Journal of Hazardous Materials 458 (2023) 131984

Contents lists available at ScienceDirect

Journal of Hazardous Materials

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

Towards continuous mass and size distributions for beach plastic litter: Spatiotemporal analyses of abundance and composition

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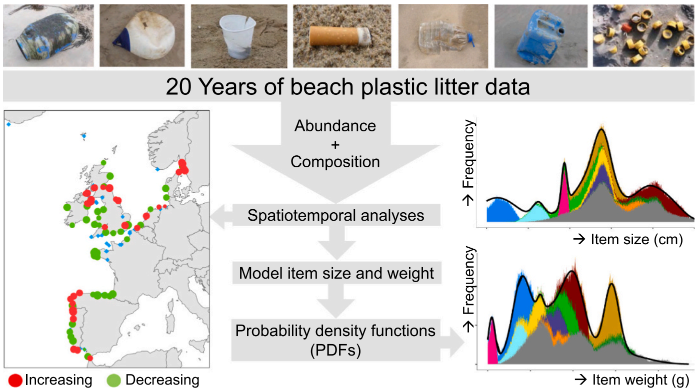
HIGHLIGHTS

- We provide a spatiotemporal analysis of 20 years of OSPAR beach plastic litter data.
- Count data for 75 plastic categories was complemented with weight and size ranges.
- We detect increasing plastic litter abundance trends for 43% of the European beaches.
- Spatial heterogeneity is largely caused by differences in total plastic abundance.
- Generic probability density functions for plastic size and weight are provided.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Joao Pinto da Costa

Keywords:
Environmental pollution
Macroplastics
Marine environment
Litter diversity
Probability density functions
OSPAR

ABSTRACT

Beaches are known as hotspots for the accumulation of plastic debris and are widely used for monitoring marine litter on a global scale. However, there is a significant knowledge gap regarding temporal trends in marine plastic pollution. Moreover, existing studies on beach plastics and popular monitoring protocols only provide count data. Consequently, it is not possible to monitor marine litter based on weights, which hampers the further application of beach plastic data. To address these gaps, we conducted an analysis of spatial and temporal trends in plastic abundance and composition using OSPAR beach litter monitoring data from 2001 to 2020. We established size and weight ranges for 75 (macro-)plastic categories to estimate the total plastic weight, enabling us to investigate plastic compositions. While the amount of plastic litter exhibits significant spatial variation, most individual beaches displayed notable temporal trends. The spatial variation in composition is primarily attributed to differences in total plastic abundance. We describe the compositions of beach plastics using generic probability density functions (PDFs) for item size and weight. Our trend analysis, method for estimating plastic weight from count data, and PDFs for beached plastic debris represent novel contributions to the field of plastic pollution science.

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https://doi.org/10.1016/j.jhazmat.2023.131984
Received 24 March 2023; Received in revised form 29 June 2023; Accepted 30 June 2023

1. Introduction

To improve the efficiency of plastic pollution mitigation strategies globally, we need to understand spatial and temporal trends in plastic litter [16,59]. Information on the spatiotemporal distribution of plastics is important for identifying the hazards and risks for organisms and ecosystems globally, and hence support mitigation of the impacts hereof [24,48,59,7]. Despite a growing number of plastic pollution studies, the transport and accumulation processes of marine plastics remain poorly understood [16,46,5,58]. The fate of plastic litter that enters the marine environment remains highly uncertain, and the majority of plastic mass that we know has entered our oceans remains unaccounted for [16,24,46,5,50,58].

As plastic is an indicator for the environmental quality of marine ecosystems, the abundance and composition of plastic on beaches can be used to compare the environmental quality and to identify major sources of plastic pollution [15]. For this reason, standardized beach litter monitoring protocols have been established, for example the beach litter monitoring guidelines established by the OSPAR commission, providing the most detailed and widely implemented monitoring protocol to date [61]. Systemic monitoring of beach plastic litter can additionally contribute to the identification of spatiotemporal distribution patterns, sources of pollution and accumulation hotspots [24,48,59,7]. Moreover, information about the composition and abundance of plastic litter on beaches can improve our understanding of the transport and accumulation processes of plastics in marine environments. However, only a handful of recent beach litter studies have been performed with more than 5 years of data, which in turn are performed at a limited spatial scale: hampering the identification of large-scale plastic litter patterns and trends (e.g. [20,37,44,46,47,59]).

