Volume 65—issue 3 April 2011 ISSN 1385-1101

In Collaboration with
the Royal Netherlands Institute for Sea Research

JOURNAL OF SEA RESEARCH

CONTENTS

Journal of Sea Research 65 (2011) 368–379

Contents lists available at ScienceDirect

Journal of Sea Research

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

Spatio-temporal distribution of floating objects in the German Bight (North Sea)

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ARTICLE INFO

Article history:
Received 17 December 2010
Received in revised form 4 March 2011
Accepted 6 March 2011
Available online 13 March 2011

Keywords:
Floating algae
Driftwood
Anthropogenic debris
Dispersal
Rafting
North Sea

ABSTRACT

Floating objects facilitate the dispersal of marine and terrestrial species but also represent a major environmental hazard in the case of anthropogenic plastic litter. They can be found throughout the world's oceans but information on their abundance and the spatio-temporal dynamics is scarce for many regions of the world. This information, however, is essential to evaluate the ecological role of floating objects. Herein, we report the results from a ship-based visual survey on the abundance and composition of flotsam in the German Bight (North Sea) during the years 2006 to 2008. The aim of this study was to identify potential sources of floating objects and to relate spatio-temporal density variations to environmental conditions. Three major flotsam categories were identified: buoyant seaweed (mainly fucoid brown algae), natural wood and anthropogenic debris. Densities of these floating objects in the German Bight were similar to those reported from other coastal regions of the world. Temporal variations in flotsam densities are probably the result of seasonal growth cycles of seaweeds and fluctuating river runoff (wood). Higher abundances were often found in areas where coastal fronts and eddies develop during calm weather conditions. Accordingly, flotsam densities were often higher in the inner German Bight than in areas farther offshore. Import of floating objects and retention times in the German Bight are influenced by wind force and direction. Our results indicate that a substantial amount of floating objects is of coastal origin or introduced into the German Bight from western source areas such as the British Channel. Rapid transport of floating objects through the German Bight is driven by strong westerly winds and likely facilitates dispersal of associated organisms and gene flow among distant populations.

1. Introduction

Floating objects play an important role in various ecological processes and in species dispersal along the sea surface (Barnes and Milner, 2005; Williams et al., 2005; Thiel and Gutow, 2005a,b). Natural floating objects (e.g. seaweed and wood) and anthropogenic debris (e.g. plastics items) have been suggested as dispersal vectors for a wide range of species from marine and terrestrial environments (Ingólfsson, 1995; Barnes and Milner, 2005; Johansen and Hytteborn, 2001; Waters, 2008); recent molecular studies have added support to this view (Muhlin et al., 2008; Nikula et al., 2010). Anthropogenic floating objects (mainly plastic debris) may facilitate long-distance dispersal of invasive species, and furthermore impact marine wildlife (e.g. Gregory, 2009).

Floating objects occur throughout the world's oceans (Thiel and Gutow, 2005a) but their types, abundance and temporal occurrence are largely unknown for many regions of the world. Nevertheless, this information is essential to understand their seasonal dynamics and role in organism dispersal in a particular area (e.g. Hinojosa et al., 2010; 2011). Interestingly, various studies indicate that several types of floating objects are common along the coasts of NW Europe, and in particular in the North Sea, but no quantitative estimates of their spatio-temporal distribution are available. In the North Atlantic, rafting on floating objects has been repeatedly inferred as a common dispersal process for marine organisms (e.g. Ingólfsson, 1995; Vandendriessche et al., 2006). It was suggested to explain the occurrence of apparently disjoint populations and/or the (re)colonization of isolated shores by marine invertebrates without a planktonic larval stage (Johannesson, 1988; Johannesson and Warmoes, 1990; Ingólfsson, 1992; Thiel and Haye, 2006). Molecular studies have added support for the rafting hypothesis. For example, European and North American populations of the isopod *Idotea baltica* are closely related to each other, suggesting rafting dispersal across the North Atlantic (Wares, 2001). Similarly, Muhlin et al. (2008) found that in the Gulf of Maine (NW Atlantic) reproductive fragments of *Fucus vesiculosus* floating in coastal currents can explain the genetic pattern of this intertidal seaweed. For the North Sea coasts, Reusch (2002) suggested that rafting shoots of *Zostera marina* can explain the low genetic variability among populations of this seagrass (distance <150 km, see also Olsen et al., 2004). While rafting appears to be an important dispersal processes in the North Atlantic and in adjacent seas (Gulf of Maine, North Sea), it is not known on what type

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doi:10.1016/j.seares.2011.03.002

of floating objects organisms are dispersed and whether there are time periods of high flotsam abundances when rafting dispersal is more likely. Herein we examine the type and spatio-temporal distribution of both natural and anthropogenic floating objects in the south-eastern part of the North Sea (German Bight) in order to identify possible sources and accumulation areas.

The dynamics of floating objects in a particular area are determined by different factors, namely (i) size and location of sources (e.g. seaweed beds, rivers, fishery and shipping activity), (ii) temporal supply dynamics (e.g. annual growth seasons for vegetation or river runoff for wood and litter) (Kingsford, 1992; Johansen, 1999; Hirata et al., 2001; Moore et al., 2002), (iii) their floating potential at the sea surface (Barnes and Fraser, 2003; Vandendriessche et al., 2007; Rothäusler et al., 2009), and (iv) winds, currents and other hydrographic features such as frontal systems that drive dispersal, accumulation and sink processes (Valle-Levinson et al., 2006; Komatsu et al., 2007; Pichel et al. 2007; Astudillo et al., 2009; Martinez et al., 2009). In the German Bight floating wood and anthropogenic debris come through the major rivers, and supply may vary during the year due to seasonally varying river runoff. Vauk and Schrey (1987) suggested that merchant ships passing through the southern German Bight are another important source of floating litter. Dense seaweed populations growing on the rocky island of Helgoland, on mussel beds in the Wadden Sea area, and on artificial shore defenses and harbor structures (Munda and Markham, 1982; Reichert and Buchholz, 2006; Reichert et al., 2008) are local sources of floating algae which originally grow on solid benthic substrata. Seasonal or interannual growth dynamics of seaweeds (Munda and Markham, 1982; Hartnoll and Hawkins, 1985) are expected to produce seasonal patterns in the supply of floating alga (Hirata et al. 2001).

While a substantial amount of flotsam has its origin in the German Bight, there is indication that some floating objects enter the area from elsewhere. For example, floating specimens of the seaweed *Himanthalia elongata* collected near Helgoland were overgrown by algal epiphytes that are common in Brittany and southern England, suggesting that they came from sources in the British Channel (Bartsch and Kuhlenkamp, 2000; see also Cadée, 2002). The occasional immigration of the obligatorily rafting isopod *Idotea metallica* into the German Bight has been related to the appearance of floating algae and litter from the North Atlantic (Franke et al., 1999). The large number of local and distant sources for floating objects found in the German Bight suggests that this area functions as a retention zone.

Once afloat in the German Bight, floating objects are subject to the effects of wind and currents, which might transport them out of the system or accumulate them in particular areas. For example, Franke et al. (1999) observed accumulations of floating algae and anthropogenic debris around Helgoland. Dixon and Dixon (1983) described a distinct distribution of marine litter in the surface waters of the North Sea, composed mainly of plastics, with highest abundances in coastal waters and in the central North Sea. Litter accumulations are also found on the seafloor of the eastern-central North Sea (Galgani et al., 2000). These specific accumulation patterns of floating objects and sunken litter indicate that wind and oceanographic features such as frontal zones modulate the distribution of flotsam in the German Bight (Galgani et al., 2000), similar as observed in other regions (Acha et al., 2003).

The present study is a first step in revealing the processes that drive the distribution and occurrence of floating objects in the German Bight. The aim of this study is to evaluate the types, potential sources and spatio-temporal variability of floating objects in relation to wind and current patterns in the study area.

