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Distribution and trajectories of floating and benthic marine macrolitter in the south-eastern North Sea

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Abstract

In coastal waters the identification of sources, trajectories and deposition sites of marine litter is often hampered by the complex oceanography of shallow shelf seas. We conducted a multi-annual survey on litter at the sea surface and on the seafloor in the south-eastern North Sea. Bottom trawling was identified as a major source of marine litter. Oceanographic modelling revealed that the distribution of floating litter in the North Sea is largely determined by the site of origin of floating objects whereas the trajectories are strongly influenced by wind drag. Methods adopted from species distribution modelling indicated that resuspension of benthic litter and near-bottom transport processes strongly influence the distribution of litter on the seafloor. Major sink regions for floating marine litter were identified at the west coast of Denmark and in the Skagerrak. Our results may support the development of strategies to reduce the pollution of the North Sea.

Keywords North Sea, marine litter, seafloor, surface, composition, trajectory

Introduction

Marine litter has accumulated over recent decades in all habitats of the world’s ocean from urban coastal waters (Browne et al. 2011) to most remote, supposedly unspoiled environments, such as the polar regions (Obbard et al. 2014) and the deep sea (Bergmann & Klages 2012, Pham et al. 2014). Marine litter is causing harm to a great variety of organisms (Kühn et al. 2015), affects the functioning of marine ecosystems (Green et al. 2015) and has adverse economic and human health effects (Thompson et al. 2009). Although numerous national and international legislative measures have been brought into action to combat marine litter (Hastings & Potts 2013) quantities of marine litter are still increasing worldwide (Jambeck et al. 2015) indicating a poor control of major litter sources and inappropriate waste management.

There is a consensus that preventing litter from entering the marine environment should be given priority over the removal of litter which has already escaped from controlled waste streams (van Franeker & Law 2015) because the broad and unselective removal of large quantities of litter from the oceans is inevitably associated with a simultaneous extraction of considerable amounts of marine biological production and damage to sensitive environments. However, the ecological impacts of clean-ups can be reduced if extraction activities are focused on strategically selected and easily accessible sites where litter accumulates, for example, due to local oceanographic conditions (Sherman & van Sebille 2016). Therefore, a sustainable and environmentally sound strategy to reduce marine litter requires the identification of major input pathways of marine litter as well as an understanding of the trajectories and deposition sites of litter items in the marine environment.

Major sources of marine litter can often be inferred from the litter composition. For example, derelict fishing gear and shipping equipment clearly hint at maritime activities as a source. A spatial correlation of the quantities of certain litter items and their supposed source activity strongly indicate local input and deposition. For example, Tekman et al. (2017) identified intensified fisheries activities around the Svalbard archipelago as a source of increasing amounts of litter on the seafloor of the nearby Fram Straight. Alternatively, a diffuse distribution of litter unrelated to possible source activities may indicate near-bottom transport of objects after deposition. Resuspension and near-bottom transport of seafloor litter may be induced by the joint action of waves and tidal currents as well as other environmental factors, such as seafloor topography and river plumes (Schlining et al. 2013).

The global distribution of marine litter and major accumulation zones in the oceans, such as the oceanic subtropical convergences, are well known from extensive field surveys and oceanographic modelling (Lebreton et al. 2012, Maximenko et al. 2012, Cózar et al. 2014, Eriksen et al. 2014). However, in coastal waters and shelf sea regions the distribution and trajectories of marine litter are more variable and often less understood due to the diverse coastal sources of marine litter and the difficulties in modelling the trajectories of flotsam in oceanographically complex coastal waters. The prediction of trajectories and distribution patterns of marine litter is further complicated by the poor skill of predicting the sinking of items. The loss of buoyancy of a floating litter item can be induced by colonization by marine organisms (Ye & Andrady 1991) or by water intrusion upon damage, e.g. in PET drinking bottles. Accordingly, the distribution and composition of litter on the seafloor are the result of at-site deposition from local activities, the import of sinking items from the sea surface, and near-bottom transport. The relative importance of the import of sinking items from the surface may become evident from the degree of similarity in the composition and distribution of litter at the sea surface and on the seafloor with strong correlations indicating frequent import from the sea surface whereas no correlation would indicate that other processes than import from the surface shape the distribution and the site specific composition of benthic litter.

In this study we investigate the distribution and composition of marine debris at the sea surface and on the seafloor of the south-eastern North Sea. We conducted a multi-annual survey which produced an extensive data base on the spatio-temporal distribution of marine litter with considerable spatial coverage. Oceanographic models were used to investigate forward and backward trajectories of real floating items on the scale of the entire North Sea in order to identify potential source regions and important sites of deposition. Additionally, advanced methods of species distribution modelling were applied to benthic litter to infer the processes that shape the distribution of marine debris on the seafloor.

Material and Methods

Study area

The North Sea, which is part of the north-eastern Atlantic shelf, is a marginal sea with a surface area of 575,300 km² (ICES 1983). The largest exchange of waters between the North Sea and Atlantic Ocean is between the Shetland Islands and Norway. According to Otto et al. (1990) two main water bodies can be distinguished in the North Sea. The water masses in the northern and central parts bear characteristics of oceanic water with surface salinities above 34 (Weichart 1986, Huthnance 1991) and seasonal stratification (Pingree et al. 1978). The southern North Sea receives oceanic waters mainly through the British Channel. This area is subject to large continental runoff resulting in salinities below 30 in the coastal regions. Due to strong tides the shallow southern North Sea waters are permanently well mixed. Tidal and wind forcing in concert drive an anti-clockwise residual circulation along the coasts (Otto et al. 1990, Huthnance 1991, Pohlmann 2006). Several frontal systems separate the oceanic-like water masses of the central North Sea from the coastal waters.

The German Bight in the south-eastern North Sea is bordered by the Frisian Islands. Large tidal flats extend between these barrier islands and the coast constituting the major part of the Wadden Sea. This shallow water body is one of the most prominent regions of freshwater influence world-wide being under riverine influence of the rivers Rhine, Meuse, Ems, Weser, Elbe and Eider. The runoff from some of these rivers is considerable (e.g. ~1000 $m^3 s^{-1}$ for the River Elbe; Dippner 1993). Salinity increases from about 30 in the Wadden Sea to 31-33 at the island of Helgoland, which is located about 50 km offshore. Water moves from the German Bight along the Danish coast into the Skagerrak. A pronounced frontal system along the 30 m depth contour separates the coastal waters from the more saline offshore waters of the German Bight (Krause et al. 1986, Budéus 1989, Becker et al. 1992, Dippner 1993, Skov & Prins 2001).

Quantities and distribution of floating litter

Floating marine litter was quantified between 2006 and 2016 on 9 cruises of the German research vessel *Heincke* in the German sector of the North Sea, which were part of extensive marine benthos surveys. Data collected between 2006 and 2008 have been published previously by Thiel et al. (2011). Floating litter items were counted from aboard the vessel during transits between benthos sampling stations. We recorded type and position of all floating macrolitter items (i.e. objects detectable with the naked eye) within a range of 20 to 70 m perpendicular to the ship’s track for the years 2006 to 2008. During subsequent surveys (years 2014 to 2016) objects were recorded within a shorter range of 10 to 20 m. For each transect we recorded the start and end position from a hand-held GPS. The position of each floating litter item was recorded as the observer position at the time when the item was passing by.

Floating litter was recorded only at daytime and during periods of good visibility. During the observations the ship speed varied between about 5 and 11 knots. In total, 78 sea surface transects were surveyed (Figure 1). The length of transects varied between 4.7 and 25.1 km. The strip transect method was used to calculate the density D (items km^{-2}) of floating litter items for each transect (for details see Hinojosa et al. 2011) using the following equation:

$$D = N / ((W / 1000) \cdot L) \qquad \text{Eq. 1}$$

where N = the number of items counted, W = the width of the transect and L = the length of the transect in km.

Given the patchy distribution of flotsam visual ship based observations along extended transects are a particularly good method to determine the quantity and distribution of surface litter. The exact position of each single item is recorded allowing for a precise description of mesoscale variations in litter densities. Additionally, the considerable area covered by single transects allows for integration at different spatial scales to obtain representative average densities.

