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Positively buoyant but sinking: Polymer identification and composition of marine litter at the seafloor of the North Sea and Baltic Sea

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ABSTRACT

Different litter types accumulate in all marine environments. Plastics are of special interest because of their high abundance and possible threats to marine organisms. Polymer type is crucial for their distribution and fate in marine environments. Seafloor litter abundance and composition in the Baltic and North Sea were analysed based on three sampling campaigns according to the protocol of ICES International Bottom Trawl Survey. Polymers were identified via attenuated total reflection-Fourier transform infrared spectroscopy. General litter abundances differed significantly between the Baltic and North Sea with 9.6 items/km^2 and 70.7 items/km^2, respectively. Plastic built the dominating litter group in both seas (62.2% and 91.3%, respectively). Polymer identification revealed clear dominance of polyethylene, polypropylene and polyamide. Most polymers were positively buoyant in seawater (89.5%), thereby excluding polymer density as the main driver of vertical plastic litter transportation. Plastics at the seafloor basically reflected the entirety of polymers entering marine environments.

1. Introduction

The constant planetwide input of anthropogenic litter into all environments is one of the most urgent man-made threats to nature of our times. Marine environments are especially pressured by this pollution, since up to 12.7 million tons of plastic litter entered the oceans only in 2010 (UNEP, 2009; Jambeck et al., 2015). The majority of marine litter items (LI) comprises of plastics. Estimations for European seas vary from 35% (Zablotski and Kraak, 2019) and 80% (Kammann et al., 2018) to up to 90% (Galgani et al., 2015). LI accumulate at the sea surface (Eriksen et al., 2013) or at shorelines (Monteiro et al., 2018; Reinold et al., 2020). Partly depending on their specific density, around 70% of marine LI end up at the seafloor (UNEP, 2005; OSPAR, 2014). Common plastic polymers show densities from 0.92 g/cm^3 (low-density polyethylene; LDPE) to 1.44 g/cm^3 (polyvinyl chloride; PVC). When considering that most produced polymers (Zalasiewicz et al., 2016; PlasticsEurope, 2020) and most detected (micro)plastic polymers in marine environments are polyethylene (PE) and polypropylene (PP) (e.g. Hidalgo-Ruz et al., 2012; Enders et al., 2015; Andrady, 2017; Vermeiren et al., 2016; Lorenz et al., 2019) the majority of plastic litter is neutrally or positively buoyant in seawater (~1.02 g/cm^3 for the Baltic Sea and ~1.024 g/cm^3 for the North Sea) (Iversen and Ploug, 2010; Andrady, 2015; Graca et al., 2017). It could be hypothesised that these polymers are not found in high quantities at the seafloor, compared to high density plastics.

The main transport mechanisms of marine plastics are winds and ocean currents, spreading plastics horizontally and vertically (Moore, 2008). Although the horizontal transport is probably predominant, there is a considerable vertical transport of plastics to the seafloor (Wang et al., 2016; Canals et al., 2021). This vertical transport is often driven by mechanisms, which change their initial buoyancy, such as biofouling, attachment of sessile organisms or leaching of specific additives. But also incorporation in marine aggregates or downwelling facilitate vertical transport of plastics with an initially neutral or positive buoyancy (Tubau et al., 2015; Fazey and Ryan, 2016; van Sebille et al., 2020). However, the exact spatio-temporal distribution of marine plastic litter and its driving forces are still not completely understood (Tekman et al., 2020). Low temperatures, low wave action and the absence of UV radiation at the seafloor, together with material properties of plastics, result in long persistence in those habitats (Cole et al., 2011; Tekman et al., 2017). Hence, the seafloor might function as a final sink for marine plastics with continuously growing quantities (Woodall et al., 2014; Abel et al., 2021).

Information on seafloor litter can be gathered with different sampling techniques, mainly bottom trawling and video imaging, where

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bottom trawling enables further investigations of the LI samples (Canals et al., 2021). Mean litter densities reported from video imaging are highly diverse when comparing different regions, ranging from 202–279 LI/km^2 in the Barents and Norwegian Sea (Buhl-Mortensen and Buhl-Mortensen, 2017) and 1200–7100 LI/km^2 in the NW Pacific Ocean (Shimanaga and Yanagi, 2016) to 346–8082 LI/km^2 in the Fram Strait (Tekman et al., 2017). Similarly various outcomes are reported by bottom trawling. Here, mean litter densities range from 3.4 LI/km^2 off the South African coasts (Ryan et al., 2020) to 30–128 LI/km^2 along the US west coast (Keller et al., 2010) and 81–2926 LI/km^2 in Japanese seas (Kuroda et al., 2020). Even comparing litter densities in the same sea reveals highly diverse numbers. While Gerigny et al. (2019) found 50–289 LI/km^2 in the French Mediterranean, Koutsodendris et al. (2008) reported 72–437 LI/km^2 for the Greek Mediterranean and Mifsud et al. (2013) 97 LI/km^2 for the Central Mediterranean. Mean litter densities reported for the North Sea vary from 16.9 LI/km^2 (Kammann et al., 2018) and 40.5–49.0 LI/km^2 (Maes et al., 2018) to 156 LI/km^2 (Galgani et al., 2000) and 96–33,675 LI/km^2 (Gutow et al., 2018). Kammann et al. (2018) found 5.1 LI/km^2, Urban-Malinga et al. (2018) 20 LI/km^2 and Galgani et al. (2000) 126 LI/km^2 at the seafloor of the Baltic Sea.

Marine plastic litter causes several problems for ecosystems and single organisms. Main negative effects for the marine fauna are entanglement and blockages of digestive tracts after ingestion (Gregory, 2009; Werner et al., 2016; Fossi et al., 2018). Negative effects of entanglement have been shown for e.g. turtles (Digka et al., 2020), seabirds (Ryan, 2018) and cetaceans (Knowlton et al., 2012). The ingestion of plastics was identified for several species of fish (Jabeen et al., 2017; Anastasopoulou and Fernández Ojeda, 2019), turtles (Matiddi et al., 2017) as well as for marine birds and mammals (Lusher et al., 2018; Kühn and van Franeker, 2020). Plastics in marine environments are subject to physico-chemical forces, which precipitate their embrittlement and the formation of microplastics (<5 mm). Ingestion of microplastics has been proven for various marine biota (e.g. Rummel et al., 2016; Sun et al., 2018; Perez-Venegas et al., 2020). Negative effects for marine ecosystems comprise such different phenomena as drifting of invasive or pathogenic (micro)organisms (Kirstein et al., 2016) or formation of artificial hardgrounds at the seafloor (Harms, 1990).

The increasing pollution of marine environments with anthropogenic LI was firstly reported in the 1970s (e.g. Carpenter and Smith, 1972; Shiber, 1979). As scientific evidences for its increase and harmful effects became more apparent, this topic drew the attention of the general public and policy makers. Consequently, marine litter was introduced as an environmental indicator by several international authorities. In 2008 (updated in 2017) EU's Marine Strategy Framework Directive (MSFD, 2008/56/EC) was established. Its aim is to achieve or maintain the Good Environmental Status (GES) of European seas. Seafloor litter is included as one of the eleven qualitative descriptors (D10C1). Here, GES is achieved when "the composition, amount and spatial distribution of litter [...] on the seabed, are at levels that do not cause harm to the [...] marine environment" (European Commission, 2017). Descriptor D10C1 is explicitly referring to the composition of marine LI and we think the polymer composition of plastic litter is a valid part of the overall litter composition.