2. Materials and methods

2.1. Study area

The North Sea is a shallow, semi-enclosed shelf sea of the North Atlantic with a surface area of 575,300 km² (ICES, 1983; Fig. 1). Oceanic waters enter the North Sea mainly from the north between the Shetland Islands and Norway. Two main water bodies can be distinguished in the North Sea (Otto et al., 1990). The northern and central part is under strong oceanic influence and characterized by surface salinities above 34 psu (Weichart, 1986; Huthnance, 1991) and seasonal stratification (Pingree et al., 1978). The southern part is continentally influenced and permanently well mixed. It receives oceanic water mainly through the British Channel. Salinity is lower in coastal waters due to strong river runoff. In the Wadden Sea area salinity varies considerably around 30 psu and can be influenced by for example strong storm events (Reuter et al., 2009). The oceanic water masses of the central North Sea are separated from shallow coastal waters by frontal systems. The semi-diurnal tidal

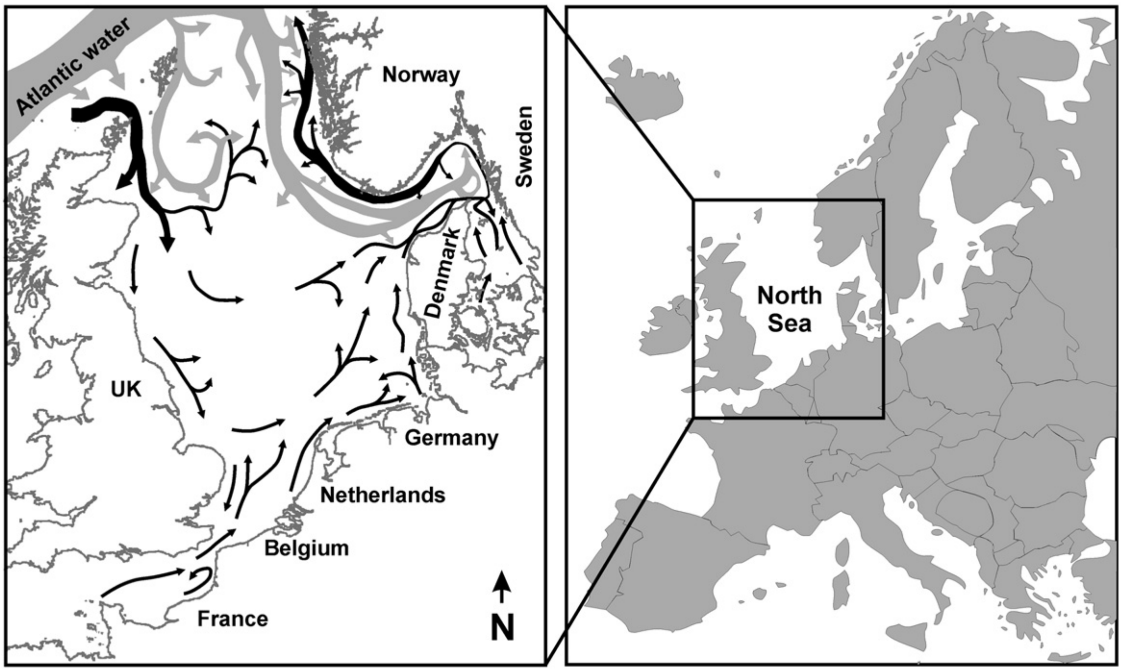

Fig. 1. Main current patterns in the North Sea and in the German Bight (based on Pohlmann, 2006).

motion is the dominant force that, in concert with other forces, drives the anti-clockwise residual circulation along the North Sea coasts (Otto et al., 1990; Pohlmann, 2006). Winter sea surface temperatures decrease from between 5 and 7 °C in the northern and central North Sea to 3 °C in the German Bight. In summer, surface waters reach up to 18 °C in the coastal waters of the German Bight and 13–15 °C in the northern and central North Sea (Elliott et al., 1991).

The German Bight in the south-eastern North Sea extends from the East and North Frisian German Wadden Sea coast towards the White Bank (55°00 N; 6°00 E) in the north-west. The German Bight receives oceanic water from the British Channel (Heyen and Dippner, 1998), but also from the northwestern North Sea (Pohlmann, 2006). During transport along the Wadden Sea coasts the water masses are under strong riverine influence. Runoff from the rivers Rhine, Meuse, Ems, Weser, Elbe and Eider reduces the salinity of the coastal waters. Main freshwater discharge into the German Bight is from the river Elbe at a rate of ~1000 $m^3 s^{-1}$ (Dippner, 1993). Salinities increase from below 30 psu in front of river outlets to 31–32 psu at about 30 km distance from the coast. At Helgoland (i.e. about 50 km offshore) salinity fluctuates inter-annually between 31 and 33 psu (Wiltshire et al., 2008) while at about 75 km offshore the long-term mean salinity is >33 psu (Heyen and Dippner, 1998). The White Bank area is under the influence of central North Sea waters with relatively stable salinities of 34–35 psu (Skov and Prins, 2001). In the north-eastern sector, water moves from the German Bight into the northern North Sea and into the Skagerrak (Fig. 1).

The hydrography of the German Bight is characterized by strong mesoscale variability with numerous transient fronts, meanders and eddies resulting from the complex bottom topography and unstable meteorological conditions (Becker and Prahm-Rodewald, 1980; Becker et al., 1992; Dippner, 1993, 1998). Two major frontal systems separate the more haline central North Sea water of the outer German Bight from the estuarine coastal waters along the 30 m depth contour (Krause et al., 1986; Budéus, 1989; Becker et al., 1992). A permanent front is generated by the plume of the river Elbe off the North Frisian coast (Krause et al., 1986; Dippner, 1993; Skov and Prins, 2001). A thermal front occurs seasonally parallel to the East Frisian coastline (Krause et al., 1986; Budéus, 1989; Dippner, 1993). Eddy transport across frontal boundaries allows for exchange processes between the water bodies (Becker et al., 1992; Dippner, 1998). Wind direction and speed strongly influence currents and transport processes in the German Bight (Huthnance, 1991). Easterly winds promote the formation of the North Frisian gyre, and of a large cyclonic circulation in the central German Bight, which has substantial influence on the distribution and residence time of pollutants in the south-eastern North Sea (Dippner, 1993). Westerly winds prevail with an average speed of 9 $m\,s^{-1}$ in winter and 6 $m\,s^{-1}$ in summer (Siegismund and Schrum, 2001). On average, one or two major annual storm events occur over the North Sea (Weisse et al., 2005), and these likely have a strong influence on the spatio-temporal distribution of floating objects.

2.2. Abundance estimation of floating objects

The composition and abundance of floating objects were estimated by ship surveys in the German Bight between summer 2006 and summer 2008 from aboard RV *Heincke* (Fig. 2). In spring, summer and autumn we quantified flotsam on a variable number of random transects (Table 1). Three main sectors within the German Bight were surveyed: Helgoland (HEL), East Frisia (EF) and White Bank (WB) (Fig. 2).

One observer surveyed the sea surface from the bearing deck of the research vessel, which is situated above the bridge at ~11 m above sea level and ~20 m behind the bow. Observations were done during regular navigation of the ship at a speed of 5–12 knots. The observer recorded the type and position of floating objects passing on one side of the ship. The side of the ship that was surveyed was chosen according to the visibility conditions (sun angle, wind direction, sea state, etc.). Floating objects that were at a perpendicular distance of ~20 to ~70 m from the ship were recorded. We excluded the area close to the ship (0 to ~20 m) because of strong turbulences in the bow wave of the vessel. We did not survey distances beyond 70 m from the ship in order to avoid a bias in the flotsam composition through underestimation of small objects. However, a certain underestimation, particularly of small objects at the outer edge of the transect, is probably unavoidable. Transect width was controlled by estimating the distance between the ship (i.e. observer position) and the closest and the farthest transect edge from known distances such as ship length and width. Binoculars were used for identification of floating objects but not for searching. No data were collected during adverse weather conditions such as rain, wind >50 km h^{-1} and waves