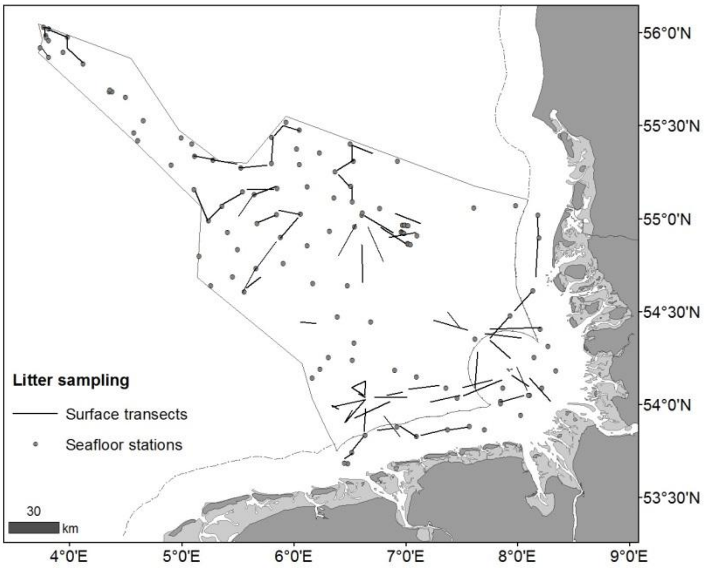

Figure 1 Positions of surface transects (black lines) and bottom trawls (black dots) for the quantification of floating and benthic marine litter in the south-eastern North Sea. The solid grey line depicts the German Exclusive Economic Zone; the dashed line depicts national territorial waters.

Quantities and distribution of litter on the seafloor

Densities of litter on the seafloor were determined from beam-trawl hauls which were taken routinely during benthos surveys in the years 2014 and 2016. A 2 m-beam trawl (mesh size: 1 cm) was towed at an average speed of about 1-3 knots. Trawling distance was calculated from the GPS positions where the winch stopped veering (start trawling) and started hauling (end trawling). The beam trawl was operated during day and night time and was largely independent of the sea state allowing for a total of 122 hauls (Figure 1). All litter items retrieved from the net were identified and counted. Photographs were taken of each item. At two stations numerous fibres from fishing nets were tightly knotted to bunches and could not be counted individually. The number of single fibres in those bunches were estimated from photographs. Equation 1 was also used to calculate the density D of benthic litter items (items km^{-2}) for each haul with W = the width of the beam trawl (here: 2 m) and L = the trawling distance in km.

For the qualitative description of the litter composition at the sea surface and at the seafloor we adopted the litter categories defined by Thiel (2013): plastics, styrofoam, glass, metal, wood, paper and other. Additionally, we added the category “organic matter” (e.g. peels of citrus fruits). Wooden items were recorded as litter if they showed clear signs of manufacturing. We contrasted the composition of the total surface litter and the total seafloor litter (i.e. data from all years pooled) with a χ^2-test based on a 2 × 8 contingency table.

We tested for correlation of litter densities at the surface and at the seafloor. Densities of floating litter at the surface were estimated on transects between the seafloor stations. To obtain spatially corresponding density estimates from the surface and the seafloor a 10 × 10 km grid (European Environment Agency reference grid; http://www.eea.europa.eu/data-and-maps/data/eea-reference-grids-2) was laid over the study area using ArcGIS 10.3.1 (www.esri.com/arcgis). For each surface transect and bottom trawl the central position was used as the geographic reference position. Density estimates from the two habitats within the same cell were accepted as spatially corresponding irrespective of the sampling time. If a cell contained more than one count from the same habitat we used the mean of the multiple estimates resulting in a total of 18 corresponding density estimates from the surface and the seafloor. Since a Kolmogorov-Smirnov test confirmed that the data did not follow a Gaussian distribution, a non-parametric Spearman rank correlation was used to test for correlation between surface and seafloor densities.

Drift trajectories of floating litter

For each single litter item that was encountered floating in the German North Sea during the multi-annual survey we modelled the drift trajectory of a Lagrangian particle forward and backward in time to identify areas of deposition and origin, respectively. We assumed that surface transport of floating litter items is driven by the joint action of currents and wind. Trajectories were simulated with a Lagrangian model using the passive tracer module of the open-source software OpenDrift (Dagestad et al. 2017).

Data on current velocities were obtained from the Forecasting Ocean Assimilation Model Atlantic Margin Model 7 km (FOAM AMM7) configuration of the Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu/) based on the ocean model Nucleus for European Modelling of the Ocean (NEMO). The AMM7 setup has a horizontal resolution of 1/9° longitude × 1/15° latitude (ca. 7.4 km) with 51 σ-layers providing daily mean surface velocity fields. Details of NEMO are given in Madec (2008) and an extensive validation is provided in O’Dea et al. (2012). The AMM7 model domain covers the North Sea and the shelf edge. For this study the area was restricted to 48.0 to 61.4°N and -5.0 to 13.0°E which covers the North Sea, Skagerrak, Kattegat, The British Channel and is cut off north of the Shetland Islands (Figure S1).

Wind data were provided by the German Weather Service (DWD) with a horizontal resolution of 1/16° (ca. 7 km). Due to limited data availability the wind data were divided into two periods. For the first 2 years (starting on 01/06/2006) the temporal resolution is 3 h and for the last 8 years and 9 months (ending on 11/3/2017) the temporal resolution is 1 h. All other properties are identical among the two periods.

Marine litter items appear in various forms and sizes and it is impossible to actually define and specify suitable wind drag coefficients and leeway drift (or deflection angles) as it is common in search-and-rescue models for specific object classes like ship containers, life rafts or people with life jackets in the water (see e.g. Breivik et al. 2011, 2013). Therefore, particle trajectories were simulated using three different hypothetical wind drag coefficients: 0.0%, 0.5% and 1.0%. The wind drag coefficients were multiplied by the wind speed and added to the current velocity. We used a 2nd-order Runge-Kutta algorithm as advection scheme. The trajectory of each particle was calculated with the following equations:

$$dx(t) = \quad - \quad - \quad - \qquad \text{Eq. 2}$$

$$- \quad - \quad - \qquad \text{Eq. 3}$$

where *dx(t)*, *dy(t)* are the latitudinal and longitudinal particle displacements, *u*, *v* are the velocities at the particle position at $t+\frac{dt}{2}$, u_{wind} and v_{wind} are the wind velocities, w_d is the wind drag coefficient, *dt* is the time step and *u'* and *v'* are random velocities to parametrize subscale turbulent processes. The turbulent diffusion was implemented by adding random walk displacements (Callies et al. 2011; Neumann et al. 2014). For every time step the turbulent velocities are calculated as

$$u'(t) = \sqrt{\frac{2D}{dt}} R_x(t) \qquad \text{Eq. 4}$$

$$v'(t) = \sqrt{\frac{2D}{dt}} R_y(t) \qquad \text{Eq. 5}$$

where *D* is the eddy diffusivity calculated as proposed by Schönfeld et al. (1995) and is 15.9 m^2 s^{-1} in this setup. R_x and R_y are independent random numbers from a normal distribution with zero mean and variance one. Further details can be found in Callies et al. (2011). The model time step was *dt* = 1 h and the output time step was 1 d.

The actual processes of beaching of marine litter are not well understood and, therefore, currently only numerical artefacts of the advection process represent the beaching of particles. When the combined transport vector (ocean current plus wind drag effect) acts on a particle close to shore the particle is pushed over the model boundary onto land (given a long enough time step *dt* in eqs. 2+3). All particles that so reached land in this study, were considered beached and were not further advected. The time and position of beaching was recorded. Similarly, if a particle exited the domain through an open boundary, e.g. towards the north into the Atlantic, the time and position was saved. For each time step the fraction of particles in each region (Figure S1) is given as percentage of all particles.

