Below the surface: Twenty-five years of seafloor litter monitoring in coastal seas of North West Europe (1992–2017)

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Below the surface: Twenty-five years of seafloor litter monitoring in coastal seas of North West Europe (1992–2017)

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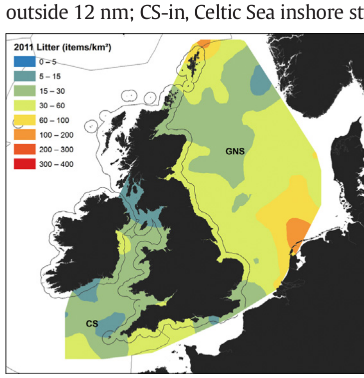
HIGHLIGHTS

- Widespread distribution of litter items on the seabed, up to 1835 pieces km^{-2}
- Over the 25-year period, 63% of the trawls contained at least one plastic litter item.
- No significant temporal trend in total number of litter items km^{-2}
- Significant trends in plastic bags (down) and fishing debris (up)
- Potential influence of behavioural changes on litter abundance?

GRAPHICAL ABSTRACT

Marine litter abundance (litter items km^{-2}) on the seafloor in North West European Seas, all data from 2011 interpolated using R, Shiny and PostGIS. The black line surrounding the UK represents the 12 nm boundary. The black line in the Western Channel and starting near the tip of Shetland symbolizes the MSFD boundary for the Celtic Sea (CS) and Greater North Sea (GNS). Key to regional divisions: GNS-off, Greater North Sea offshore stations outside 12 nm; GNS-in, Greater North Sea inshore stations within 12 nm; CS-off, Celtic Sea offshore stations outside 12 nm; CS-in, Celtic Sea inshore stations within 12 nm.



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ABSTRACT

Marine litter presents a global problem, with increasing quantities documented in recent decades. The distribution and abundance of marine litter on the seafloor off the United Kingdom's (UK) coasts were quantified during 39 independent scientific surveys conducted between 1992 and 2017. Widespread distribution of litter items, especially plastics, were found on the seabed of the North Sea, English Channel, Celtic Sea and Irish Sea. High variation in abundance of litter items, ranging from 0 to 1835 pieces km^{-2} of seafloor, was observed. Plastic tems such as bags, bottles and fishing related debris were commonly observed across all areas. Over the entire 25-year period (1992–2017), 63% of the 2461 trawls contained at least one plastic litter item. There was no significant temporal trend in the percentage of trawls containing any or total plastic litter items across the long-term datasets. Statistically significant trends, however, were observed in specific plastic litter categories

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Long term monitoring
Marine Strategy Framework Directive
Plastic waste
Plastic bags
Fishing debris

only. These trends were all positive except for a negative trend in plastic bags in the Greater North Sea - suggesting that behavioural and legislative changes could reduce the problem of marine litter within decades.

1. Introduction

Globally, marine litter has become a pollution problem, originating from a variety of land and sea-based sources. Ongoing surveys have demonstrated that man-made litter has now been documented to occur in almost every marine environment studied to date (Barnes et al., 2009; Browne et al., 2011; Derraik, 2002; Jambeck et al., 2015; Ryan et al., 2009). Marine litter consists mainly of plastic materials, both in numbers and by weight, with minor amounts of metal and glass contributing to the overall litter load. Typical plastic items such as bags, bottles and fishing related litter are omnipresent and indicative of a variety of anthropogenic pressures (UNEP, 2009). According to Jambeck et al. (Jambeck et al., 2015), population size and the quality of waste management systems largely determine where the greatest mass of uncaptured waste becomes plastic marine litter.

An ongoing challenge is in relation to reducing the amount of litter in the marine environment. This problem has been at the forefront of several international initiatives. In June 2012 at Rio + 20, the Global Partnership on Marine Litter (GPML) was launched. More recently, the Leader's Declaration of the 2015 G7 Summit acknowledged the global risks posed by marine litter, particularly plastics, to marine and coastal ecosystems and potentially human health. As such, marine litter generation and prevention are linked to a variety of human activities and policy areas operating at both national and international levels. Therefore, to address both the sources and impacts of marine litter, legislation and agreements need to relate to waste and wastewater management, product design, shipping, fisheries policies, consumption and behavioural patterns (Gold et al., 2013; Newman et al., 2013; Trouwborst, 2011). In Europe, specific legislation was introduced to deal with marine litter and its impact on the coastal and marine environment: the Marine Strategy Framework Directive (MSFD) (European Parliament and Council of the European Union, 2008). The MSFD incorporates an indicator specifically in relation to litter and requires evidence that member states are moving towards Good Environmental Status (GES). More specifically, the MSFD operates by monitoring, amongst others, trends in the amount of litter deposited on the sea floor, including analysis of its composition, spatial distribution and, where possible, sources (European Parliament and Council of the European Union, 2008).

Globally, waste management legislation is seen in the broader context of enhanced resource efficiency, now a key cross-cutting policy goal (UNEP, 2016). As an example, the first jurisdictions where plastic bag reduction policies emerged and regulatory action was taken were in South Asia in the late 1990s and early 2000s, primarily based on concerns regarding human health and livelihoods (Clapp and Swanston, 2009). Most northern industrialised countries have also seen attitudes shift in recent years (Clapp and Swanston, 2009). In Europe, the first legislation against plastic bag use was introduced by Ireland and Denmark in 2002 and 2003 respectively. In Ireland, the effect of the tax on the use of plastic bags in retail outlets has been dramatic—a reduction in use of the order of 90%, and an associated gain in the form of reduced littering and negative landscape effects (Convery et al., 2007). This tax on plastic shopping bags, previously provided free of charge to customers at points of sale, was adopted by other European member states in the following years (Convery et al., 2007). Since the plastic bag tax policy came into force in England in October 2015, the total number of carrier bags used at the UK's biggest retailers has fallen by an estimated 85% ("Single-use plastic carrier bags charge: data in England for 2015 to 2016 - GOV.UK," n.d.). In the context of a European Circular Economy, a directive to reduce the use of thin plastic bags, many of which end up as waste in the marine environment was finally agreed on the 28th of April 2015 (EEA, 2015).

