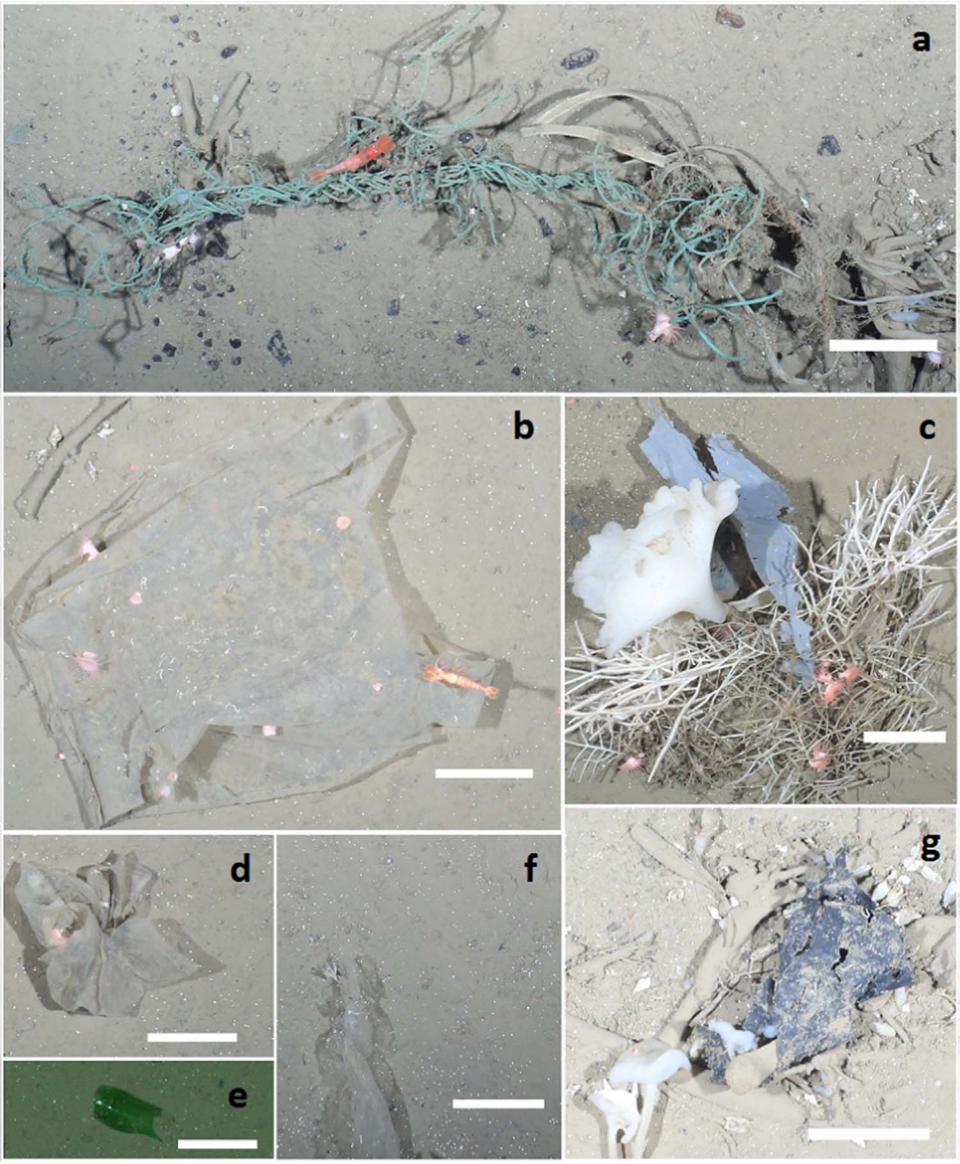

Fig. 6. Sample of images with litter from HAUSGARTEN. (a) Fishing gear and plastic strips entangled with *Caulophacus* debris, colonised by *Amphianthus* sp. and held on to by *Bythocaris* sp., (b) plastic bag colonised by *Amphianthus* sp. and held on to by *Bythocaris* sp., (c) plastic fragments entangled with *C. arcticus* and *C. gelida*, (d) plastic bag/fragment buried partly into sediment and colonised by *Amphianthus* sp., (e) piece of glass bottle, (f) plastic fragment entangled with *B. carpenterii*, (g) piece of fabric entangled with *Caulophacus* debris. Scale bars represent 10 cm.