Observations of a total of 772 floating litter items were considered for the simulation. The litter observation dates were used as the seeding dates of the particles in OpenDrift. The forward simulations started on 25/07/2006 12:00 h (date of the first litter observation) and ended on 11/03/2017 00:00 h, which was the last available velocity data at the time when the simulation was run. Alternatively, the simulation was stopped when all particles were either beached or had left the domain. The latest litter observation was on 10/04/2016 12:00 h.

Backward simulations started with the latest observed litter item and ended at the earliest on 01/06/2006 or when all particles were beached. As a consequence of the distribution of the surface transects two clusters of floating particles became apparent: an offshore cluster and a nearshore cluster. The two clusters were separated by the major salinity front of the south-eastern North Sea (Figure S1). Since fronts can efficiently separate water masses (Hill et al. 1993) and passively floating objects therein, the backward simulations were performed individually for each cluster. The influence of the wind drag factor on the origin of items from the different source regions was analysed separately for the nearshore and the offshore cluster using χ^2-tests based on 3 (number of wind drift factors) × 6 (number of source regions) contingency tables.

Factors explaining seafloor litter distribution

To understand the processes that shape the distribution of litter on the seafloor we investigated six environmental and anthropogenic factors for their role as sources of benthic marine litter and as drivers of near-bottom dispersal: bottom trawling intensity, distance to major shipping routes, bottom shear stress, mean horizontal surface velocities, water depth, and distance to coast. Data on bottom trawling intensity were available for the year 2006 from vessel monitoring system data (Schröder et al. 2008). For our analysis we assume that the data from 2006 are representative for the long-term distribution and intensity of the bottom trawling activity in the south-eastern North Sea. Distances to shipping routes were calculated from long-term annual shipping densities collected as AIS data by Baldock (2009). Bottom shear stress can lead to the resuspension and near-bottom transport of deposited material, such as sediment or litter objects. It is a composite vectorial force resulting from the joint action of vertical wave-induced lift and horizontal transport by tidal currents. The composite bottom shear stress was calculated from the specific values for shear stress induced by wave action and by bottom currents of the year 2007, assuming again long-term validity of the data. The specific shear stress values were retrieved from the coastMap Geoportal (www.coastmap.org) under CC BY-NC 4.0 license. For each day, only the higher one of the two shear stress values was used, assuming that the movement of a particle or object near the seafloor is primarily determined by the dominant force. From the daily values the 0.95 quantile was chosen as bottom shear stress characteristic. The mean horizontal surface velocities were calculated as an average of the velocity dataset used for the above simulations of trajectories of Lagrangian particles. Water depth was taken from GEBCO bathymetry (Wetherall 2015). Distance from coast is a simple derivative of a shoreline map. The explanatory variables were processed using R v.3.0.3 (R Core Team 2014) with a spatial resolution of 1 × 1 km.

We used two different methods to investigate the potential of the selected variables to explain the distribution of seafloor litter: Maximum entropy (Maxent) (Phillips et al. 2006) and Random Forest (RF) (Breiman 2001). Maxent was applied to presence data. RF was applied to presence/absence data and density data to study the quantitative relationship between the spatial distribution of litter and the environmental variables. Model accuracy was assessed as the Receiver Operating Characteristic Area Under Curve (ROC AUC), Cohens Kappa (Kappa), Brier score and root mean squared error (RMSE). We used null models to test if data locations were spatially biased with regard to the predictors. Here, performance metrics of models of randomized data act as a baseline to identify the metrics a null hypothesis situation might have. Non-trivial patterns must then significantly deviate from null model performance.

Results

Distribution of floating litter

Floating marine litter occurred along the entire German coast as well as in offshore waters (Figure 2A). Floating litter was observed on 74 out of 78 surface transects. Densities of floating litter ranged from 1 to 272 items km^{-2} (mean ± SD = 30.6 ± 41.8 items km^{-2}; median: 19.7 items km^{-2}) with highest densities occurring in the North Frisian coastal waters, in the area of the Borkum Reef Ground in the south-western part of the German Exclusive Economic Zone (EEZ), and in the central-northern part of the German EEZ off the coast of southern Denmark. Data from the southern and south-western coastal waters of the German North Sea, where floating litter was surveyed repeatedly over several years, indicate substantial temporal variability in litter densities. No clear gradient in litter densities from coastal to offshore waters was evident.

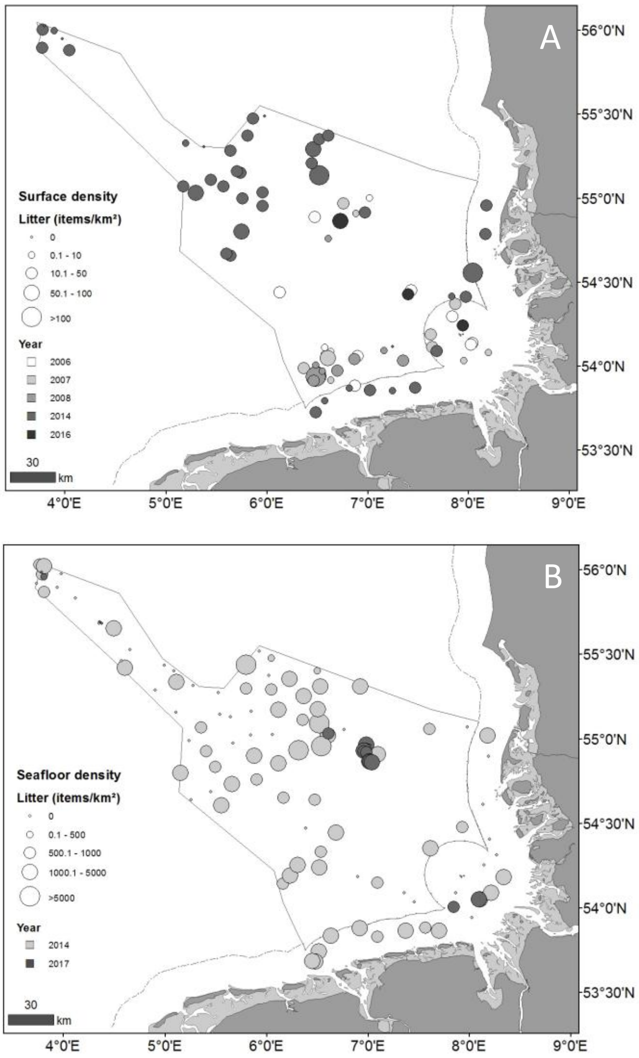

Figure 2 Densities of (A) floating and (B) benthic litter in the south-eastern North Sea.

Floating litter was dominated by plastics (Figure 3) which held a share of 64% of the total amount of litter. Floating plastics consisted of numerous small plastic pieces and fragments but also of larger items, such as plastic bottles and plastic bags. The next most common categories of floating litter were styrofoam, wood and paper. Only few items consisted of glass, metal or organic matter. The relatively large fraction of “Other” floating litter objects mostly comprised unidentifiable floating objects but also cigarette butts.

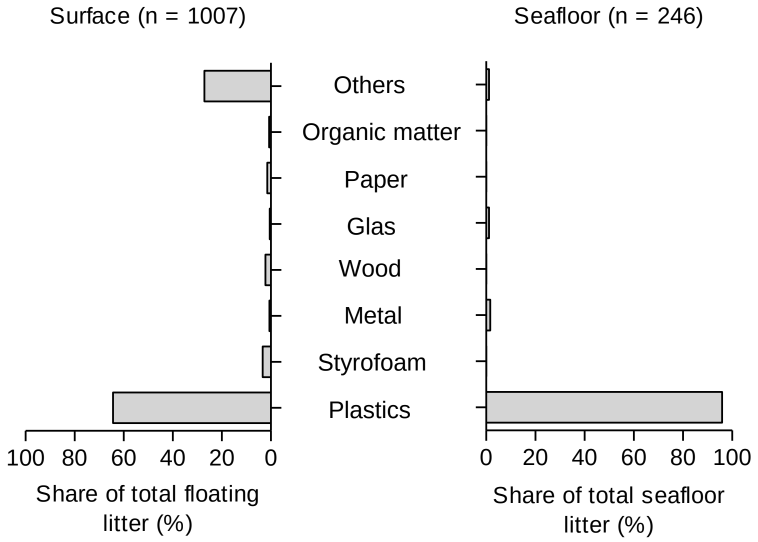

Figure 3 Composition of floating (left-hand side) and benthic (right-hand side) litter in the south-eastern North Sea. The litter composition differed significantly between the surface and the seafloor (df = 6; $\chi^2 = 65.1$; $p < 0.01$).