In relation to marine litter from sea-based sources such as the fishing industry, legal and technical measures to ensure that littering from lost or abandoned fishing gear is minimised are provided by the Food and Agriculture Organization of the United Nations (FAO): Recommendations for the Marking of Fishing Gear (FAO, 2016) and Code of Conduct (FAO, 1995). The abandonment of fishing gear is specifically prohibited by the International Maritime Organisation in its Convention for the Prevention of Pollution from Ships (Convention, 1973). From a European perspective, the Common Fisheries Policy (CFP) states that measures should be taken to conserve resources and limit the environmental impact of fishing (Council of the European Union, 2002). The European Commission also recognised the importance of the marking of fishing gear in 1994 and, more recently, in 2004 (Brown and Macfadyen, 2007). Furthermore, the European Maritime and Fisheries Fund supports measures to remove lost fishing gears from the seafloor.

This surge in marine litter related legislation has identified a requirement for long-term monitoring programmes, capable of assessing the effectiveness of newly implemented measures. To date, the majority of marine litter studies have focused on visible and easily accessible litter contamination, such as that along shorelines or floating on the surface of the water (Ryan et al., 2009). However, some litter sinks and almost all floating litter is expected to be cast onto a beach or to sink to deeper waters, eventually landing on the seafloor. This may be due to a variety of repeating processes such as degradation, fouling by marine organisms (e.g. bacteria, algae and sessile organisms), or ingestion and excretion by marine animals (Cole et al., 2013, 2011; Graham and Thompson, 2009; Gregory, 2009; Harms, 1990; Webb et al., 2009). On continental shelves, fishing trawl surveys provide a practical way in which to monitor seafloor litter because they cover a wide area and collect a suitable quantity of litter for analysis (Spengler and Costa, 2008). Nevertheless, long-term datasets on marine litter on the seafloor are sparse (Galgani et al., 2010, 2014). Where studies are available they cover relatively short time series and have catalogued seabed litter using a variety of techniques such as snorkeling, SCUBA diving, trawl surveys, sonar and the use of submersibles and ROVs (Bergmann and Klages, 2012; Galgani et al., 2014; Miyake et al., 2011; Schlining et al., 2013; Spengler and Costa, 2008; Watters et al., 2010). For example, the presence of large amounts of plastic litter has been reported in European continental shelf seas (Galgani et al., 2000; Pham et al., 2014), including in the Baltic, North (Kammann et al., 2017) and, Celtic Sea, the Bay of Biscay (Galgani et al., 1995a), the Barents Sea and Norwegian Sea (Buhl-Mortensen and Buhl-Mortensen, 2017), and the Mediterranean (Galgani et al., 1996, 1995b; Galil et al., 1995; Pasternak et al., 2017; Stefatos et al., 1999), Adriatic (Bingel et al., 1987) and Black Sea (Ioakeimidis et al., 2014). Plastic litter items have been found in deep sea canyons of the French Mediterranean coast (Galgani et al., 1996), the west coast of Portugal (Mordecai et al., 2011) and nearby to seamounts close to the Azores (Pham et al., 2014, 2013).

Since 1992, the Centre for Environment, Fisheries and Aquaculture Science (Cefas), a UK Government organisation, has been collecting seafloor litter data on environmental and fisheries stock assessment surveys. Such research provides spatial and temporal trend assessments of the abundance of seafloor litter within North West European seas and acts as a baseline against which litter reduction mitigation measures can be assessed. Here we present an assessment of 25 years of seafloor litter data (1992–2017), gathered during 39 scientific surveys at 2461 stations in the coastal seas of North West Europe. We divided the analysis in two main parts: an analysis of the trends of the major litter categories and plastic sub-categories during the 1992–2017 period and a spatial analysis in 2011, the last year in which all surveys took place, thus providing a comparison of the inshore (within 12 nm of land) and offshore (>12 nm) regions of the Celtic and Greater North Seas.

2. Materials and methods

2.1. Survey data

Cefas undertakes several fish stock assessment and environmental trawl surveys. With respect to the current study the relevant ones are: the International Bottom Trawl Survey (IBTS), the ICES Ground Fish Surveys (Q4SW) and the Clean Seas Environment Monitoring Programme (CSEMP) survey. Fig. 1 shows the spatial coverage in 2011. The selected surveys used two similar types of otter trawls: CSEMP uses the Granton trawl, while IBTS and Q4SW use the Grande Ouverture Verticale (GOV) trawl. Otter trawls derive their name from the large rectangular otter boards which are used to keep the mouth of the trawl net open; these boards act like a plough, digging up to 15 cm into the seabed. Both otter trawls have a mesh size of 40 mm at the cod end, but the GOV is considerably larger in size and volume than the Granton trawl. They are designed to trawl the seafloor and catch fish living on or near the seabed. The mean catch (either in weight or in numbers) per unit of effort or per unit of area is an index of the stock abundance (i.e. assumed to be proportional to the abundance) (Sparre and Venema, 1998). Similar assumptions can be made in relation to the number of litter items trawled.

These three surveys cover all waters surrounding the UK, including the Greater North Sea (GNS) and Celtic Sea (CS) as defined by the MSFD (Fig. 1). In this study, we have combined data from the IBTS, Q4SW and CSEMP surveys from 1992 to 2017 in two main areas: the GNS and CS. Within these, we created two more sub-divisions - inshore and offshore - based on the 12 nm boundary. The three surveys did not all take place annually (Table A - Supplemental Files). Cruises between 1992 and 1999 were all in the IBTS series and only collected litter in the offshore GNS area from 72 to 150 stations. In 2000, the CSEMP cruise started gathering litter data in the inshore parts of the GNS and in/offshore CS areas from 17 to 50 stations. Between 2009 and 2011, marine litter data collection was introduced within the Q4SW survey, covering the inshore and offshore CS area from 68 to 79 stations (Table A -Supplemental Files); therefore, full coverage of the Celtic Sea is only available for these three years (Fig. 1).