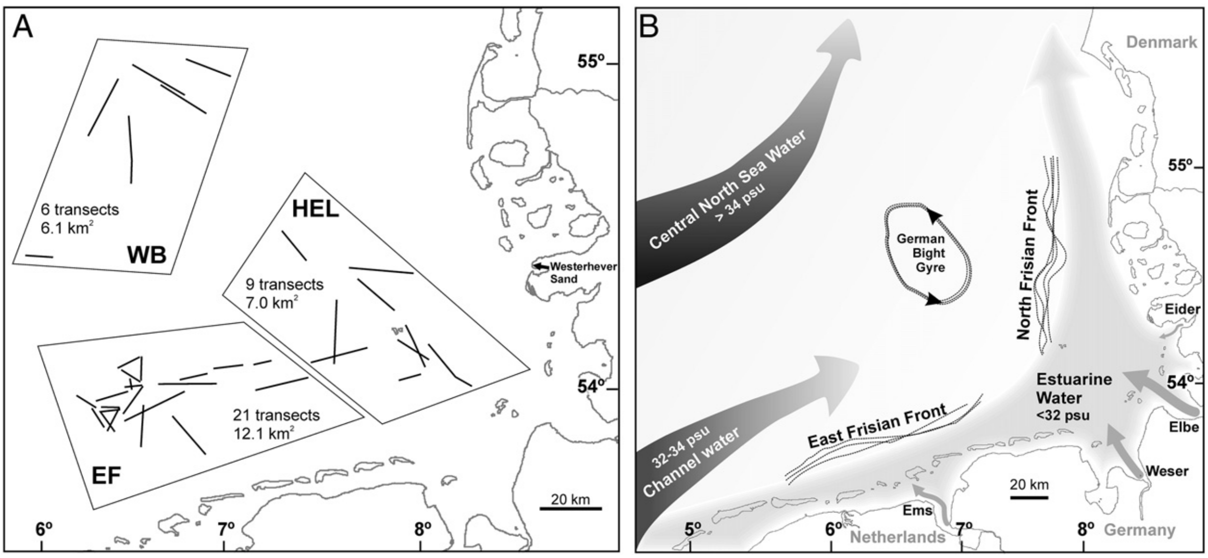

Fig. 2. (A) Flotsam survey transects in the three study sectors (WB = White Bank, EF = East Frisia, HEL = Helgoland) of the German Bight. The total number of transects and the total surveyed area are indicated for each sector. (B) Main water bodies and frontal systems in the German Bight.

Table 1

	2006		2007				2008			
	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	TOTAL
HEL	3	1		4		1				9
EF	5				3	1		8	4	21
WB	2	1		1	1			1		6
TOTAL	10	2		5	4	2		9	4	36

Number of surveyed transects in the German Bight during different seasonal survey periods in each sector (HEL; EF and WB). Gray areas indicate that no surveys are available for those seasons.

when the detection probability of floating objects within the transect width was severely compromised.

We used the strip transect method to calculate the density of floating objects for each transect (for further details see also Hinojosa et al., 2011). Based on the number of items counted and the area surveyed (transect width multiplied with transect length), densities were estimated by the following equation:

$$D = N / ((W / 1000) \times L)$$

where N is the number of floating objects, W the width of the transect (i.e. 50 m, see above), and L the total length (in km) of the transect. The beginning and the end of each search transect were recorded with a handheld GPS. Additionally, we recorded the GPS position of each sighted object. The transect length was estimated by adding the distance between each position recorded using the Arcview 3.3 software with the “Albert Equal-Area Conic” projection with a “Sphere” as a spheroid.

The total number of surveyed transects varied seasonally for each sector (HEL, EF and WB) from 1 to 8 (Table 1). We distinguished three major types of floating objects: seaweed, natural wood and anthropogenic debris. The species of floating seaweeds were identified whenever possible. It was impossible to distinguish individual taxa when seaweeds occasionally aggregated at the sea surface. Floating algae were then classified as “other Phaeophyceae”, “Chlorophyta” or “undetermined algae”. We distinguished between natural and manufactured wood. Manufactured wood was included in floating anthropogenic debris in the category “other debris”. Floating anthropogenic debris was further sub-divided into the following categories: Styrofoam (expanded polystyrene), plastic bags (typical plastic grocery bags), plastic lines (principally polypropylene ropes), plastic fragments (fragments of various non-identified hard and soft plastic items >2 cm), other plastics (e.g. plastic dishes, plastic bottles, etc.) and other debris (manufactured wood, glass bottles, tetra packs, cigarette boxes, etc.).

To account for the different nature and potential sources we ran independent statistical analyses for each floating object type. Due to the variability in the number of surveyed transects in each sector we performed independent one way ANOVAs to evaluate the spatial (sectors as a factor) and seasonal (season as a factor) variability in the density of each floating object type. This design does not allow for a statistical evaluation of interactions between the two factors. In order to meet the assumptions of parametric ANOVAs, normality and homogeneity of variances of the data sets were tested by Kolmogorov–Smirnov and Levene's test, respectively (Snedecor and Cochran, 1989). Equal variances were achieved by Log_{10} (x + 1) transformation of all data. In some cases, data transformation was unable to generate normality. In these cases, ANOVAs were performed on both, parametric and rank-transformed data (Kruskal–Wallis test), as suggested by Conover (1980). When results from both data treatments were consistent we presented the results from parametric tests only. Tukey's test was used to test for specific differences within a significant source of variation revealed by ANOVA (Zar, 1999).

2.3. Environmental data

To examine how environmental factors influence the temporal and spatial distribution of floating objects we used environmental data from official institutions. Hydrographic and meteorological data were sampled automatically by the German Federal Maritime Agency and the German Wind Energy Institute at the research platform FINO 1 in the German Bight at 54° 0.86′ N; 6° 35.26′ E. Wave direction and significant wave height were measured with a directional wave rider buoy. Current speed and direction were measured from the bottom to 2 m below the water surface with an Acoustic Doppler Current Profiler. Wind speed and direction were measured 33 m above sea level. Data on the runoff of the rivers Ems, Weser and Elbe were provided as daily averages ($m^3 s^{-1}$) by the Federal Institute of Hydrology, the Wasser- und Schifffahrtsverwaltung des Bundes, the River Basin Commission Weser, and the River Basin Community Elbe.

In order to examine the potential relationships of wind (velocity in $m s^{-1}$), waves (height in m) and river runoff ($m^3 s^{-1}$) with the density of floating items (seaweed, wood and debris; items km^{-2}), we conducted a redundancy analysis (RDA). All data were Log_{10} (x + 1) transformed for the RDA. This analysis examines the relationship between two sets of variables (i.e. the matrix of floating objects and the matrix of environmental factors) as summarized in a matrix of regression coefficients. The significance of each of the fitted factors was assessed using 999 permutations. The results of the RDA were visualized in a correlation bi-plot, in which the abundance of each floating object was standardized to zero mean and unit variance (Ter Braak and Looman, 1994). Environmental factors used for this analysis were based on average values from the days preceding the transect surveys. An average of ten days of runoff from the rivers Elbe, Weser and Ems (daily average) were used. Wind data were taken every 10 min throughout the study period. To estimate the maximum wind speed we averaged all values above the 90th percentile during the 5 days before the corresponding transect surveys; similarly, the average of significant wave height (measured every 30 min) was calculated for the 5 days preceding the survey. These average values of the environmental variables (river run off, maximum wind speed, and wave height) were used for the RDA; transects without wind data (April 2008) were not considered for this analysis.

Additionally, the relationship between the upper 10% of wind direction and speed during the 5 days before transect survey and the density of each floating object type was compared visually with the aid of a wind rose graph. For this we selected for each survey the 10% maximum measurements of wind velocities during the 5 days before each survey (one measurement every 10 min). If different surveys had the same wind directions, the averages of maximum wind velocities and floating object abundances were calculated for all surveys that fell within the same directional sector. For example, the wind came from the North (0° ± 11.25°) during the 5 day intervals preceding the surveys from 7th August of 2006; 11st August of 2007 and 22nd October of 2007, and thus for the wind rose graph the average values were calculated from the data corresponding to those surveys.

3. Results

3.1. Distribution of floating objects

3.1.1. Floating seaweed

Floating seaweed occurred on most transects regardless of season with densities ranging from 0 up to 1750 occurrences of seaweed km^{-2} (Fig. 3A). Only 3 out of the 36 surveyed transects had no seaweed. Densities of floating seaweed did not differ significantly between the three sectors (F = 0.565; DF = 2; Power = 0.049; P = 0.574). Highest densities (>500 seaweed items km^{-2}) were found around Helgoland (1750 pieces of seaweed km^{-2} in summer 2006) and in the East Frisian sector (550 and 1100 items of seaweed km^{-2} in spring 2008) (Fig. 3A).

