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Impact of returning scientific cruises and prolonged on-site presence on litter abundance at the deep-sea nodule fields in the Peru Basin

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ABSTRACT

Marine litter can be found along coasts, continental shelves and slopes, down into the abyss. The absence of light, low temperatures and low energy regimes characterising the deeper habitats ensure the persistence of litter over time. Therefore, manmade items within the deep sea will likely accumulate to increasing quantities.

Here we report the litter abundance encountered at the Pacific abyssal nodule fields from the Peru Basin at 4150 m depth. An average density of 2.67 litter items/ha was observed. Litter composed of plastic was the most abundant followed by metal and glass. At least 58 % of the items observed could be linked to the research expeditions conducted in the area and appeared to be mostly accidental disposals from ships. The data gathered was used to address temporal trends in litter abundance as well as the impact of human on-site presence and return cruises in the context of future deep-sea mining efforts.

1. Introduction

The increasing quantities of litter reaching the deep ocean floor is a major issue worldwide, yet little is known about the sources, abundance, distribution or impacts on fauna of such material (Pham et al., 2014). Often the first scientific investigations of remote areas have presented scientists with evidence of litter items upon arrival (Bergmann et al., 2015; Canals et al., 2021 and references therein). Geography and seafloor topography, hydrodynamics and human activities are all factors that affect litter transport, distribution and accumulation in the deep sea (Ramirez-Llodra et al., 2013), but knowledge on temporal trends is lacking (Schlining et al., 2013; Galgani et al., 2015). There are reports of decreases in litter concentrations in some areas, and increases in others over time, though none of these studies have investigated seafloor regions at depths deeper than 2700 m (Koutsodendris et al., 2008; Kuriyama et al., 2003; Tekman et al., 2017; Maes et al., 2018; Parga Martínez et al., 2020). While research efforts to study litter abundance and accumulation have been increasing, these primarily focus on coastal areas, European seas, North America and the Western Pacific, with the degree of litter pollution in the open oceans remaining largely unknown (Canals et al., 2021). This is evident when consulting the marine litter database (https://litterbase.awi.de/ Tekman et al., accessed February 2022) where marine litter observations reported in published scientific articles is collected, revealing the paucity of information for the South Pacific Ocean and (deep) seafloor (Haarr et al., 2022).

The South-eastern Pacific Ocean is, when compared to other oceans, a low human impact area (Halpern et al., 2008), though there are signs of increases in cumulative anthropogenic stressors in certain areas (Halpern et al., 2015). The cumulative anthropogenic impacts in these studies include demersal and pelagic fisheries and different types of pollution, but as of yet do not take into account marine litter or deep-sea mining (Halpern et al., 2015). Deep-sea mining is of particular relevance since the polymetallic nodules occurring at abyssal depths in the Pacific Ocean (as well as areas of the Atlantic and Indian oceans) are of prime commercial interest, given their abundance, high concentrations of various metals, and recent developments in nodule mining technology. Since the 1970's, these Pacific abyssal nodule fields have been subject to baseline studies, mining tests, mining impact experiments and subsequent follow-up cruises (Jones et al., 2017). In 2021, the Clarion Clipperton Fracture Zone in the North-East Pacific saw its first nodule collector trial (https://www.deme-group.com/news/metal-rich-nodules-collected-seabed-during-important-technology-trial published 22 April 2021, accessed 9/02/2022).

One of the most extensive benthic impact experiments conducted to

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date was the German long-term large-scale DISturbance and reCOLonisation experiment (DISCOL), initiated in 1989, in the abyssal Peru Basin (at 4150 m depth) (Thiel and Schriever, 1990). In 1989, 11 km^2 of deep-sea floor were disturbed with an 8-m wide plough-harrow to set a disturbance of the benthic environment and to remove the nodules from the sediment/water interface by driving them down into the seafloor sediments (burying). This first cruise and the subsequent four returning scientific cruises (after 6 months, 3 years, 7 years and 26 years) collected imagery data with an Ocean Floor Observation System (OFOS) tow-cam, resulting in tens of thousands of images from the seafloor.

During the image analysis of the first cruise from 1989, the first two litter items were observed during the third tow-cam transect, 4 days after arrival on site. Since then, cans, bottles, plastics etc. were observed sporadically on the deep-sea floor during re-visits. Marine litter or debris is defined as “any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment” (UNEP, 2009). With this definition in mind, the imagery data (from 1989 onwards) from the DISCOL area were analysed with as main objectives to (1) quantify the amount of litter, (2) analyse the types of litter, and (3) assess its abundance and increase over time. This temporal study of litter abundance over time across the abyssal deep-sea nodule fields aimed to assess the potential further impacts of long-term human on-site presence at the sea surface and the cumulative impacts of such presence on deep-sea ecosystems, in addition to the direct seafloor disturbance impacts associated with deep-sea mining.

2. Methods

2.1. Study site

The nodule fields in the Peru Basin were discovered in 1978, during SO-04 (Thijssen et al., 1981) and a second cruise SO-11 followed in 1979 (Von Stackelberg, 1997). These nodules were found to be larger in average size than in other regions of the Pacific and their abundance and grade were considered to be of economic value (Kuhn et al., 2017). After these two exploratory cruises, the DISturbance and reCOLonisation (DISCOL) experiment was initiated in 1989 and the DISCOL Experimental Area (DEA) was delineated within the Peru Basin at 7° 06′S -88°27′ W, situated about 800 km offshore (Fig. 1). The site was visited by four follow-up cruises (adding up to a total of five research expeditions) equipped with, among other instruments, the Ocean Floor Observation System (OFOS) tow-cam to visualise the deep-sea floor. Ship navigation from the five cruises is presented in Fig. 1a with the OFOS transect seafloor camera positions shown in Fig. 1b. The seafloor across the DEA area is relatively flat, with a topographic range spanning 30 m at most, but with an increased elevation associated with a seamount in the North (Fig. 1). The low relief and gentle slopes of the DEA become thus more heterogeneous towards the NE with knolls, hills and depressions (Gausepohl et al., 2020; Gazis and Greinert, 2021). Manganese nodules in the area have diameters of up to 15 cm and, prior to the DISCOL experiment, a nodule density estimated to be 5–10 kg/m^2 (Thiel and Schriever, 1990). The water currents characterising the area are typically slow (<10 cm/s) and variable in direction (Klein, 1996; Baeye et al., 2022).