time (Fig. 7), the increase in tourism and fishing vessels sightings west off Svalbard showed the strongest increase among maritime traffic information.

The mean summer sea-ice extent between 2002 and 2014 was also positively correlated with litter densities at N3 (ρ=0.83, p=0.042). Drift trajectories indicated that the sea ice above HAUSGARTEN had its origin in the Laptev and Kara Seas (Fig. 8).

4. Discussion

Our data show that litter densities at HAUSGARTEN have continued to increase after 2011 (Bergmann and Klages, 2012). The fact that a similar trend was observed at another station further north indicates that the earlier results were not an outlier but that the region is facing a pollution problem and that there is reason for real concern: in 2014, the mean litter density at HAUSGARTEN reached 6,566 items km^{-2}, similar to litter densities reported from the Lisbon Canyon (6620 items km^{-2}) (Mordecai et al., 2011), which is in close vicinity to the densely populated capital Lisbon. From the Atlantic and Indian Ocean seafloor, 480 and 550 items km^{-2} were reported during ROV dives in 2011 and 2013 (Woodall et al., 2015), whereas our figures from 2011 and 2013 indicate 4,600 items km^{-2}. Considering the remote location of the stations at HAUSGARTEN, the high density of litter found at HAUSGARTEN is surprising.

Quantification of litter is often not the main target of field work, but is carried out as an additional task to complement another focus of research (Ramirez-Llodra et al., 2011; Spengler and Costa, 2008). Although type and size of each litter item, litter count and density in items per area have been indicated as basic requirements of standards for marine litter studies (Spengler and Costa, 2008), sampling and analysis methods still lack standardisation, even in this primary area. Imaging surveys yield indirect samples as images or video footages introducing the challenge of quantification and qualification. Litter items buried in the sediment could easily be missed in imaging surveys, as can small and ambiguous items. Technological advances have led to an increasing number of imaging survey studies on litter on the deep