Brown algae (Phaophyceae) dominated the floating seaweed community (Fig. 3B). We could distinguish four taxa of brown algae: *Fucus* spp., *Ascophyllum nodosum*, *Himanthalia elongata*, and *Sargassum muticum*. Among these, *Fucus* spp. (mainly *F. vesiculosus*) dominated with >90% in all three sectors. The proportion of the different algae showed little spatial variation (Fig. 3B), but *H. elongata* did not occur on White Bank.

3.1.2. Floating wood

Floating natural wood occurred on 13 out of 36 transects (36%). The densities were generally quite low but the differences between the sectors were statistically significant (Fig. 4; $F=3.769$; $DF=2$; Power $=0.500$; $P=0.034$). Average abundances of floating wood were highest around Helgoland (Tukey test; $P<0.050$) while abundances on White Bank were comparatively low (<5 items km^{-2}). The highest incidental abundance on a single transect occurred in the East Frisian sector in spring 2008 (16.4 items km^{-2}).

3.1.3. Floating marine debris

Floating marine debris was observed on almost all surveyed transects (Fig. 5A). Only a single transect had no floating debris. Densities did not vary significantly between the sectors ($F=0.093$; $DF=2$; Power $=0.049$; $P=0.912$). However, abundances of >50 items km^{-2} were mainly found around Helgoland and off East Frisia (Fig. 5A).

More than 70% of the floating debris was made up by floating plastic items (Fig. 5B). In particular, “plastic fragments” was the most common

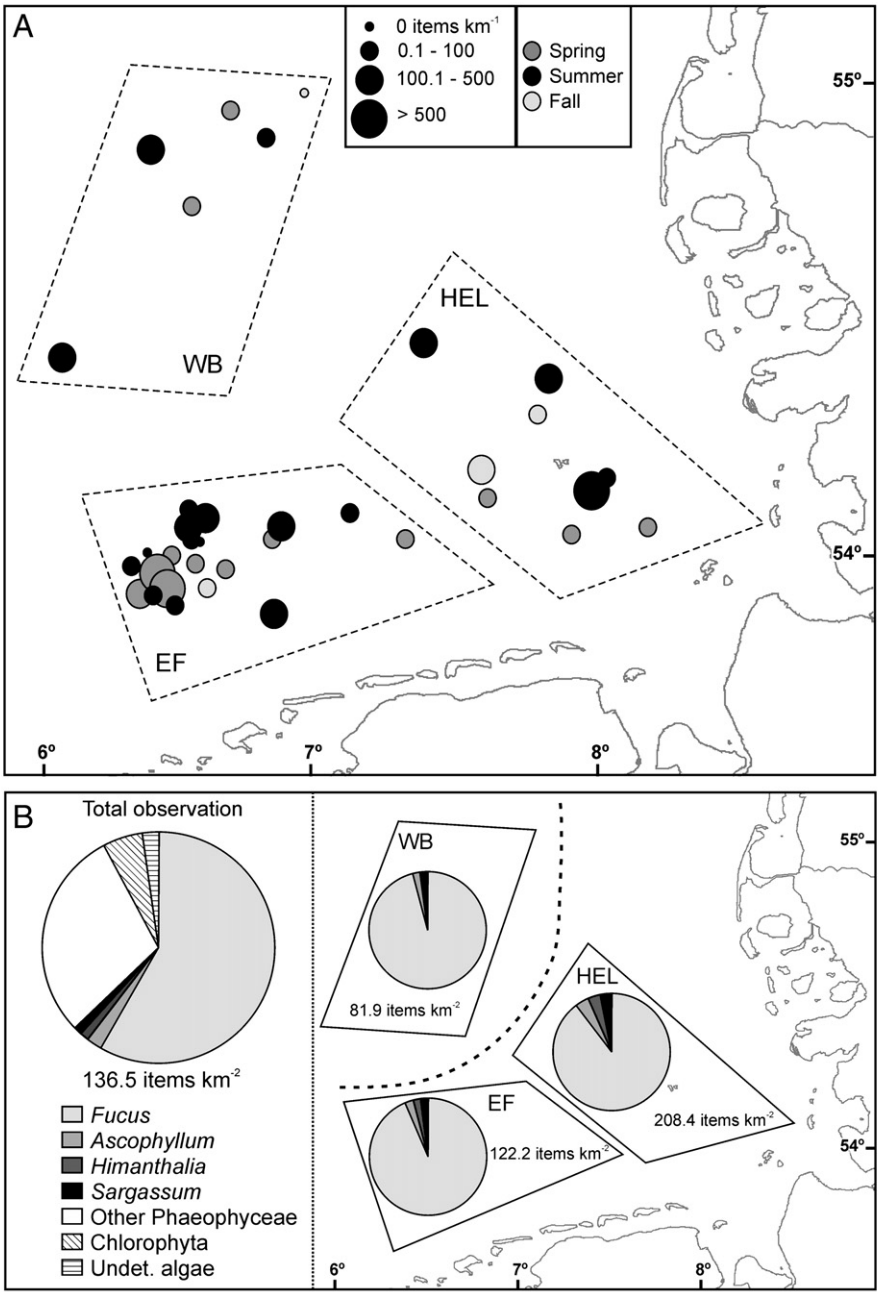

Fig. 3. (A) Seasonal densities (number of items km^{-2}) of floating seaweed on survey transects in the German Bight. (B) Species composition and overall mean densities of floating seaweed in the three study sectors (WB = White Bank, EF = East Frisia, HEL = Helgoland) of the German Bight.

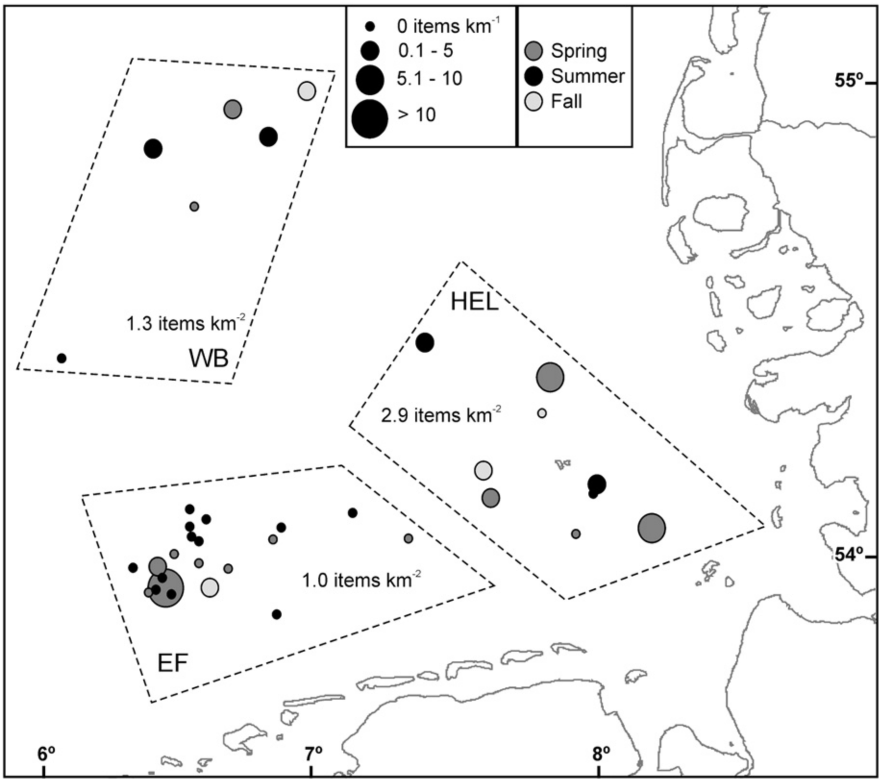

Fig. 4. Seasonal and overall mean densities (number of items km^{-2}) of floating natural wood on survey transects and within the three study sectors (WB = White Bank, EF = East Frisia, HEL = Helgoland) of the German Bight.

category. The abundance of "plastic fragments" showed some spatial variation and they were much less abundant on White Bank than around Helgoland and off the East Frisian coast. "Plastic lines" and "plastic bags" appeared more frequently on White Bank than in the other sectors.