Different transects were trawled at each station every year. As haul lengths averaged 4 km (SD 1.4 km) across all trawls, each haul is effectively a point sample in the sea. The area sampled at each station was estimated from the width of the net multiplied by the assumed distance it had been in contact with the seabed and functioning.

All historic data were translated manually from logbooks into the new database using the MSFD classification system. The IBTS data from 1992 until 2010 measured litter items by weight; this hampers our ability to accurately determine the number of items based on these weight determinations due to different weights of polymer types and processes such as biofouling and degradation. Therefore, these data were used as an indication of presence or absence only.

2.2. Marine litter and metadata collection method

For each survey, the following information was recorded: the definition and specification of the survey, the positions of stop and start of each trawl and its technical specification e.g. wing spread, mesh size of net, cod end and blinders. After each tow, fish were deposited in the fish pound or hopper before being sorted, then all litter items were manually picked from the hopper, net and cod end and classified according to the classification system in the guidance document on Monitoring of Marine Litter in European Seas (Galgani et al., 2014). The MSFD classification system is composed of six main categories of litter (Plastic, Metal, Rubber, Glass, Natural and Miscellaneous), each divided into sub-categories (39 in total) (Galgani et al., 2014). We defined two further sub-categories of plastic litter to reflect land-based household litter (Household) and fishing-based (Fishing) sources. The Household class is composed of the subcategories plastic

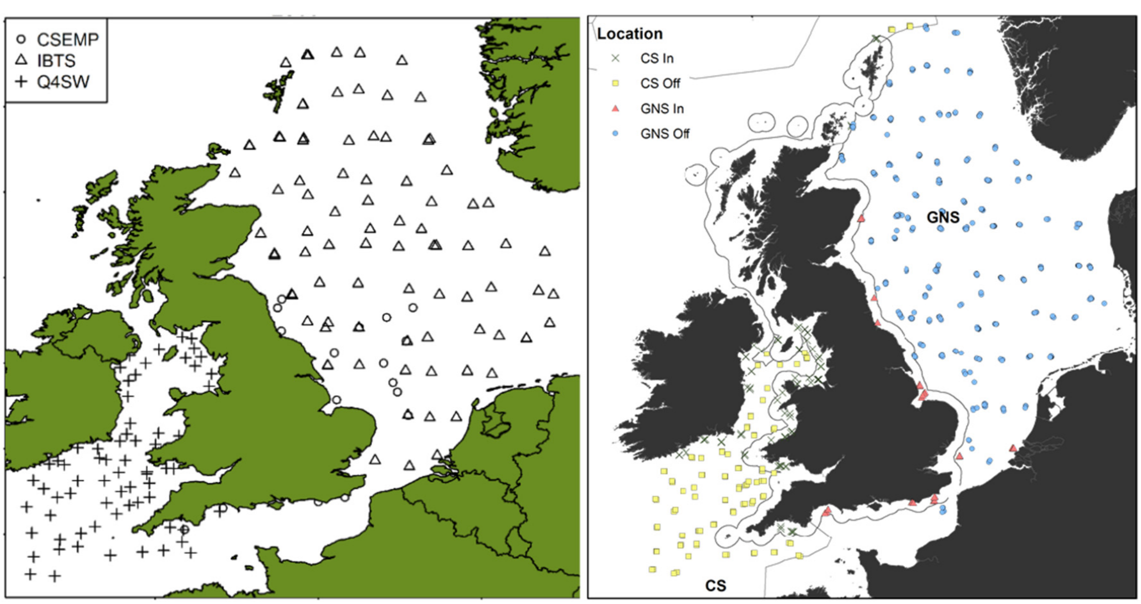

Fig. 1. LEFT PANEL: Spatial coverage of the Cefas surveys in 2011: IBTS, International Bottom Trawl Survey; Q4SW, Quarter 4 Westerly Ground Fish Survey, CSEMP, Clean Seas Environment Monitoring Programme. RIGHT PANEL: Spatial coverage and divisions of the benthic marine litter stations in 2011. The black line surrounding the UK represents the 12 nm boundary. The black line in the Western Channel and starting near the tip of Shetland symbolizes the MSFD boundary for the Celtic Sea (CS) and Greater North Sea (GNS). Key to regional divisions: GNS-off, Greater North Sea offshore stations outside 12 nm; GNS-in, Greater North Sea inshore stations within 12 nm; CS-off, Celtic Sea offshore stations outside 12 nm; CS-in, Celtic Sea inshore stations within 12 nm. The two CS offshore stations at the top of the map were added to the GNS offshore region in the spatial and temporal analysis.

bottles, sheeting and bags. The Fishing class comprises the subcategories fishing net, fishing line (monofilament/entangled), synthetic rope, cable ties, strapping band, crates and containers. The litter data from surveys prior to 2009 were collected using the same main categories as the MSFD classification system, although with fewer subcategories. Several plastic subcategories (caps, sheet, fishing line, crates, straps, cable ties, diapers and sanitary towels/tampons) were added in 2009 and thus trends for those were calculated based on data from 2009 onwards.

2.3. Data presentation and analysis

The IBTS data prior to 2010 reflects only presence or absence of litter items. Thus, to give a good representation of the extent of litter on the seafloor and to make correct comparisons across time, for each year, we have created the variable "percentage of trawls in which the litter item was recorded". While we are confident that the data generated by CSEMP correctly counted litter items, we have used the same percentage variable to define litter for this survey as for IBTS above. This is partly for ease of comparison with IBTS which used a GOV otter trawl but also because the distribution of the number of litter items caught per trawl is often highly skewed. That is, generally observations are 0 or 1, but there are also some very high counts. These high counts could overly influence simple yearly means and transforming the data by taking natural logs prior to statistical treatment proved problematic due to the high proportion of zeros. For temporal trend analysis (1992–2017) the data are thus expressed as the percentage of trawls in which the litter item was recorded. In the spatial analysis (2011), the data are presented as abundance in number of marine litter items km^{-2} of seafloor.

