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Spatial distribution of foreshore litter on the northwest European continental shelf

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ABSTRACT

Foreshore litter data from a UK citizen-science programme, combined with OSPAR data, were analysed for possible spatial patterns around Scottish and North Sea coastlines. Loading distributions were positively skewed, and statistics commensurate with such distributions were used. When considering coast type, litter loadings on Scottish harbour and river foreshores were influenced by local litter sources. When considering exposure to the predominant westerly winds over Scotland, litter loadings on the west coast (i.e. predominant onshore winds) were greater on foreshores on open coasts compared to those within embayments. The opposite was true for the Scottish east coast (i.e. predominantly offshore winds). The north east coast of the UK appeared to have an organised pattern of plastic litter loading, increasing in magnitude (median) and spread (inter quartile range) in the direction of the coastal flow. Four other coastal segments with similar patterns were suggested from the west of Scotland to Denmark.

1. Introduction

Plastics released into the sea are increasingly being identified as a major source of pollution and the cause of potential harm to ecosystems and marine life. Marine plastic and non-plastic solid anthropogenic debris and wastes have been found in seabed sediments, the water column, floating on the sea surface and on beaches and foreshores (e.g. Derraik, 2002; Galgani et al., 2015). The amount of plastic litter found on beaches is being monitored globally, and there have been attempts to use variations in the observed foreshore loadings as proxies for variations in plastics in the sea, particularly floating plastics (Ryan et al., 2009). Plastic and non-plastic foreshore litter loadings are also monitored in order to provide evidence to managers and policy makers as to how to control the possible sources of marine litter, and to determine if management strategies are working or not (e.g. Ogunola et al., 2018; Schulz et al., 2013).

Observed foreshore litter loadings may vary because of how much litter is being discharged into the sea, but also because of variations in the forces driving litter onto, and off from, beaches. It is therefore important that we try to understand the mechanisms which result in floating litter beaching on marine foreshores, and perhaps more importantly how these processes may vary over time and space, so that we can separate out natural variations from those related to human activities (Ryan et al., 2009; Browne et al., 2015).

1.1. Physical beaching processes

A previous study (Turrell, 2018) proposed a mechanism controlling foreshore litter loadings for macro tidal, mid-latitude foreshores that are typical of northwest European shelf seas. The mechanism is the result of the interaction between variable wind and variable water levels (the “VaWWL” effect). Consideration of the VaWWL effect suggests that the direction a foreshore faces with respect to the predominant wind direction, i.e. blowing onshore or offshore for the majority of the time, but having reversals episodically, may be important. The VaWWL effect would also suggest that the landscape context within which a foreshore is situated may also have an influence on the action of the effect, i.e. the local topography (or more correctly orography) surrounding a foreshore may be of relevance. For example, a foreshore situated within a high sided valley would experience severally modified onshore/offshore winds compared to a near-by open coast foreshore (e.g. Critchell et al., 2015). If the VaWWL effect is active, we might expect a difference between foreshores on simple, flat, open exposed coasts compared to foreshores within embayments, river valleys or fjords (sea lochs in Scotland).

1.2. Scotland

It might be said that Scotland is in a unique position, possibly globally. It is a relatively thin, long northern limb of the British Isles

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extending in an approximate north-south direction perpendicular to the prevailing westerly winds. This means it has two long approximately parallel coasts, one facing into the prevailing winds (the west coast of Scotland) and one facing away from the prevailing winds (the Scottish east coast). Along these coasts lie a multitude of varied foreshores including embayments and long open-coast beaches. Apart from the Firths of Tay, Clyde and Forth, most foreshores are remote from urban or industrial sources of marine litter.

Scotland is surrounded by a coherent and consistent coastal circulation, and has a variety of tidal ranges owing to the placement of semi-diurnal tidal amphidromes in relation to its coasts (e.g. Pugh, 1987). Finally, sitting as it does between latitudes 55°N and 61°N, it experiences the passage of multiple atmospheric cyclones and anti-cyclones through a typical year, including major storms in the winter. Scotland is thus an excellent laboratory within which to examine macro-tidal, mid-latitude foreshores in relation to the beaching of marine plastics and floating litter.

1.3. Citizen science beach litter data

Within Scotland, and much of the British Isles, we are fortunate to have an extensive beach litter data set generated by the citizen science programme initiated and run by the Marine Conservation Society (Marine Conservation Society, 2018; Nelms et al., 2017). This data set has allowed us to exploit the properties of the Scottish coastline in order to investigate whether we can detect general underlying spatial patterns in wind-driven, beached litter along the two coasts of Scotland, and within the different coast types that are present in Scotland.

1.4. Study objectives

Hence the objective of this study is to use the available beach litter data, generated by the Marine Conservation Society, in order to investigate whether there are discernible spatial differences in beach litter loadings along the Scottish coast. Differences may arise between different types of coastline, between the Scottish west (predominantly onshore wind) and east (predominantly offshore wind) coasts, and spatially along coasts. Additionally, data from the northwest European shelf provided by OSPAR have been used to extend the along-coast analysis around the perimeter of the North Sea.

2. Methods

2.1. Foreshore litter data

The Marine Conservation Society (2018) data set has been used to describe beach litter loadings within Scotland, and this data was combined with the OSPAR (2018) data from the North Sea. The original data sets were placed in the same format, which included location details (foreshore name, latitude and longitude, survey date and time, survey foreshore length) as well as litter counts for 118 individual litter items organised in 8 overall categories of plastic, cloth, wood, metal, pottery, glass, rubber and pollution (which principally included waxes).

The two principal derived analytical quantities used in this study were the total plastic litter loading recorded by each survey, calculated by summing the counts of 54 plastic litter categories and dividing by the survey foreshore length to give number of litter pieces per 100 m (np/100 m), and the total non-plastic litter loading, calculated similarly but using the sum of the remaining 64 non-plastic litter categories (see Table S1 for complete list of 118 litter items), also calculated to give number of litter items per 100 m. In addition, litter composition was investigated using the 8 overall categories listed above. The percentage loading within the eight categories was calculated for different groupings of surveys as described below.

2.2. Coast types

Each survey foreshore was allocated to one of five coast types. These were:

Open Coast (*O*) – Open coast foreshores were typified by long rectilinear sandy, gravel or cobble foreshores with no obstructions to the adjacent coastal sea.

Embayment (*Y*) – An embayment was defined as relatively short foreshores having semi-enclosing adjacent coastlines extending out to sea either side of the foreshore.

Sea Loch (*L*) – Sea loch is the Scottish geographical term for glacially-cut fjords. As such, they are typically long, narrow semi-enclosed water bodies with a restricted access to the open sea. Sea lochs are generally found on the west coast of Scotland.

River (*R*) – Some surveys were performed within tidal channels of rivers and estuaries.

Harbour (*H*) – Surveys designated to this coast type were conducted on beaches or foreshores adjacent to industrial or urban areas. Foreshores contained, or were adjacent to, man-made substrates and/or retaining structures such as sea walls, jetties or piers. Thus surveyed foreshores designated as "harbours" were adjacent to local sources of urban or industrial litter, as well as having hydrodynamic properties disturbed by built infrastructure.

Using the foreshore location (latitude and longitude), each foreshore was examined using the satellite images contained in Google maps. The nature of the coast within which the surveyed foreshore lay was then decided based on expert judgement. Fig. 2 provides some example imagery of the five coast types.

Allocating foreshore survey sites to coast types is consistent with previous beach litter analyses. For example, Schulz et al. (2013) suggested a range of criteria for index beaches to be used in OSPAR assessments, including specifying that the foreshore should be composed of sand or gravel, exposed to the open-sea, free of man-made structures (i.e. "buildings") and of a length preferably > 1 km. Their criteria match those of the "Open Coast" coast type described above.