26 years after the disturbance experiments the plough tracks were still very prominent and the impact on the fauna significant (e.g. Boetius and Haeckel, 2018, Stratmann et al., 2018, Simon-Lledó et al., 2019, Gausepohl et al., 2020, Vonnahme et al., 2020, Boehringer et al., 2021).

2.2. Imagery collection, annotation and analysis

Imagery data collected by the OFOS tow-cam from the five different cruises between 1989 and 2015 were analysed (Table 1). A total of 41,335 images were screened for litter and were annotated in the online image annotation system BIIGLE (Langenkämper et al., 2017). Litter items >2 cm that could be undoubtedly identified as such following the definition of marine litter (UNEP, 2009) were annotated. If a certain item was visualised again in a subsequent cruise, it was only counted during its first observation, to avoid duplication, but its state and degradation were assessed. Arrival times were estimated based on the state and condition of the litter item. Items were considered recent when there were no signs of degradation (e.g. no rust, decolouration, corrosion, deformation) and appeared to have arrived recently to the deep seafloor. When signs of degradation were present, a litter item was labelled as old. In case of doubt about its arrival time, items were considered of “undetermined” age. Sediment cover on top of a litter item could not be used as an indication of age, since it could be attributed to sediment deposition and resettlement as a result of the impact disturbance and/or other scientific activities and therefor it was visible in larger quantities than to be expected after 19 years of natural sedimentation. Litter degradation is very slow in the abyss (no measurable signs after decades, Krause et al. (2020)), where there is no light, low temperatures and low oxygen concentrations (Andrady, 2015). Hence, items observed here, based on their size and man-made/synthetic

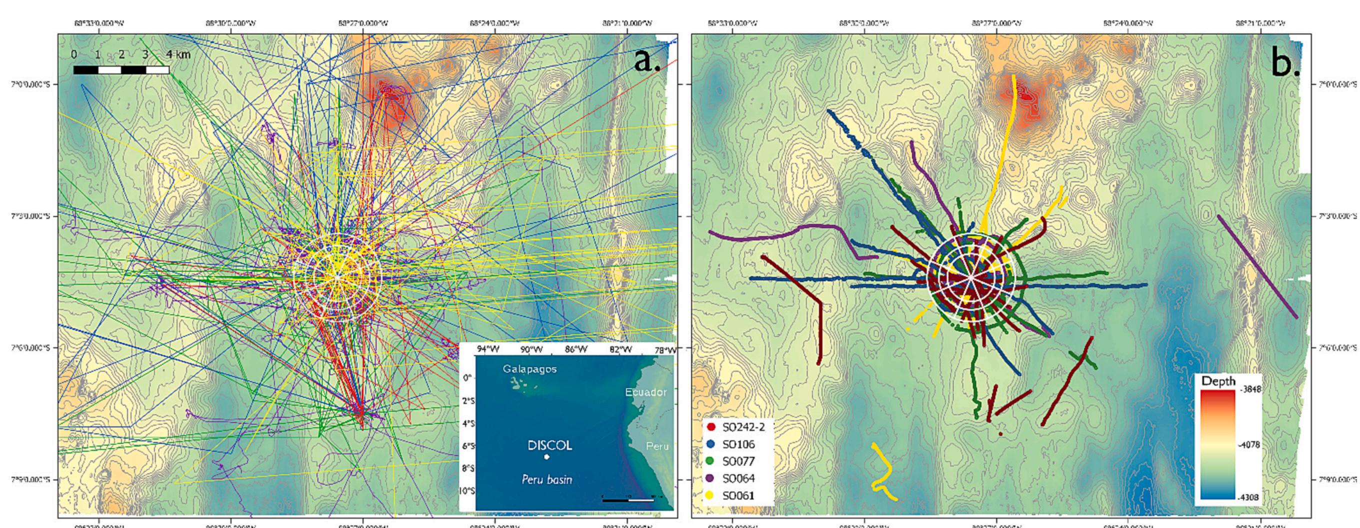

Fig. 1. Location of the DISCOL study site in the Peru basin of the SE Pacific Ocean as inset of the left panel (the white dot is not to scale). The white circle divided into sectors is the DISCOL Experimental Area (DEA) and the main focus of the cruises. (a) Ship navigation of the five cruises analysed and (b) OFOS imagery transects analysed. Bathymetry from Gausepohl et al. (2019).

Table 1
Summary of the cruises to the region, imagery transects, image count, area covered, litter count, litter items per km^2 and per ha, and days on site.

Cruise	Data collection	Year	Time (years) since first cruise	No. transects	No. images	Area covered (m^2)	No. litter items	Litter items/km^2	Litter items/ha	Days on site
SO061	OFOS/images	1989	–	18	8154	87,050.08	20	229.75	2.30	44
SO064	OFOS/images	1989	0.5	7	4437	50,142.25	7	139.60	1.40	19
SO077	OFOS/images	1992	3	7	5341	62,525.84	14	175.93	1.76	22
SO106	OFOS/images	1996	7	7	5380	54,705.24	17	310.76	3.11	20
SO242-2	OFOS/images	2015	26	20	18,023	89,754.54	43 + 2[a]	479.08	4.79	29

[a] 2 litter items that were previously identified and counted.

material, were likely to be present for the entire timespan of this study and were therefore assumed to represent material which would add to the cumulative total abundances in the area for the remaining period of study. The area covered (m^2 and ha) in Table 1 corresponds to the amount of seafloor visualised by imagery, as estimated from the image collection altitude of the OFOS and average image footprint area, and were used to calculate litter density.