3.2. Temporal variability of floating objects

Densities of floating seaweed in the German Bight were generally highest in spring and summer but exceptionally low in the summer of 2007 ($F = 3.574$; $df = 6$; Power = 0.761; $P = 0.009$; Fig. 6). Abundances of floating algae differed between summer 2006 and summer 2007 (Tukey test; $P < 0.050$) but not between summer 2006 and summer 2008 (Tukey test; $P > 0.050$). Densities of floating natural wood tended to vary seasonally ($F = 2.061$; $df = 6$; Power = 0.344; $P = 0.089$) with elevated densities in spring and low densities in summer. Floating natural wood was relatively abundant in 2007 while densities were low in 2008. Densities of floating marine debris were similar for all seasons ($F = 0.509$; $df = 6$; Power = 0.049; $P = 0.796$) but highest in spring 2008.

3.3. Environmental factors influencing the densities of floating objects

Wind, waves and river runoff had an influence on the abundance of floating items in the German Bight (Fig. 7). The RDA indicated that during time periods with high wind speeds the abundances of floating algae and debris were low. Clearly, the highest density of floating seaweed was found during surveys accompanied by relatively low wind speeds ($6\ m\ s^{-1}$) and mostly associated with northern winds (Fig. 8). In contrast, when winds came from the southwest at higher speeds ($12\ m\ s^{-1}$) the abundance of floating seaweed was generally low (Fig. 8). Floating wood showed a strong relationship with the runoff from the three main rivers flowing into the German Bight (Fig. 7). Higher abundances of floating wood were also associated with winds coming from the east (Fig. 8). The abundances of floating debris were not related to one particular pattern of wind direction; high densities were observed during time periods with winds from WNW and from ESE (Fig. 8).

4. Discussion

4.1. Abundance, distribution, composition and temporal variability of floating objects

4.1.1. Floating seaweed

The abundance of floating seaweed in German Bight was similar to those in coastal waters from other regions. We observed densities ranging from 1 to more than 1000 items km^{-2}, which is comparable to values reported from the fjords of Southern Chile (Hinojosa et al., 2010) and coastal waters of California (Kingsford, 1995), New Zealand (Kingsford, 1992) and Japan (Segawa et al., 1960). Despite previous reports of floating seaweed and their associated fauna from the North Sea (Franke et al., 1999; Vandendriessche et al., 2006) the abundances of these items had so far not been estimated for this area. We found highest abundances of floating seaweed to the south-east of the island of Helgoland and in the western area off the East Frisian coast. Accumulations of floating objects around Helgoland Island had previously been mentioned by Franke et al. (1999). The high densities in waters near Helgoland could be related to accumulations in the quasi-stable estuarine front in this area (Skov and Prins, 2001, Fig. 1), while the accumulation in the western area of the East Frisian sector might also receive input of floating seaweeds from the British Channel (see also Vandendriessche et al., 2006).

The origins of floating seaweed can be inferred from the relative proportion of each species. For example, Vandendriessche et al. (2006) found approximately equal proportions of *Fucus* spp. (33%), *A. nodosum*

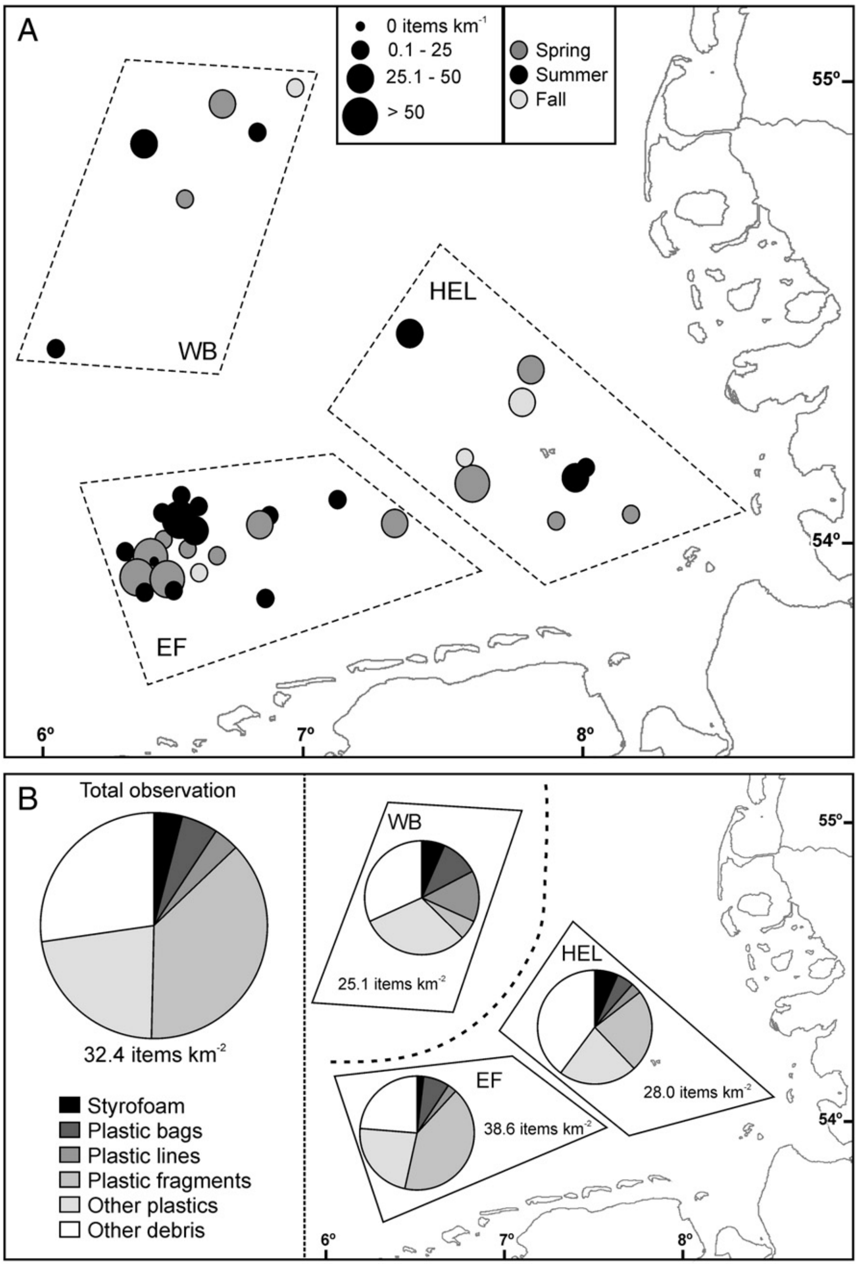

Fig. 5. (A) Seasonal densities (number of items km^{-2}) of floating anthropogenic debris on survey transects in the German Bight. (B) Composition and overall mean densities of floating anthropogenic debris in the three study sectors (WB = White Bank, EF = East Frisia, HEL = Helgoland) of the German Bight.

(31%), and *S. muticum* (22%) in Belgian coastal waters (SW-North Sea), while we observed >90% *Fucus* spp. in all three sectors of the German Bight. The higher proportion of *Fucus* spp. in our study might suggest that species from this genus persists longer at the sea surface than the other seaweeds and/or accumulate in the German Bight. However, both *A. nodosum* and *F. vesiculosus* survive for similar time periods at the sea surface (Vandendriessche et al., 2007). Gutow (2003) also found that associated herbivores consume detached *F. vesiculosus* and *A. nodosum* at similar rates. Thus, the high proportion of *Fucus* spp. in the German Bight is most likely not due to differential survival but rather due to high local supply of this seaweed. The relatively low proportions of *A. nodosum* and *S. muticum* in all three study areas suggest that the supply of seaweeds from Helgoland, where *A. nodosum*, *S. muticum* and *Fucus* spp. grow in dense populations (Kornmann and Sahling, 1977; Munda and Markham, 1982; Bartsch and Kuhlenkamp, 2000), only contributes a minor fraction of the standing stocks of floating seaweeds in the German Bight. Instead, the high proportion of *Fucus* spp. may be supplied from the Wadden Sea area where this seaweed grows abundantly on mussel beds, harbor piers and shore defenses (Fig. 9).

The higher proportion of *A. nodosum* and *S. muticum* observed in Belgian coastal waters (Vandendriessche et al., 2006), as well as the higher abundances of these species in the western area of the East Frisian sector most likely indicate an origin from the British Channel. Similarly, Kornmann and Sahling (1977) also inferred that *H. elongata*, stranded on Helgoland in late summer, probably comes from sources in the British Channel because this seaweed often harbors algal epiphytes that are common in Brittany and southern England. The import of floating seaweed from the British Channel is likely supported by a strong coastal current that is also responsible for intensive gene flow among populations of eelgrass *Zostera marina* along the Wadden Sea coast (Ferber et al., 2008).