2.3. Wind exposure

The effect of wind exposure on Scottish foreshore litter loadings was investigated by grouping surveyed foreshores dependent on whether they were on the west coast or east coast, and whether they were on open coast or embayment type coastlines. Hence this analysis did not use survey data from foreshores within harbours, in rivers or within sea lochs.

The location of a surveyed foreshore on either of Scotland's coasts was used, as winds over Scotland predominantly blow from the west, hence the west coast (facing the Atlantic) is exposed to predominantly onshore winds, while the east coast (facing the North Sea) is exposed to predominantly offshore winds (Fig. 1). The differentiation between open coast and embayment was used, as a local modification of wind exposure may be created by the topography (orography) of the coastline adjacent to a surveyed foreshore.

2.4. Sub-regions

Surveyed foreshores were also grouped into sub-regions using their location along the coast (Fig. 1). Schulz et al. (2017) took an identical approach when aggregating data, noting that sub-regions used to group beach loading data should have physically similar conditions, as well as similar local litter sources. Sub-regions need to contain enough surveys

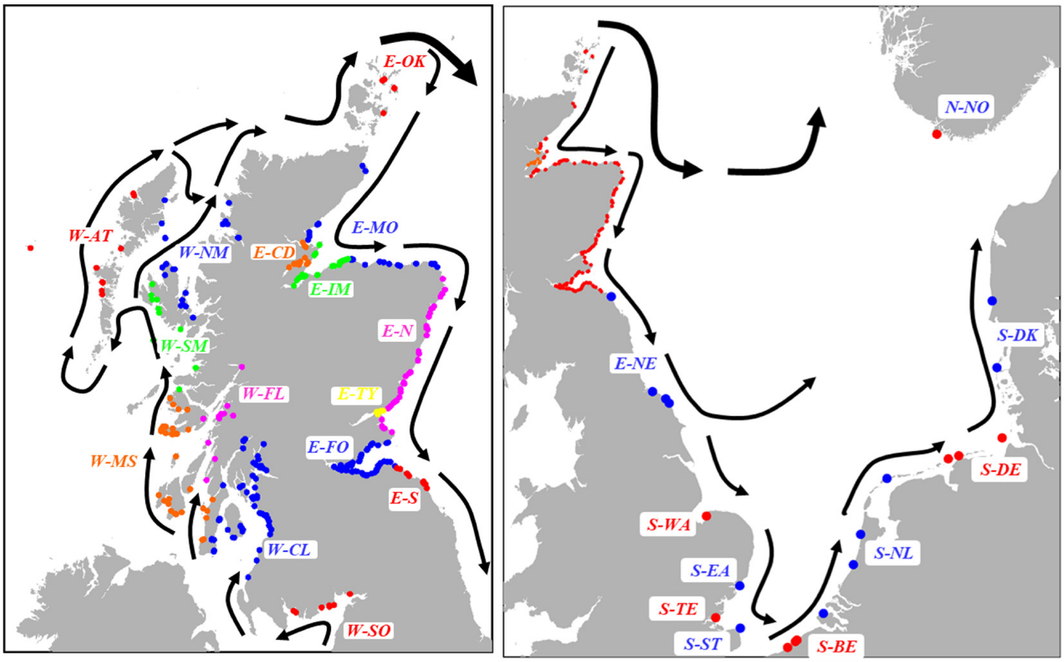

Fig. 1. Map showing the sub-regions used in this analysis, along with a schematic of coastal circulation (only currents relevant to this study are shown). Coloured symbols show survey locations in each sub-region. Left figure (Scotland). Clockwise from west coast: *W-SO* - Solway (red); *W-CL* – Clyde (blue); *W-MS* – Malin Shelf (orange); *W-FL* - Firth of Lorn (purple); *W-SM* – South Minch (green); *W-AT* – Atlantic (red); *W-NM* – North Minch (blue). East Coast: *E-OK* – Orkney (red); *E-MO* – Moray Firth (blue); *E-IM* – Inner Moray Firth (green); *E-CD* – Cromarty and Dornoch Firths (orange); *E-N* – East Coast (N Forth) (purple); *E-TY* – Tay (yellow); *E-FO* – Firth of Forth (blue); *E-S* – East Coast (South) (red). Right figure (North Sea) Anti-clockwise from Orkney: Upper red – Scottish Sub-Regions. *E-NE* – Northern England (blue); *S-WA* – The Wash (red); *S-EA* – East Anglia (blue); *S-TE* - Thames Estuary (red); *S-ST* – South Thames (blue); *S-BE* – Belgium (red); *S-NL* – Netherlands (blue); *S-DE* – Germany (red); *S-DK* – Denmark (blue); *N-NO* – Norway (red). See Table 1 for details of sub-regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Summary statistics describing the surveys used in this study. Surveys have allocated to 25 sub-regions around the northwest European continental shelf. *L* – region code number. *Code* – code letters for a region used in Figs. 6, 7, and 8. Sub-Region Name – Suffixes are: W – Scottish west coast; E – Scottish and English east coasts; S – Southern and eastern boundary of the North Sea. *X* – distance around the northwest European land masses in an anti-clockwise direction from the inner Solway Firth – units are km. Number of surveys within each coast type: *O* – Open Coast; *Y* – Embayment; *L* – Sea Loch; *H* – Harbour; *R* – River; *Tot* – Total number of surveys in the sub-region. First Year/Last Year indicates period from which data was available.

L	*Code*	Sub-region name	X (km)	Number of surveys within each coast type						First year	Last year
				O	*Y*	*L*	*H*	*R*	*Tot*		
1	W-SO	W-Solway	0	11	8	0	0	0	19	2008	2017
2	W-CL	W-Clyde	163	107	17	52	2	8	186	2008	2018
3	W-MS	W-Malin Shelf	300	15	25	25	0	0	65	2008	2017
4	W-FL	W-Firth of Lorn	300	15	21	20	6	0	62	2008	2018
5	W-SM	W-South Minch	423	2	6	6	0	0	14	2010	2017
6	W-AT	W-Atlantic	500	6	6	1	0	0	13	2008	2018
7	W-NM	W-North Minch	550	12	9	12	0	0	33	2013	2017
8	*E*-OK	E-Orkney	762	51	0	0	0	0	51	2008	2017
9	E-MO	E-Moray Firth	860	54	18	0	3	0	75	2008	2017
10	*E*-IM	E-Inner Moray	860	38	13	0	0	0	51	2008	2017
11	E-CD	*E*-Crom/Dorn	860	25	0	0	8	0	33	2009	2017
12	E-N	E-COAST N Forth	1020	171	51	0	9	3	234	2008	2017
13	E-TY	E-Tay	1070	31	1	0	0	0	32	2008	2017
14	E-FO	E-Forth	1098	154	109	0	128	17	408	2008	2018
15	E-S	E-COAST S Forth	1140	25	32	0	0	0	57	2008	2018
16	E-NE	N England	1300	96	24	0	0	0	120	2001	2016
17	S-WA	The Wash	1489	9	0	0	0	0	9	2001	2003
18	S-EA	East Anglia	1602	102	0	0	0	0	102	2002	2016
19	S-TE	Thames Estuary	1729	30	0	0	0	0	30	2010	2016
20	S-ST	S Thames	1760	3	0	0	0	0	3	2001	2003
21	S-BE	Belgium Coast	1830	70	0	0	0	0	70	2002	2016
22	S-NL	Netherlands Coast	2000	219	0	0	0	0	219	2001	2016
23	S-DE	German Coast	2269	96	0	0	0	0	96	2002	2016
24	S-DK	Danish Peninsula	2530	69	0	0	0	0	69	2001	2016
25	N-NO	Norwegian Coast	2900	10	0	0	0	0	10	2011	2016

Fig. 2. Examples of the five different coast types used in the analysis, determined from examination of Google Maps satellite imagery for each survey beach. *O* – Open Coast (Balmedie Beach, Sub-Region *E-N*); *Y* – Embayment (Braiden Bay, Sub-Region *E-N*); *L* – Sea Loch (Battery Beach, Sub-Region *W-MS*); *H* – Harbour (Crammond, Sub-Region *E-FO*); *R* – River (Erskine Beach, Sub-Region *W-CL*). See Table 1 for list of sub-regions. (All images ©2018 Google. Data SIO, NOAA, US Navy NGA, GEBCO, Map Data ©2018 Google).

so that their statistics are meaningful, while at the same time small enough to resolve physical gradients or differences along the shoreline. Where possible, natural coastal morphology or changes in circulation patterns were used as divisions between sub-regions and, as with Schulz et al. (2017), care was taken to ensure sub-regions contained surveyed foreshores exposed to similar oceanographic conditions. For this reason, only surveys from foreshores on open coasts or embayments were used in the regional analysis as both of these coastline types were present in all sub-regions.