Distribution of seafloor litter

Seafloor litter was found in both coastal and in offshore waters of the German North Sea (Figure 2B). Marine litter was found in 70 out of 122 bottom trawls. Densities of litter at the seafloor varied between 96 and 33,675 items km^{-2} (mean ± SD = 1307.3 ± 3352.3 items km^{-2}, median: 610 items km^{-2}) with highest densities occurring in the central-northern part of the German EEZ off the west coast of southern Denmark. Seafloor litter was found in coastal waters along the East Frisian coast and off the mouths of the rivers Elbe and Weser but was almost entirely absent along the North Frisian coast. Similarly, in the north-western stretches of the German EEZ a considerable number of stations were free of seafloor litter.

Litter on the seafloor consisted almost exclusively of plastics (Figure 3). The by far most common plastic items on the sea floor were fibers from fishing nets but pieces of plastic foil and other packaging material made of plastics were also common. Overall, fishing related litter items made up 76% of the total seafloor litter. Few metal and glass items were encountered while paper, wood, styrofoam and organic material were entirely absent from the seafloor samples. The few “Other” litter items were pieces of coal slag and a tire (consisting of rubber and metal). Although plastics dominated the litter at both the surface and the seafloor the overall litter composition differed significantly between the two habitats (df = 7; $\chi^2 = 111.7$; $p < 0.01$). Moreover, densities of litter at the surface and at the seafloor were not correlated with each other (Spearman rank r = 0.26; p = 0.23).

Drift trajectories of floating litter

The simulation showed that the trajectories of the floating particles in the south-eastern North Sea are typically characterized by an initial northward drift resulting in a rapid initial drop of particles in the German Bight and an increase in particle densities in the wider North Sea, i.e. the area of the North Sea outside the German Bight, and in the Skagerrak (Figure 4). On their way north a considerable number of particles was deposited along the Danish west coast or forced into the Skagerrak where they were trapped by eddies between the incoming North Sea water and the outflow from the Baltic. Consequently, the fraction of particles floating in the Skagerrak increased while the proportion of particles in the wider North Sea decreased. In the Skagerrak particles may be deposited on the Danish, the Norwegian or the Swedish coast. When released from the Skagerrak the particles drifted north to become either deposited along the Norwegian coast or to exit the North Sea into the North Atlantic.

The drift trajectory and, thus, the probability of being deposited on a shore or transported out of the North Sea into the North Atlantic strongly varied with the wind drag coefficient (Figure S2). Particles which were transported solely by currents (wind drag = 0.0%) had a relatively high chance of entering the North Atlantic (Figure 4A) or being deposited along the Norwegian North Sea coast (Figure 4B). Particles which were more strongly controlled by wind were more rapidly pushed eastward towards the coast by the prevailing westerly winds (Figure 4C-F). Consequently, at a wind drag coefficient of 1.0% a considerable number of particles did not leave the German Bight but became quickly washed ashore along the German and the Danish coast. The probability of particles beaching at the Swedish coast also increased with the wind drag coefficient whereas particles rarely reached the Norwegian coast or left the North Sea when a high wind drag coefficient was used. The fraction of particles deposited on the Danish coast was generally high at about 40% of the total number of particles floating in the German North Sea.

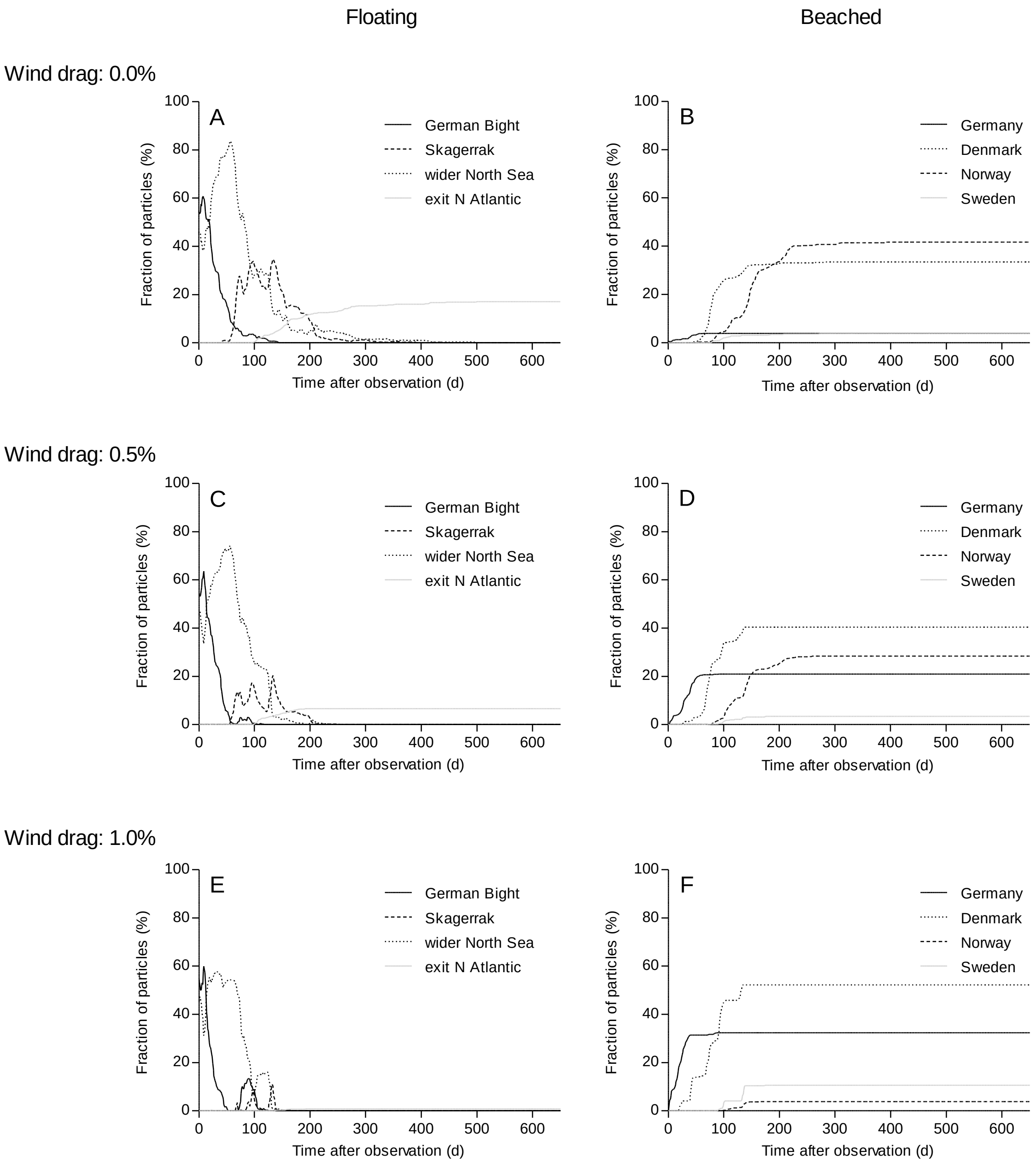

Figure 4 Results of the drift simulation of Lagrangian particles in the North Sea. Simulations were run for particles using different wind drag coefficients (A, B: 0.0%; C, D: 0.5%; E, F: 1.0%). A, D and E show the temporal variations in the number of active particles floating in different regions of the North Sea. B, D and F show the number of particles beached in different coastal regions of the North Sea. Each particle represents a specific floating litter item observed during the survey and for each particle the simulation starts at the time when it was observed (day 0). For each day of the simulation the proportions of floating and beached particles, respectively, sum up to 100%.