3. Results

3.1. Litter abundance over time

During the first cruise (SO061), first litter items were observed four days after arrival on site on 11/02/1989 (OFOS03). These items were a plastic bag and a beer can from a German brand (see items 1 and 2 in Table S1), apparently newly arrived at the deep-sea floor and likely to have originated from the ship. Over 26 years, during 134 days on site and a visualised area of 34 ha of seafloor, 101 unique litter items were encountered (Fig. 2, Table S1).

Highest abundance and densities of litter items were encountered during the most recent cruise SO242-2 (2015) (n = 43, dens = 4.79 items/ha), followed by the first cruise, SO061 (03/1989) (n = 20, dens = 2.3 items/ha) (Table 1, Fig. 3). Lowest densities were observed 6 months after the first cruise (during SO064, 09/1989) and corresponded to the year with the least area of seafloor covered by the OFOS tow-cam (Fig. 3). During SO106 (1996), the second lowest area of seafloor was visualised, but litter densities increased compared to the previous year (s) (Fig. 3). There was a positive but non-significant relationship between the area covered during a cruise and the number of litter items observed ($R^2 = 0.64$, $p = 0.1$). In comparison, the relationship between the amount of litter observed was less influenced by the number of days on site ($R^2 = 0.13$, $p = 0.55$). However, with an increasing number of days on site, the overall area covered by the imagery tended to increase ($R^2 = 0.68$, $p = 0.085$ or >0.05).

80 % of the litter items were found in and immediately around the central DEA (Fig. 2) where the majority of ship time (ca. 80 %) was spent (Fig. 1a) and where the majority of the OFOS transects were carried out (Fig. 1b). 15 transects were carried out within the DEA area and 35 extended >250 m outside the DEA area. Only nine transects were carried out entirely outside the DEA. Northern seamounts were visualised with one transect (1989, SO061) extending from the DEA towards the North while the South-eastern areas were visited by one transect extending from the DEA (SO077, 1992) and by five separate transects to that specific locality (1 during SO077 (1992) and 4 during SO242-2 in 2015). The eastern reference area was visited once (in SO064), as was the South-western area (in SO061) and the western reference area twice (during S0064 and SO242-2) and by transects extending from the DEA during SO106 (Fig. 1b).

3.2. Litter type

Plastic (bags, fragments, packaging, lids, etc.) was the most abundant

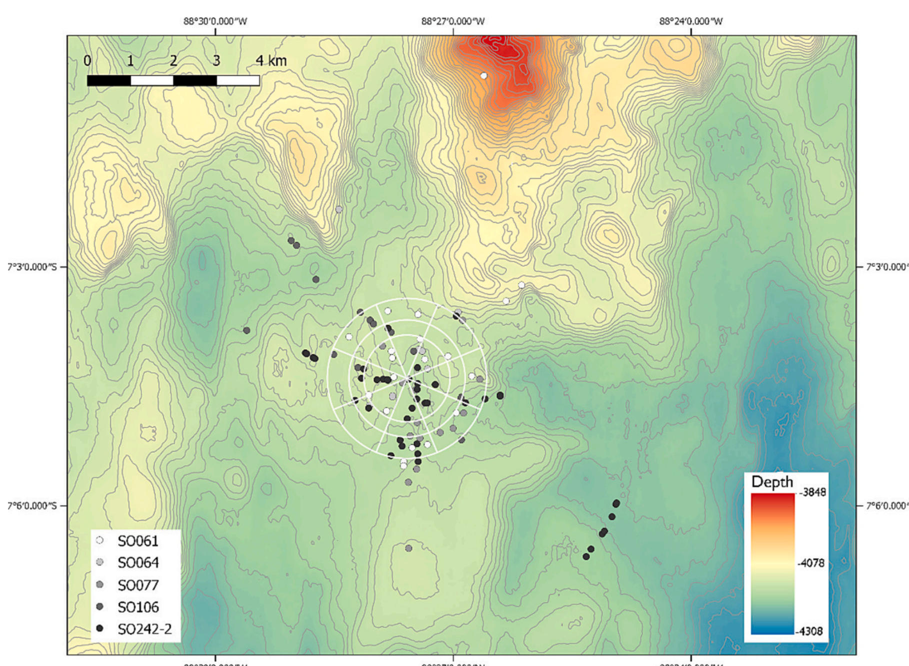

Fig. 2. Litter occurrence in the DISCOL area and the location of central DEA area added for reference. Each dot represents a single and unique litter item and is colour-coded according to the cruise it was first observed in. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