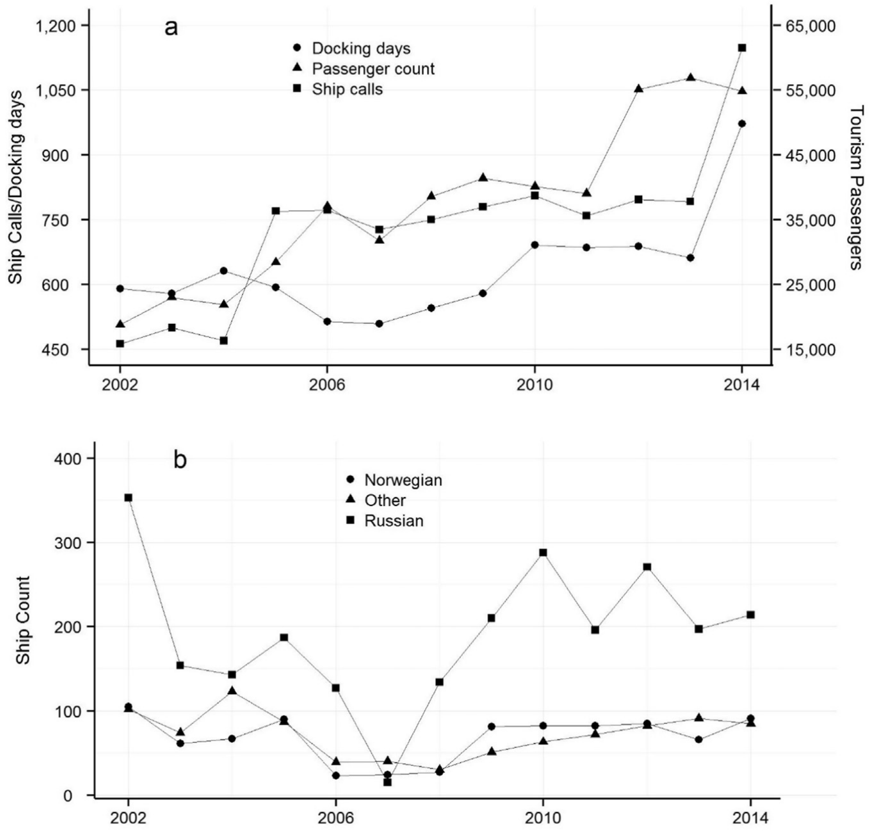

Fig. 7. Temporal trends in tourism and shipping between 2002 and 2014 around the LTER observatory HAUSGARTEN. (a) Annual ship arrivals (tourism, cargo, research, navy / coastguard, governor vessel), docking days and tourism passenger counts at the harbour of Longyearbyen (Svalbard) between 2002 and 2014 (source: Harbourmaster of Longyearbyen). (b) Annual counts of fishing vessel sightings west of Svalbard recorded during patrols by Svalbard's coastguard (source: Norwegian Directorate of Fisheries).

seafloor. However, financial, logistical and technical limitations still restrict the area surveyed in deep sea research. While calculating litter densities per km^2 in trawl, sea surface or beach sampling studies does not necessarily imply extrapolations due to large survey areas, the same method would lead to bias in deep sea litter studies. Therefore, it should be noted that litter densities given in this study should not be considered as extrapolations or actual amounts, instead, they are transformations of litter counts into area (Spengler and Costa, 2008). For the reasons outlined above, when calculated litter densities are taken into account directly as actual litter densities, it may lead under- or overestimation of marine litter at HAUSGARTEN.

Until the 1990 s, there was an ongoing increase in the quantities of plastic litter entering into the open ocean, with this flux stabilising in the 1990 s, though increasing coastal litter quantities continued to be recorded (Barnes et al., 2009). Either litter has been washed up to the coastal areas, or it sank to the deep seafloor unnoticed. In addition, plastic litter may fragment into smaller pieces (microplastic), which cannot be observed directly. With a growing focus on microplastic research, more studies have emerged describing the potential fragmentation mechanisms, pathways and sinks and evidence suggest an increase in microplastics (Thompson et al., 2004). Contrary to the common notion that most plastic litter floats at the sea surface, 50% of plastic from municipal waste sources has a higher density than seawater and can thus sink directly to the seafloor (Engler, 2012). Solar radiation and heat cause fragmentation of plastic into smaller pieces aided by wind and wave actions. Biofilm formation on the plastic surface can slow down degradation processes (O'Brine and Thompson, 2010). Regardless of density, plastic fragments can still be transported by currents (Engler, 2012). Additionally, hydrographic processes such as vertical mixing (Kukulka et al., 2012) and deep-water cascading events (Tubau et al., 2015) may play a significant role in the distribution of plastic and may have aided transport of plastic litter to the deep Arctic seafloor. Indeed, a cascading event was reported in 2002 (Wobus et al., 2013) which may explain the relatively high quantities of litter at the central HAUSGARTEN station in 2002 at the beginning of our time series. On the deep seafloor, low temperatures, the absence of solar radiation and strong wave action may cause plastic to be even more persistent than in shallower areas (Andrady, 2015), which can lead to relatively higher densities of plastic litter on the deep Arctic seafloor compared with other locations.