Details of each sub-region used are given in the Supplementary Material, along with the criteria used to define each sub-region. In summary, twenty five sub-regions were defined, moving clockwise around the British Isles, and then anti-clockwise around the North Sea (Fig. 1). The Scottish west coast was sub-divided into seven sub-regions, stretching from the Solway Firth in the south to the North Minch in the north. Sub-regions were between 100 km and 150 km in length along the coast. No data exists yet from the northern coast of Scotland. Hence after the North Minch sub-region, the next sub-region in a clockwise direction around the Scottish coast was the Orkney islands, situated at the entrance to the North Sea. Eight sub-regions were defined along the Scottish east coast, stretching from Orkney in the north to the border with England in the south. These sub-regions ranged between 60 km and 130 km in length. The remainder of the English coast was sub-divided into a further five sub-regions, using similar spatial separations. The continental coast, from Belgium to Denmark, was separated into larger units of between 120 km and 250 km in length.

For purposes of analysis, an additional parameter was added to each sub-region. This was the nominal distance from the mid-point of the Solway Firth sub-region (*W-SO*, Fig. 1. $X = 0$ km) to the mid-point of each sub-region (X km), measured along the median line approximately 30 km off from the coast. Thus the along-coast distance located the position of each sub-region along the coastal circulation in a clockwise direction around Scotland, and then in an anti-clockwise direction around the North Sea.

2.5. Statistical analysis

In order to determine the type of statistical analysis to apply to the beach litter survey data, a preliminary analysis was performed. Fig. 3 shows the distribution of normalised beach litter loadings from the total data set used in this study (i.e. all 2061 surveys, from 25 sub-regions, all coastline types included). The distribution is obviously positively

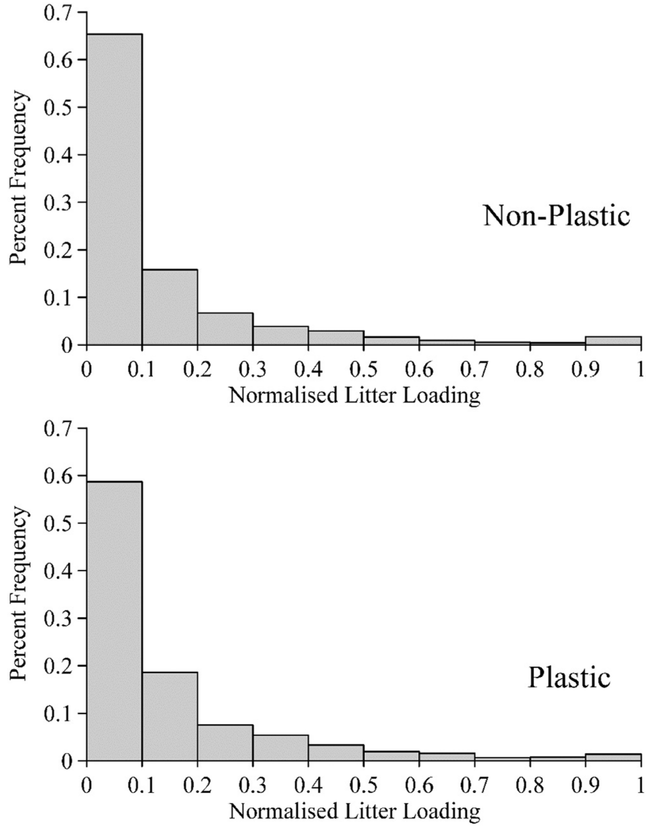

Fig. 3. Percentage frequency distribution of all foreshore normalised survey beach loadings used in this study (i.e. 2061 surveys from 25 sub-regions). Data split into plastic litter items (54 plastic litter categories), and non-plastic litter items (rubber, cloth, paper, wood, metal, glass, pottery, sanitary items, medical items, other polluting items – 64 categories in all). Within each sub-region, individual survey data (plastic and non-plastic) were normalised using the corresponding maximum sub-region survey value. Thus all sub-regions returned data ranging from 0 to 1, and hence could be combined. This plot confirms that the basic data set is positively skewed.

skewed. Such a distribution typifies all beach survey data, at least on the northwest European continental shelf, with more frequent low litter loadings and less frequent higher loadings. The beaching/debeaching mechanism proposed by Turrell (2018) for mid-latitude, macro tidal beaches predicted such a positively skewed loading distribution as a product of the interaction between variable water level and wind forcing (the VaWWL effect). As the beach loading data used in this study is clearly positively skewed, statistics must be selected which do not assume a normal distribution.

Statistical properties selected to characterise the data, and different groupings of data, in this study were the lower quartile (Q_L), upper quartile (U_L) and median values. Box-whisker plots were used to show these (Q_L bottom of box, Q_U top of box, median central bar in box), and to present data outliers where an outlier was defined as any point that fell below ($Q_L - 1.5.IQR$) or above ($Q_U + 1.5.IQR$), where IQR is the inter quartile range.

In order to test the significance of differences between groupings of foreshore surveys, the data were analysed by fitting a generalised linear model (GLM), comprising foreshore group as an explanatory variable, assuming a negative binomial error distribution. Differences between foreshore groups were evaluated by comparing log likelihoods using nested models. Probability values < 0.05 were categorised as statistically significant. Foreshore groups used were coast type (Fig. 4), west/east coast, embayments/open coast (Fig. 5), and sub-region (Fig. 6). The GLM and ANOVA models used were from the R-code libraries (R Core Team, 2019).

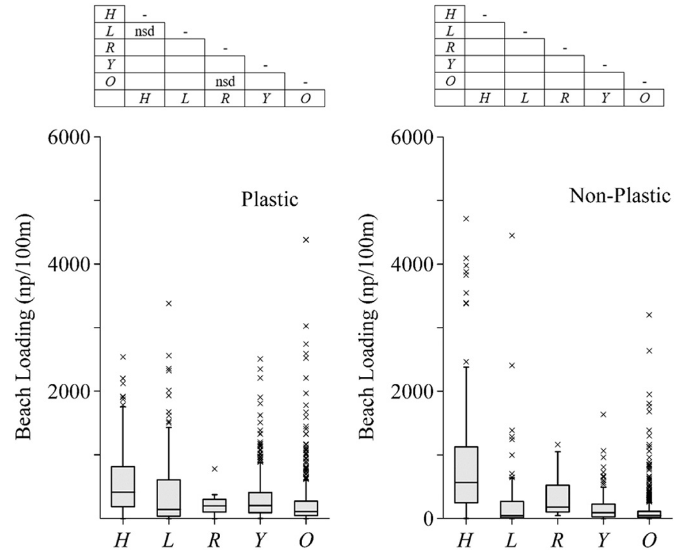

Fig. 4. Summary of Scottish foreshore marine litter loadings (plastic and non-plastic): box-whisker plots from different coastline types. Numbers of surveys were: Harbours (*H*) – 156; Lochs (*L*) – 116; Rivers (*R*) - 28; Embayments (*Y*) - 316; Open Coast (*O*) - 717. Surveys from both Scottish coasts are combined, i.e. all 15 Scottish sub-regions. Box: Central bar – median; lower edge – first quartile (25%); upper edge – third quartile (75%). Whisker: Lower point – minimum value; Upper point – maximum value (excluding outliers – see text); outliers shown as symbols. Tables above plots indicate statistical significance between coast types evaluated by comparing log likelihoods using nested models: *empty cell* – coast types are significantly different; *nsd* – no significant different between coast types (see Methods section for further details).