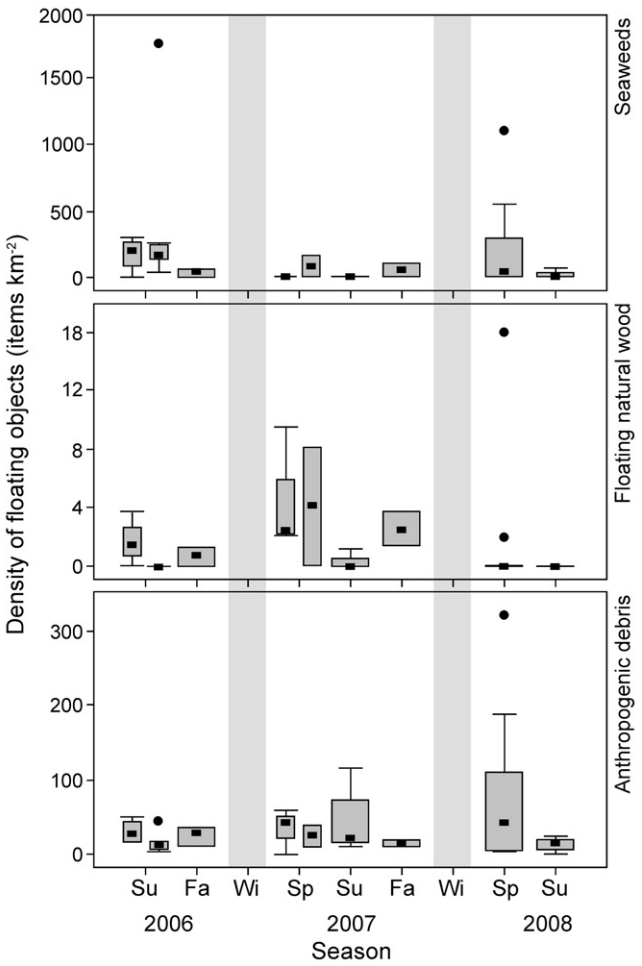

Fig. 6. Seasonal density variations of floating seaweed, natural wood and anthropogenic debris in the German Bight between summer 2006 and summer 2008. Gray areas indicate seasons without surveys.

The seasonal variations of floating seaweed abundances in the German Bight were similar to those reported from other regions (Thiel and Gutow, 2005a). The highest abundances during spring and summer months were closely linked to seasonal seaweed growth cycles. Similar observations come from Japanese waters where abundances of floating *Sargassum* spp. were highest during the main growth season of the benthic sporophytes in spring and early summer (Hirata et al., 2001). The high abundances of floating seaweed in spring are possibly also due to growth on inadequate substrata (small stones or mollusk shells) that lead to rapid detachment from benthic substrata, similar as suggested for other floating algae (Hinojosa et al., 2010). Detachment of *Fucus* spp. during summer might be a part of the reproductive strategy of these species.

Besides seasonal oscillations we found interannual variations in the amounts of floating seaweed. Strong interannual fluctuations, as reported for benthic populations of *F. vesiculosus* in NW Europe (Hartnoll and Hawkins, 1985), might explain the lower abundances of floating seaweed in 2007.

4.1.1.1. Floating wood. Abundances of natural floating wood were relatively low in the German Bight, but are comparable to abundances reported from other regions. For example, along the Patagonian coast Hinojosa et al. (2011) reported average abundances of ~10 items km^{-2}. In the open N Pacific abundances of floating wood are usually <1 item km^{-2} (Matsumura and Nasu, 1997; Pichel et al., 2007).

The slightly enhanced abundances of floating wood near Helgoland (similar as for seaweed—see above) are probably related to accumulations close to the North Frisian front (Skov and Prins, 2001; Fig. 1). Intermediate abundances on the White Bank indicate a continuous transport of wood from coastal supply sites to the outer German Bight. This appears to be in contrast to the above suggestion that offshore areas in the German Bight are separated from the coastal areas through frontal systems, but it is also possible that floating wood comes from western sources. The high abundance of floating wood in the western part of East Frisia (Fig. 4) also suggests a potential input from the British Channel or from the river Rhine. Thus, floating wood in the German Bight appears to come from local (the Elbe, Weser and Ems rivers) and distant sources (British Channel or Rhine river). In order to identify source regions, future studies might apply dendrochronological techniques (Johansen and Hytteborn, 2001), histology (Pailleret et al., 2007), or molecular approaches (Hurr et al., 1999).

The higher abundance of floating wood during spring surveys is related to increased river runoff during that season (Fig. 7). This relationship between seasonal variation of river runoff and the amount of floating wood is commonly observed (e.g. Caddy and Majkowski, 1996; Hinojosa et al., 2011).

4.1.2. Anthropogenic marine debris

Anthropogenic debris is commonly found on the shorelines and beaches of the German Bight (Vauk and Schrey, 1987; Fleet, 2003). The abundances observed in the present study (0 to >300 items km^{-2}) are higher than those reported by Dixon and Dixon (1983) for the North Sea (0 to >3 items km^{-2}). This is possibly due to methodological differences (their ship traveled twice as fast as our ship) but abundances of floating litter might also have increased over the past 25 years. Regardless of these differences, litter abundances in our study were similar to those reported in other coastal regions (e.g. Thiel and Gutow, 2005a; Barnes et al., 2009). Abundances were slightly lower on White Bank than in the East Frisia and Helgoland areas, which appears to parallel distribution patterns observed in other regions, where floating litter is often more abundant in coastal waters (Ryan, 1988; Thiel et al., 2003).

Floating debris in the German Bight is dominated by plastics (Vauk and Schrey, 1987; Fleet, 2003; see also Fig. 5), similar as in the remaining North Sea (Dixon and Dixon, 1983) and in other oceanic areas of the world (Thiel and Gutow, 2005a; Barnes et al., 2009). The high longevity

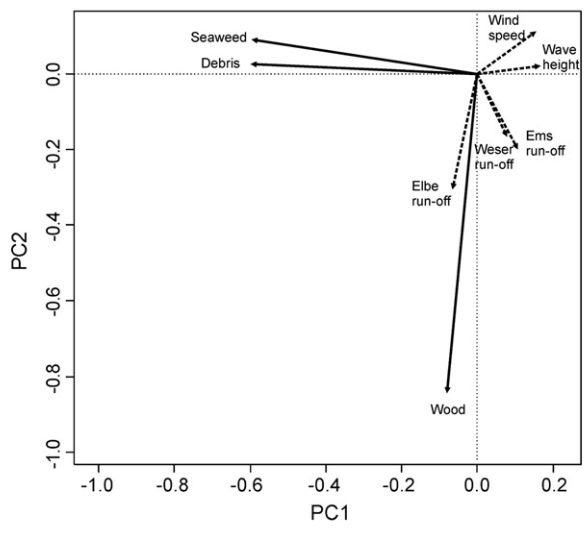

Fig. 7. Redundancy analysis (RDA) explaining density variations of floating objects (seaweed, anthropogenic debris and natural wood) on transects in the German Bight. Environmental factors are an average of the days preceding the transect surveys. An average of ten days before the surveys was used for the runoff data from the rivers Elbe, Weser and Ems (daily average m^3 s^{-1}). For wind speed (measured every 10 min, m s^{-1}) an average of the 10% highest velocities during the 5 days before the transect surveys was used and for significant wave height (measured every 30 min, m) we considered the average for the 5 days before the survey.