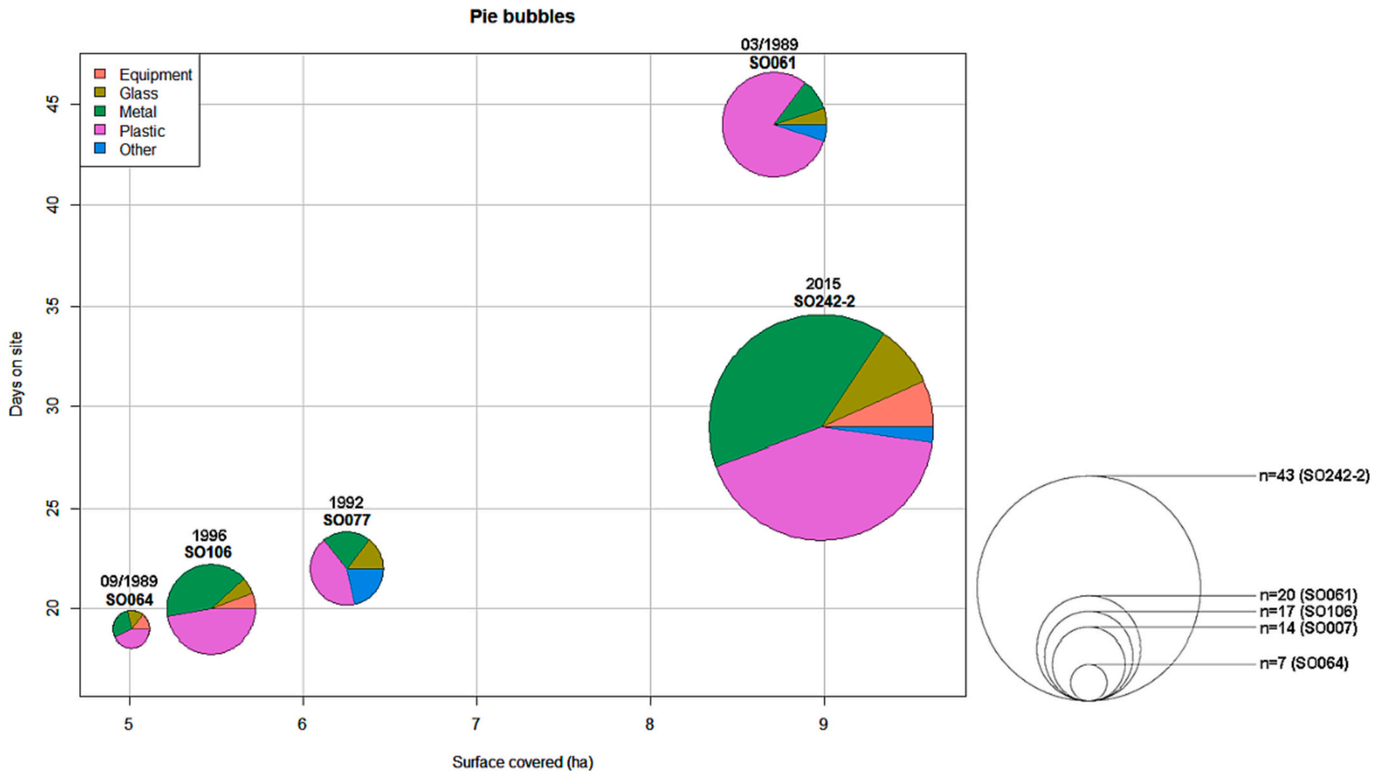

Fig. 3. The amount of litter and its composition as a function of the seafloor surface area visually surveyed (ha) on X-axis and Days on site (n) on Y-axis. Bubble size corresponds to total abundance of litter items (n) encountered during the cruise as is shown in the legend. SO061 was carried out in 03/1989, SO064 6 months later: 09/1989, SO077 in 1992, SO106 in 1996 and SO242-2 in 2015, see Table 1.

material observed during all cruises with highest densities recorded during SO242-2 (2.1 items/ha) followed by SO061 (1.8 items/ha) and totalled 51.5 % of all observed items (Figs. 3 and 4). The second most abundant litter items were comprised of metal (29.7 %, mostly soda cans, beer cans, lids), with highest densities during SO106 (1.3 items/ha) and SO242-2 (1.8 items/ha) and glass (8.9 %, mostly bottles) (Figs. 3 and 4). Litter labelled as “Equipment” comprised scientific equipment (e.g. instrument pressure housings) or any other type of equipment used in anthropogenic activities (e.g. fishing gear) and equalled 5 %. The same percentage was observed for the category “other” which comprised organic items (a lemon wedge), cardboard and undetermined items.

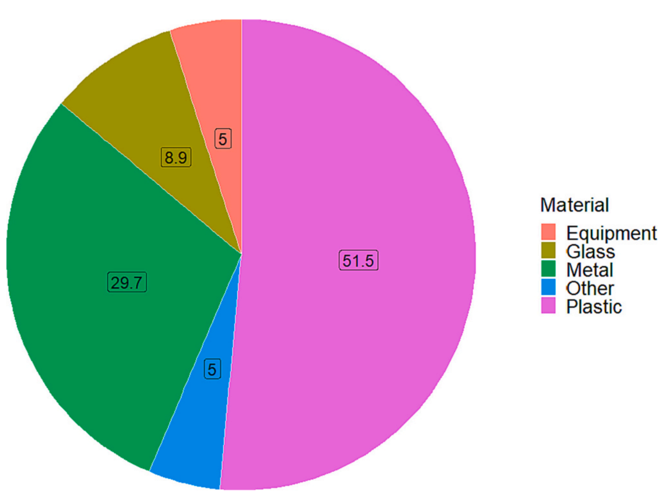

Fig. 4. Overall litter composition and proportion. The numbers indicated on each pie of the chart represent percentages (%) of the total number of litter items encountered (n = 101). “Other” material includes cardboard, organic litter and undetermined items.

More than 50 % of the litter items was >10 cm, with the largest item being >50 cm in diameter (see item 58 Table S1). Smaller items identified were 2 cm < x < 10 cm.

The origin and time at seafloor (recent vs. old vs. undetermined) of observed litter items are presented in Fig. 5 and Table S1. The numbers of recent items represent a minimum number because, when in doubt, items were classified as of undetermined age. This was mostly the case for plastic items such as bags and fragments. During SO061 (1989), 85 % of the items observed (1.95 items/ha) were considered recent and thus likely originated from the cruise itself. A high number of recent items were also encountered during SO077 (1992) and SO106 (1996), 71 % (1.6 items/ha) and 76 % (2.4 items/ha) respectively. Lowest densities of recent items were observed during SO064 (1989, 6 months after SO061) with 29 % of items identified as recent (0.4 items/ha) and during SO242-2 (2015) with 30 % identified as such (1.4 items/ha). While the low density of recent items during SO064 corresponded to overall lower litter densities observed and could be attributed to the lower area of seafloor visualised, this was not the case for SO242-2. Of the total 101 items found, an average of 58 % or 1.6 items/ha were considered recent. The proportion of old items increased with the number of visits to the DISCOL area, reaching its highest concentration during SO242-2 in 2015 with 2.1 items/ha or 44 % of the observations (Fig. 5). Of all litter items observed at the seafloor, n = 11 (10.9 %) could be clearly attributed to the German on site presence, due to the brand on cans or bottles. Another seven items consisted of more international soda brands, but were likely to have the same origin as the ones mentioned above (adding up to 17.8 %). Again, plastic bags and other plastic or metal fragments or lids were impossible to attribute an origin to.