Previous studies have shown that the highest densities of litter on the seafloor are found in submarine canyons, driven by their associated hydrodynamic regime (Mordecai et al., 2011; Ramirez-Llodra et al., 2013; Tubau et al., 2015), followed by seamounts, banks, mounds, continental slopes and ocean ridges (Galgani et al., 2015; Pham et al., 2014). Although the two HAUSGARTEN stations only represent open-slope environments, the litter densities in 2011 at HG IV and in 2014 at N3 were close to 8,000 items km^{-2}. This is a figure similar to one of the highest litter densities ever reported from the deep seafloor, in La Fonera and Cap de Creus canyons (NW Mediterranean), with litter densities of ~15,000 and ~8,000 items km^{-2}, respectively (Tubau et al., 2015). There is a general consensus that land-based inputs are the prime sources of marine litter (Barnes and Milner, 2005; Galgani et al., 2000; Mordecai et al., 2011; Pham et al., 2014). However, it was concluded that the strong increase in litter densities at HAUSGARTEN after 2008 were unlikely to be caused by direct terrestrial inputs from Svalbard, whose population decreased during that time (Bergmann and Klages, 2012). If the litter from HAUSGARTEN is of terrestrial origin, it probably entered into the Atlantic or North Sea and was transported by currents over long distances to the North (Bergmann and Klages,

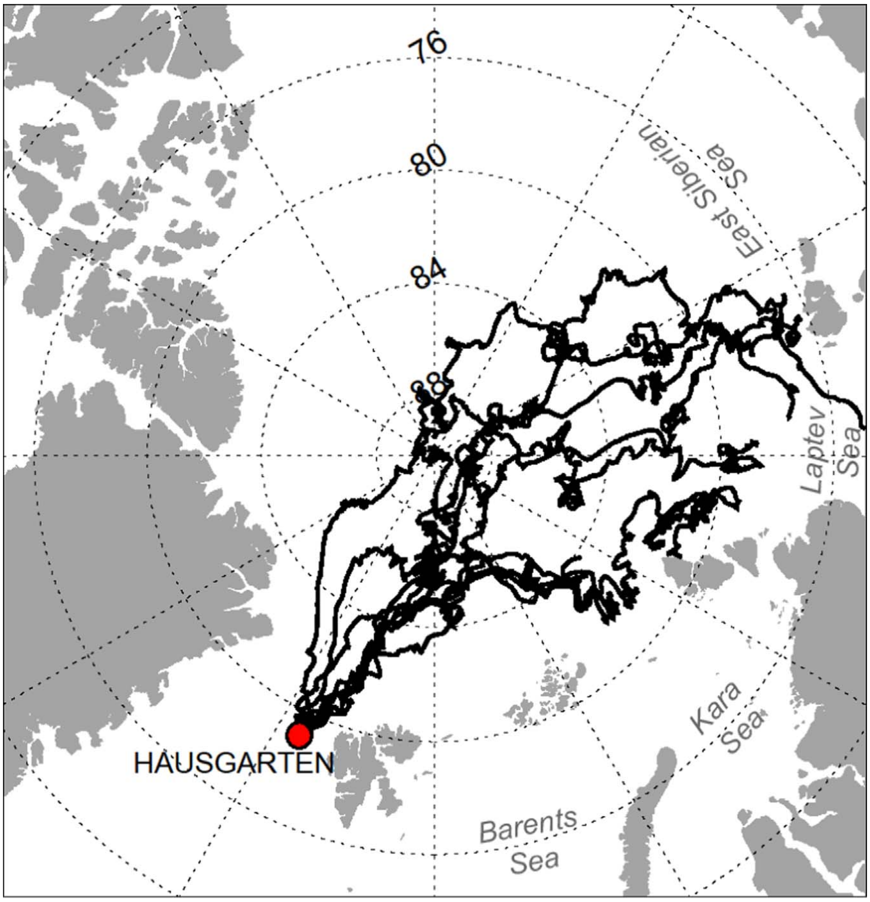

Fig. 8. Drift trajectories and source areas of sea ice tracked backward in time starting from the HAUSGARTEN observatory (red dot).