Different international organisations developed guidelines and protocols to monitor seafloor litter (Galgani et al., 2013; ICES, 2015; GESAMP, 2019). The International Council for the Exploration of the Sea (ICES) provides a harmonized protocol (International Bottom Trawl Survey; IBTS) for the collection and categorisation of LI from scientific fishery bottom trawling in the North and Baltic Sea (ICES, 2015). Monitoring of seafloor LI is mandatory for the North Sea, recommended for the Baltic Sea and has been carried out since 2011 (ICES DATRAS, 2021).

Former studies present litter composition in the IBTS (sub)categories, thereby providing helpful information about size and morphology (Maes et al., 2018; Urban-Malinga et al., 2018). However, the polymer composition of the plastic category is rarely addressed in studies on LI at the seafloor. This indicates missing analyses on shares of certain polymers, preventing subsequent analyses on their density composition, possible sources or modelling of their spatial distribution (Canals et al., 2021).

This study provides polymer identification of LI from the seafloors of the North and Baltic Sea originating from three consecutive scientific bottom trawl surveys. The objectives of this study are:

- To give an overview of the general regional distribution, composition and abundance of LI at the seafloors of the study areas.
- To identify the polymers of the plastic LI and analyse their regional distribution, composition and abundance.
- To relate certain polymer groups to their specific density and discuss transport mechanisms of neutrally or positively buoyant plastics to the seafloor.
- To give recommendations for future monitoring programs of seafloor litter.

2. Material and methods

2.1. Collection of litter and calculation of litter abundance

LI > 2.5 cm in longest cross section were collected from 90 bottom trawl catches during three consecutive scientific fisheries surveys on the research vessel Walther Herwig III, conducted in 2017, 2018 and 2019.

Sampling comprised seven areas in the North Sea and four areas in the Baltic Sea (Fig. 1, Table 1). Sampling was performed with two different types of bottom trawls. In the North Sea a Grande Ouverture Verticale bottom trawl (GOV) in standard IBTS configuration was deployed, while stations in the Baltic Sea were sampled with a 140 ft. bottom trawl with rock hoppers. Both gears were equipped with otter boards and had a mesh size of 20 mm in the cod-end. All catches were accomplished with a towing speed of 3.0–3.7 kn (mean 3.5 kn) for 60 min. Sampling was only conducted at wind speeds below 7 bft and during daylight hours.

After hauling all LI > 2.5 cm in the cod-end were collected. While former studies (e.g. Kammann et al., 2018) only considered LI in the cod-end, all LI entangled, also in the outer meshes of the nets, were included in this study. The nets were checked after every catch and all LI found were recorded. Collection, categorisation and recording of LI were conducted based on the IBTS protocol of ICES (2015).

Litter abundance was calculated as LI per km^2 [LI/km^2] using the mean towing speed of 3.5 kn recorded by GPS sensors during trawling with seafloor contact. The trawled area was calculated by using the wingspread (distance between the tips of the net wings) as a measure. The wingspreads of the GOV and the 140 ft. bottom trawl were 18.5 m and 18.85 m, respectively. These numbers are averaged, as the wingspread is varying with water depth, warp length and the resulting doorspread. Hence, LI from about 0.12 km^2 of seafloor were collected during 60 min of trawling at 3.5 kn. Data visualisation was conducted using R package ggplot2 (version 2.2.1, default parameters) (Wickham, 2009).

2.2. Categorisation and sizing of litter

Based on the IBTS protocol and its classification system (ICES, 2015) all items of potential anthropogenic origin were differentiated into six categories: plastic, metals, rubber, glass/ceramics, natural products or miscellaneous. All LI were classified into several subcategories (40 in total) within each category. The 14 subcategories of plastic are shown in Table 2. All non-anthropogenic items, like undressed stones or wood, and LI recognisably deriving from the vessel (paint flakes, parts of the deployed nets, etc.) were excluded. Exact numbers of classified items per year are given in Table A.1.

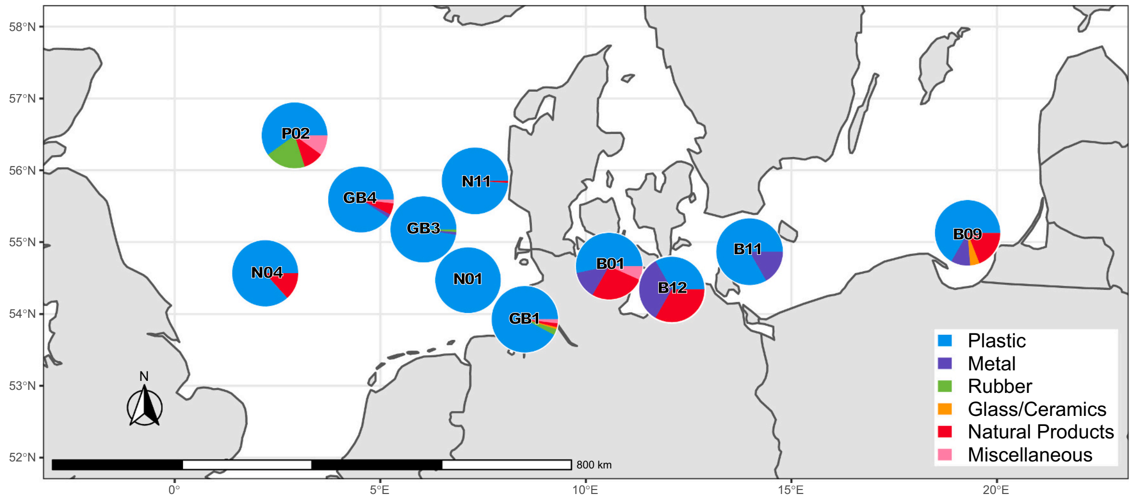

Fig. 1. Spatial distribution of mean litter abundances originated from 90 bottom trawl catches in seven areas of the North Sea and four areas of the Baltic Sea. Litter items were categorised according to the International Bottom Trawl Survey's (IBTS) classification system (ICES, 2015).

Table 1
Size, mean depth and position of sampling areas; trawls conducted per area.

Sea	Area	Trawls	Mean Depth	Latitude	Longitude	Box area
		n	m	Degree min	Degree min	km^2
Baltic Sea	B01	8	19	54 25.00 N–54 45.00 N	010 07.00 E–011 00.00 E	6650
Baltic Sea	B09	13	70	55 04.00 N–55 16.00 N	018 09.00 E–018 35.00 E	1900
Baltic Sea	B11	10	29	54 34.00 N–55 00.00 N	013 55.00 E–014 20.00 E	3900
Baltic Sea	B12	5	35	54 40.00 N–54 55.00 N	013 00.00 E–013 55.00 E	4900
North Sea	GB1	8	37	54 03.00 N–54 09.00 N	007 43.00 E–007 55.00 E	400
North Sea	GB3	8	42	54 55.00 N–55 02.00 N	006 15.00 E–006 24.00 E	400
North Sea	GB4	11	45	55 22.00 N–55 25.00 N	004 25.00 E–004 34.00 E	200
North Sea	N01	10	39	54 14.00 N–54 26.00 N	007 22.00 E–007 41.00 E	1500
North Sea	N04	3	29	54 25.00 N–54 52.00 N	001 59.00 E–002 32.00 E	5300
North Sea	N11	6	25	55 29.00 N–55 41.00 N	006 49.00 E–007 39.00 E	3550
North Sea	P02	8	68	56 16.00 N–56 42.00 N	002 39.00 E–003 26.00 E	7100

A main contributor to marine plastic pollution is the fishing industry (Buhl-Mortensen and Buhl-Mortensen, 2017). In order to scrutinise this source, the composition of the LI was checked concerning fishing-related LI. Following Maes et al. (2018) nine subcategories were directly related to fishing activities and grouped as fishing-originated LI (Table A.2).