To perform formal statistical evaluation of potential trends, the Mann-Kendall (MK) non-parametric test was used (Mann, 1945; Maurice G Kendall, 1975). This was performed on the yearly means of the particular litter value being considered using the R (R Core Team, 2014) software and the emon package (Barry et al., 2017), with the function mannkendall. Two-sided tests were performed as there was no a priori knowledge of whether the trend might be positive or negative.

To look at temporal trends, due to the unbalanced nature of surveys and otter trawls (GOV and Granton) over this sampling period, the data were not integrated from different surveys. This allows temporal comparisons to be made for the same survey. For the GNS, data from the IBTS surveys (1992–2000, 2005, 2008–2017) was included for the offshore area and data from the CSEMP survey for inshore waters (2000–2008, 2010–2014, 2016–2017). The CSEMP survey also covered inshore waters on the Celtic Sea side (2000–2008, 2010–2014, 2016–2017). The IBTS and CSEMP surveys are spatially consistent across years. There was a limited amount of long-term data covering the CS-offshore area, because the Q4SW survey collected marine litter data only from 2009 until 2011. Therefore, no attempt was made to carry out a temporal analysis for the inshore CS area.

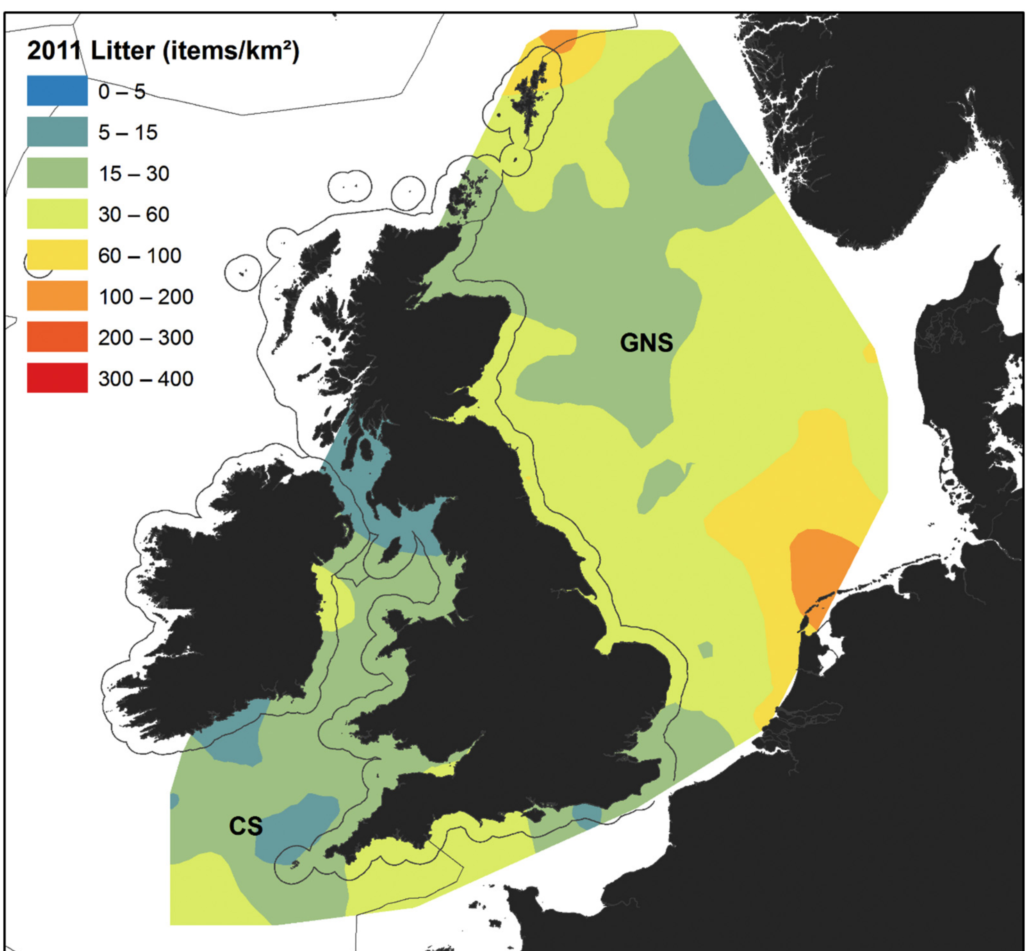

Fig. 2. Marine litter abundance (litter items km^{-2}) on the seafloor in North West European Seas, all data from 2011 interpolated using R, Shiny and PostGIS. The black line surrounding the UK represents the 12 nm boundary. The black line in the Western Channel and starting near the tip of Shetland symbolizes the MSFD boundary for the Celtic Sea (CS) and Greater North Sea (GNS). Key to regional divisions: GNS-off, Greater North Sea offshore stations outside 12 nm; GNS-in, Greater North Sea inshore stations within 12 nm; CS-off, Celtic Sea offshore stations outside 12 nm; CS-in, Celtic Sea inshore stations within 12 nm.

Table 1
Total number of marine litter items km^{-2} of seafloor and percentage of trawls containing marine litter items km^{-2} of seafloor. Comparisons between the surveys using the Manly (2007) approach. Data are for the CSEMP, IBTS and Q4SW surveys in 2011. Key to regional divisions: GNS-off, Greater North Sea offshore stations outside 12 nm; GNS-in, Greater North Sea inshore stations within 12 nm; CS-off, Celtic Sea offshore stations outside 12 nm; CS-in, Celtic Sea inshore stations within 12 nm. N = number of stations.