2012) as supported by recent evidence from model projections (van Sebille et al., 2016). Marine litter is known to travel long distances; bivalves from SE USA or the Caribbean have been found on plastic jars on British and Irish coasts, proving their long trans-Atlantic journey (Holmes et al., 2015). Most of the litter observed at HAUSGARTEN could not be clearly allocated to any particular industrial sector, looking more like general household litter, which matches findings from the Atlantic (Woodall et al., 2015).

Surface currents converge in specific locations because of wind and geostrophic forces. To date, five such convergence zones have been identified as accumulation areas of marine litter, so-called ‘garbage patches’, which match subtropical convergence zones and harbour very high litter quantities (Maximenko et al., 2012). In the context of our results, the projection of a sixth garbage patch in the Barents Sea, fed by litter from the North Atlantic (van Sebille et al., 2012), is particularly striking as it could explain increasing litter densities further north in the HAUSGARTEN area. Indeed, microplastic concentrations from the nearby Barents Sea surface resembled quantities reported from the North Pacific (Lusher et al., 2015) and corroborate this projection. Floating litter was also recently reported in the Fram Strait and Barents Sea (Bergmann et al., 2015). Although strictly speaking the data are not comparable because of important differences in the methodology adopted, the density of floating litter was 1–2 orders of magnitude lower compared with litter on the seafloor in the same area, indicating that the seafloor may act as a sink for litter.

There are only very few long-term studies for inter-annual variation of litter from deep-sea regions. Most of these are based on specific sampling times. However, a study from the Pacific coast off northern Japan (Goto and Shibata, 2015) showed a two- to six-fold increase in litter densities from 54 to 94 items km^{-2} in the 2003/2004 period to 233–332 items km^{-2} in 2011 after the Tohoku earthquake and tsunami. Intriguingly, our results indicate a much higher increase in mean litter densities at HAUSGARTEN for the same years, without any known catastrophic event. On the contrary, recent time-series studies of litter from other marine ecosystems do not indicate any clear temporal trends. Figures for litter from the open NW Atlantic (Moret-Ferguson et al., 2010) did not show any temporal increase in litter counts, nor did those from SE North Sea coasts and beaches (Schulz et al., 2015a, 2015b). Still, litter density at the central HAUSGARTEN station almost doubled in 2011 compared to 2002, and there is a clear peak in 2014 at the northern station. So, what factors could have driven this strong increase in litter?

Maritime activities including fisheries have been indicated as one of the main sources of anthropogenic litter in various studies (Pham et al., 2014; Ramirez-Llodra et al., 2013; Vieira et al., 2015). Data for ship calls at Longyearbyen can be considered as an indicator of maritime traffic west of Svalbard, although these ships may not necessarily have passed HAUSGARTEN, or there may be ships operating in the area that have not called at Longyearbyen. Interestingly, even though N3 is located in the marginal ice zone, the strong correlation between tourism ship counts and litter densities at N3 may imply tourism activities around Svalbard as a possible source of anthropogenic litter. Touristic areas generate up to 40% more marine litter on beaches during summer. (Galgani et al., 2015). It should be noted, however, that a strong correlation between tourism ship counts and litter densities indicating a similar increase over time, does not necessarily mean increasing litter discharges from ships. On the other hand, one cruise ship of 2500 passengers and 800 crew can generate 1 t of solid waste in a day (National Research Council, 1995) and even though most of the vessels probably strictly abide with regulations, accidental loss of solid waste from such a quantity of garbage may be inevitable. Unfortunately, it is difficult to obtain precise information for fishing activities in the area, as there is no obligation for vessels to report their activity outside the 12-nm limit and Automatic Identification System (AIS) data from the Norwegian satellite AISSAT-1 only commenced in 2011. However, counts of sightings during coastguard patrols indicate a strong increase in fishing activities west of Svalbard from 47 sightings in 2002 to 102 in 2014. Additionally, evidence from the programme 'Clean Up Svalbard' suggests that a great proportion of washed-up litter originates from fisheries (Governor of Svalbard, unpubl. data). The positive correlation between litter densities and total ship counts indicates that the increased presence of ships west of Svalbard has contributed to the increased litter densities observed at HAUSGARTEN.