3. Results

3.1. Survey data

Table 1 summarises the 25 sub-regions, giving the number of surveys within each sub-region, by coast type, along with the time period from which data was derived within each sub-region. Fig. 1 provides maps of the sub-regions and surveyed foreshores, while Fig. 2 shows examples of the coast types used in this analysis. In all, 2061 surveys were used in the analysis, 392 from the west coast of Scotland, 941 from the east coast and 728 from the remainder of the UK coast and the European coast of the North Sea.

3.2. Effect of coast type

Scottish surveyed foreshores were split into the various coast types (as illustrated in Fig. 2), and plotted in Fig. 4. Litter loadings in all foreshore groups were significantly different from one another in terms of plastic litter loadings, except for two pairings: river and open coast foreshores, and sea loch and harbour foreshores. The lack of a statistically significant difference does not necessarily indicate a lack of difference per se. For example, the difference between plastic litter distributions on river and open coast foreshores may be because of the low numbers of surveys available on river foreshores (28). All foreshore groups were significantly different from one another for non-plastic litter loadings.

Foreshores located within harbours had the greatest median plastic litter loading (Table 2) and median non-plastic litter loading of all coast type groups. The median plastic litter loading of Scottish harbours (414 np/100 m) was a factor of 2 greater than the coast type grouping with the next greatest median plastic loading (202 np/100 m), which characterised the embayment grouping (Table 2). Non-plastic litter loadings within harbours had a median value (565 np/100 m) which was a factor of 3 greater than the median loading of the river coast type (180 np/

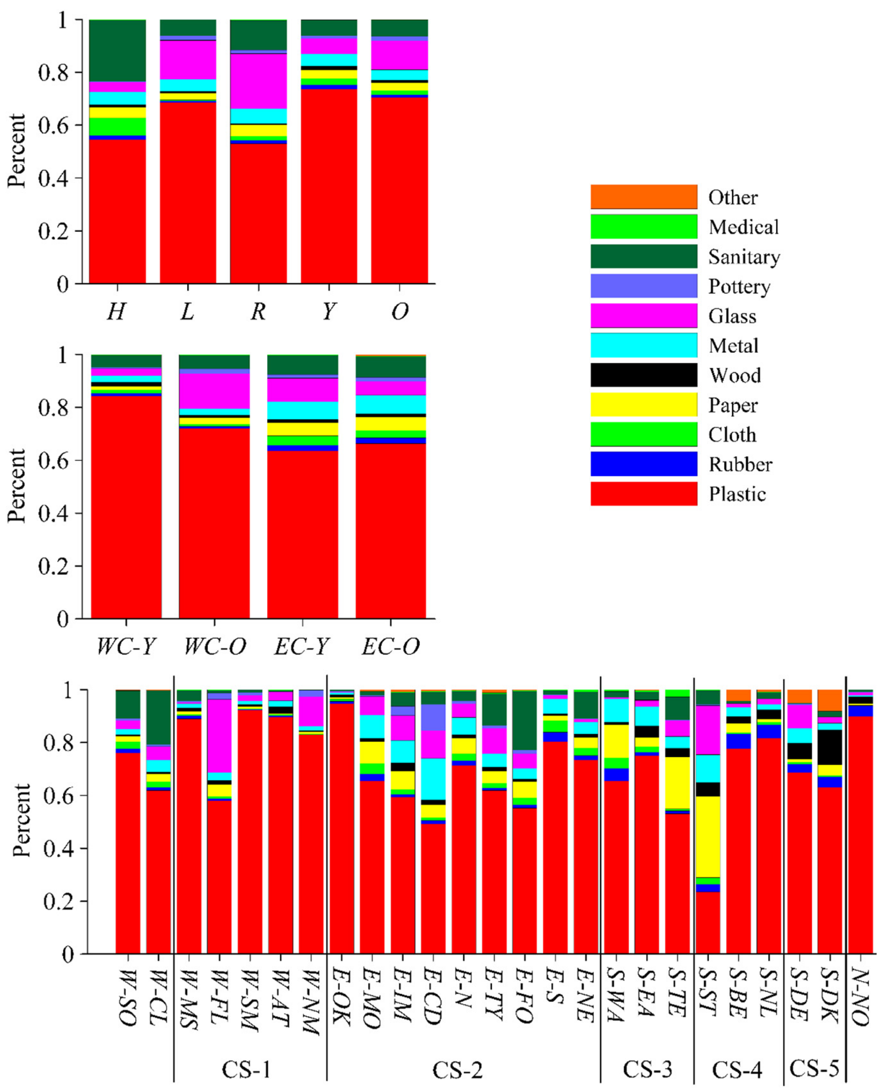

Fig. 5. Details of percentage litter composition in eight overall litter categories (plastic, cloth, wood, metal, pottery, glass, rubber and pollution, which principally included waxes). Upper figure - corresponds to foreshore groupings presented in Fig. 4 (All Scotland – by coast type: *H* – Harbours; *L* – Sea Lochs; *R* – Rivers; *Y* – Embayments; *O* – Open Coasts); Middle figure – Fig. 6 (Scottish east/west coasts: *WC-Y* West Coast – Embayments; *WC-O* West Coast – Open Coast; *EC-Y* East Coast – Embayments; *EC-O* East Coast – Open Coast); Lower figure – Fig. 7 (Sub-regions, open coast and embayment foreshores only. Location of sub-regions shown in Fig. 1). All percentage values are given in Tables S28, S29, S30). CS-1 to CS-5 refer to the coastal segments defined in Fig. 8 and shown in Fig. 9.

100 m), which was the next greatest non-plastic loading.

The composition of litter found on foreshores within harbours, and within the four other coast type groupings, in Scotland is shown in Fig. 5 (upper). One clear difference is that litter within harbours had, on average, 23% of the total litter load derived from sanitary related litter items. This can be compared to 11% for foreshores within rivers, and of the order of 6% for foreshores within embayments, on open coasts and within sea lochs.

3.3. *Effect of wind exposure*

Fig. 6 presents box-whisker plots for foreshore groupings within embayments on the Scottish east (*EC-Y*) and west (*WC-Y*) coasts, and on open coasts on the Scottish east (*EC-O*) and west coasts (*WC-O*). The litter loadings found within all four groupings were statistically significantly different from one another except for two pairings; plastic loadings in *EC-Y* and *WC-Y* groupings, and non-plastic loadings in *EC-O* and *WC-Y* groupings. Both of these non-significant pairings were probably influenced by the comparatively low number of surveys in the *WC-Y* grouping (Table 2).

On the Scottish west coast, foreshores located on open coasts had median plastic litter loadings a factor of 1.2 greater then foreshores within embayments (247 np/100 m compared to 200 np/100 m, Table 2). The same was true for non-plastic litter, but with a greater ratio of 2.9 (89 np/100 m compared to 31 np/100 m).

On the Scottish east coast the reverse relationship was found, with litter loadings on foreshores in embayments having greater median values than litter loadings on open coasts. For plastic litter items east coast embayments had median loadings 2.2 times greater than open coasts (203 np/100 m compared to 91 np/100 m). The same ratio for non-plastic items was 3.3 (i.e. 138 np/100 m compared to 42 np/100 m).