2011	Mean	95% CI for mean	Median	N	% non-zero
CS-in	24.4	(13.0,35.8)	14.1	24	70.8
CS-off	21.7	(14.5,28.9)	14.1	44	59.1
GNS-in	49.0	(23.8,74.3)	40.0	10	100
GNS-off	40.5	(30.8,50.3)	28.4	95	78.9

For the spatial analysis, only data from 2011 were used to create identical areas to these previously used in the temporal analysis: CS-in, CS-off, GNS-in, GNS-off. For this analysis, mixed data was used to cover all four areas. Data were pooled based on their location (GNS/CS) and distance from coast (in or outside the 12 nm boundary). The CS inshore area uses a mixture of inshore stations from the Q4SW and CSEMP surveys. The CS offshore area is made up entirely of Q4SW offshore stations. Similarly, the GNS offshore area compromises mostly IBTS stations and some CSEMP offshore stations. The GNS inshore area included stations within the 12 nm boundary from CSEMP and IBTS (Fig. 1). Comparisons between the different trawl areas of surveys within 2011 are made possible by transforming the litter counts to numbers per km^2.

Baseline values of litter abundance (litter items km^{-2}) were calculated for all four areas; 2011 data were selected as it was the latest year with the largest spatial cover, and to synchronise with the start of the MSFD (initial assessment). A non-parametric randomisation test (see e.g. Manly, 2007) using the function permute.groups in emon (Barry et al., 2017) was used to make comparisons between the UK areas.

To generate a visual overview, our analysis interpolated the litter abundance data for 2011 to create a raster distribution map using Geostatistical Analyst extension from ArcGIS 10.1 (Krivoruchko, 2011) (Fig. 2). The data exhibited a non-stationary distribution, the mean is not equal across the whole region, so a detrending surface with exponential function was applied in order to remove the existing trend (Wu et al., 2007). A declustering and a Normal Score transformation was applied before interpolating the data. A simple kriging interpolation using a stable semivariogram model in the R package sgeostat was used to create the litter distribution surface. Using the semivariogram correlation distance parameters, the value in a non-sampled location was estimated, with a searching radius of 80 km an using a number of 5 maximum neighbours (Atkinson and Lloyd, 2007).

3. Results

3.1. Litter distribution in the CS and GNS

In 2011, the inshore CS area contained statistically significantly less items km^{-2} than the inshore GNS region ($p = 0.01$, means are 24 and 49 respectively). Similarly, the offshore CS area contained statistically significantly less items km^{-2} than the offshore GNS region ($p = 0.04$), no statistically significant differences were observed in the number of items km^{-2} between the GNS inshore and offshore area ($p = 0.59$). All trawls conducted in the inshore GNS area contained litter in 2011 (Table 1). However, the two highest litter counts in the 22-year dataset, 1816 and 1835 items km^{-2} were observed in 2003 and 2004 at CSEMP Station 616 (Carmarthen Bay, 51.63 Lat; −4.59 Long), situated in the inshore Celtic Sea area. High counts, more than a hundred marine litter items km^{-2}, were also detected in samples from parts of the English Channel, off the Dutch and Danish coasts, in the Irish Sea, the Bristol Channel and along the Devon and Cornwall coastline (Fig. 2).

3.2. Litter composition in the CS and GNS

Many types of litter items were commonly detected in the trawls, especially pieces of plastic sheeting, bags and bottles, metallic objects, glass, and diverse materials including fishing gear. Items of natural origin, like driftwood and branches were less prominent. Most litter items were partially degraded; although still recognizable, they were often functioning as a substratum and were populated by organisms e.g. bryozoans, hydroids, tunicates and bivalves. Like results for floating and beach litter findings, a high percentage of litter items detected on the seafloor were made of plastic. Around 38% (931) of all tows (2461) across all three surveys (CSEMP, Q4SW, IBTS) over the entire 25-year period (1992–2017) contained solely plastic litter items. In 2011, plastic items accounted for 77% (CS-in), 94% (CS-off), 65% (GNS-in) and 79% (GNS-off) of the total number of litter items (Table 2). Although, high proportions of plastic items km^{-2} were observed in the offshore areas of the CS, we did not find quantities to be significantly different (based on 2011 data only and using permutation tests) from the inshore ($p = 0.06$) and offshore area of the GNS ($p = 0.16$). Additionally, there were no statistical differences observed between the CS and GNS areas (inshore and offshore) in 2011 in terms of household or fishing related litter items km^{-2} ($p > 0.05$). High quantities of metal items were also found in the inshore parts of the GNS. Items made of rubber, glass and ceramics were absent in the offshore CS samples (Table 2). Table 3 expands on the information in Table 2 for plastic, household plastic and fishing-related plastic items. We can see, for example, that 90% of the trawls in the GNS-in region contained at least one plastic item.

3.3. Litter trends in the CS and GNS

Surprisingly, no significant temporal trends were detected in the percentage of trawls containing any litter and in almost all main litter categories (total plastic, metal, glass/ceramics, natural items) across the long-term datasets in the 3 regions (GNS-off, GNS-in, CS-in) (Table B – Supplemental Files & Fig. 3a–b). The category Rubber is decreasing in the offshore and inshore GNS ($p = 0.01$) (Fig. 3c) and the category Miscellaneous is increasing in the inshore CS ($p = 0.002$).

Our analysis considered the plastic category in a greater level of detail by looking at trends in its components and in the two newly created categories, Household and Fishing (Table 4). No trend was detected in the proportion of household litter in all 3 regions (GNS-in, GNS-off,

Table 2
Mean number of items km^{-2} of seafloor by main litter categories in the four regions: CS-in, CS-off, GNS-in, GNS-off in 2011. Key to regional divisions: GNS-off, Greater North Sea offshore stations outside 12 nm; GNS-in, Greater North Sea inshore stations within 12 nm; CS-off, Celtic Sea offshore stations outside 12 nm; CS-in, Celtic Sea inshore stations within 12 nm.