LI were sized based on the size classes given in the IBTS protocol: A (<25 cm^2), B (<100 cm^2), C (<400 cm^2), D (<2500 cm^2), E (<10,000 cm^2) and F (>10,000 cm^2).

Table 2
Composition of plastic litter as mean percentages for the North Sea, Baltic Sea and the total study area based on 90 bottom trawl catches in 2017, 2018 and 2019, categorised according to International Bottom Trawl Survey (IBTS) subcategories (ICES, 2015). N = 449 plastic litter items.

IBTS plastic subcategory	North Sea	Baltic Sea	Total
	%	%	%
Bottle	0.48	0.00	0.45
Sheet	13.06	14.29	13.14
Bag	1.90	10.71	2.45
Caps/lids	0.00	0.00	0.00
Fishing line (monofilament)	68.65	7.14	64.81
Fishing line (entangled)	4.28	7.14	4.45
Synthetic rope	6.89	32.14	8.46
Fishing net	0.95	7.14	1.34
Cable ties	0.71	0.00	0.67
Strapping band	0.24	0.00	0.22
Crates/containers	0.24	0.00	0.22
Diapers	0.48	0.00	0.45
Sanitary towels/tampons	0.24	0.00	0.22
Other plastic	1.90	21.43	3.12

2.3. Subsampling of plastic litter

All potential plastic LI were subsampled for spectroscopic analyses. After first cleaning on board, pieces of at least 3 cm in diameter (3 cm length for fibrous items) were cut off and stored in paper bags. In the lab any organic aufwuchs was removed and LI were cleaned with ultra-pure water and ethanol (96%; BrüggemannAlcohol Wittenberg GmbH, Wittenberg, Germany). In cases where this cleaning procedure was not sufficient, LI were cut and intersections were used for subsequent spectroscopic analyses.

2.4. Polymer identification and density assignment

All potential plastic LI samples were analysed for their polymer types using attenuated total reflection-Fourier transform infrared (ATR-FTIR) spectroscopy, performed on a Spotlight 400 FTIR Imaging System (PerkinElmer Inc., Waltham, USA). Samples were pressed on a Lithium tantalate crystal by the pressure lever of the spectrometer and all measurements were conducted in ATR-mode with identical settings. IR spectra were measured in the wavenumber range of 4000–650 cm^{-1} with a spectral resolution of 4 cm^{-1}. For every spectrum 32 scans were co-added and detector speed was set to 0.2 cm/s. A strong Norton Beer apodization was used and phase correction was set to “magnitude”.

The resulting spectra were compared against two reference spectra databases (PerkinElmer Inc., Waltham, USA and S.T. Japan Inc., Tokyo, Japan) using the SPECTRUM software (PerkinElmer Inc., Waltham, USA). Just LI spectra showing correlation factors above 0.90 compared to the reference spectra were included. Afterwards, identified polymer groups were assigned to their specific densities (see Fig. 2), which were defined through an abundant literature search and correspondence with manufacturers (e.g. Morét-Ferguson et al., 2010; Hidalgo-Ruz et al., 2012; Andrady, 2015; Vermeiren et al., 2016; Mintenig et al., 2020). They refer to polymer groups and not to certain polymers, as this material group is highly diverse.

3. Results

3.1. Litter per catch

In total, 90 bottom trawl catches in eleven sampling areas were checked for their content of marine LI, 72 of them contained LI, representing 80.0% of all conducted catches. In 73.3% of catches containing LI, plastics were found. The probability to find LI in a catch, but no plastics was 8.3% (Table 3).

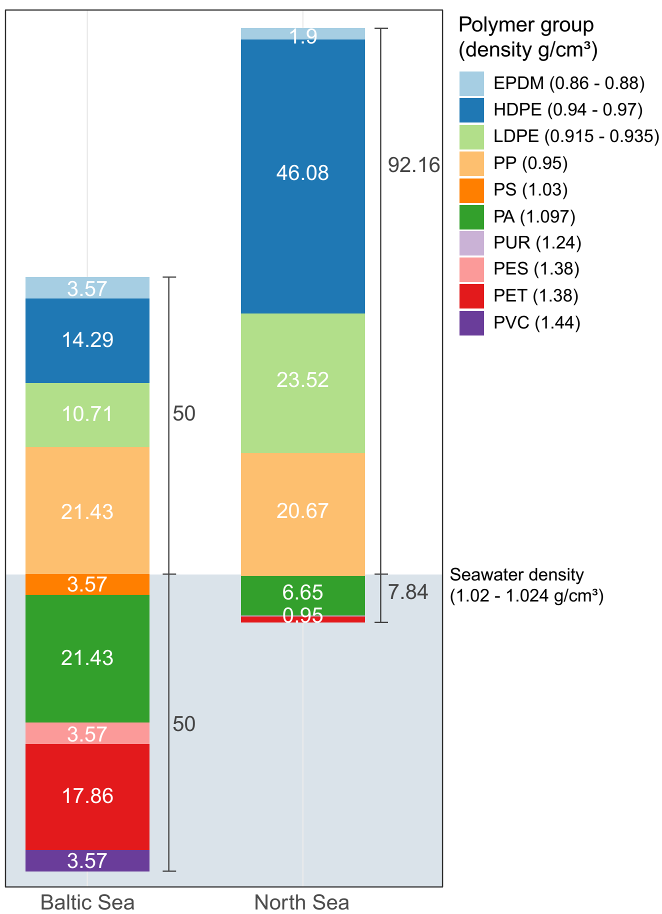

Fig. 2. Mean percentages of identified plastic polymer groups for the North Sea and the Baltic Sea. All litter items were collected during three consecutive bottom trawl surveys in 2017, 2018 and 2019.
The white area represents a density above and the grey area a density below the seawater density.
Density values refer to polymer groups and are not experimentally determined. The following polymers were detected: ethylene propylene diene monomer (EPDM), high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), polyamide (PA), polyester (PES), polyethylene terephthalate (PET), polystyrene (PS), polyurethane (PUR) and polyvinylchloride (PVC). $N = 449$ plastic litter items.

3.2. Litter per (sub)category

A total of 492 LI were found in this study. The plastic category represented the vast majority, with 91.3%. The other categories contributed in the following order: natural products, rubber, metals, miscellaneous and glass/ceramics (Fig. 3).

The plastic category was dominated by four out of 14 subcategories: “fishing line (monofilament)”, “sheet”, “synthetic rope” and “fishing line (entangled)” in descending order (Table 2).

Following Maes et al. (2018) nine subcategories were considered as fishing-originated LI, which stand for 73.4% of total LI and 80.4% of total plastic LI. Within the fishing-originated LI “fishing line (monofilament)” stood for more than the half of LI, followed by “synthetic rope” and “fishing line (entangled)”. Fishing-originated LI accounted for 77.9% and 35.6% of the total LI in the North and Baltic Sea, respectively (Table A.2).

3.3. Litter size

More than three-quarters of total LI in the North Sea were found to be <25 cm^2 (size class A). The larger the LI, the less they were frequently found. Plastic LI showed a similar distribution with descending numbers of items with increasing size and three-quarters of LI represented by size class A.

Total and plastic LI in the Baltic Sea showed a trend of descending numbers of items with increasing size as well, although small items were not as dominant as in the North Sea, with nearly the half of identified total and plastic LI being <25 cm^2. For exact numbers of all size classes see Tables A.3 and A.4.