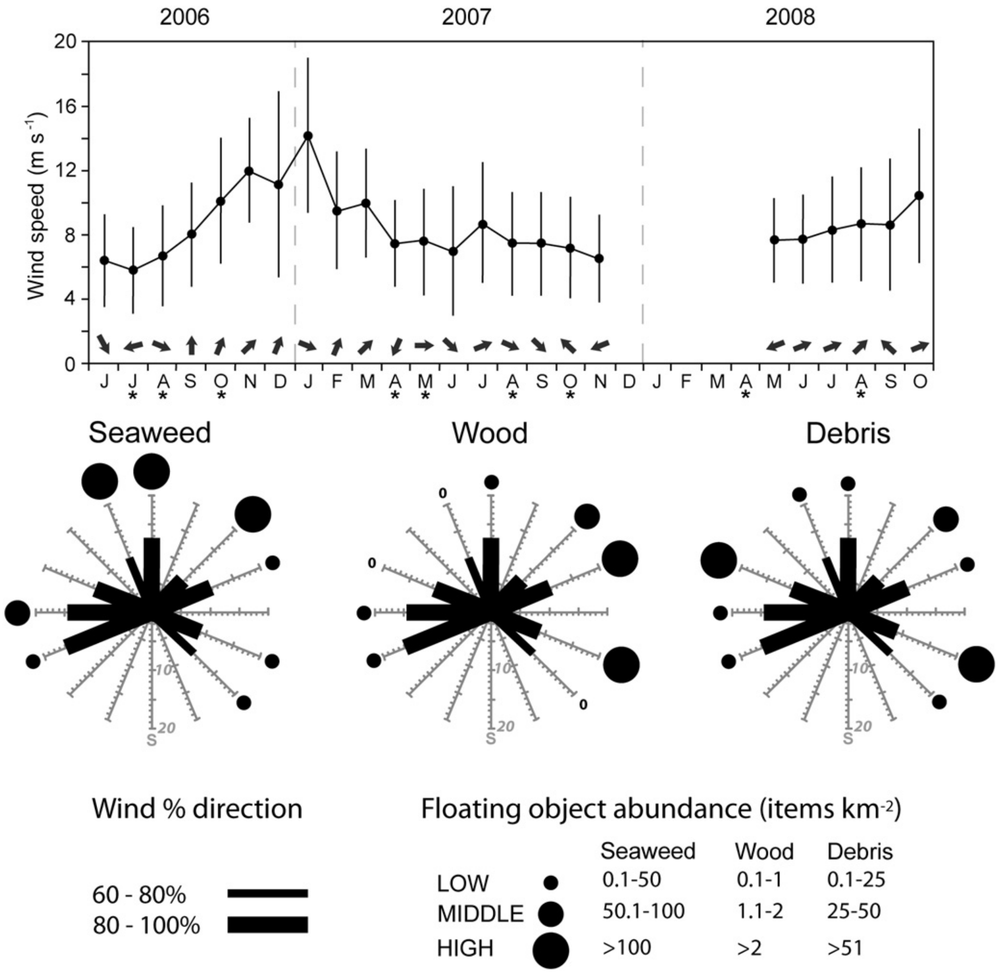

Fig. 8. Monthly average wind-speed in the German Bight (measured at the research platform FINO 1 in the German Bight at 54° 0.86′ N; 6° 35.26′ E). Arrows indicate the monthly average wind direction. Wind roses represent the main wind direction and speed registered during the 5 days preceding the transect surveys (one measurement each 10 min; figure based on the 10% highest velocities during the 5 days before the survey). Wind direction distribution and densities (items km^{-2}) of floating seaweed, natural wood and anthropogenic debris are given as bold bars and circles, respectively.

of plastics at the sea surface combined with their disproportionally high supply is most likely responsible for this pattern. The high amount of large plastic fragments observed in the German Bight is probably also an indication of the long persistence of plastics at the sea surface, accompanied by initial fragmentation. Sources of anthropogenic debris may be local and distant. Vauk and Schrey (1987) inferred that most stranded litter on the island of Helgoland came from ships passing the German Bight. Galgani et al. (2000) suggested fisheries as an important source of anthropogenic debris in the North Sea. These authors also emphasized the importance of rivers in transporting litter into coastal areas (see also Williams and Simmons, 1997). Herein we found no clear indication for rivers as important sources of anthropogenic debris, which might be due to the fact that in the German Bight the large input from shipping overshadows riverine transport. The accumulation of floating debris in the western part of the study area (Fig. 5) also suggests input from distant sources in the British Channel and the western parts of the North Sea.

Floating debris will end up on nearby beaches or may accumulate in convergence zones, where it might finally sink to the seafloor (Acha et al., 2003). Highlighting the relationship between litter accumulation on the beaches of Helgoland and southerly winds, Vauk and Schrey (1987) suggested that these winds pushed anthropogenic debris from source regions (shipping lanes) onto local beaches. Galgani et al. (2000) proposed that the predominant northward currents in the eastern part of the German Bight transport floating debris out of the study region and accumulate it in an area to the west of Denmark, where a large proportion finally sinks to the seafloor, probably due to loss of buoyancy caused by a progressive accumulation of organisms (e.g. Harms, 1990; Lobelle and Cunliffe, 2011).

4.2. Source and sink dynamics of floating objects in the German Bight

The dynamics of the three main types of floating objects differ substantially. This appears to be related to differences in (i) spatial distribution of sources, (ii) temporal supply, (iii) persistence at sea surface, and (iv) transport by winds and currents. The spatial distribution of sources differs between the three types. Floating seaweed is supplied from western source areas, the surrounding Wadden Sea areas and from Helgoland. In contrast, the main sources of floating wood seems to be rivers entering the German Bight directly or in the southern North Sea (e.g. Rhine and Meuse), while anthropogenic debris comes mainly from ships and probably also through rivers. Intensity of seaweed supply varies in response to the annual growth season and depending on storms, which contribute more seaweed from western source regions (enhanced import) and from within the study area (enhanced detachment). Wood supply is mostly related to seasonal variations in river runoff. Temporal supply of anthropogenic debris does not vary much since the main source (ships) remains constant throughout the year (Wulf 2010).

The fact that floating seaweed apparently reaches the German Bight from western source regions (Franke et al., 1999; Bartsch and Kuhlenkamp, 2000) suggests that its survival at the sea surface is high, since it must have been floating for some time (days to weeks) before

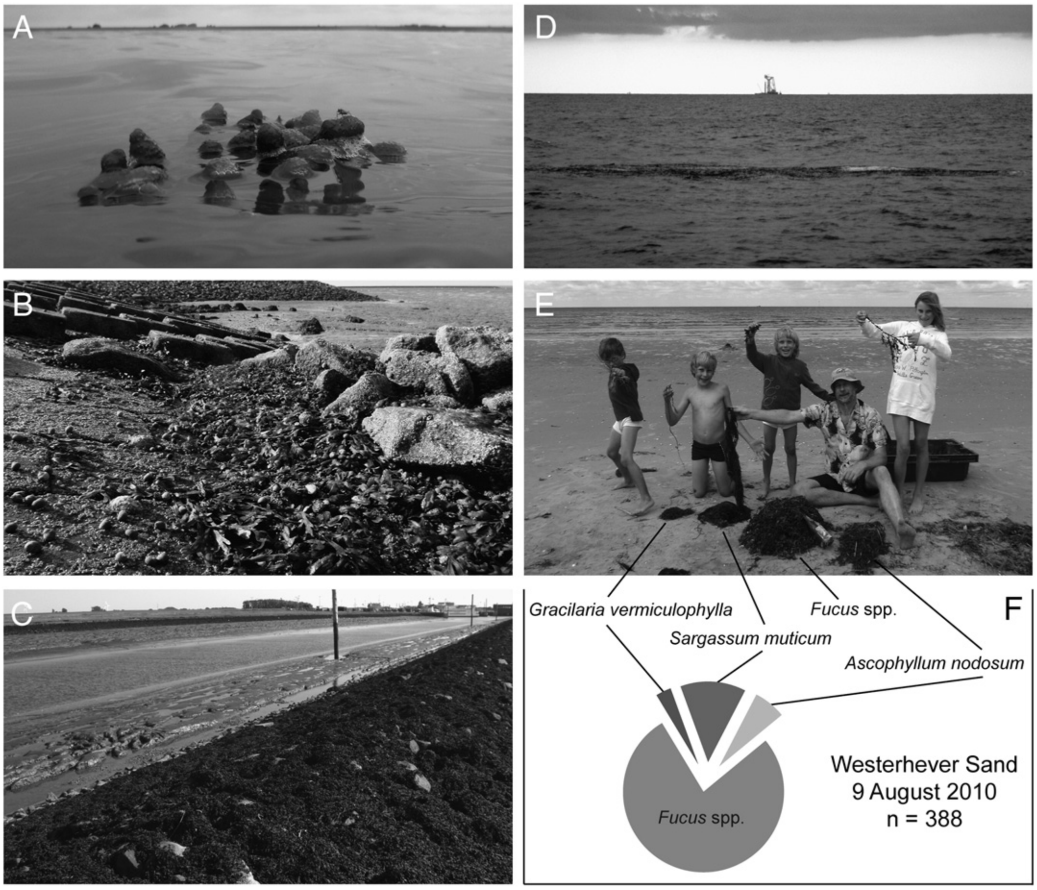

Fig. 9. Floating objects, sources and sinks in the German Bight. (A) Floating *Fucus vesiculosus* in the Wadden Sea. (B) *F. vesiculosus* growing on shoreline defense. (C) Jetties (foreground and background) densely covered by *F. vesiculosus*. (D) Dense multi-species patch of floating macroalgae in the southeastern part of the North Sea; photo courtesy of Sofie Vandendriessche. (E, F) Floating macroalgae stranded on Westerhever Sand in the eastern part of the German Bight, showing for each taxon the amounts (photograph) and proportion of individual plants or fragments (pie-chart); note the bottle which had growth of *Ulva* sp. and contained a hand-written message with origin in the Netherlands (the message was in Dutch).