2011	Stations	Mean litter items km^{-2}						
		Total	Plastics	Metal	Rubber	Glass/ceramics	Natural	Miscellaneous
CS-in	24	24.3	18.8	1.0	0.4	0.6	2.9	0.6
CS-off	44	21.6	20.4	0.3	0.0	0.0	0.9	0.0
GNS-in	10	49.1	31.8	8.9	2.2	0.5	3.6	2.1
GNS-off	95	40.5	32.1	1.2	2.1	0.4	4.3	0.4

Table 3
Mean and median number of items km^{-2} and percentage of trawls containing AT LEAST ONE ITEM. The data are for plastic items, plastic household items and plastic fishing related items in the inshore and offshore regions of the CS and GNS in 2011. Key to regional divisions: GNS-off, Greater North Sea offshore stations outside 12 nm; GNS-in, Greater North Sea inshore stations within 12 nm; CS-off, Celtic Sea offshore stations outside 12 nm; CS-in, Celtic Sea inshore stations within 12 nm. N = number of stations.

2011	Mean	95% CI for mean	Median	Stations	% non-zero
1. Plastic items					
CS-in	18.8	(8.4,29.3)	13.4	24	58.3
CS-off	20.4	(13.6,27.3)	13.8	44	59.1
GNS-in	31.8	(16.3,47.3)	26.1	10	90
GNS-off	32.1	(24.5,39.7)	27.8	95	73.7
2. Plastic household items					
CS-in	10.5	(2.5,18.5)	0	24	37.5
CS-off	7.4	(3.8,11.0)	0	44	34.1
GNS-in	13.7	(5.2,22.1)	12.6	10	80
GNS-off	10.9	(7.7,14.1)	0	95	46.3
3. Plastic fishing related items					
CS-in	7.9	(1.1,14.7)	0	24	37.5
CS-off	9.9	(6.1,13.7)	0	44	45.5
GNS-in	15.4	(5.3,25.5)	13.9	10	70
GNS-off	17	(11.8,22.1)	13.7	95	54.7

CS-in) assessed. The percentage of plastic sheeting (including packaging) showed an upward trend in all regions. A statistically significant upward trend was also detected in the proportion of fishing related litter in the offshore area of the GNS ($p = 0.02$). This was caused by upward trends in the plastic subcategories: fishing line ($p < 0.001$), cable tie ($p < 0.001$), cable strap ($p < 0.001$) and crates ($p = 0.003$).

Plastic bags were the only category with a statistically significant downward trend in both the inshore ($p = 0.05$) and offshore ($p = 0.01$) regions of the GNS. The trend plots for plastic bags and the Fishing category are shown in Fig. 4a–b.

Our analysis compared the proportion of plastic bags prior to 2010 against the percentage from 2010 to 2017. All three regions (GNS-in, GNS-off, CS-in) demonstrated statistically significant reductions ($p < 0.05$) between the mean annual percentages. The actual mean percentages were (pre2010 vs 2010 onwards): GNS-off (43% vs 16%); GNS-in (53% vs 21%); CS-in (65% vs 24%).

4. Discussion

4.1. Litter distribution in the CS and GNS

To date, centralized information on marine litter quantities and its distribution on the continental shelves of the North-East Atlantic is still fragmentary. The range of litter densities on the seafloor found at our study sites was within the same range as those reported in other parts of the Atlantic Ocean (Bergmann and Klages, 2012; Galgani et al., 2015, 2000, 1995a; Mordecai et al., 2011; Pham et al., 2014, 2013; Schulz et al., 2015b; Woodall et al., 2015). In 2011, between 13 and 74 litter items km^{-2} were detected at stations across the GNS and CS. The density of seafloor litter in the Barents Sea and Norwegian Sea is 202 and 279 items/km^2 respectively, and highest densities were found close to coast and in canyons (Buhl-Mortensen and Buhl-Mortensen, 2017). Litter evaluations at deep sea sites (seamounts, banks, mounds, and ridges) in the Atlantic Ocean around Europe using a trawl or dive studies, indicated a density of 180 plastic items km^{-2} (Pham et al., 2014). Other seafloor litter studies in the deep sea of the southern Indian Ocean and Atlantic Ocean, using a ROV, found densities of 555 and 483 items km^{-2} (Woodall et al., 2015). In 2014, at the Arctic seafloor, a mean litter density of 6566 items km^{-2} was measured with a tow camera system (Tekman et al., 2017). Similar litter densities were reported at canyons near Lisbon (6620 items km^{-2}) using video footage and still images from ROVs (Mordecai et al., 2011). We found maximum values, reaching up to 1816 and 1835 items km^{-2}, at Carmarthen Bay in previous years (2003 and 2004). Based on material input, caused by a clockwise gyre, sediment accretion studies suggest a direct linkage between the Bristol Channel, a major river inlet, and Carmarthen Bay (Collins and Balson, 2007), which could explain the high abundance of litter at this location. Worldwide surveys in coastal waters have indicated an average seafloor litter concentration of 723 plastic items km^{-2} (Galgani, 2015). Two studies, using the same MSFD protocol (Galgani et al., 2014), indicated a mean litter abundance of 16.8 items km^{-2} in the North Sea, 5.07 items km^{-2} in the Baltic Sea (Kammann et al., 2017), 24 items km^{-2} in the Eastern Mediterranean and 1211 items km^{-2} in the Black Sea (Ioakeimidis et al., 2014). Although data obtained with similar sampling methods might permit some comparisons between studies, dissimilarities in the sampling sizes, techniques and equipment implies that the different results should be treated with caution when compared directly (Ryan et al., 2009).