3.4. Distribution and abundance of litter

Altogether 447 LI were found in 54 bottom trawl catches in seven North Sea areas and 45 LI in 36 catches in four Baltic Sea areas. The probability to find at least one LI in a catch was 92.6% and 61.1% for the North Sea and Baltic Sea, respectively. Probabilities to find plastics were 90.7% and 47.2%, respectively. The chances to catch LI but no plastics were 4.0% for the North and 18.2% for the Baltic Sea.

The share of plastics on total LI was 94.2% for the North Sea, followed by natural products (2.2%) and rubber (1.8%). In the Baltic Sea the plastic category contributed with 62.2% to total LI. Here, natural products (20%) and metals (13.3%) showed higher shares than the second and third ranked categories in the North Sea (Fig. 3).

Overall, for both studied seas a mean value of 48.5 LI/km^2 was found. The abundances in the North and Baltic Sea were significantly different. While the North Sea showed a high mean abundance of 70.7 LI/km^2, the mean abundance in the Baltic Sea was 9.6 LI/km^2. In the North Sea a mean value of 66.4 plastic LI/km^2 was found, while the Baltic Sea showed a mean abundance of 5.7 plastic LI/km^2. Concerning both seas, a mean value of 44.4 plastic LI/km^2 was identified (Table 3).

3.5. Distribution and polymer composition of plastic litter

Overall, 487 potential plastic LI were investigated and 449 items were confirmed to consist of synthetic polymers. The average correlation factor, when comparing measured spectra with the reference databases, was 0.976 (data not shown). In total, 38 LI were excluded due to too low correlation factors or assigned to another category if ATR-FTIR spectroscopy identified different materials than plastic polymers. These excluded LI were predominantly black potential plastic items, which showed weak correlation factors or were assigned to rubber subcategories.

Altogether nine polymer groups were confirmed: PE, PP, PVC, polyamide (PA), polyester (PES), polyethylene terephthalate (PET),

Table 3
Mean abundance (litter items (LI)/km^2, LI/h trawling time, LI count) of International Bottom Trawl Survey (IBTS) litter categories in sampling areas in the North and Baltic Sea collected during three consecutive bottom trawl surveys in 2017, 2018 and 2019, including standard deviation (SD) and standard error of the mean (SEM). Additionally, LI count, LI/km^2 and amount [%] for the plastic category in total and for the Baltic and North Sea, respectively.

Sea	Area	Trawls	Trawls containing LI	Plastic	Metal	Rubber	Glass/ceramics	Natural products	Miscellaneous	Total LI	Total LI	LI count	Plastic count	Total plastic	Plastic amount
		n	n	LI/h	LI/h	LI/h	LI/h	LI/h	LI/h	LI/h	LI/km^2	n	n	LI/km^2	%
Baltic Sea	B01	8	7	1.00	0.25	0.00	0.00	0.50	0.13	1.88	15.35	15	8		
Baltic Sea	B09	13	8	1.08	0.15	0.00	0.08	0.31	0.00	1.62	13.22	21	14		
Baltic Sea	B11	10	4	0.50	0.10	0.00	0.00	0.00	0.00	0.60	4.91	6	5		
Baltic Sea	B12	5	3	0.20	0.20	0.00	0.00	0.20	0.00	0.60	4.91	3	1		
Baltic Sea	**Mean**			**0.69**	**0.18**	**0.00**	**0.02**	**0.25**	**0.03**	**1.17**	**9.60**			**5.68**	**62.22**
	SD			**±0.36**	**±0.06**	**±0.00**	**±0.03**	**±0.18**	**±0.05**	**±0.58**	**±4.75**				
	SEM			**±0.18**	**±0.03**	**±0.00**	**±0.02**	**±0.09**	**±0.03**	**±0.29**	**±2.37**				
Baltic Sea	**Sum**	**36**	**22**									**45**	**28**		
North Sea	GB1	8	7	11.88	0.00	0.38	0.13	0.25	0.25	12.88	107.37	103	95		
North Sea	GB3	8	8	9.38	0.13	0.13	0.00	0.00	0.00	9.63	80.26	77	75		
North Sea	GB4	11	10	4.45	0.09	0.00	0.00	0.27	0.09	4.91	40.94	54	49		
North Sea	N01	10	9	7.90	0.00	0.00	0.00	0.00	0.00	7.90	65.88	79	79		
North Sea	N04	3	3	4.33	0.00	0.00	0.00	0.67	0.00	5.00	41.70	15	13		
North Sea	N11	6	6	16.33	0.00	0.00	0.00	0.17	0.00	16.50	137.60	99	98		
North Sea	P02	8	7	1.50	0.00	0.50	0.00	0.25	0.25	2.50	20.85	20	12		
North Sea	**Mean**			**7.97**	**0.03**	**0.14**	**0.02**	**0.23**	**0.08**	**8.47**	**70.65**			**66.44**	**94.18**
	SD			**±4.70**	**±0.05**	**±0.19**	**±0.04**	**±0.21**	**±0.11**	**±4.57**	**±38.07**				
	SEM			**±1.78**	**±0.02**	**±0.07**	**±0.02**	**±0.08**	**±0.04**	**±1.73**	**±14.39**				
North Sea	**Sum**	**54**	**50**									**447**	**421**		
Total	**Mean**			**5.32**	**0.08**	**0.09**	**0.02**	**0.24**	**0.07**	**5.82**	**48.52**			**44.39**	**91.26**
	SD			**±5.13**	**±0.09**	**±0.17**	**±0.04**	**±0.20**	**±0.03**	**±5.07**	**±42.35**				
	SEM			**±1.55**	**±0.03**	**±0.05**	**±0.01**	**±0.06**	**±0.03**	**±1.53**	**±12.77**				
Total	**Sum**	**90**	**72**									**492**	**449**		

The bold numbers in Table 3 are those numbers which belong to the whole sampled seas (Baltic and North Sea) and are used to provide an easier distinction between numbers regarding specific sampling areas and mean numbers of complete seas.

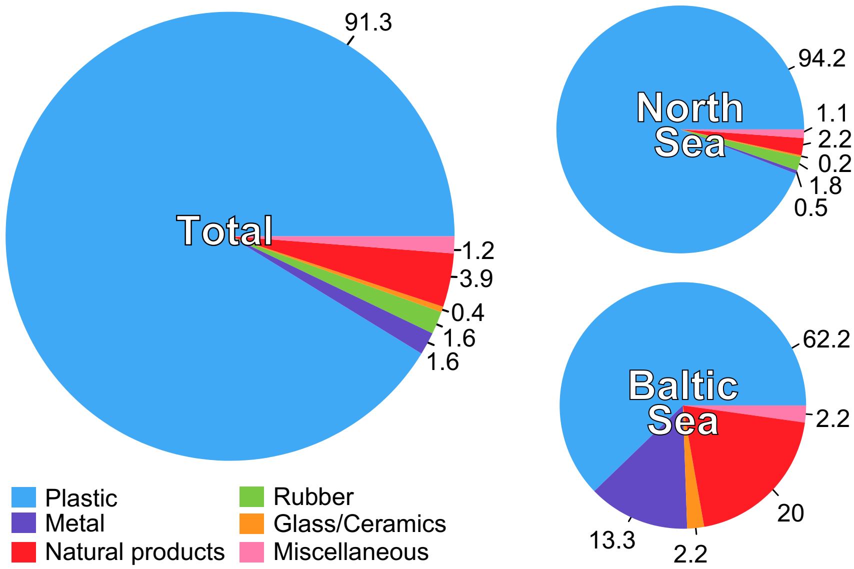

Fig. 3. Mean percentages of litter categories for the North Sea (54 bottom trawls), the Baltic Sea (36 bottom trawls) and the whole study area (90 bottom trawls). Litter items were categorised according to the International Bottom Trawl Survey's (IBTS) classification system (ICES, 2015).

ethylene propylene diene monomer (EPDM), polystyrene (PS) and polyurethane (PUR). Most synthetic LI were found to consist of PE (66.8%), followed by PP (20.7%) and PA (7.6%). Spectra of all identified polymer groups are shown in Fig. A.1. The other polymer groups contributed only slightly to the plastic pollution. The polymer group PE was subdivided into LDPE and high-density PE (HDPE) (Table 4).