The residence time of floating items was longest in the wider North Sea. The average residence time of floating items in the German Bight was largely independent of the wind drag coefficient and varied between 16 and 23 days (Figure 5). In both the Skagerrak and the wider North Sea the average residence time of floating items declined continuously with increasing wind drag factor from about 33 to 2 days and from 79 to 48 days, respectively.

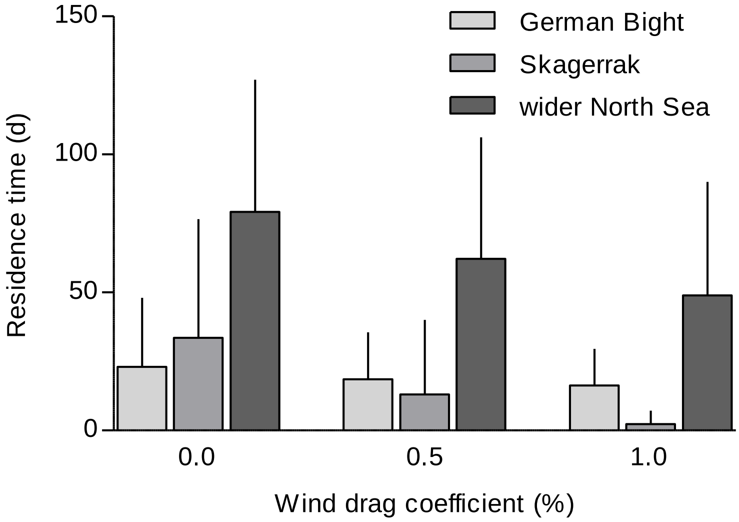

Figure 5 Results of the drift simulation of Lagrangian particles in the North Sea: average residence times of particles of different wind drag coefficients in different regions of the North Sea. Error bars indicate standard deviation.

The backward simulation revealed that particles from the offshore and the nearshore cluster had different source regions (Figure S3). Depending on the wind drag coefficient, 87-96% of the particles from the nearshore cluster originated from the German and Dutch coast, with major contributions from the rivers Ems, Jade, Weser and Elbe, whereas only 14-27% of the particles from the offshore cluster came from the German and the Dutch coast (Table 1). The majority of particles from the offshore cluster originated from more distant western source regions with major contributions from the British Channel and the river Rhine but also from the coasts of France and the British Isles. Generally, only a small number of particles originated from the relatively short Belgian coastline.

The wind drag coefficient influenced the contribution of the different source regions, particularly the contributions from the German and the Dutch coasts (Figure S4). The proportion of particles originating from the German coast decreased with increasing wind drag factor whereas the Dutch coastal zone had a higher contribution of items with elevated wind drag factor. For the contribution from the more distant source regions the effect of the wind drag factor was less pronounced. The effect of the wind drag factor was statistically significant for both the nearshore (χ^2 = 90.3, df = 10, $p < 0.01$) and the offshore cluster (χ^2 = 54.6, df = 10, $p < 0.01$).

Table 1 Results of the backward drift simulation of Lagrangian particles in the North Sea: source regions of particles from the nearshore and the offshore cluster computed using different wind drag coefficients. The numbers are percentage values according to the share of particles originating from the respective source region.

	Nearshore (n = 507 items)			Offshore (n = 265 items)		
Wind drag coefficient	0.0%	0.5%	1.0%	0.0%	0.5%	1.0%
France	0.39	2.17	0.59	25.28	30.94	16.60
British Isles	0.00	8.88	7.69	30.94	20.76	34.34
Belgium	0.20	0.20	0.00	0.00	1.89	0.38
The Netherlands	36.89	33.53	44.58	15.85	15.09	22.64
Germany	60.55	54.83	46.75	9.06	7.92	3.40
Floating	1.97	0.39	0.39	18.87	23.40	22.64

Factors explaining seafloor litter distribution

The models used to identify factors that shape the distribution of seafloor litter showed only moderate quality in terms of ROC AUC and Kappa (Table 2). Both Brier scores for the probabilistic models from presence-only and presence/absence data and RMSE for the density predictions suggest rather low explanatory power. According to the sensitivity analysis based on Jansen estimators (Jansen 1999) shear stress was the most influential variable whereas distance to major shipping routes was less important.

Null models calculated from 5-fold cross validation runs revealed no spatial bias with respect to the explanatory variables employed. Spatial autocorrelation was low. For a lag distance of 30 nm the Moran I value was 0.25 ($p < 0.001$). This can be attributed to the predictors used, as the Moran I test of the residuals was negative (0.06 at $p = 0.21$).

Table 2 Diagnostic model accuracy metrics (± SD) for litter at seafloor form repeated 5-fold cross validation.

Response	Method	ROC AUC	Kappa	RMSE	Brier score
Presence	Maxent	0.48 ± 0.06	0.18 ± 0.08	-	0.31 ± 0.00
Presence/absence	Random forest	0.55 ± 0.13	0.27 ± 0.15	-	0.31 ± 0.07
Density	Random forest	0.57 ± 0.13	0.29 ± 0.15	1590 ± 73	-

Discussion

The results of this study reveal considerable quantities of marine litter at the sea surface and on the seafloor of the south-eastern North Sea. The great majority of marine litter consisted of plastics, and fisheries activities were identified as a major source of marine litter. The drift simulations indicated that a large fraction of the floating marine litter in the North Sea is deposited on the beaches of Germany and Scandinavian countries. However, the factors which control the distribution of litter on the seafloor are still poorly understood. The identification of major sources and sites of deposition of marine litter may help developing strategies to reduce the pollution of the North Sea.

Composition and distribution of floating and benthic marine debris

It is well established since decades that the North Sea is substantially polluted with marine anthropogenic litter (Vauk & Schrey 1987). Since the first survey by Dixon and Dixon (1983) the density of floating litter in the North Sea has increased by an order of magnitude to an average of about 30 items km^{-2} (Thiel et al. 2011). The data from the recent survey by Thiel et al. (2011) have been incorporated in our dataset to achieve a temporally more integrated estimate of the distribution and composition of floating litter with a higher spatial coverage, which can be contrasted with the densities on the seafloor.

The average litter density on the seafloor was about 40 times higher than at the sea surface. Direct comparisons of surface and seafloor densities of marine litter are still scarce. Globally, however, litter densities seem to be generally higher in benthic than in pelagic environments (Galgani et al. 2015). In our study the difference may have been amplified by the different methods applied to quantify litter in the two habitats. To enhance the comparability of the densities, towed devices with similar mesh size could have been used to quantify litter at the surface (neuston net) and on the seafloor (beam trawl). The use of a neuston net may have led to higher surface densities. However, we would expect only a minor effect on the overall distribution pattern of floating litter because the majority of small items collected from the seafloor originated from bottom trawling activities and were directly deposited in the benthic environment. Moreover, due to the relatively small net aperture litter densities estimated with a neuston net are sensitive to spatial clumping of floating litter (Ryan et al. 2009). Therefore, visual ship based surveys are a common, non-invasive method for the quantification of floating macrolitter (Thiel & Gutow 2005).

Higher litter densities on the seafloor than at the surface indicate (a) continuous vertical import of marine litter from the sea surface and the water column and/or (b) direct deposition of litter on the seafloor. The average density of about 1300 items km^{-2} on the seafloor was about one to two orders of magnitude higher than average seafloor densities reported in previous studies from the North Sea including the German EEZ (Galgani et al. 2000: 156 items km^{-2}, Kammann et al. 2017: 11-24 items km^{-2}, Maes et al. 2018: 40-49 items items km^{-2}). The previous studies presented data from fishery surveys (e.g. ICES international bottom trawl survey – IBTS) which uses nets with mesh sizes of 20-40 mm in the cod-end and, hence, the authors suggested that the amount of litter on the seafloor was probably underestimated (Galgani et al. 2000, Kammann et al. 2017). The beam-trawl with a mesh size of 10 mm used in our study probably produced a better estimate of macrolitter quantities on the seafloor of the North Sea, which was in the range of some densities measured in heavily polluted regions such as the South China Sea (Zhou et al. 2011) and the Mediterranean (Tubau et al. 2015).