In terms of litter composition (Fig. 5, centre) there was little difference between the four foreshore groupings. West coast foreshores had the greatest percentage of plastic litter; 84% for embayments and 72% for open coast foreshores, compared to about 60% on all east coast foreshores. Thus east coast foreshores had greater loadings of non-plastic items, possibly suggesting the greater influence of local litter sources. The percentage of sanitary-related litter items was greater on the east coast (> 7%) than on the west coast (< 5%, Table 2).

3.4. *Spatial variation of foreshore litter loading*

Fig. 7 presents the box-whisker plots for the litter loadings recorded in the 25 sub-regions used in this study, and Table 3 presents the results of the statistical tests of independence between sub-region litter loadings. On the Scottish east coast, the eight sub-regions contained plastic litter distributions which were statistically significantly different from each other, apart from the pairing Firth of Forth (*E-FO*) to Scottish east coast (north) (*E-N*). Four pairings were not statistically different in

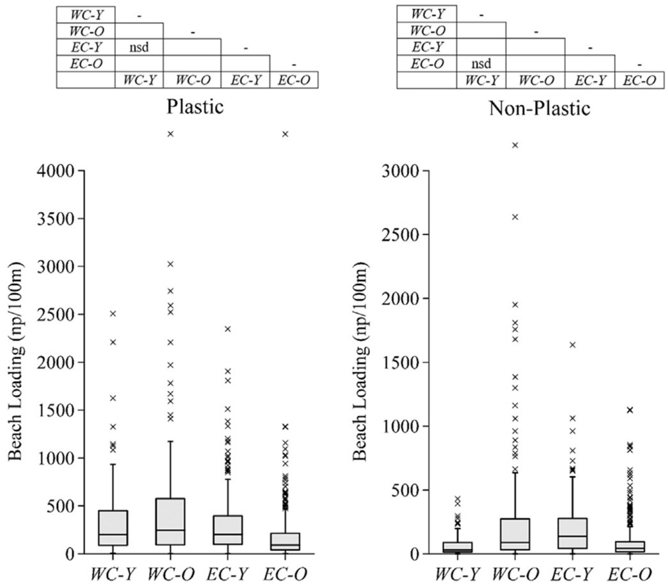

Fig. 6. Box-whisker plots of Scottish foreshore loadings within embayments (*Y*) compared to foreshores on open coasts (*O*) on the west coast (*WC* - sub-regions 1 to 7) and the east coast (*EC* - sub-regions 8 to 15). Units are number of litter items per 100 m beach survey length (parallel to sea; np/100 m). Box: Central bar – median; lower edge – first quartile (25%); upper edge – third quartile (75%). Whisker: Lower point – minimum value; Upper point – maximum value (excluding outliers – see text); outliers shown as symbols. Numbers of surveys are: *WC-Y* – 92; *WC-O* – 168; *EC-Y* – 224; *EC-O* - 549. Tables above plots indicate statistical significance between survey groupings: *empty cell* – coast types are significantly different; *nsd* – no significant different between coast types (see Methods section for further details).

terms of non-plastic litter loadings (Table 3). This is very different for survey groupings on the west coast, where no sub-region contained statistically different litter plastic loadings. This was most likely due to the lower numbers of surveys available on the west coast than in sub-regions on the east coast. However, at the current time these are all the data available.

3.5. North east coast – coastal segment 2

On the north east coast of the UK, there appears to be a clear spatial organisation of litter loadings within sub-regions, increasing in the direction of the coastal current (i.e. Fig. 1). Plastic median litter loadings were least in the Orkney sub-region (*E-OK*, 4 np/100 m. Table 2) and these generally increased southwards along the coast until the North England sub-region (*E-NE*, 419 np/100 m), i.e. an increase by a factor of 100 in a distance of approximately 540 km. This increase is also seen in Fig. 8, where the median litter loading in each sub-region is plotted against its along-coast nominal distance (*X,* Table 1). In Fig. 8, the median plastic litter loadings from the *E-OK* sub-region to the *E-NE* sub-region form the coastal segment labelled as segment 2. The location of this coastal segment may be seen in Fig. 9.

In coastal segment 2, another aspect of the sub-regional litter loadings which increased in the direction of the coastal circulation was the spread of loadings within each sub-region. This can be seen both in the values of the inter-quartile range (*IQR*), as well as in the maximum loadings (excluding outliers). In northern sub-regions (i.e. *E-OK, E-MO, E-IM, E-CD*), the *IQR* and maximum values varied between 15 and 180 np/100 m and 20–388 np/100 m respectively. At the southern end of coastal segment 2, the IQR and maximum values increased to 1431 np/100 m and 3439 np/100 m respectively, increases by a factor of approximately 10 over the 540 km long coastal segment.

The spatial pattern of change was not so pronounced in non-plastic loadings, but there was some evidence of increases in median and spread of values within sub-regions along the coastal segment towards the south (Table 2), from *E-OK* to *E-NE*.

The composition of beach litter (open coast and embayment foreshores only) in the sub-regions of this coastal segment, in the eight litter classifications, may be seen in Fig. 5. The Orkney sub-region, at the northern end of the segment, had the highest plastic percentage (94.7%), and thus the lowest percentage of non-plastic litter (5.3%). This probably was the result of few local sources of litter on these largely rural islands. Orkney foreshores had just 0.4% of the litter derived from sanitary items. The proportions of non-plastic litter items increased southwards along the coastal segment, although the variation can in most part be related to the size of coastal populations. For example, the Tay (location of the city of Dundee) and the Firth of Forth (city of Edinburgh) both had much greater contributions from sanitary-related litter items, i.e. 12% and 22.5% respectively. Thus the change in the composition of foreshore litter along the coastal segment suggests the influence of local litter sources.

3.6. Scottish west coast

The Solway Firth (*E-SO*) and Firth of Clyde (*E-CL*) are somewhat separated from the remainder of the coastline by the narrow and constricted North Channel. Both sub-regions have quite high contributions from sanitary-related litter (10% and 20% respectively, Fig. 5), and probably have sources of local litter from urban centres.

The remainder of the coastline is exposed to the Atlantic to the west, is generally rugged and remote with no large urban centres and low population density. The mainland coastline is frequently interrupted by long, linear glacially cut fjords. The remoteness of many foreshores, coupled with the low population density, results in fewer data available from the citizen science programme along this coast, reflected in the low degree of statistical independence between the foreshore litter loadings in the remaining five sub-regions (Table 3). However, examination of Fig. 7 suggests that the pattern observed on the Scottish east coast may be repeated, with increasing magnitude (Fig. 8) and spread (Fig. 7) of plastic litter distribution in the direction of the coastal flow (i.e. northwards along this coast, Fig. 1). Based on this we have suggested Coastal Segment 1 (Fig. 9). The North Minch sub-region (*W-NM*), at the northern limit of this coastal segment has the second largest inter quartile range for plastic litter of any of the 25 sub-regions on the north west European shelf, 809 np/100 m, while the neighbouring Atlantic sub-region has an IQR of 800 np/100 m.

3.7. Southern UK and European coasts

There may be further organised coastal segments along the remainder of the European North Sea coast, "downstream" from Coastal Segment 2. These are suggested in Fig. 8 based on the observed median plastic litter loadings, and located in Fig. 9. The composition of foreshore litter suggests multiple local sources of foreshore litter in the two sub-regions close to the Thames.