In the North Sea plastic LI of six polymer groups were found: PE, PP, PA, PET, EPDM and PUR. PE was identified most with 69.6% of plastic LI, followed by PP (19.7%) and PA (6.7%). In the Baltic Sea eight polymer groups were ascertained: PE, PP, PA, PET, EPDM, PES, PS and PVC. PE was slightly dominant at 25.0%, PP and PA were found in equal shares at 21.4% (Table 4, Fig. 2). Information of identified polymer groups per year are given in Table A.5.

The polymer composition analysis of plastic subcategories showed large proportions of the polymer groups PE, PP and PA, reflecting their overall dominance. Three of the four predominant plastic subcategories mostly consist of PE: "fishing line (monofilament)" (79.0%), "fishing line (entangled)" (70.0%) and "sheet" (57.6%). The fourth dominating subcategory, "synthetic rope", was denoted by a high share of PA (52.6%). Some other polymer groups were identified in just one subcategory, PES, PUR and PS in "other plastic" and PVC in "sanitary towels/tampon". The shares of the polymer groups for all plastic subcategories are shown in Fig. 4.

3.6. *Densities of plastic litter*

Most of the polymer groups found at the seafloor showed initial positive buoyancy in seawater. The average density of the North Sea water is ~1.024 g/cm^3 (Ducrotoy et al., 2000; Iversen and Ploug, 2010). Baltic Sea water is reported to have a slightly lower mean density of ~1.02 g/cm^3 (Petereit et al., 2014; Graca et al., 2017). Overall, 402 of 449 polymers had densities below these seawater densities, representing

Table 4

Numbers of polymers identified for seafloor plastic litter collected during three consecutive bottom trawl surveys in 2017, 2018 and 2019; shares of polymers on total plastic litter and on total plastic litter of the North and Baltic Sea, respectively. The following polymers were detected: polyethylene (PE), high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), polyamide (PA), polyethylene terephthalate (PET), polyester (PES), ethylene propylene diene monomer (EPDM), polyurethane (PUR), polyvinylchloride (PVC) and polystyrene (PS).

Sea	Area	Polymer									
		PE (HDPE/LDPE)	PP	PA	PET	PES	EPDM	PUR	PVC	PS	Total
Baltic Sea	B01	1 (1/0)	3	1	2	0	0	0	0	0	**7**
Baltic Sea	B09	3 (2/1)	3	5	2	1	0	0	1	0	**15**
Baltic Sea	B11	2 (0/2)	0	0	1	0	1	0	0	0	**4**
Baltic Sea	B12	1 (1/0)	0	0		0	0	0	0	1	**2**
Baltic Sea	**Sum**	**7 (4/3)**	**6**	**6**	**5**	**1**	**1**	**0**	**1**	**1**	**28**
Baltic Sea	**% of total plastic LI**	**25 (14.29/10.71)**	**21.43**	**21.43**	**17.86**	**3.57**	**3.57**	**0.00**	**3.57**	**3.57**	
North Sea	GB1	64 (41/23)	19	8	1	0	2	0	0	0	**94**
North Sea	GB3	50 (32/18)	19	4	1	0	2	0	0	0	**76**
North Sea	GB4	29 (20/9)	12	7	1	0	0	0	0	0	**49**
North Sea	N01	61 (48/13)	13	3	0	0	2	0	0	0	**79**
North Sea	N04	8 (7/1)	2	2	0	0	0	1	0	0	**13**
North Sea	N11	76 (44/32)	18	1	1	0	2	0	0	0	**98**
North Sea	P02	5 (2/3)	4	3	0	0	0	0	0	0	**12**
North Sea	**Sum**	**293 (194/99)**	**87**	**28**	**4**	**0**	**8**	**1**	**0**	**0**	**421**
North Sea	**% of total plastic LI**	**69.60 (46.08/23.52)**	**20.67**	**6.65**	**0.95**	**0.00**	**1.90**	**0.24**	**0.00**	**0.00**	
Total	**Sum**	**300 (198/102)**	**93**	**34**	**9**	**1**	**9**	**1**	**1**	**1**	**449**
Total	**% of total plastic LI**	**66.82 (44.10/22.72)**	**20.71**	**7.57**	**2.00**	**0.22**	**2.00**	**0.22**	**0.22**	**0.22**	

The bold numbers in Table 4 are those number which belong to the whole sampled seas (Baltic and North Sea) or to total numbers per area and are used to provide an easier distinction between numbers regarding specific sampling areas and percentages per polymer or total numbers per area.

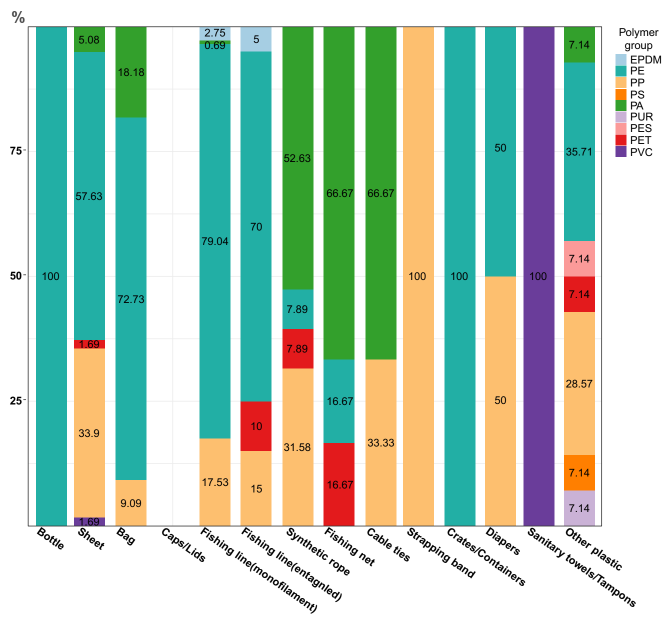

Fig. 4. Shares of identified plastic polymer groups for all plastic subcategories of the International Bottom Trawl Survey (IBTS) of the International Council for the Exploration of the Sea (ICES) (ICES, 2015). All litter items were collected during three consecutive bottom trawl surveys in 2017, 2018 and 2019 in the North and Baltic Sea.
The following polymers were detected: ethylene propylene diene monomer (EPDM), high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), polyamide (PA), polyester (PES), polyethylene terephthalate (PET), polystyrene (PS), polyurethane (PUR) and polyvinylchloride (PVC). $N = 449$ plastic litter items.

89.5% of all detected plastic LI (Fig. 2). The three polymer groups showing a positive buoyancy in seawater were: EPDM, PE (LDPE and HDPE) and PP. Six detected polymer groups showed a negative buoyancy in seawater: PS, PA, PUR, PET, PES and PVC, representing 10.5% of all plastic LI. Proportions of plastic LI buoyancies were highly different in the North and Baltic Sea. The plastic LI at the North Sea seafloor comprised up to 92.2% of natural positively buoyant polymer groups, mainly dominated by HDPE. This proportion was completely different in the Baltic Sea, where positively and negatively buoyant polymer groups appeared in equal shares (Fig. 2).