3.3. Litter persistence

All litter items were only observed once, with the exception of two metal beverage cans (one “Schweppes” and one “Coca cola” can) that

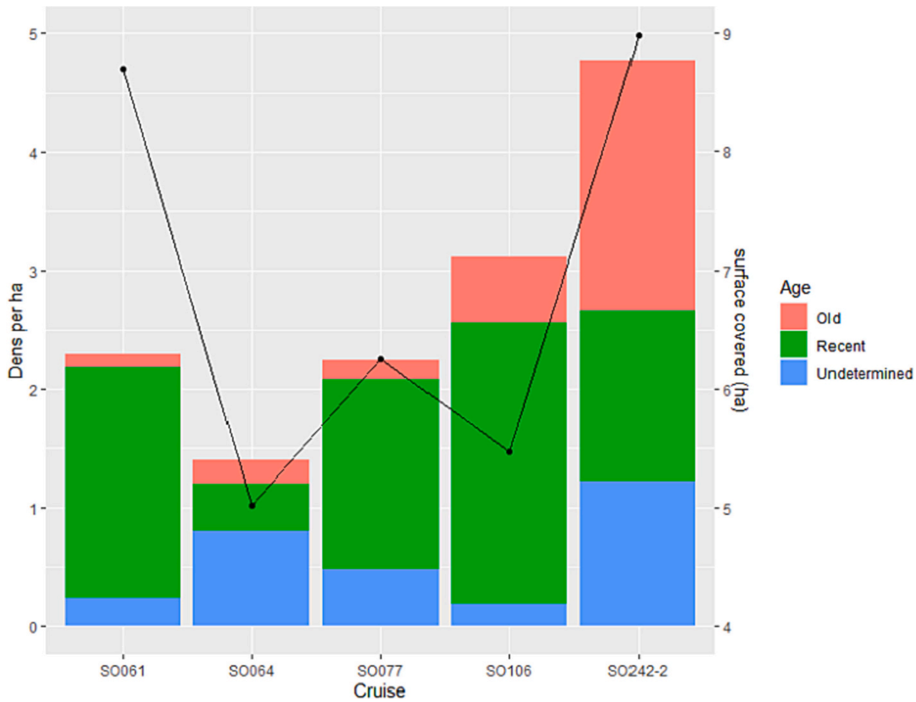

Fig. 5. Litter densities (on the left Y-axis) according to their deposition age classification, colour-coded going from recent at the time of observation, to old and undetermined. Items that were visualised during more than one cruise (n = 2) were only counted upon their first observation. The black line represents the surface covered (ha) by the OFOS to-cams imagery collection (on the right Y-axis).

were first encountered during SO106 (1996) and again during SO242-2 (2015) (Fig. 6). In the 19 years separating the two images depicting the same litter item, there was almost no degradation or corrosion noticeable on the "Schweppes" soda can (Fig.6, top). The only indication that it had been at the seafloor for some time was the rusty interface between the can and the sediment. The "Coca cola" can on the other hand, was clearly empty and damaged with the metal crushed. Its state 19 years later showed a far more accelerated degradation with corroded stains and holes where the can was damaged (Fig. 6, bottom).

3.4. Interaction between fauna and litter

Litter items were not visibly or recognisably colonised by macrofauna over the timespan of this study, though some organisms were found interacting with the items, mostly seeking shelter. Eight interactions between fauna and litter were observed from the total of 101 litter items encountered. Four interactions consisted of Ophiuroidea that were either buried and positioned in close proximity (n = 2) or underneath a litter item (n = 2) (Fig. 7b, d, e and f). Two small Peracarida crustaceans were also observed to interact with a plastic bag (Fig. 7f). On one occasion a Galatheidae (Crustacea) was observed on top of a plastic bag and a Parapaguridae (Crustacea) under a soda can (Fig. 7a and c respectively). One case of "entanglement" was observed with 3 (dead) pyrosomes (Pyrosoma, Chordata) intertwined in a fishing line (Fig. 7g) and one event showed a piece of plastic on top of a xenophyophore (not depicted).

4. Discussion

Abyssal plains, while not exempt from temporal variations and seasonal influx from the surface, are considered one of the more stable environments in the deep sea (Tyler, 2003, Glover et al., 2010). Hence, manmade items that reach the abyssal deep-sea floor are there to stay in continuously growing quantities, due to the persistence of such material over time and under the slow degradation rates associated with the absence of light, low temperatures and low energy regimes (Canals et al., 2021). Over extended periods, they are likely to fragment and be buried within the sediments to influence the subsurface environment. Generally, litter densities on the coastlines are higher than on the seafloor resulting from an additional input of waste coming from manmade and natural inland sources (Pham et al., 2014). Nevertheless, the abyssal

Fig. 6. Observation of the same metal (aluminium) beverage can in 1996 (SO106, left) and 2015 (SO242-2, right). The undamaged "Schweppes" can showed almost no signs of corrosion or decolouration after 19 years at the deep-seafloor, while the already damaged "Coca cola" can clearly degraded. Images were not processed.