The heat map, using data from 2011 (Fig. 2) reveals that predicted litter density ranges between 0 and 60 items km^{-2} with higher amounts of litter near shore. Similar to the findings in French coastal

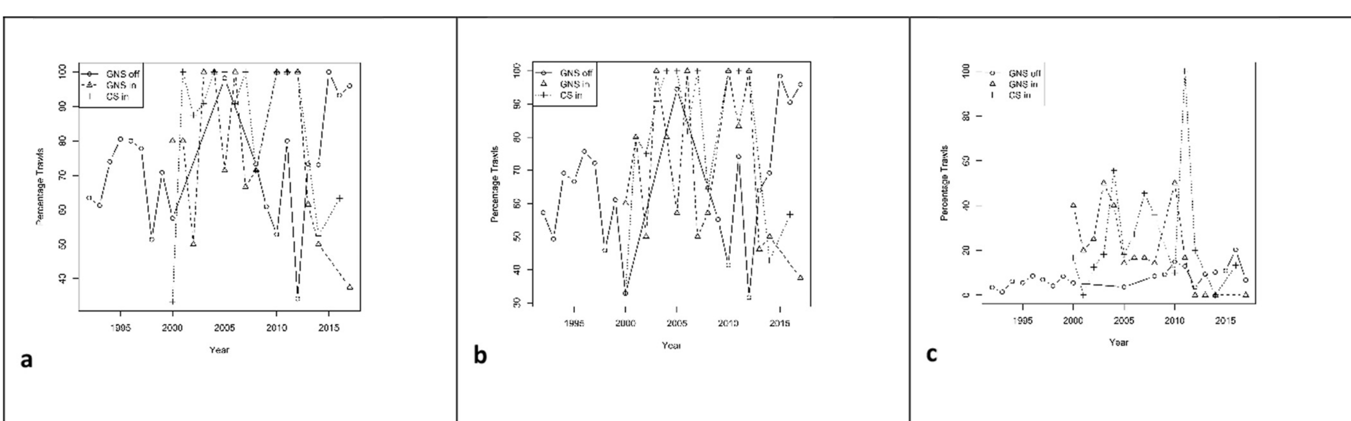

Fig. 3. a: Percentage of trawls containing any litter item for the three areas by year. b: Percentage of trawls containing a plastic item items for the three areas by year. c: Percentage of trawls containing a rubber item for the three areas by year. Key to regional divisions: GNS-off, Greater North Sea offshore stations outside 12 nm; GNS -in, Greater North Sea inshore stations within 12 nm; CS-in, Celtic Sea inshore stations within 12 nm.

Table 4
p-Values for trend as assessed by the Mann-Kendall test for percentage of trawls containing plastic litter categories by region. For p-value of 0.05 or less, the direction of the trend is shown. Key to regional divisions: GNS-off, Greater North Sea offshore stations outside 12 nm; GNS-in, Greater North Sea inshore stations within 12 nm; CS-in, Celtic Sea inshore stations within 12 nm.

Category	GNS-off	GNS-in	CS-in
Household	*0.39*	*0.81*	*0.70*
Bottles	0.30	0.35	0.43
Sheet	<0.001 (+)	0.005 (+)	0.01 (+)
Bag	0.01 (−)	0.05 (−)	0.40
Fishing	0.02 (+)	0.81	0.71
Rope	0.63	0.34	0.06
Fishing net	0.09	0.52	1.00
Fishing line	<0.001 (+)	0.10	0.02 (+)
Cable tie	<0.001 (+)	0.67	0.17
Cable strap	<0.001 (+)	–	0.71
Crates	0.003 (+)	0.08	0.11

waters, accumulations of litter were observed around urban areas and major estuaries (Galgani et al., 2000), indicating that rivers might be driving litter inputs. Worldwide, large rivers running through urban areas have been found to be major sources of marine litter (Gasperi et al., 2014; Lechner et al., 2014; Moore et al., 2011; Rech et al., 2014; Thiel et al., 2013). One can clearly observe the effects of the Rhine ROFI (Region Of Freshwater Influence) (van Leeuwen et al., 2015) creating a significant input of buoyant water and probably floating litter from freshwater river sources, which seem to have important implications on the distribution of seafloor litter.

4.2. Litter composition in the CS and GNS

Similar to other seafloor litter studies (Galgani et al., 2015; Pham et al., 2014), in most stations sampled in our study, plastic accounted for a very high percentage (between 65 and 94%) of the total number of litter items. The most prevalent plastic litter items were bags, plastic sheeting and derelict fishing gear items. Although no significant difference in the number of total plastic, plastic household or fishing items was observed between GNS and CS regions in 2011, the confidence intervals indicated the presence of more plastic items in the GNS inshore compared to the CS inshore. Similarly, no significant difference in fishing related litter items was found between the offshore GNS and CS ($p = 0.08$) area; however, the confidence intervals indicated a higher presence in the offshore GNS area. The North Sea is surrounded by many industrialised countries, an international fishing ground and contains some of the world's most important shipping lanes – all of which could explain this high abundance of litter. Foekema et al. (Foekema et al., 2013) speculated that the higher frequency of fish with ingested plastics the southern North Sea resulted from higher, localised plastic pollution levels. In spite of existing regulations to prevent waste from maritime industry (Convention, 2013), several studies reported litter pollution from ships in the German Bight (Thiel et al., 2011; Vauk and Schrey, 1987). High amounts of litter were also reported on beaches and the seafloor in the southeastern North Sea (Schulz et al., 2015a, 2015b). These higher numbers of fishing related litter in the GNS compared to the CS could reflect fishing efforts, which are far greater in the GNS than in the Celtic and Irish Sea (STEFC, 2015). It seems that the pattern of accumulation and composition of the litter is determined by a complex range of environmental and anthropogenic factors.

4.3. Litter trends in the CS and GNS

In our study, Rubber (including tyres) and Miscellaneous were the only main categories which showed a significant trend in one or more of the assessed areas. For all other main categories, we were not able to detect a statistical change over time in any of the three regions (GNS-in, GNS-off, CS-in). Such absence of a clear or statistically significant trend with regard to variations in seafloor litter quantities was also reported by Galgani (Galgani et al., 2015) when analysing seafloor litter data from French trawls undertaken between 1994 and 2014. Temporal trends indicated a stable situation in the Gulf of Lion and seasonal variations in the northern part of the Bay of Biscay (Galgani et al., 1995a, 1995b).