4. Discussion

4.1. Aspects of sampling and monitoring

Due to different seafloor properties, two different gear types were used for sampling, a GOV in the North Sea and a 140 ft. bottom trawl in the Baltic Sea. The GOV is rigged with a ground rope with attached rubber discs. In contrast, the 140 ft. bottom trawl is equipped with rock hoppers showing a larger diameter due to varying seafloor characteristics in the Baltic Sea. Theoretically, the GOV fishes closer to the seafloor, while increasing the efficiency to catch LI at the seafloor surface. At the same time the 140 ft. bottom trawl is assumed to penetrate more deeply into soft sediments, due to its heavier equipped accessories. These different gear types may lead to distinct catchabilities of LI in the two sampled seas (Canals et al., 2021). If spatial seafloor characteristics require different gear types, ways to compensate for gear-related effects on the catchability of LI need to be considered. In order to achieve comparable results, there is an urgent need for a standardisation of means to factor in gear-related effects (Strand et al., 2015). Possible means to tackle this problem could be statistical approaches and field experiments on the varying catchabilities of used gear types concerning LI. Besides the differences in equipment, the two gear types show slightly distinct wingspreads: 18.5 m for the GOV and 18.85 m for the 140 ft. bottom trawl. These different wingspreads were considered when calculating LI/km^2 densities by using the respective value for each sea. Physical forces that further influence the wingspreads were considered to be constant to simplify statistical analyses.

Which LI to include in seafloor litter monitoring also requires further discussion. Most studies include all LI in the cod-end (e.g. Kammann et al., 2018). In contrast, this study additionally includes all LI entangled in the outer meshes of the nets. Here, three aspects need to be taken into account. First, the total number of LI is increasing. While Kammann et al. (2018) found 11.8 LI/km^2, this study revealed 48.52 LI/km^2 in the same study areas using the same gear types and the IBTS classification system. Apart from a possible subjectivity during sampling, this may account for the higher LI numbers in this study, corroborated by 40.5–49.1 LI/km^2 found by Maes et al. (2018) for the Greater North Sea, where attached LI were included, while sampling with similar gear types according to IBTS. Generally, most LI are mobile and not evenly distributed at the seafloor, thereby affecting the numbers of LI caught by bottom trawling (Pham et al., 2014). Secondly, certain (sub)categories might be underrepresented, if attached LI are not considered. This could lead to incorrect ratios of litter (sub)categories and an inadequate picture of seafloor pollution, followed by errant political mitigation measures. For example, in Kammann et al. (2018) the subcategory “sheet” represents 32.5% and “fishing line (monofilament)” 19.2% of the plastic litter in the North Sea. In the present study “sheet” accounts for 14.3% and “fishing line (monofilament)” is the most dominant subcategory, representing 68.7%. Fishing lines and other fibrous LI are frequently entangled in the nets and therefore widely missed if these LI are not considered. This clearly shows, that consideration of attached LI changes the total numbers of identified LI as well as their composition. The third aspect is the prevention of cross contamination between different sampling areas. Attached LI may be transported from one sampling area to another, causing false positives in the latter area and leading to inadequate monitoring results.

4.2. Categories of litter

The categorisation of LI using the ICES classification system is a crucial step in the seafloor litter monitoring included in the IBTS. The classification system is clear and important to harmonise monitoring approaches, but a closer look reveals some inaccuracy and dependency on expert knowledge. For example the subcategories “fishing line (monofilament)” and “synthetic rope” are not further defined and contradicting classifications are conceivable. In their IBTS report on LI at the seafloor of the Dutch North Sea O'Donoghue and van Hal (2018) report “synthetic rope” to be the most abundant subcategory with 55.8% of all plastic LI. Photographs of identified LI show, that most items defined as “synthetic rope” are categorised as “fishing line (monofilament)” in our study, which is the dominant subcategory with 64.8% of plastic LI. This reflects the subjectivity of such monitoring approaches. Small additions to the IBTS manual, like a photo collection and clear descriptions of all subcategories could help to further decrease the subjectivity in seafloor litter monitoring.

4.3. Size of litter

Using the six size classes given in the IBTS gives rough estimates of the sizes of LI. Nevertheless, it clearly reveals smaller LI to be more abundant than bigger items, emphasising the role of embrittlement of macroplastics in the formation of smaller LI and consequently microplastics. By using size classes of standardised protocols, sizing data is comparable across studies and habitats; and could be used to approximate the litter mass (Canals et al., 2021).

The distribution of the size classes is highly different comparing the North and Baltic Seas. Litter in the North Sea is dominated by items <25

cm^2 (size class A), while other size classes occur in small numbers. In the Baltic Sea the dominance of small items is weaker and bigger size classes appear more frequently (see Tables A.3, A.4). These differences might be partly affiliated to the different gears used for sampling, although both gears have the same mesh sizes (see Section 4.1).

The size of LI is directly correlated to their surface area and consequently to their exposure to external forces responsible for changing their buoyancy and retention time in the water column (Ryan, 2015). Knowledge about the size distribution of LI, together with polymer information of plastics, could improve the accuracy of litter distribution modelling.

4.4. Composition and abundance of litter

The seafloor pollution of the North and Baltic Sea had not yet been extensively investigated. In general, there are fewer studies tackling LI at the seafloor compared to studies on more easily accessible marine habitats like water surface, coastal areas or beaches (Aliani et al., 2003; Zhou et al., 2011; Reinold et al., 2020). Nevertheless, LI abundances of 156 LI/km^2 are reported by Galgani et al. (2000) for the Southern North Sea by trawling according to IBTS. Higher abundances might derive from an Atlantic influence or proximity to coastal urban areas. Maes et al. (2018) presented a study investigating seafloor LI in the Greater North Sea using data from 25 years of seafloor monitoring. Their reported abundances are in accordance with this study (48.5 LI/km^2), showing 40.5–49.0 LI/km^2. The lower abundances of 16.9 LI/km^2 stated by Kammann et al. (2018) for the North Sea might be mainly attributed to the different sampling approach excluding LI attached to the net. The mentioned studies sampled (at least partly) according to IBTS. Nevertheless, Maes et al. (2018) used gears with a different cod-end mesh size (40 mm) compared to this study (20 mm). LI abundances reported by Maes et al. (2018) might be higher if gears with a mesh size of 20 mm would have been deployed. This is emphasised by our finding of small LI being more abundant than large ones (see Section 4.3 and Table A.4). Deployed gears in Galgani et al. (2000) and Kammann et al. (2018) had identical mesh sizes than in this study.

The mean LI abundance of 9.6 LI/km^2 in this study lies in the lower range of reported LI abundances in the Baltic Sea. While Kammann et al. (2018) found 5.07 LI/km^2, other studies reported higher abundance values: 126 LI/km^2 (Galgani et al., 2000) or 20 LI/km^2 (Urban-Malinga et al., 2018). The lower abundance compared to the latter two studies might be derived from different gear types used for sampling, and smaller numbers of trawls conducted and LI identified in this study. The comparatively higher abundance reported by Urban-Malinga et al. (2018) might derive from a lower mesh size of 10 mm in the cod-end of their sampling gear. A closer look on the effects of different cod-end mesh sizes is prevented by missing size data in the mentioned studies.