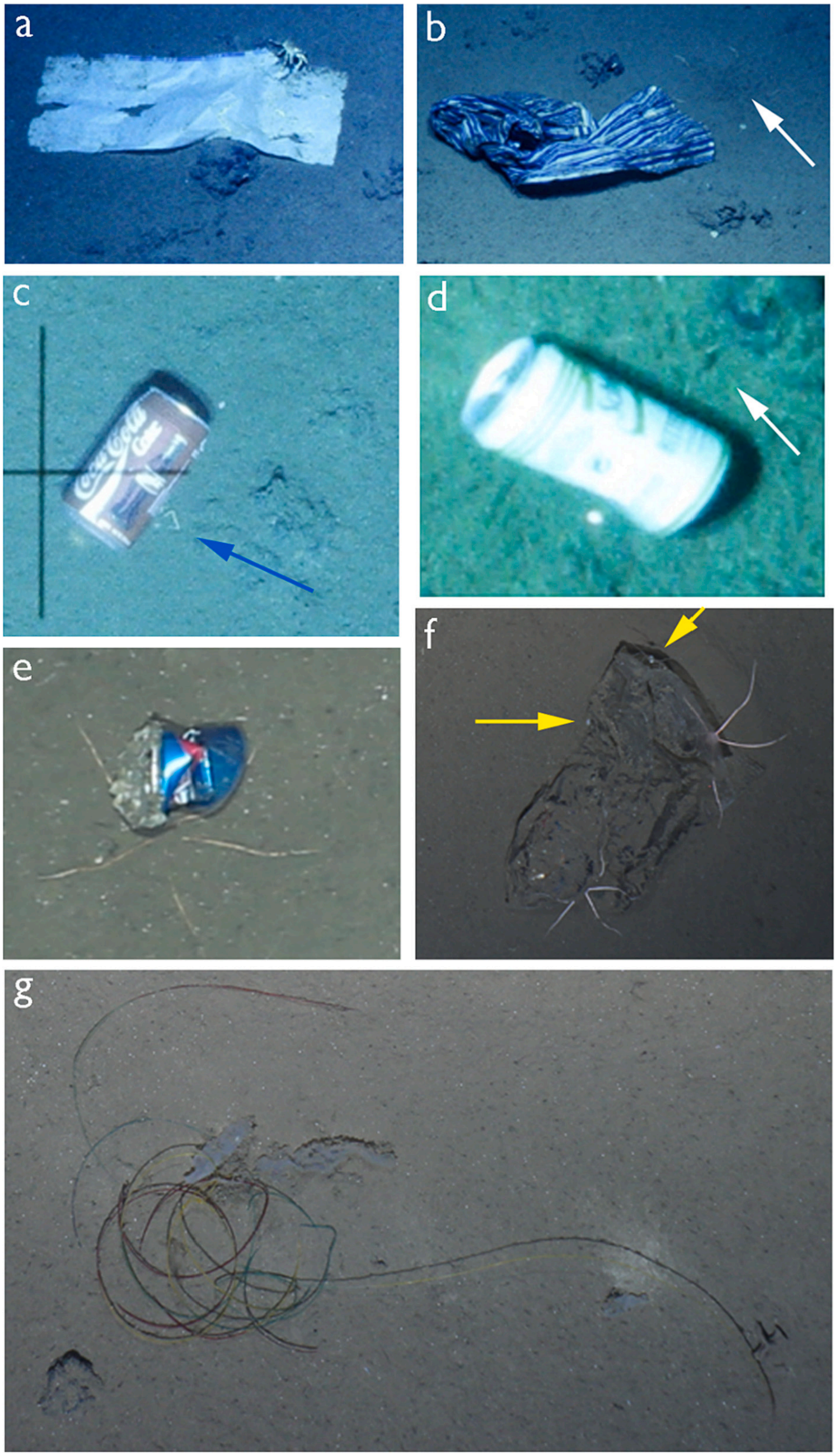

Fig. 7. Interactions between fauna and litter items. A Galatheidae positioned on top of a plastic bag (a), Ophiuroidea seeking shelter next or underneath a variety of plastic and metal items (white arrows) (b, d, e, f) as well as 2 small crustaceans (Peracarida, yellow arrows) in (f), a Parapaguridae hiding underneath a soda can (blue arrow) (c) and (dead) pyrosomes entangled in a fishing equipment (g). (f) was sampled by Krause et al. (2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deep-sea floor and trenches, even when situated far from land, show signs of litter pollution (Chiba et al., 2018). Shipping is considered a major source of marine litter, though litter items have been found in areas far removed from major shipping lanes as well (Bergmann et al., 2015). Litter densities at abyssal plains are understudied and very spatially variable, highlighting the complex variables at play in litter accumulation and exposing the need to address the role of the deep sea as a sink for marine debris and the possible impacts on abyssal fauna (Woodall et al., 2014; Chiba et al., 2018; Nakajima et al., 2021).

4.1. Litter abundance over time

The majority of litter items observed during this study appeared to be accidental disposals (items that fell overboard). Due to the lower chemical reactivity and low temperatures within the deep sea, there is a prolonged residence time of litter items such as plastics (Krause et al., 2020) that extends to periods >20 years. Based on this litter persistence, we discuss here the total abundance of 101 items/34 ha and an average density of 2.67 items/ha (±1.35 items/ha) of unique items observed over 26 years, for comparison with litter density estimations for other areas. With time, there is an overall increase in litter densities at the study site but variations were observed in flux and increase rates when comparing separate cruises, subject to parameters of the data collection (time spent on site, surface area visualised etc.).

The average density of 2.67 litter items/ha at the abyssal nodule fields can be considered low densities (2–10 items/ha) for the deep sea (Pham et al., 2014). The latter study categorised highest densities as >20 items/ha, generally encountered closer to shore, intermediate densities as between 10 and 20 items/ha and lowest densities to be <2 items/ha. However, none of the sites included in Pham et al. (2014) were comparable to the DISCOL site as that study did not contain data on abyssal plains or nodule fields.

Since our observations are based on imagery, densities reported here are minimum densities and possibly underestimate the densities of litter material, as they do not take into account small (<2 cm) and buried litter (Pham et al., 2013). The presence of microplastics smaller than 1 mm in deep-sea sediments from 1100 to 4800 m depth was first demonstrated by Van Cauwenberghe et al. (2013). Typically, microplastics (<0.5 cm) are not included in routine monitoring and represent a largely undocumented accumulation of debris in the deep-sea sediment (Woodall et al., 2014). Also, in analogy with biodiversity assessments in the deep sea, survey design, visualisation and/or sampling of a larger area will increase the amount of litter observed or encountered (Haarr et al., 2022). Here, we revealed a positive, though not significant, relation between the number of litter items observed and the amount of area covered/visualised.