In both habitats, the surface and the seafloor, the majority of litter items consisted of plastics. The proportion of 64% at the surface is lower than the global contribution of plastics to the overall amount of litter in the world ocean of 73% (Bergmann et al. 2017a). The share of plastics of 95% on the seafloor is clearly above previous estimates of a 50-80% contribution of plastics to the benthic litter in the North Sea (Galgani et al. 2000, Schulz et al. 2015a, Kammann et al. 2017, Maes et al. 2018). The composition of litter differed significantly between the surface and the seafloor. Furthermore, litter densities did not correlate among the two habitats indicating that the contribution of vertical import from the surface to the benthic litter may be negligible relative to the direct deposition in the benthic habitat. Additionally, near-bottom transport processes may have redistributed benthic items thereby obscuring the spatial pattern of litter deposition on the seafloor.

The majority of litter items on the seafloor were related to fishing activities including numerous fibers and yarn from fishing nets and dolly ropes clearly pointing at bottom trawling as the major source of benthic litter. Fisheries have previously been identified as an important source of marine litter on the seafloor and on beaches of the North Sea (Galgani et al. 2000, Schulz et al. 2015a) and in other regions of the world ocean (Merrell 1984, Walker et al. 1997, Edyvane et al. 2004, Buhl-Mortensen & Buhl-Mortensen 2017). An analysis of data from OSPAR beach monitoring indicated that the amount of fishery related litter on the coasts of the North-East Atlantic, including the German North Sea, is decreasing presumably due to declining coastal fishery activities (Schulz et al. 2013, 2015b). However, our data reveal that the contribution of fishery related items to the overall benthic litter in the south-eastern North Sea has increased from 60% (Schulz et al. 2015a) to 76% (this study). Schulz et al. (2015a) reported litter quantities by weight. Therefore, the comparability of the share of fishery related debris among the two studies is limited. Bergmann et al. (2017b) suggest that quantifying marine debris by weight may overestimate the contribution of fisheries activities because of the potential occurrence of exceptionally heavy fishing gear or remains thereof. Accordingly, the increasing share of fishery related debris may indicate a disproportional and rapid accumulation of this litter category in the North Sea probably due to chronically high bottom trawling activity in this region (Stelzenmüller et al. 2014, Kenny et al. 2017).

Drift trajectories of floating litter

It is impossible to determine where exactly an object, which was observed floating at the sea surface, has entered the marine environment. Hence, each floating object observed during our survey could have started its floating journey at any point along the modelled backward trajectory of the corresponding Lagrangian particle. Nevertheless, the simulation permitted to identify two clusters of particles which differ considerably in their backward trajectories, pointing at different source regions. The offshore cluster had a larger proportion of particles that could be traced back to more distant western source regions at the British Isles, France and the English Channel whereas the great majority of particles in the nearshore cluster could be traced back to nearby source regions in the Netherlands and Germany. Accordingly, the distribution of floating marine debris in the south-eastern North Sea is decisively determined by the geographic location of the sources (see also Hainbucher et al. 1987). A large proportion of the particles were discharged from rivers into the North Sea confirming that riverine transport substantially contributes to the littering of coastal seas (Rech et al. 2014). The rivers Ems, Jade, Weser and Elbe along the Dutch and German coast are major sources of particles of the nearshore cluster. The offshore cluster is fed by the Rhine and the East Anglia Plume, which is responsible for an eastward transport of particles discharged by the rivers Thames and Humber into the central North Sea (supplementary material S5, see also Pietrzak et al. 2011).

The two clusters were located on different sites of the major salinity front of the German Bight (Figure S1). Previous studies have shown that oceanic features, such as fronts and convergences, can efficiently constrain the dispersal and mixing of flotsam. For example, large amounts of marine litter were observed below a salinity front in the Rio de la Plata estuary (Argentina) indicating that floating items are retained by the front before they sink to the bottom (Acha et al. 2003). Similarly, floating kelps have been found to accumulate along an estuarine front in the Chilean fjord system (Hinojosa et al. 2010). Likely, the distribution pattern of floating marine debris in the south-eastern North Sea, which is determined by the origin of the flotsam, is consolidated by the frontal system that may prevent mixing of the two clusters.

The further trajectories of particles in the German Bight are strongly influenced by wind drag. The anticlockwise current system of the North Sea transports particles northward out of the German Bight (Hainbucher et al. 1987, Schönfeld 1995) while prevailing westerly winds push particles towards the shore (Neumann et al. 2014) suggesting an early beaching of buoyant objects with considerable freeboard, such as buoys and PET drink bottles. Contrarily, particles with a low wind drag coefficient, analogous to objects which do not extend above the surface such as plastic bags and foils, are less strongly forced by wind and become later deposited on the shore or are transported by currents out of the North Sea into the North Atlantic. Hence, differential transport likely results in a segregation of objects with different floating behavior (Laxague et al. 2018). The interaction of currents and wind may lead to a fractionation of deposited items along the eastern shore of the German Bight, with objects with high freeboard in the south and objects with less or no freeboard further north. Denmark is situated in the centre of this coastal deposition line and receives a high share (about 40%) of particles irrespective of the wind drag coefficient. Consequently, the western coast of Denmark appears to be a major sink region for floating marine debris in the German Bight. However, the deposition of particles on the shore is a simplifying assumption as the actual behavior of floating objects in complex and turbulent coastal currents cannot be modelled yet. Moreover, the final deposition pattern along the coast is probably influenced by resuspension of stranded items which is not considered in our drift trajectory model. However, Thiel et al. (2003) observed that a large fraction of the litter found in coastal waters in the SE Pacific was of local origin indicating that objects floating in coastal waters unlikely escape to offshore waters but have a high probability of being washed on the nearby shore.

The trajectory and the destination of a floating object strongly depend on its buoyancy and persistence at the sea surface (Thiel & Gutow 2005). Loss of buoyancy and sinking of floating litter can be accelerated by biofouling when colonizing organisms enhance the specific gravity of an object (Ye & Andrady 1991) especially in objects with a high surface:volume ratio (Chubarenko et al. 2016). Submerged objects are more densely colonized by fouling organisms than objects with large freeboard that substantially extent above the sea surface (Bravo et al. 2011). Accordingly, objects floating below the surface, such as plastic bags, are probably at particular risk of losing buoyancy. Similar to the results of Schönfeld (1995) our drift simulation showed that many particles with low wind drag coefficient are transported out of the German Bight and trapped for a considerable period of time in the Skagerrak. The extended residence time in the Skagerrak likely enhances the probability of local sinking and deposition on the seafloor. Already in the 1970s, Holmström (1975) reported on abundant plastic bags and foils on the seafloor of the Skagerrak. Typically, those plastic sheets showed considerable colonization by sessile organisms which have probably induced sinking. Accordingly, the Skagerrak and particularly its seafloor seem to represent another important sink for floating marine litter from the south-eastern North Sea.

Particles, which are released from the Skagerrak, are mostly transported northward along the Norwegian coast to exit the North Sea into the North Atlantic. Huge amounts of floating marine litter entering the North Atlantic in European waters are travelling towards the Arctic (Cózar et al. 2017). Depending on buoyancy, persistence and wind drag of the objects, floating marine litter from the German Bight may substantially contribute to the pollution of the sensitive Arctic marine ecosystem.

Factors explaining seafloor litter distribution

Our models did not confirm a correlation of the distribution of marine litter on the seafloor with any of the selected variables. Accordingly, a clear identification of the sources of benthic litter based on these results was not possible although the composition of the seafloor litter collected during our survey clearly hint at fisheries as a major source. This suggests that the distribution of seafloor litter in the south-eastern North Sea is rather governed by near-bottom transport processes rather than by the source regime and is corroborated by our finding that bottom shear stress influences the distribution of benthic litter. Schulz et al. (2015a) also suggested near-bottom transport to be an important process shaping the distribution of litter on beaches and on the seafloor of the south-eastern North Sea. Considerable near-bottom transport is also indicated by the distribution of benthic litter on larger spatial scales. Pham et al. (2014) observed particularly high densities of benthic litter in submarine canyons indicating re-mobilization of benthic litter by near-bottom currents and movements down the slope of the seafloor.