The mean abundance of plastics in this study is 44.4 LI/km^2 for both seas, which represents 91.3% of all identified LI. Similar values are observed by other studies: 76% along the Portuguese coast (Neves et al., 2015), 70% in various European Seas (Galgani et al., 2000), 92.8% in the Mediterranean (Ramirez-Llodra et al., 2013) and 80% in the North and Baltic Sea (Kammann et al., 2018). Mean numbers of plastic LI/km^2 in the North Sea are higher in this study (66.4 LI/km^2) than the reported 31.8–32.1 LI/km^2 by Maes et al. (2018), who investigated a dataset starting in 1992, where possibly fewer plastics were present in this marine environment. This might explain their lower abundance of plastic LI. In the North Sea, 94.2% of total LI are represented by plastics in this study, which perfectly matches with the 95% described by Gutow et al. (2018). Comparable values of 85.2% (O'Donoghue and van Hal, 2018) and 83% (Kammann et al., 2018) are reported by other studies.

The mean abundance of plastics (5.7 LI/km^2) and their share in total LI (62.2%) are lower in the Baltic Sea. These results confirm findings of earlier studies: Kammann et al. (2018) reported 66% and Urban-Malinga et al. (2018) 67% of total LI to be plastic. Zablotski and Kraak (2019) found less plastic LI with 35%. The latest value can be partly explained by high findings of natural products (burned coal and clinker; 42–57%), which seem to be typical for certain areas of the Baltic Sea, but were not identified in the present study.

Besides the regional differences and varying sampling approaches one fact remains: plastic is the dominant litter category at the seafloors of the North and Baltic Sea. Considering production values and material properties of plastics, which lead to a long persistence and wide distribution in marine environments, it is coherent that plastics show a cumulative character, while being the main source of seafloor pollution.

Some studies suggest fishing-originated LI to be a main contributor of marine pollution (e.g. Bergmann et al., 2017; Buhl-Mortensen and Buhl-Mortensen, 2017). Following Maes et al. (2018) we defined nine subcategories to represent fishing-originated LI (see Table A.2). We found fishing-originated LI accounting for 77.2% of all LI and for 82.0% of all plastic LI in the North Sea, which matches the 76% of total LI found by Gutow et al. (2018). These numbers are higher than those reported by Maes et al. (2018) (31.4–42.0% of total LI; 63.4–78.7% of plastic LI) or Schulz et al. (2015) (60% of total LI), but all studies show a high influence of fishing-originated LI on the litter composition at the seafloor. Comparisons to other studies are generally complicated due to different definitions of fishing-originated subcategories. In other studies using the IBTS classification system values range from 2.2–5.6% in the Baltic Sea (Zablotski and Kraak, 2019) to 51% in the Celtic Sea (Moriarty et al., 2016). Lopez-Lopez et al. (2017) reported 74% of LI in the southern Bay of Biscay to consist of fishing-originated items, while not using the IBTS classification system. In their time series study investigating entanglements of a continuous plankton recorder with anthropogenic items Ostle et al. (2019) found a significant increase in entanglements with fishing-originated LI in recent decades, with the North Sea being the hotspot of these incidences. The numbers for fishing-originated LI need to be interpreted carefully. While some subcategories (e.g. "fishing lines (monofilament/entangled)" or "bobbins (fishing)") are clearly related to fishing activities, for some ("synthetic rope", "cable ties", "strapping band" and "crates & containers") the fishery origin is highly presumable. Nevertheless, the last four mentioned subcategories only sum up for 8.7% of fishing-originated LI in our study (see Table 1, Table A.2).

4.5. Polymer identification and composition

Polymer information of plastic LI at the seafloor could be correlated with results of marine microplastic studies to further underline the hypothesis of fragmentation being the main source of microplastics in the oceans (Andrady, 2017; Cole et al., 2011). In terms of environmental risk assessment and ecotoxicology polymer information could be beneficial as well, since certain polymers harbour specific additives, which partly drives their potential environmental impacts (Rani et al., 2015; Gallo et al., 2018). Additionally, this information could be used for a more detailed back tracing of the sources of marine LI.

Monitoring of seafloor litter is demanded by the MSFD and a detailed monitoring guideline exists (GESAMP, 2019), but international monitoring programs like IBTS are not requiring a determination of the polymers of plastic LI. However, the goal of the MSFD is to define and reach the GES, also by MSFD descriptor D10C1 including litter monitoring. Here, litter composition is addressed, disregarding polymer types as a prominent factor of this composition, which is needed for a better understanding of sources, distribution and final fate of plastic LI as well as to support political measures taken, e.g. ban of specific products or reduction targets (Veiga et al., 2016). Polymer identification can contribute to define the possible harm of plastic litter to the ecosystem and support the determination of future threshold values. Therefore, we recommend to regularly implement polymer identification in monitoring programs for marine LI when feasible.

This study confirmed the presence of nine different polymer groups at the seafloor of the North and Baltic Sea. The polymer composition differed between both studied seas. While in the North Sea eight polymer groups were identified, the number of polymer groups in the Baltic

Sea was six (see Fig. 2). This is partly explained by the higher share of the subcategory "other plastic" in the Baltic Sea (21.4%) compared to the North Sea (1.9%) (see Table 2). This subcategory showed the highest number of seven different identified polymer groups (see Fig. 4), which appears logical as all items that did not fit into any plastic subcategory were pooled here. Hence, "other plastic" represents a broad variety of items made of various synthetic polymers, in contrast to the rest of the plastic subcategories, which represent certain kinds of items that are usually produced of a distinct polymer group to match required product properties. For example, the subcategories "bottle" (PE), "strapping band" (PP) and "crates/containers" (PE) were found to be exclusively composed of one certain polymer group. The numbers of polymer groups per plastic subcategory ranged from zero to seven with a mean number of 2.7.

The North Sea was clearly dominated by the polymer group PE (69.9%) and, concerning the plastic subcategories, by "fishing line (monofilament)". This plastic subcategory was found to be mainly made of PE (79.1%), so high findings of "fishing line (monofilament)" subcategory were associated with the high shares of the polymer group PE. LI in the Baltic Sea comprised to 25.0% of PE, which corresponds to low finding of "fishing line (monofilament)" (7.14%). Both studied seas showed nearly the same share of PP with 20.7% and 21.4% in the North Sea and Baltic Sea, respectively. Regularly found plastic subcategories that comprise of PP were particularly "sheet", "synthetic rope" or "other plastic". In the Baltic, these subcategories, but especially the high shares of "synthetic rope", were driving the amount of LI made of PP. The dominance of "fishing line (monofilament)" (17.5% PP) in the North Sea, together with the above mentioned regularly found subcategories, was influencing the amount of PP in this study area. The higher findings of PA (21.5%) in the Baltic compared to the North Sea can be related to the higher abundance of "synthetic rope" (32.1% of plastic litter in the Baltic Sea; 52.6% PA).

In general and concerning to both studied seas the majority of polymer groups present at the seafloor were PE (66.7%) and PP (20.7%). These findings mirror the European production values of the corresponding polymer groups. In 2019 PE and PP were the most produced polymers, with 29.8% and 19.4% of all produced polymers (PlasticsEurope, 2020).

Information on polymer composition of marine seafloor macrolitter is generally scarce and non-existing for the North and Baltic Sea. A meta-analysis conducted by Erni-Cassola et al. (2019) revealed a predicted relative abundance of 23% of PE and 13% of PP in global marine environments. Although this data referred to all marine habitats and not particularly to seafloor environments, the relative abundances show a general trend underlining our results. Comparisons to our data can be done using studies dealing with microplastic contamination in marine sediments or biota, which often present polymer composition. Lorenz et al. (2019) found PE and PP in 75% of their 23 sediment samples in their study on microplastics in the southern North Sea, showing their wide spread in seafloor habitats of the North Sea. Three studies dealing with microplastic contamination of surface waters are underlining the broad distribution of the polymer groups PE and PP in the study areas: Microplastics found in surface samples in the North and Baltic Sea were mainly made of PE (50.2%) and PP (24.1%) (Hänninen et al., 2021). Similar results were shown by Cabernard et al. (2018) for North Sea surface waters and by Mintenig et al. (2017) for treated waste water flowing into the North Sea via receiving waters.