reaching the German Bight. No information is available for persistence of floating wood, but accumulations on White Bank indicate that some wood remains sufficiently long at the sea surface to reach areas distant from riverine sources. Anthropogenic debris is well known for its high resistance to decay (Ryan, 1988; Barnes et al., 2009) and its prolonged persistence at the sea surface (see also above).

The distribution of floating objects in the German Bight is driven by winds and surface currents. During calm weather, when relatively stable fronts form in the German Bight (Dippner, 1993; Skov and Prins, 2001), floating objects accumulate near these frontal zones, as frequently noted by other authors (e.g. Ryan, 1988; Pichel et al., 2007). Also temporary gyres (Dippner, 1998) might act as retention zones for floating items. For example, moderate northwesterly winds induce the formation of a large eddy off the East Frisian coast (Dippner, 1998), which is possibly responsible for the accumulation of the large abundance of seaweed in this area (see Fig. 3). Northerly and easterly winds favor the formation of stable frontal systems and of the German Bight Gyre (Becker et al., 1992; Dippner, 1993; Schrum, 1997), which might accumulate floating objects on White Bank. These winds may also retain floating seaweed against the prevailing surface currents in the German Bight, similar as had been suggested for kelps in the Patagonian fjords (Hinojosa et al., 2010).

Strong winds also enhance supply of floating objects, e.g. of seaweed, from local source populations. During storm events, current velocities in the Wadden Sea can be very high (Stanev et al., 2009), leading to sediment erosion (Bartholomä et al., 2009) and probably also detachment of seaweed, which may then enter the German Bight. The abundances of floating seaweed and debris were negatively affected by south-westerly winds (Fig. 7). Strong winds are known to push floating objects along the sea surface (Carruthers, 1930; Neumann, 1966; Astudillo et al., 2009), suggesting that strong (westerly) wind events quickly remove these items from the sea surface in the German Bight. South-westerly winds also lead to the disintegration of frontal systems and gyres (Dippner, 1993, 1998), thus dissolving the surface features that accumulate floating objects. They probably push seaweed onto beaches in the eastern parts of the study region (Fig. 9), and they might also enhance export to the north. During westerly storms, floating stocks may be replenished from western source regions (see above). However, even this seaweed entering the German Bight from western source regions might rapidly pass the study region resulting in the observed low standing stocks. Therefore, strong winds are probably responsible for the rapid passage of floating objects through the German Bight and their removal out of that region. The low flotsam densities during periods of strong winds might be also artificially amplified by the poor visibility of floating seaweed on a rough sea surface.

4.3. Outlook

The results of this study indicate that the dynamics of floating objects in the German Bight are driven by supply and transport within the study area. Several observations together with the prevailing hydrographic conditions suggest that the net transport of floating objects in the German Bight is mainly in an east- and then northward direction along its eastern border (e.g. Pohlmann, 2006). During calm weather and northerly and easterly winds (mostly during the spring and summer months) floating objects appear to be retained for longer periods in the German Bight, leading to local accumulations (Fig. 10). In contrast, during stormy weather with prevailing westerly winds (fall and winter) floating

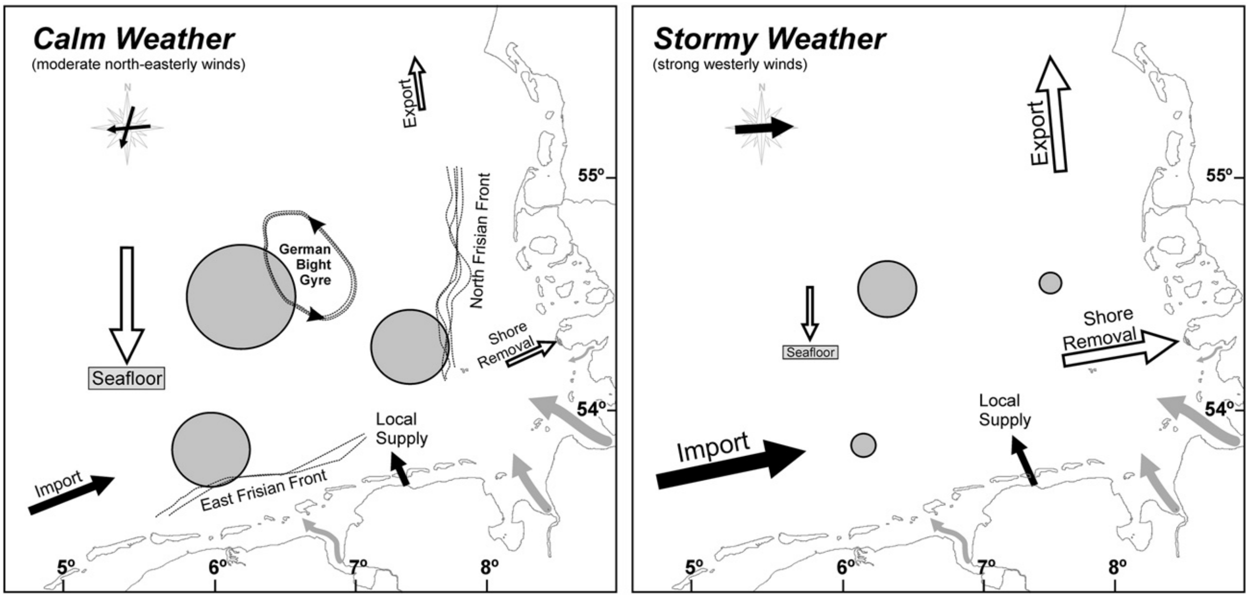

Fig. 10. Hypothetical scenario of the spatio-temporal dynamics of floating objects in the German Bight. During calm weather with winds from easterly and northerly directions, several fronts and local gyres develop, which retain floating objects (indicated by filled circles); these then accumulate in the German Bight, and during extensive residence times start to disintegrate or become overgrown and some unknown fraction of these will sink to the seafloor. In contrast, during stormy weather with mainly westerly winds, fronts and gyres dissolve and floating objects rapidly traverse the study area; more floating objects will end up on beaches in the eastern part of the study area or be exported to the north, while fewer items will sink to the seafloor (due to short residence times).

objects seem to move rapidly through the area, partly being replenished by imported supply from western source regions (Fig. 10). Future studies should carefully examine the temporal input and removal of floating objects from the system. Combined studies of (i) standing stocks at sea, (ii) import from local seaweed beds, ships and rivers, (iii) persistence at the sea surface, and (iv) export to local shorelines and to the seafloor will help to estimate the origin and residence time of floating objects in the German Bight. This will be particularly important for understanding their role in population connectivity along the shores of the southeastern North Sea.

Acknowledgments

The authors would like to thank the German Federal Maritime Agency and the German Wind Energy Institute for the kind provision of meteorological and hydrographic data measured at the offshore research platform FINO 1. We also thank the German Federal Institute of Hydrology, the Wasser- und Schiffahrtsverwaltung des Bundes, The River Basin Commission Weser and the River Basin Community Elbe for providing data of river runoff into the North Sea. We are grateful to Nelson Valdivia for comments and for statistical advice. Gerhard Cadée and one anonymous reviewer provided many constructive suggestions that helped to improve the manuscript. Finally, we thank Anna, David, Johannes and Julian Thiel for helping collect stranded algae on Westerhever Sand.

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