Conclusions

Our survey together with the results from model simulations allowed for identifying important sources, distribution and trajectories of marine litter in the south-eastern North Sea. Similar to findings from previous studies we identified fisheries as a major source especially of seafloor litter. Therefore, reducing the input of litter from fisheries would substantially reduce the rapid accumulation of litter in the North Sea environment.

The distribution of floating litter in the North Sea is primarily determined by the origin of the litter whereas the destination and final deposition is strongly dependent on the wind drag coefficient of the litter items. Major rivers are releasing substantial amounts of floating litter into the south-eastern North Sea whereas the west coast of Denmark as well as the Skagerrak could be identified as major sink regions. Frequent clean-ups of the Danish coastline would allow for the removal of substantial amounts of litter from the marine environment. There is common agreement that the unselective extraction of litter with heavy gear can induce substantial damage to sensitive marine ecosystems. However, the negative environmental implications may be minimized by the strategic and careful removal of stranded litter from easily accessible coastal locations where litter is known to accumulate.

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Supplementary material

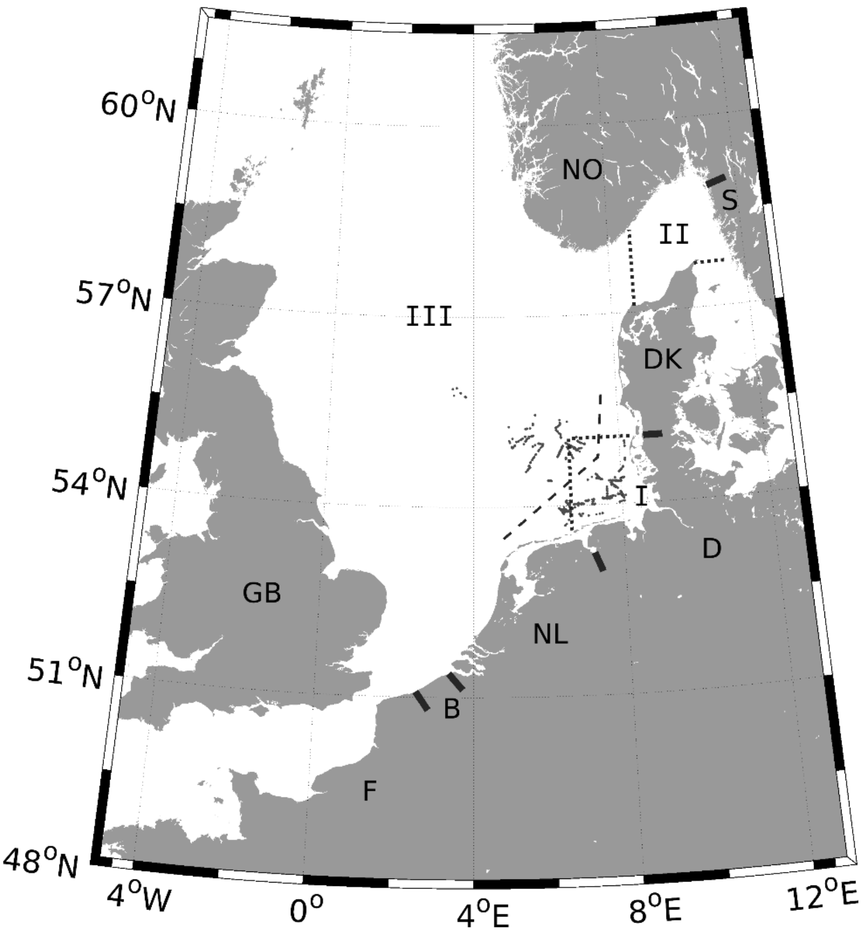


Figure S1 Map of the North Sea. Small dots in the south-eastern North Sea denote the positions where floating litter items were observed during the survey. Floating objects of the nearshore cluster and the offshore cluster are separated by the major salinity front of the German Bight (dashed line). Borders between marine regions (I: German Bight, II: Skagerrak, III: wider North Sea) are indicated as dotted lines. National frontiers between coastlines of different countries are indicated as bold black marks.

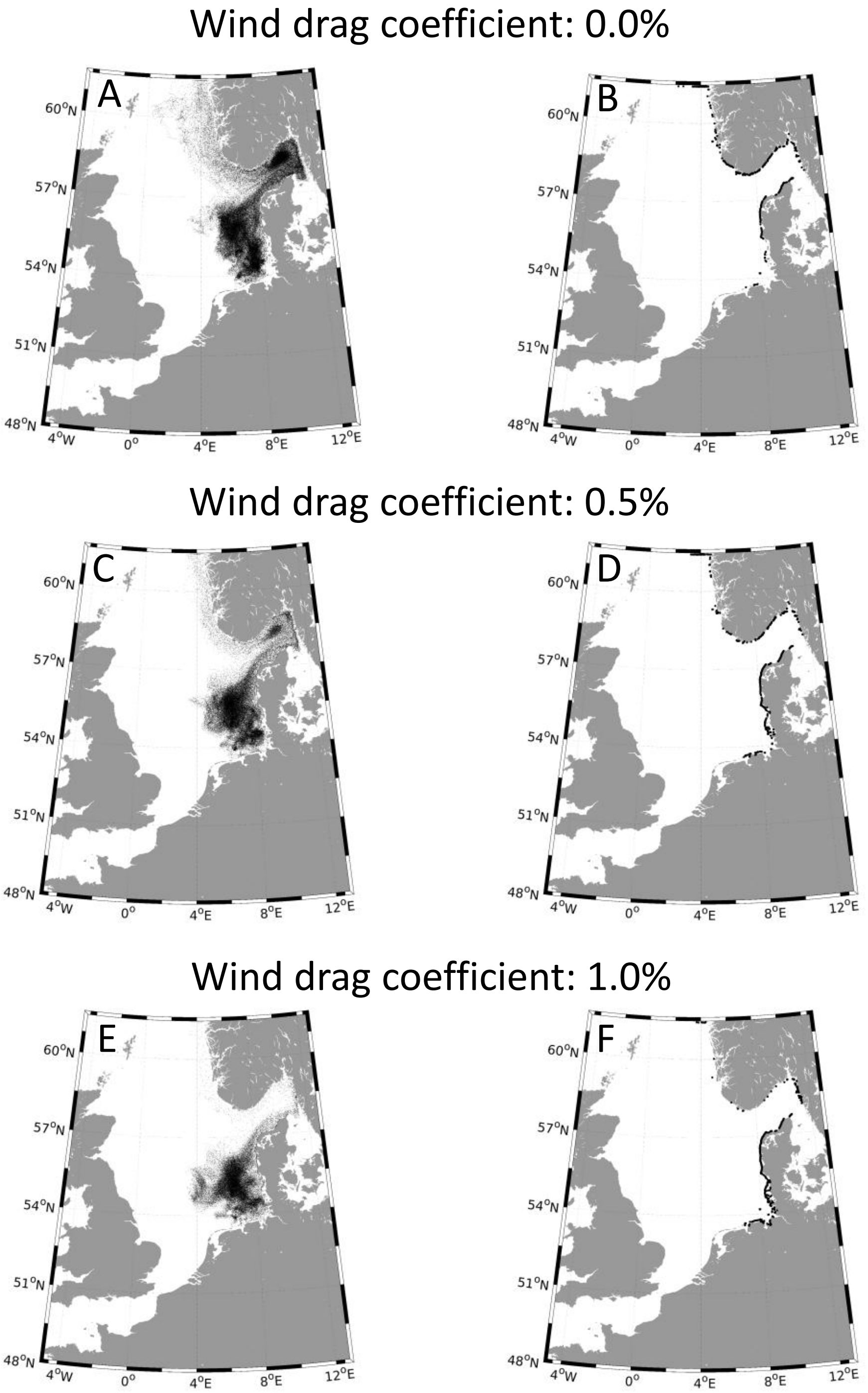


Figure S2 Results of the forward drift simulation of all 772 Lagrangian particles in the North Sea: trajectories (A,C,E) and sites of deposition (B,D,F) of particles using different wind drift coefficients (A,B: 0.0%; C,D: 0.5%; E,F: 1.0%)