While litter densities at the DISCOL abyssal plains in the South-East Pacific are to be considered low, Amon et al. (2020) reports lower densities between 0.17 and 1.73 items/ha for the central and western pacific abyss, including sites within marine protected area's largely devoid of human activity. Contrastingly, the abyssal plains off Japan in the Northwest Pacific feature the highest recorded litter densities yet reported for an abyssal plain with a mean 45,61 items/ha of mostly plastic items (Nakajima et al., 2021). In the latter study, the Kuroshio Extension current system appears to be one of the major transit pathways for marine debris resulting in a large accumulation at the deep seafloor (Nakajima et al., 2021). Whereas strong water flow tends to transport litter from shelves and slopes down to deeper waters the currents in the deep ocean and in the Peru Basin are typically slow (<10 cm/s) (Klein, 1996; Baeye et al., 2022). While it cannot be excluded that items may drift with the slow bottom currents, decade-old items linked to the older research cruises were deposited in the close vicinity of the central area (i.e. within maximum 1–2 nm distance), corroborating limited current influence for this study site. Besides hydrography, other factors at play in litter accumulation are human activity and geomorphology (Ramirez-Llodra et al., 2013). Human activity in this part of the Peru basin to date appears rather restricted to the scientific cruises and occasional cargo vessels/fishing vessels passing through. It is situated far from shore, in an area with low shipping intensity and is not part of an important fishing ground (Halpern et al., 2008, 2015). Regarding its geomorphology, the DISCOL Experimental Area (DEA) has low relief and gentle slopes (Gazis and Greinert, 2021). The majority of cruise time was spent in the central DEA area where >80 % of litter items were found. The litter items found towards the northern and south-eastern areas were few and were either classified as recent or undetermined, none of them showed clear signs of degradation indicative of being at the seafloor for a long time, corresponding to the fewer and more recent visits to the area as well.

Given that the DISCOL region is characterised by low currents, low shipping intensity and low relief, it does not meet the typical characteristics of a sink for retention of debris. We therefore deduce that the majority of litter items encountered in this study tend to originate from the human on site presence, in this case from the scientific cruises.

4.2. Type of litter

Overall, the majority of items found here at 4150 m depth are rather similar to those found on beaches, consisting of plastic bags, lids, metal (aluminium) cans and glass bottles often linked to recreational activities (Galgani et al., 2015). In absence of strong current systems (surface currents at DEA: 10 cm/s (Lumpkin and Johnson, 2013), near-bottom currents at DEA: <10 cm/s (Klein, 1996)) and situated at considerable distance from the coast, these type of litter items are thus an indication of human presence on site. Litter composition can differ from site to site and from ocean to ocean (Pham et al., 2014; Woodall et al., 2015). Some areas of the seafloor harbour non-buoyant material directly dumped from ships, e.g. metal and clinkers (Pham et al., 2014), but that is not the case here, affirming the assumption that the majority of the litter items are accidental disposals from ships.

As in many other marine litter studies, plastic was the dominant litter type, accounting for more than half of the items observed. Plastics, depending on its composition, can be (or become, e.g. due to fouling) negatively buoyant and sink or remain positively buoyant and float. Hence, the origin or source of the plastic litter items is generally harder to determine, as plastic gets easily taken by the currents and can thus travel long distances (Pham et al., 2014). The colour of plastic is often used as a proxy for exposure to the environment and weathering due to sun or heat discolouring the item and increasing fragmentation. However, these two factors (sun and heat) are absent in the abyssal deep sea and little decolouration of plastics was observed, thus highlighting the differences with floating plastic debris as reported by Martí et al. (2020).

Globally, plastic accounts for 75 % of marine litter, and comprises 62 % of litter at the seafloor (Canals et al., 2021). In contrast to plastic, glass and metal tend to sink to the seafloor (Pham et al., 2014). Since the majority of the items at the seafloor were in the proximity of the DEA, a fast sinking velocity is assumed (Krause et al., 2020).

Some beverage cans (10–18 %) were from a German brand and could thus be attributed to the German research cruises, but plastic bags and other generic items were impossible to link to a source based on imagery. Upon sampling of one of these plastic bags (Fig. 7f), by ROV during SO242-2, the presence of a coke can, special edition produced in Germany for the “Davis Cup” in December 1988 and an expiry date in 1990 was revealed (Krause et al., 2020), linking it back to one of the first German cruises. A plain white curd box sampled during the same study (not observed during OFOS transects) was dated back based on its production information (German manufacturer and type of postal number) to the RV Sonne cruises from 1992 or 1996 (Krause et al., 2020). Some of the more generic older items (e.g. plastic bags), density of which increased over time, are thus likely to have originated from the research cruises as well. Based on the repeated observation of two soda cans over time; it takes >20 years for an empty, already damaged metal (aluminium) can to degrade at the deep-seafloor in this region of the Pacific. An undamaged metal can only showed very minor traces of degradation after 19 years, implying a residence time of many more decades at the deep-sea floor.

The lower volumes of recent items observed during the last cruise (SO242-2, 2015), despite the extensive seafloor OFOS surveys, may be an indication of the more stringent on-board environmental policies adopted by the research community and by many ships in recent years. The International Maritime Organization (IMO), the United Nations' specialized organisation with a responsibility, among other topics, for the prevention of marine pollution by ships, issued guidelines in 2017 to avoid single-use litter items on board: "all ship owners and operators should minimize taking on board material that could become garbage" (RESOLUTION MEPC.295(71)), as well as an action plan in 2018 which was adopted as a Strategy in 2021 to address the marine plastic litter from ships (RESOLUTION MEPC.310(73)).