However, across the entire dataset, we detected a clear downward trend in the percentages of trawls containing plastic bags in the inshore and offshore GNS area. Our results also showed a reduced proportion of plastic bags in all three regions (GNS-in, GNS-off, CS-in) from 2010 onwards. This could be the result of the implementation of measures against the use of plastic bags (Clapp and Swanston, 2009), changes in plastic bag composition and thus degradation rates (O'Brine and Thompson, 2010) or underlying hydrodynamics (Galgani et al., 2015, 2000).

Our results also indicated an increase in the proportion of fishing debris in the GNS. The following subcategories were rising: fishing line, cable tie, straps and crates. In the last two decades, specific actions and measures to target the loss of fishing nets have been introduced. Extensive seafarer training and specific industry actions might be useful to target some of these sea-based items.

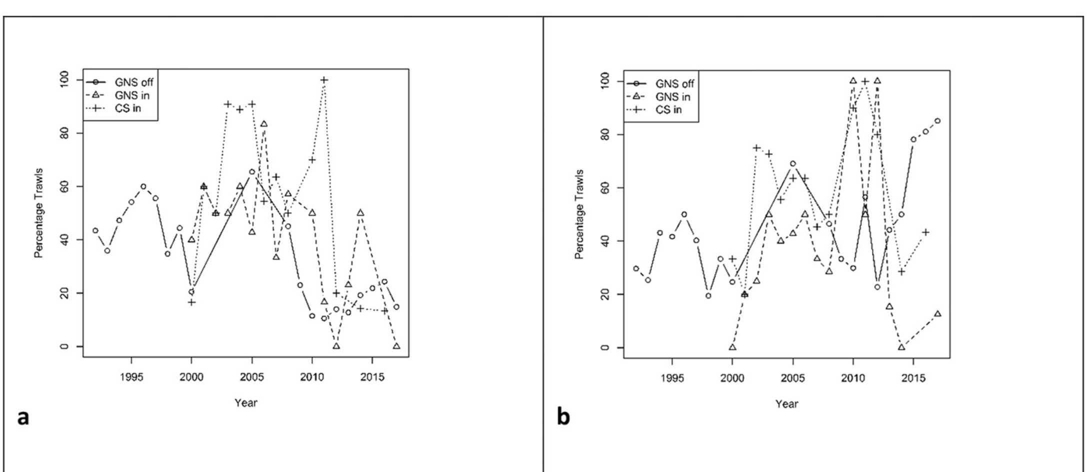

Fig. 4. a: Percentage of trawls containing plastic bags for all three areas by year. b: Percentage of trawls containing plastic Fishing items for all three areas by year. Key to regional divisions: GNS-off, Greater North Sea offshore stations outside 12 nm; GNS-in, Greater North Sea inshore stations within 12 nm; CS-in, Celtic Sea inshore stations within 12 nm.

4.4. Conclusions and outlook

The results of this work have indicated that large quantitative variations occur, and that the geographical distribution of litter could be affected by hydrodynamics, seasonal variation geomorphology and human factors. Moreover, fishing effort is not uniformly distributed and shifts locations over the years. Since the late 1990s, both fishing effort and trawling effort have decreased substantially in both the GNS and CS regions (Jennings and Cotter, 1999; STEFC, 2015). The combined effects of improved measures, changing inputs and shifting fishing pressures make it difficult to make firm conclusions in relation to marine litter.

Our data for 2011 did not show a clear difference in litter density between inshore and offshore areas, a pattern previously reported for European Seas (Galgani et al., 2000; Pham et al., 2014) and off California (Watters et al., 2010). In the Gulf of Lion, Galgani et al. (Galgani et al., 1995b) suggested that low litter density on the shelf was caused by strong water flow from the Rhone River, transporting litter to the south into deeper waters. The main inflow of water into the North Sea is from the North Atlantic into the northern basin where we observed rather low amounts of litter. Water also enters from the English Channel, the water movements and general circulation in the English Channel are presumably responsible for the dilution of the litter in the center of the Channel, pushing it towards the Southern North Sea (Galgani et al., 1995a) into the Skagerrak and along the Scandinavian coast into the Norwegian Sea and deeper canyons (Huthnance, 1991). A similar situation occurs in Monterey Bay, California, where sediment and litter are being swept off the continental shelf down into Monterey Canyon (Schlining et al., 2013). This suggests that the amounts of litter on the seabed are not static and thus the observed marine litter abundance on the seafloor results from a dynamic equilibrium between continuous input and output. Some litter items will transfer into the deep or remote parts of the Atlantic Ocean. Several reports have indicated the presence of litter in deep sea trenches, canyons and at the poles (Barnes and Milner, 2005; Barnes et al., 2009; Bergmann and Klages, 2012; Galgani et al., 1996; Mordecai et al., 2011; Tekman et al., 2017). We observed far lower litter densities on the seafloor of the GNS and CS compared to surveys at submarine canyons and deep sea locations in the North East Atlantic (Pham et al., 2013). Plastic items and their breakdown fragments seem to dissipate into the wider North East Atlantic (Pham et al., 2014, 2013; Van Cauwenberghe et al., 2013), Baltic (HELCOM, 2007) and Mediterranean Sea (Ramirez-Llodra et al., 2013), which could cause trends in larger litter and plastic items km^{-2} of seafloor to remain stable in the GNS and CS despite increasing inputs. Controversially, the observed presence of a downward trend in plastic bags in the GNS indicates that we can influence the abundance and distribution of certain marine litter items over short time scales, within decennia.

The present study illustrated several opportunities and limitations of using trawl surveys to evaluate abundance, spatial distribution and qualitative composition of benthic marine litter. Seafloor litter data can easily be obtained from environmental and fisheries surveys using bottom trawls. Such monitoring occurs at several times a year with similar trawling equipment undertaken by several countries with adjoining sea borders. Therefore, international co-operation and data sharing, will facilitate regional assessments and improve the power of detecting trends in future years. The higher the power of a survey, the more accurately one can assess the effectiveness of marine litter measures.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.02.245.

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