4. Discussion

4.1. Effect of coast type

Foreshores within harbours in Scotland have the greatest median plastic and non-plastic litter loadings, by factors of 2 to 3 times greater compared to foreshores in all other coast type groupings. Harbours and rivers also have greater percentages of sanitary litter items (23% and 11% respectively) than other coast types (∼ 6%). This suggests that harbours and rivers receive sewage related debris (SRD) from local sources. Owing to the potential influence of local sources of litter items, surveyed foreshores within harbours and rivers were excluded from the analyses which follow. Foreshores within sea lochs were also excluded as these principally are located on the Scottish west coast.

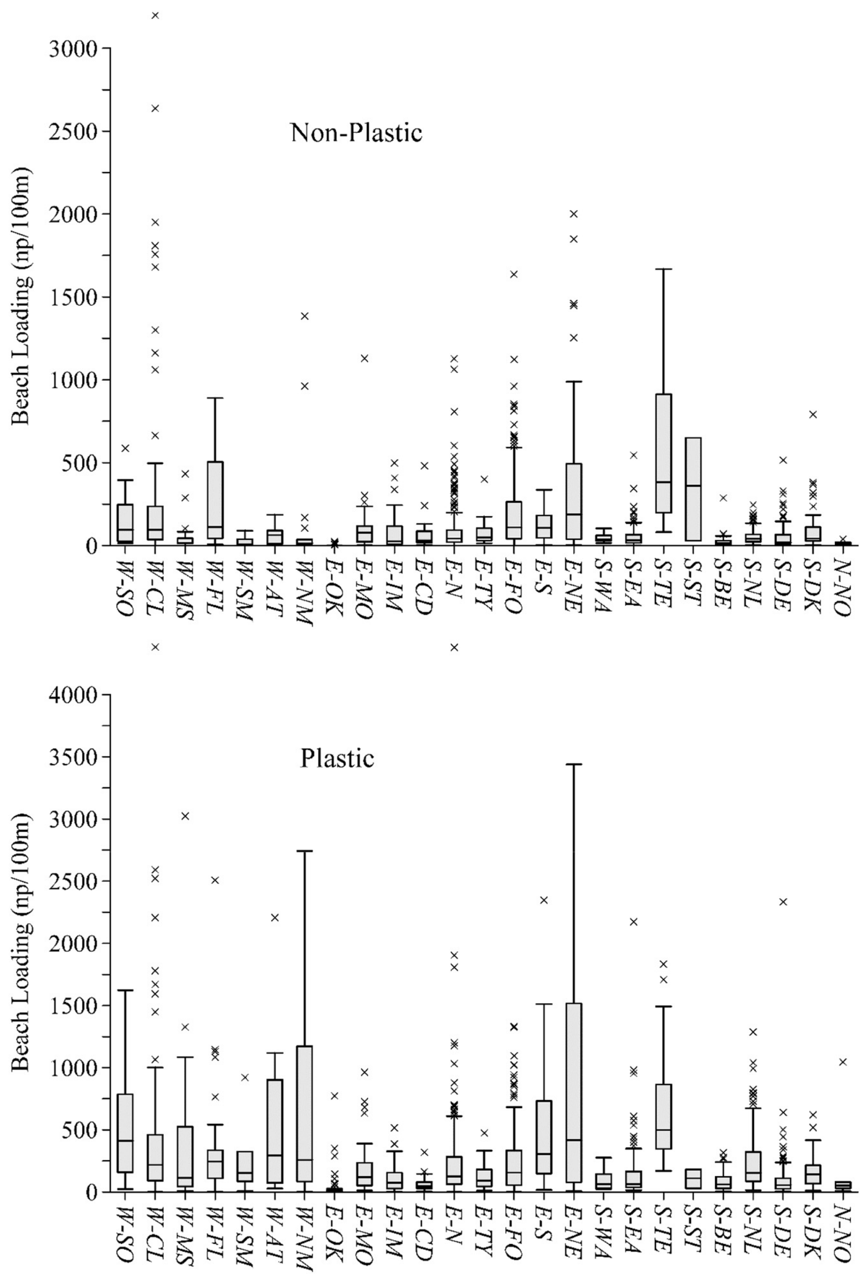

Fig. 7. Box-whisker plots of Scottish and North Sea foreshore loadings by sub-region (sub-regions 1 to 25). Only coastline types embayments (*Y*) and open coast (*O*) were included in the analysis in all sub-regions. Units are number of litter items per 100 m beach survey length (parallel to sea; np/100 m). Box: Central bar – median; lower edge – first quartile (25%); upper edge – third quartile (75%). Whisker: Lower point – minimum value; Upper point – maximum value (excluding outliers – see text)l outliers indicated by symbols. Sub-region codes are explained in Table 1. Statistical significance between regions given in Table 3.

4.2. Effect of wind exposure

Previous authors have noted differences between simple, open-coast foreshores, and embayments. For example, modelling by Critchell and Lambrechts (2016) highlighted the importance of local winds and processes such as "wind shadowing" in controlling some aspects of litter dynamics and coastal circulations in and around complex topography such as headlands and embayments. Kataoka et al. (2015) made a detailed study of the litter dynamics within a small bay, and noted strong internal circulations that could result in litter retention and/or dispersion under differing conditions.

On the Scottish west coast, which faces into the predominantly westerly winds, litter loadings on foreshores on open coasts were greater than on foreshores within more sheltered embayments. We may speculate that in the case of predominantly onshore winds, a wind-driven beaching mechanism for floating litter may be somehow impaired within sheltered embayments compared to open coasts. One reason for such impairment might be that the direction of wind which results in beaching is restricted to a smaller sector by the adjacent protruding boundaries of embayments, compared to the almost 180° sector of winds leading to beaching for open coasts. Hence, with variable winds, the frequency when winds blow from the directions which result in beaching in embayments is less than for open coasts.

On the east coast the reverse situation occurred on Scottish beaches, with greater median loads in embayments than on open coasts. A way of explaining this which is consistent with the mechanism proposed above for predominantly onshore-wind coasts, is that on offshore-wind coasts it is the de-beaching mechanism in embayments which is impaired. Again the shape and topography of embayments may restrict the sector from which offshore winds must blow in order to clear a

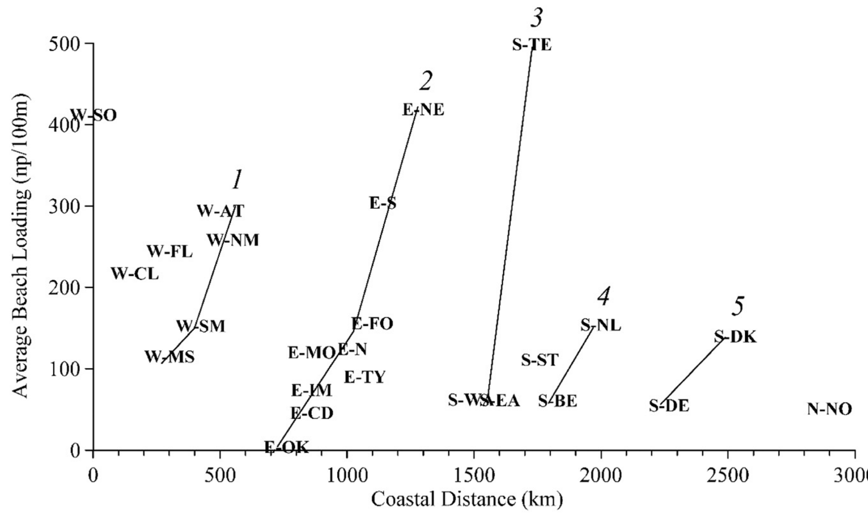

Fig. 8. Median foreshore plastic loadings for 25 sub-regions including Scottish and North Sea waters, plotted against along-coast distance, with an origin in the Solway Firth on the Scottish west coast (See Table 1). Coastal types embayments and open used. Numbers in italics refer to coastal segments shown in Fig. 9.