Between 2000 and 2013, mean sea-ice thickness has decreased by 0.58 m (Lindsay and Schweiger, 2015) and sea-ice extent measured in the month of September has decreased by 24% decade^{-1} (Meier et al., 2014) in the Arctic. These changes may affect the temporal and spatial variability of litter at HAUSGARTEN. The Fram Strait is the only place for intermediate and deep-water mass exchange between the North Atlantic and the Arctic Ocean (Fahrbach et al., 2001; Rudels et al., 2000). The inflow of warm Atlantic water from Nordic Seas into the central Arctic Ocean characterises the water masses. The eastern and western currents meet at the East Greenland Polar Front (Soltwedel et al., 2016). These dynamic currents also affect the sea-ice cover: while the western areas are covered with ice year-round, the south-eastern areas are ice-free and changing ice cover is observed in the central and NE Fram Strait depending on the season. The northern station in our HAUSGARTEN study, which is located within the marginal ice zone, saw an extensive increase in litter density, especially in the amount of small-sized plastic and glass litter, between 2004 and 2014. The decreased ice cover could have allowed more maritime activities in the area, which may have played an indirect role in the increase of litter. This explanation is supported by the correlation found between shipping and litter density. Since glass can be assumed to sink quickly to the seafloor close to its entry point, the high density of glass at the northern station in recent years proves increasing ship traffic in the marginal ice zone and indicates ships as sources. Glass items were seen at the northern HAUSGARTEN in the last three years of the study only. It should be noted that the disposal of glass in this area was only prohibited by MARPOL in 2013.

Recent research suggests that sea ice is an important sink of microplastic (Obbard et al., 2014). Drift ice in the Arctic Ocean is known to contain ice-rafted debris, driftwood and biota (Johansen and Hytteborn, 2001). Indeed, debris and driftwood were analysed to assess their origin and transportation pathways in several studies. It was shown that driftwood came from Siberian rivers pouring their waters into the Kara Sea, where they were entrained in drift ice (Johansen, 1999). Most debris on the Arctic seafloor originates from shelf areas (Nurnberg et al., 1994), river discharges and from terrestrial sources transported by winds. Even though ice-rafted debris mostly comprises fine-grained small-sized particulate matter, up to 8 mm carbonate minerals in many shapes were observed in the samples from particle traps in the eastern Fram Strait, whose source was rafting ice (Sanchez-Vidal et al., 2015). Unlike driftwood or particle trap samples, image surveys do not generate physical samples, which prevented the assessment of source and transportation pathways. However, our results indicated positive correlation between litter and summer sea ice extent and the drift trajectories concur with an earlier study based on driftwood specimen analysis (Johansen, 1999). Along with the finding of sea ice trapping microplastic, it can be suggested that the presence of sea ice probably facilitates the release of plastic litter entrained in drifting sea ice upon melting, which may partly explain the observed increase in smaller plastic items at the northern station.