4.3. Fauna/litter interactions

Impact of litter on fauna is still poorly understood but the topic is gaining more attention. Eight interactions on 101 items were recorded, equalling 7.9 % of litter items, which is a significantly lower number than observed in the western Pacific with almost 40 % (Amon et al., 2020) and 37 % off the coast of California (Schlining et al., 2013). Moreover, no items were visibly colonised, again contrary to what has been observed elsewhere, where faunal encrustations were found on litter items, as well as Actiniaria colonising plastic and other items (e.g. Bergmann and Klages (2012) and Parga Martínez et al. (2020) at arctic Hausgarten, Ruhl (2013) at the Atlantic Porcupine Abyssal Plain, Woodall et al. (2015) in Indian Ocean and to a lesser extent in the Atlantic, Amon et al. (2020) in West Pacific Ocean). The visible absence of encrusting organisms or identification thereof could be due to the limitation of the imagery collected by a tow-cam at a predefined altitude, which did not allow for a closer approach, in situ zoom-ins, or sampling. Krause et al. (2020) on the other hand reported a significantly different and much less diverse microbial composition, in comparison to the surrounding environment, living on the surface of two sampled litter items originating from the DISCOL area (see Section 4.2).

Most interactions observed were of larger organisms apparently seeking shelter. The use of litter as shelter has been previously observed for a number of deep-sea taxa (Watters et al., 2010, Mordecai et al., 2011, Schlining et al., 2013, Woodall et al., 2015, Amon et al., 2020) and here include decapod crustaceans and ophiuroids. Seeking shelter is not a negative interaction per se, but when plastic bags are involved it can become detrimental as these can smother or damage the sheltering organisms (Gregory, 2009). Three dead pyrosomes were found entangled with fishing gear in 2015. These pyrosomes were already dead on reaching the seafloor, so the observed entanglement was not the cause of death but rather a result of them rolling over the seafloor with the bottom currents (Hoving et al., in revision). Due to their pelagic lifestyle, they are not a typical nodule fauna, though a Pyrosome bloom in 2015 may have served as a food source for benthic organisms (Hoving et al., in revision). Entanglement at other localities also affected Porifera (Parga Martínez et al., 2020) and coral colonies (Pham et al., 2013; Woodall et al., 2015; Amon et al., 2020), this was not observed here with the low occurrence of fishing gear (n = 2).

The overall low degree of faunal interaction with foreign elements such as litter is likely to be a response to the overall faunal densities of the study site, which decreased over time at the DISCOL area as a consequence of the disturbance experiment which took place in 1989. The total megafaunal densities dropped from an average of ~1100 ind./ha (pre-impact, Bluhm, 2001) to an average of ~700 ind./ha, 26 years post impact in 2015 (Simon-Lledó et al., 2019). The lower overall densities at an abyssal plain with buried nodules could contribute to the lower number of interactions observed.

The age of the introduced items is likely to also play a role in the sense that smooth surfaces can be harder to colonise than a degraded rougher surface. As such, the items visualised in other studies with faunal colonisation could either be items that were at the seafloor for longer time than monitored here or, alternatively those studies took place in more reactive areas with increased litter degradation or breakdown.

4.4. Implications for on-site presence

A scientific cruise consists generally of one research vessel that remains for days to weeks in a certain area, carrying out a variety of sampling or observational events. Therefore, the area of deep-seafloor covered in proportion to the time at the surface is rather small compared to what is to be expected during a mining action. A mining action is expected to be economically viable if a contractor mines 200–400 km^2/year (Sharma, 2017), subject to the quality of the ore, during a 20 year mining period (Smith et al., 2020). Vessels of a mining operation would thus cover a larger area than a scientific cruise, due to the collection of resources adding up to 0–5–1.1 km^2/day mined area.

Here, all five cruises combined spent approximately 80 % of the time within the DEA and immediate surroundings, adding up to a coverage of 20km^2 or 0.19km^2/day, which is 4.3 times smaller on a daily average than what is expected for a mining action. Besides having (at least) one mining production support vessel on site, there will be large bulk carriers going back and forth for transporting the ore. A mining operation thus covers a much larger area of deep-sea floor than any other scientific cruise. Hence, accidental litter disposals during a possible mining action will be scattered over a much larger area as well. In addition to this, the loss of parts or components of machinery or mining equipment to the deep sea needs to be taken into account as well. If the more stringent environmental policies regarding litter production on-board vessels are upheld, it could help limit the influx of new litter items to the deep seafloor.

Here we show that, in a remote area with low currents (both at the surface (Lumpkin and Johnson, 2013) and at seafloor (Klein, 1996)) and low shipping and fishing intensity (Halpern et al., 2008, 2015), the human presence on-site in the Peru Basin is the cause of at least 1.6 items/ha (160 items/km^2) or 58 % of the litter observed. Based on the average density of litter items found over time, and taking into account that survey design and surface covered/visualised influence the density estimates (Haarr et al., 2022), we estimate that over 100,000 items will be delivered to the seafloor for an extrapolated mined area during a year. This presents a significant contribution to litter abundance in the deep sea and needs to be taken into account when planning assessment and mitigation strategies to reduce the cumulative impacts of any mining operation.

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CRediT authorship contribution statement

Daphne Cuvelier: Conceptualization, Investigation; Data collection, Writing - original draft, review and editing, Visualisation.
Sofia P. Ramalho: Investigation; Data Collection, Writing - review, and editing.
Autun Purser: Investigation; Data Collection, Writing - review, and editing.
Matthias Heackel: Investigation; Data collection, Writing - review, and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availabilityData generated for this study are available as Supplementary materials (Table S1). The full resolution seafloor images are available in BIIGLE and the images from SO242-2 are also available in PANGAEA: Purser A., Marcon Y., Boetius A. (2018). Seafloor images from the Peru Basin Disturbance and Colonization (DISCOL) area collected during SO242/2. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, PANGAEA, doi:https://doi.org/10.1594/PANGAEA.890634.

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