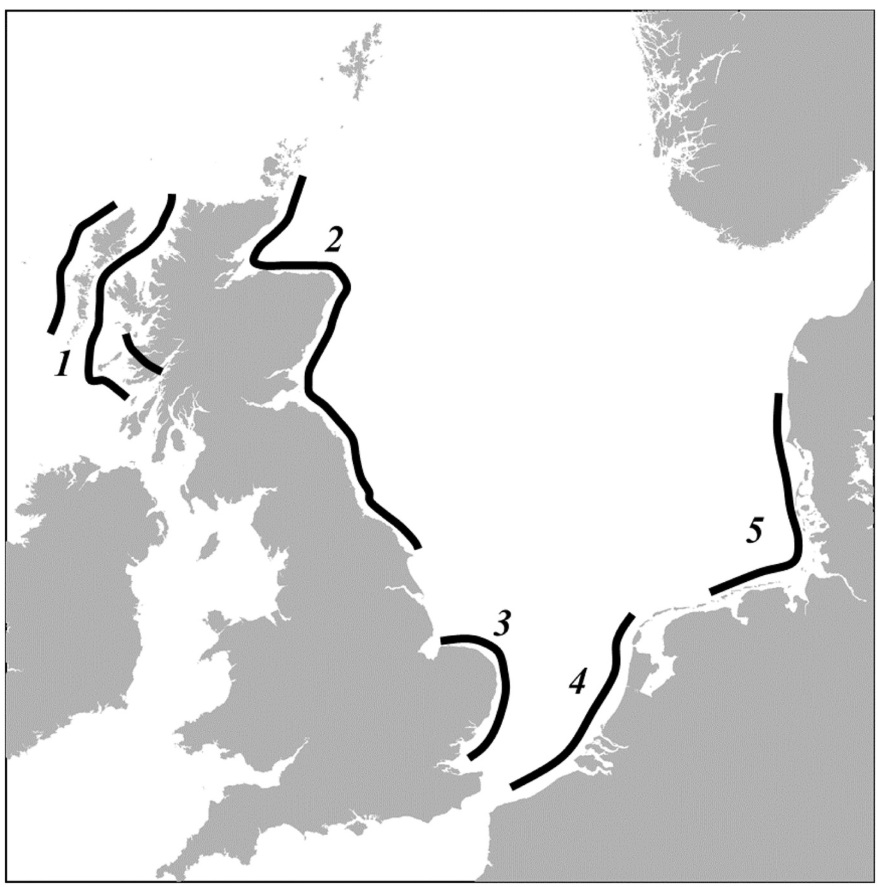

Fig. 9. Coastal segments along which foreshore litter enhancement may be linked. See Fig. 8 for median beach litter loadings within each segment.

beach within the embayment of litter. The restricted directional sector results in less frequent winds capable of clearing an embayment beach.

The difference in the actual composition of litter between west and east coasts was not great. However, there was some indication that east coast foreshores had higher percentages of non-plastic items, perhaps suggesting more local litter sources on this coast compared to the more remote and rural west coast.

4.3. Spatial variation of foreshore litter loading

The analyses above inform us that when looking for trends or patterns in foreshore litter loadings, factors such as coast type and foreshore relationship to the predominant wind direction can influence results. These are all local effects influencing a single foreshore independently from its neighbours. The final analysis looked for an along-coast effect, where potentially one foreshore may influence the litter loading of its neighbour “downstream”, i.e. in the direction of the local

Table 2
Summary statistics of foreshore litter survey data analyses, Figs. 4, 6 and 7. *N surveys* – number of surveys in the data grouping; *N regions* – number of sub-regions in the data grouping. *Q1* – first quartile (25%); *Q3* – third quartile (75%); *IQR* – Inter Quartile Range; *Max* – Maximum loading in the data grouping (excluding outliers). All units are litter items per 100 m surveyed foreshore (np/100 m).

		N surveys	N regions	Coastline type	Coastal segment	Plastic					Non-plastic				
						Q1	*Median*	*Q3*	*IQR*	*Max*	*Q1*	*Median*	*Q3*	*IQR*	*Max*
Fig. 4															
Scotland	All	156	15	H	–	199	414	805	607	1756	261	565	1103	841	2387
Scotland	All	116	15	L	–	36	139	590	554	1427	14	42	245	231	622
Scotland	All	28	15	R	–	107	197	292	186	371	108	180	458	351	1044
Scotland	All	316	15	Y	–	93	202	400	307	841	28	92	220	192	498
Scotland	All	717	15	O	–	46	111	266	220	571	17	49	113	96	224
Fig. 6															
Scotland	West Coast	92	7	Y	–	91	200	437	346	941	14	31	88	74	199
Scotland	West Coast	168	7	O	–	95	247	570	475	1172	33	89	268	236	642
Scotland	East Coast	224	8	Y	–	98	203	395	297	781	43	138	274	231	607
Scotland	East Coast	549	8	O	–	41	91	213	172	439	16	42	95	79	205
Fig. 7															
W-SO	West Coast	19	1	Y and O	–	170	412	702	532	1624	36	96	222	186	401
W-CL	West Coast	124	1	Y and O	–	91	217	453	362	1014	35	94	232	197	502
W-MS	West Coast	40	1	Y and O	1	47	115	516	469	1087	14	17	43	29	78
W-FL	West Coast	36	1	Y and O	1	122	245	333	211	554	48	111	461	414	890
W-SM	West Coast	8	1	Y and O	1	93	153	250	158	333	4	9	20	16	89
W-AT	West Coast	12	1	Y and O	1	93	294	901	800	1105	23	64	89	66	186
W-NM	West Coast	21	1	Y and O	1	83	258	892	809	2743	3	13	33	30	42
E-OK	East Coast	51	1	Y and O	2	1	4	16	15	20	0	0	1	1	24
E-MO	East Coast	72	1	Y and O	2	53	120	234	181	388	23	77	113	91	233
E-IM	East Coast	51	1	Y and O	2	27	74	153	126	324	8	26	116	108	252
E-CD	East Coast	25	1	Y and O	2	28	46	76	48	140	19	30	77	58	132
E-N	East Coast	222	1	Y and O	2	63	124	282	219	619	22	42	93	71	203
E-TY	East Coast	32	1	Y and O	2	47	90	175	127	333	32	48	100	68	174
E-FO	East Coast	263	1	Y and O	2	56	156	334	277	683	42	109	263	221	591
E-S	East Coast	57	1	Y and O	2	148	304	663	515	1511	47	106	176	129	336
E-NE	England	120	1	Y and O	2	80	419	1511	1431	3439	40	188	479	439	986
S-WA	England	9	1	Y and O	3	31	62	72	41	275	28	37	55	27	102
S-EA	England	102	1	Y and O	3	39	62	166	127	352	17	31	66	48	132
S-TE	England	30	1	Y and O	3	357	499	842	485	1502	204	382	875	671	1668
S-ST	England	3	1	Y and O	4	70	111	147	77	182	195	361	505	310	649
S-BE	Belgium	70	1	Y and O	4	30	61	121	91	250	9	16	29	20	62
S-NL	Netherlands	219	1	Y and O	4	88	154	322	234	674	24	41	68	44	138
S-DE	Germany	96	1	Y and O	5	26	55	103	77	250	8	19	65	58	144
S-DK	Denmark	69	1	Y and O	5	67	140	199	132	425	28	42	109	81	186
N-NO	Norway	10	1	Y and O	–	34	51	75	42	95	12	16	18	7	25

coastal circulation.