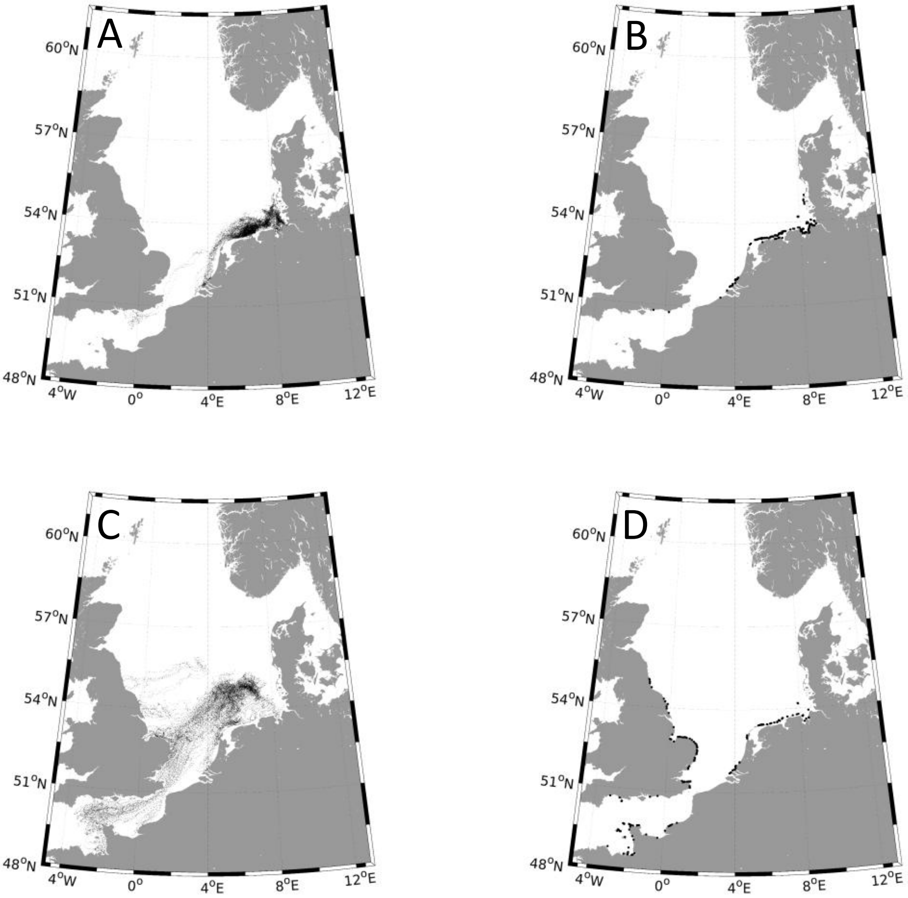
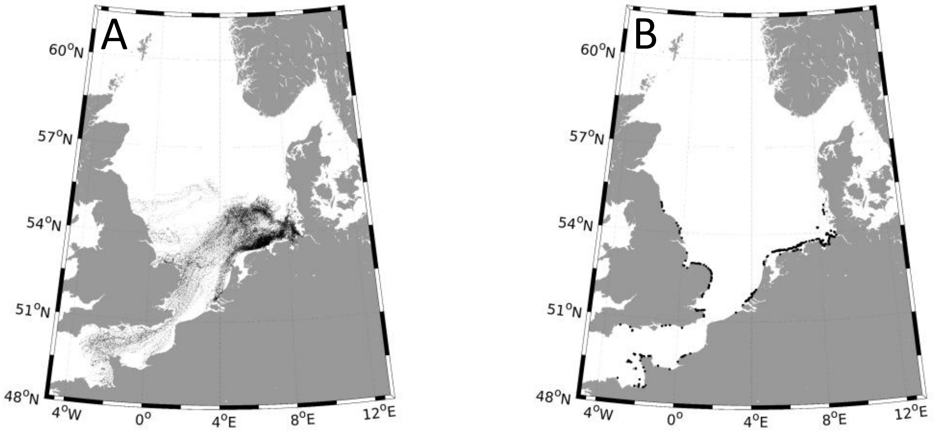
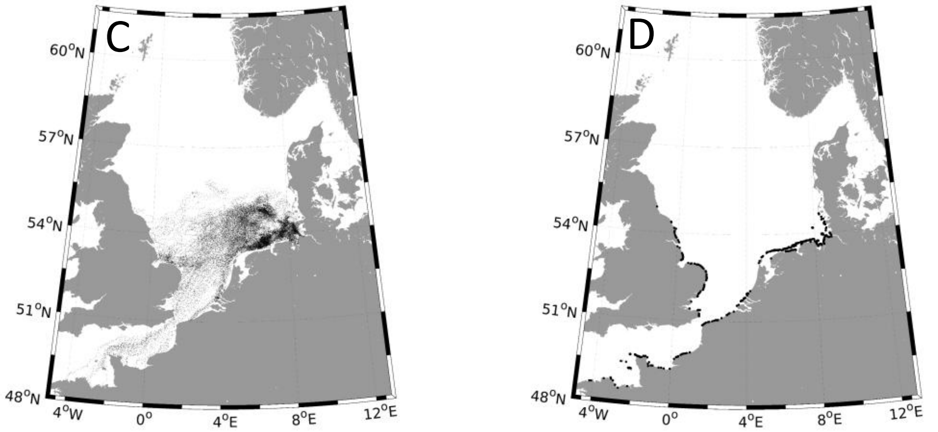


Figure S3 Results of the backward drift simulations of Lagrangian particles in the North Sea: A) backward trajectories for particles observed in the nearshore cluster, B) backward trajectories for particles observed in the offshore cluster, C) computed source (or starting) point for the particles later observed in the nearshore cluster and D) same as in C) but for the offshore cluster. Both simulations used a wind drag coefficient of 0.0%.

Wind drag coefficient: 0.0%



Wind drag coefficient: 0.5%



Wind drag coefficient: 1.0%

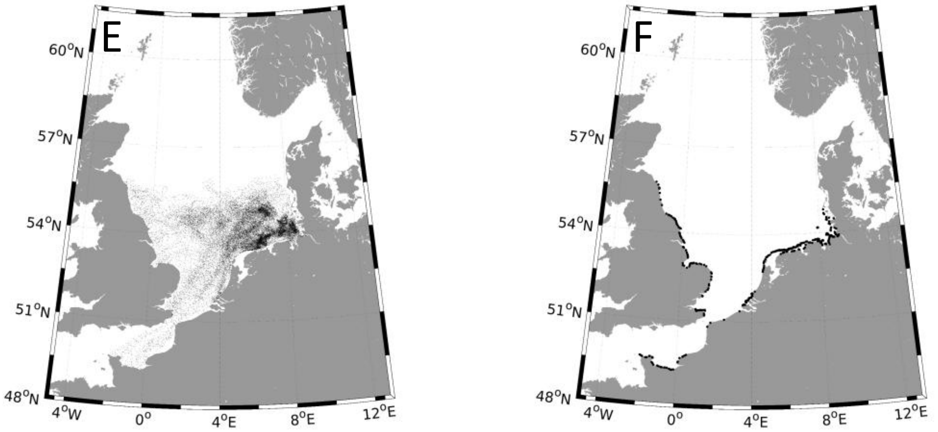


Figure S4 Results of the backward drift simulations of all 772 Lagrangian particles in the North Sea for different wind drag coefficients: (A,C,E) backward trajectories and (B,D,F) computed source (or starting) point of the particles representing observed floating litter items. Wind drag coefficients in those simulations are 0.0% (A,B), 0,5% (C,D) and 1.0% (E,F).

Animation S5 Drift animation of Lagrangian particles discharged by major rivers into the southern North Sea. Particles are released at intervals of 12 h and wind drag was set to 0.0%. The animation shows the particle positions every 24 h over a time period of 1 year. The velocity data input was the same as for the litter simulations. Beached particles are not resuspended but stay at the positions where they enter land.