Impacts of marine litter, plastics in particular, on 'charismatic megafauna' such as turtles, marine birds, mammals or fishes have been relatively well documented compared to on other biota (Kühn et al., 2015). Deep-sea ecosystems are still poorly known, thus, it is not surprising that studies about the impacts of marine litter on deep-sea fauna are scarce (but see (Bergmann and Klages, 2012; Fabri et al., 2014; Mordecai et al., 2011; Taylor et al., 2014)). One of the reasons for the scarcity of these studies may be that only camera-based methods show litter *in situ* with species. Our study showed a high proportion of megafaunal encounters with litter, particularly with suspension feeders. Surprisingly, the encounter rate was higher at the central station compared with the northern one, despite the fact that the northern station harbours a significantly higher megafaunal stock, including the sponges *C. gelida* and *C. arcticus* (Taylor et al., 2016), in which most litter items were entangled. On the contrary, a long-term litter study in Monterey Canyon (California) showed that litter was used primarily as shelter or hard substratum for settlement by hydroids, anemones, asteroids, serpulid worms, crinoids, holothurians and rockfish (Schlining et al., 2013). Most interaction with megafauna was reported as 'simple' entanglement in other deep-sea studies (Pham et al., 2013; Woodall et al., 2015). Entanglement can cause abrasion and necrosis of tissue increasing the risk of predation or infection (Chiappone et al., 2005). Although several studies showed toxic leaching of additives to marine animals in laboratory studies (Browne et al., 2013; Lithner et al., 2011), in situ concentrations in marine environments, pathways into the marine food web and consequences to human health is not yet clear. Plastic was more often colonised by actinians at HAUSGARTEN than other litter items, which may be due to the material's long persistence. Marine litter provides hard substratum for sessile organisms to settle on, which could be considered a positive effect on muddy or sandy ecosystems with few hard substrata available. However, a study of litter that was experimentally deployed on the Greek seafloor showed that it altered both species abundance and community structure (Katsanevakis et al., 2007). Increasing litter quantities thus raise questions about effects on biodiversity. During our study, some plastic items were also observed covering sediments. A study in intertidal sediments has shown that plastic covering sediments caused anoxic conditions in the sediment underneath, reduced primary production, organic matter and the number of infaunal invertebrates (Green et al., 2015). Such changes in ecosystem composition and function may occur in deep-sea communities, too.

5. Conclusions

Our findings indicate that the Arctic faces a pollution problem and that it is spreading to the north. Litter densities at HAUSGARTEN were substantially higher compared with other locations, despite its remote location. Small-sized plastics increased in observed abundance between 2002 and 2014, which indicates fragmentation of plastic litter and raises concerns about contamination by microplastics. Increasing quantities of litter from northern Europe may drift to the North and the receding sea ice has opened hitherto largely inaccessible environments to human activities, including shipping, fisheries and tourism. Considering the variety of matter transported by drift ice, increasing amount of plastic items at HAUSGARTEN in recent years raises the question if sea ice is a transport vehicle also for plastic. Whatever the causes, the present study highlights once more that our current waste management frameworks are inadequate to tackle the problem of marine litter pollution and that we have to re-think our usage of plastic materials. Considering the importance of the Arctic region for global climate and ecosystem health, identifying the changes in anthropogenic stress and its direct or indirect sources provide information for future projections to regulate human activities.

Acknowledgements

The authors thank the crew of RVs Polarstern and MS Merian, B. Sablotny, T. Soltwedel, I. Schewe, J. Taylor, E. Bauerfeind, R. Degen, and the HGF-MPG Group for Deep-Sea Ecology and Technology of AWI in general for gathering the data and support needed for the analysis of the data during this study. C. Hasemann gave valuable advice on statistical data analysis. T. Soltwedel kindly provided a map of the study area (Fig. 1). The authors thank the Harbour Master of Longyearbyen, K. Bråten, for sharing information about ship calls, P. Finne from FMC Norway Directorate of Fisheries for providing VMS and inspection data of fishing vessels and D. Langenkämper for BIIGLE user support.

MB was funded by the Helmholtz Alliance ROBEX (Robotic Exploration of Extreme Environments), and this study contributes to the Pollution Observatory of the Helmholtz-funded programme FRAM (Frontiers in Arctic Marine Research). This publication is Eprint ID 31691 of the Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung.

Appendix A. Supporting material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dsr.2016.12.011.

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