Such a mechanism was suggested by the VaWWL effect model of Turrell (2018). In this model, what characterises an isolated single mid-latitude, macro-tidal beach is a slow, repeated flux of floating litter directed onto the beach, interrupted by episodic and large fluxes of litter off from the beach. For Aberdeen beach, located in sub-region 12, East Coast (North), typical low tide to low tide onshore fluxes were of the order 0 to 3 np/100 m per hour whereas the episodic offshore directed fluxes of litter were of the order of 0 to 40 np/100 m per hour. These "pulses" of litter off from the beach would characteristically result in patches of high density litter entering the coastal flow. These patches may well then influence the on-beach flux of the next beach along in the direction of the coastal current. Hence looking for variability in average beach loadings in the direction of the coastal circulation is not an unreasonable thing to do.

A coherent spatial pattern of beach litter loadings, at least in the plastic component, was most evident for the north east UK coastal segment (Segment 2, *E-OK* to *E-NE*, Fig. 9). This stretch of coastline had a good coverage of surveys, and hence foreshore loading distributions had the greatest degree of statistical independence. There appeared to be two clear aspects to the spatial change of plastic beach litter loadings; the median loading increased along the coast in the direction of the coastal circulation, as did the spread of observed beach loadings. Hence "upstream" in the north of the segment, beach loadings had low median values, and little variation of observed beach loadings, whereas foreshores "downstream" had plastic litter distributions with much greater variability, higher maximum values, more outliers, and greater median values.

Despite the reduced statistical significance in other parts of the northwest European coastline, caused by the availability of fewer surveys in some sub-regions, there appeared to be a total of four other coastal segments with similar characteristics to the north east UK coast (i.e. increasing median and increasing spread in the direction of coastal flow). These coastal segments lay on the Scottish west coast (Segment 1, Fig. 9), southern UK coast (Segment 3), western North Sea European coast (Segment 4) and eastern North Sea European coast (Segment 5).

If a mechanism is present which enhances litter loadings in the direction of coastal flow, we may ask two questions: what is the mechanism, and why are there breaks along the coast? It is noted above that the VaWWL mechanism proposed by Turrell (2018) suggest a foreshore "downstream" from another foreshore may receive pulses of high density floating litter when the upstream beach is emptied by the correct combination of wind and water level. However, the effect of additional litter joining the coastal current both from land-based sources and offshore sources must also be relevant.

The "breaks" in the spatial increase in litter loadings along the coastal circulation may be caused by floating litter that is retained within the coastal currents being moved offshore. At the northern end of Coastal Segment 1, we do not know for sure what occurs as there is no data available along the Scottish north coast. However, we know that flows along that coast turn north, west of Orkney and enter the North Sea as the Fair Isle Inflow (e.g. Turrell, 1992). Thus floating litter

Table 3
Statistical significances between sub-regions plotted in Fig. 7. Lower left of each table – plastic litter loadings. Upper right of each table (shaded) – non-plastic loadings.

Coast 1: Scottish West Coast					
					Non–Plastic
W–AT	–			nsd	
W–FL	nsd	–			
W–MS	nsd	nsd	–		nsd
W–NM	nsd	nsd	nsd	–	
W–SM	nsd	nsd	nsd	nsd	–
	W–AT	*W–FL*	*W–MS*	*W–NM*	*W–SM*
Plastic					

Coast 2: Scottish East Coast									
									Non–Plastic
E–OK	–								
E–MO		–			nsd				
E–IM			–	nsd					
E–CD				–		nsd			
E–N					–			nsd	
E–TY						–			
E–FO					nsd		–		
E–S								–	
E–NE									–
	E–OK	*E–MO*	*E–IM*	*E–CD*	*E–N*	*E–TY*	*E–FO*	*E–S*	*E–NE*
Plastic									

Coast 3: English East Coast			
			Non–Plastic
S–WA	–	nsd	
S–EA	nsd	–	
S–TE			–
	S–WA	*S–EA*	*S–TE*
Plastic			

Coast 4: England/BE/NL			
			Non–Plastic
S–ST	–	nsd	
S–BE	nsd	–	
S–NL			–
	S–ST	*S–BE*	*S–NL*
Plastic			

Coast 5: DE/DK		
		Non–Plastic
S–DE	–	
S–DK		–
	S–DE	*S–DK*
Plastic		

passing along the coastal circulation may be injected into the North Sea to become an offshore source. Similarly, at the "downstream" end of Coastal Segment 2, the coastal circulation turns offshore (at least when the North sea is stratified) to form the oceanographic feature known as the Flamborough front (Hill et al., 1993; Hill et al., 2008). Thus once again coastally trapped floating litter may get injected into the main body of the North Sea. Coastal Segment 3 is interrupted at its southern "downstream" end by the inflow into the North Sea through the English Channel (Fig. 9). However, it is not clear what oceanographic feature might explain the break between Coastal Segments 4 and 5.

4.4. Litter monitoring and indicators

It is worth noting the possible effect of the spatial variations in foreshore litter loadings observed here on methods of monitoring beach litter, including beach litter indicators developed within Europe for statutory purposes, such as the Marine Strategy Framework Directive (MSFD). Measures (indicators) of beach litter may be developed for several purposes, e.g. assessing the status of a region's foreshores, assessing the impact of local litter management policies, and assessing trends in "global" remotely-sourced litter.

In relation to the first purpose, all coast types would be included to get a fair assessment of litter conditions in a region, irrespective of litter source. In relation to the second, monitoring foreshores heavily influenced by local litter sources (e.g. harbours and rivers) might be more appropriate than monitoring foreshores where local management actions will have little effect, as litter is sourced remotely, from outside the region.

Finally, when trying to determine trends in "global" levels of marine plastic several factors need to be considered. Within Scotland at least, foreshores within harbours and rivers would be excluded as these are influenced by local litter sources. Care would need to be taken if foreshores from the west and east Scottish coasts were combined, especially if a mixture of open coast and embayment foreshores were used. Around Scotland and the North Sea, care must also be taken when combining foreshores from within coastal segments where loadings are influenced by where they lie along the segment. Hence in order to design a coastal litter monitoring strategy, it is first important to understand the dynamics of beach litter in a region, its spatial variation and how this may influence the selection of index beaches.

5. Summary

Beach litter data was obtained from the Marine Conservation Society citizen-science data collection programme, and the OSPAR database. Litter loading distributions on north west European foreshores were positively skewed, hence statistics appropriate to such distributions were used.

Examination of the coastal morphology of Scottish beach litter survey sites, using readily available satellite imagery, allowed the sites to be allocated to five coast types: harbour, river, sea loch, open coast and embayment. The distribution of litter loadings recorded within the five coast type groupings was statistically different.

Results suggested that litter loadings on foreshores within the coast types harbour and river were influenced by local litter sources, particularly sewage-related sources. Owing to this result, foreshores in harbours and rivers were excluded from further analyses as these were aimed at understanding the movement of litter within and along coasts, rather than focussing on the effect of local litter inputs. Foreshores within sea lochs were excluded as these are generally only found on the Scottish west coast.

In Scotland, on coasts exposed predominantly to onshore winds, litter loadings were greater on open coast foreshores than in foreshores within embayments. The reverse was true for coasts with predominantly offshore winds. It is suggested that the coastal topography associated with embayments restricts the directional sectors from which wind can beach or de-beach litter.

Along the north east UK coast, a clear spatial arrangement of litter loadings was evident, characterised by increasing magnitude (median) and spread (inter quartile range) of foreshore litter distributions in the direction of the coastal current. Similar spatial change was suggested in four other coastal segments around the north western European coastline, from the Scottish west coast to Denmark.

The mechanisms producing the increased magnitude and spread in the direction of the coastal flow may be related to litter being passed from "upstream" foreshores to "downstream" foreshores, as well as the addition of litter from land-based or offshore sources.

The mechanisms resulting in breaks between coastal segments exhibiting coherent change in foreshore litter loadings along the coastal flow were related to oceanographic features that turn coastally trapped flow offshore. These features were a sharp change in along-coast direction, a seasonal front formed by tidal mixing characteristics, and the inflow from a channel.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2019.04.009.

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