A study conducted in the Skagerrak, a water body connecting the North and the Baltic Sea, found the majority of polymers in marine (*epi*) benthic species in the inner Oslofjord to be consisting of PE (54%) and PP (16.8%) (Bour et al., 2018). This proves a similar polymer composition at the seafloor of the passage from the North and Baltic Sea than found for both seas.

In the western Baltic Sea, Schröder et al. (2021) detected four different polymers in microplastics deriving from sediment samples. The most abundant polymer was PS (30%), followed by PE (28.6%), PP (12.9%) and PA (5.7%). A slightly different polymer composition was reported by Ory et al. (2020) for surface waters of the same study area. Here, PE was dominating with 45%, followed by PP (17%) and PS (8%). In a study investigating microplastics in surface waters of the Stockholm Archipelago a dominance of PE (54%) and PP (24%) polymers was confirmed as well (Gewert et al., 2017). Uurasjärvi et al. (2021) found six polymers in water samples from different depths of the northern Baltic Sea. The polymer composition was clearly dominated by PE (47%), followed by high concentrations of PP (26%) and PET (25%), the other three polymers occurred in small numbers. These comparisons show that our data is in general accordance with other studies on polymer composition of (micro-)plastic at the seafloor of the North and Baltic Sea. Certain differences in the polymer composition are most likely caused by different investigated size classes (microplastic) and sampled marine compartments (sediments, biota), but also varying vertical transport mechanisms of microplastics. The mobility of seafloor litter and applied identification techniques may lead to differences in the polymer composition when comparing studies.

These general findings on polymer composition of seafloor plastic LI are underlined by studies accomplished in other seas. Frère et al. (2017) found PE (53.3%) and PP (30%) to dominate the microplastic in sediments of the Bay of Brest, North Atlantic. Polymer composition in the surface waters of the same area showed 67.4% of PE and 16.5% of PP (Frère et al., 2017). Sediments of the Lagoon of Venice were predominantly contaminated by PE (48.4%) and PP (34.1%) microplastic particles (Vianello et al., 2013). Cincinelli et al. (2021) identified microplastics in sediments of the Black Sea to be mostly made of PE or PP (44.5%), followed by PA (32%).

As mentioned before, investigated area, compartment and size class are possible arguments of varying polymer composition. In contrast to this study Renzi and Blaškovic (2020) found small numbers of PE and PP in marine sediments around Croatian islands, but higher levels in benthic Holothurians. The majority of microplastics found in deep sea sediments of the northwest Pacific comprised of PP (33.2%) and acrylates/PUR (19%) (Abel et al., 2021). Nevertheless, by comparing the results of this study with the above mentioned studies it is apparent, that PE and PP are usually detected most in marine environmental samples.

4.6. *Density of plastic polymers*

Each synthetic polymer has a specific density, which partly drives its spatio-temporal distribution, especially in the first time period after entering marine environments. Polymer data on plastic LI at the seafloor can be used for a better prediction of the dissemination of plastic litter in distribution models (Canals et al., 2021). Particularly the driving factors of the vertical transportation of marine plastic LI are still not fully understood (Lebreton et al., 2019). One open question is, how plastics with a density lower than seawater are transported to the seafloor (van Sebille et al., 2020). Information about which polymer groups are present at the seafloor and which are dominating, could be one first step to answer this question. Additionally, it fosters an enhanced understanding of the distribution of certain plastic types.

The density is the main plastic-immanent driving factor of the vertical transport of marine plastics. We show, that this plastic-immanent density is not significantly driving the vertical transport in the oceans. Nearly 90% of the plastic LI in this study show densities lower than seawater (Fig. 2), which means that other, external driving factors are particularly directing their vertical transport. Next to oceanographic forces, the attachment of sessile organisms and biofouling are considered to be main factors of vertical plastic transportation. Most detected plastic LI were affected by biofouling and organic aufwuchs to different extends in our study (data not shown). A missing link for a better understanding of the spatio-temporal distribution of (positively buoyant) plastic LI is the retention times of different plastic polymers in the water column prior to reaching the seafloor. The composition of the polymer groups of plastic LI at the seafloor is not a consequence of plastic-immanent density but a reflection of the whole range of polymers present in respective marine environments.

Several studies report high concentrations of positively buoyant polymers (especially PE and PP) in the composition of microplastic in seafloor habitats (e.g. Frère et al., 2017; Bour et al., 2018; Hänninen et al., 2021; Uurasjärvi et al., 2021). Lorenz et al. (2019), Porter et al. (2018) and Möhlenkamp et al. (2018) discussed possible factors for the vertical transport of small positively buoyant plastic particles and for changing densities, including incorporation in marine aggregates, ingestion and subsequent sinking as part of faecal pellets, leaching of additives or biofouling. We show that not just small plastic particles are prone to be vertically transported towards the seafloor, but also large, positively buoyant LI are present in seafloor environments. Fragmentation of large items made of PE or PP could be another possible source of high concentrations of those polymer groups found in microplastic studies investigating seafloor habitats.

5. Conclusion

The seafloor is polluted with considerable amounts of marine litter. The North Sea shows higher abundances of litter than the Baltic Sea. Data on this pollution is recently increasing, but detailed information on polymer composition is very scarce. Next to investigations on general litter distribution and composition, we conducted polymer identification of plastic seafloor litter by attenuated total reflection-Fourier transform infrared spectroscopy. Plastic litter is the dominant litter category in both seas and in total, although pollution in the Baltic Sea is less dominated by plastic. Certain litter subcategories can be directly related to fishing activities, which account for a substantial part of litter present at the seafloor in both studied seas. Polymer identification of the plastic litter reveals this litter category to be mainly comprised of PE, PP and PA. Six further polymer groups are present in small amounts. When assigning polymer groups to their specific densities, it becomes apparent that most of the plastic litter at the seafloor has a positive buoyancy in seawater. Plastic-immanent density is not an important driving factor for the plastic composition and a positive buoyancy is not an exclusion criterion for the presence at the seafloor. Other, external driving factors, like ocean currents or biofouling, seem to be more influential for the vertical transport of marine plastic litter.

Some methodological aspects could potentially affect seafloor litter monitoring: (1) We recommend to not just consider the litter in the codend for sampling, but also take litter attached to the nets into account to avoid a bias in total amount and composition of litter. In addition, the risk of carryover effects of litter from one area to another is minimised by checking the nets for litter after each haul. (2) The IBTS classification system is an important and helpful tool to harmonise litter monitoring internationally. Nevertheless, the subjectivity within the system is still high and further detailed definitions are needed to improve the comparability of monitoring results. We think a photo collection depicting and defining every subcategory will help to improve the objectivity within this monitoring approach. (3) Conclusively we recommend to include polymer type identification for future monitoring of seafloor litter whenever possible.

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CRediT authorship contribution statement

Ivo Int-Veen: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Pedro Nogueira:** Writing – review & editing, Resources. **Jason Isigkeit:** Investigation, Resources. **Reinhold Hanel:** Funding acquisition, Supervision, Writing – review & editing. **Ulrike Kammann:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

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