Previous beach plastic litter studies commonly aim to “quantify and characterize” plastic litter using descriptive analyses: quantifying litter using counts and characterizing compositions using qualitative categories [15,19,20,3,36,4,45–47,49,50]. Because all plastic litter will eventually break down into micro- and nanoplastics, the common use of litter counts complicates accurate monitoring and comparison of the total quantity of plastic litter [19,50,52,53]. For example, a plastic bottle may fragment into two parts which can be recorded as two items of the category “Plastic bottles” (e.g. as categorized by the OSPAR Monitoring Protocol) - or even three when its cap is found separately - whereas a similar unfragmented bottle will be recorded as one [61]. The total weight of plastic litter on two beaches with an equal number of plastic litter items can be drastically different, even if their litter composition in terms of categories is comparable. Hence, the application of measures on continuous scales, total weight for example, are considered more appropriate for monitoring plastic litter [52].

In addition, a common constraint of many plastic litter studies and popular beach litter monitoring protocols (including the protocol from OSPAR), is their failure to consider the physical characteristics of plastic items, such as weight and size [15,61]. As weight and size information is crucial for understanding the underlying dynamics of movement and accumulation of marine plastics, lack of this knowledge hampers the further application of plastic litter data in e.g. plastic fate modelling efforts [15,35,58]. Describing the amount and composition of plastic litter on continuous scales, as well as the establishment of probability density functions (PDFs), can support the use of beach litter data for further research into the dynamics behind transport and accumulation of hazardous marine plastics.

The aim of this paper is two-fold. Firstly, we aim to conduct a comprehensive investigation into the patterns and trends concerning the abundance and composition of plastic litter on European beaches over a period of 20 years. By incorporating a larger temporal and spatial scope than previous studies, we seek to explore the spatial, temporal, and spatiotemporal patterns of beach plastic litter on a more extensive scale than ever before. Second, we introduce the use of PDFs for describing beach plastic litter, a method previously proposed for analysing microplastics [1,29,31,32]. Additionally, we present a method to convert counts per qualitative plastic litter category, following the categorization protocol defined by OSPAR, into ranges of item size and weight measurements. This conversion method allows us to study the total weight of plastic litter instead of solely focusing on the number of litter items, as commonly reported in previous beach litter studies. Moreover, it broadens the range of potential future applications for number-based plastic litter datasets such as those provided by OSPAR. Furthermore, in conjunction with the presented PDFs, we show how physical characteristics can be incorporated into macroplastics research. Supported by our findings, we present generic PDFs for the composition of beach plastic litter in terms of item weight and size. This represents a novel contribution to the study of beach macroplastics, as such PDFs have not been previously presented.

2. Methods

2.1. Data

We analysed 20 years of plastic beach litter data, collected on beaches throughout the OSPAR maritime area. The data used in this study is derived from ODIMS, the public database from the Oslo/Paris convention Commission (OSPAR) by EU’s Maritime Strategy Framework Directive [41]. Hence, all beach plastic litter data in the presented study was collected according to the OSPAR beach litter monitoring protocol [61]. This protocol is the most detailed and comprehensive beach litter monitoring protocol available [49,61]. There are two types of surveys: 100 m and 1000 m length beach transects, for which the distinguished litter categories are slightly different. We only used data from the 100-metre transects, as it has a more detailed categorization protocol focusing on items $<$ 150 cm (the 1000-metre transects focus on larger, industrial litter) and substantially more data was available. Our study was performed using data from 2001 to 2020, covering 4480 surveys at 218 different beaches across the OSPAR Maritime region, including beaches in Europe and the Arctic region. Some beaches have been monitored only once, whereas others have been monitored systematically since 2001.

The OSPAR protocol defines 146 different debris categories which are grouped into material categories: paper, plastics, metal, rubber and wood. From the list of 146 debris categories, 58 are subdivided in the group “plastics”. In the present study, we additionally considered rubber items as plastic litter. Similarly, cigarette stubs are grouped under ‘paper’ in the protocol, but since their core is made from plastic material, we included them in our study [27]. From the entire OSPAR list of categories, 75 were selected that were regarded as plastic debris based on the authors’ expert judgement (Table S1). When referring to “OSPAR categories”, we refer to these 75 selected categories, unless stated otherwise.

2.2. Exploratory analyses of spatiotemporal trends

All analyses were performed in RStudio (version 2022.12.0). We explored spatiotemporal patterns for both the amount and composition of beach plastic litter. The total amount of plastic per survey was originally represented by abundance (total number of items), which are supplemented with simulated total plastic weight (grams). The way in which the plastic weights were determined and total litter weights were simulated are described below (Section 2.6). The diversity in composition of different litter types was represented using three diversity indices: Shannon-Wiener diversity (H), richness (S) and evenness (E) [21,51,60]. These indices are commonly used in community ecology and have recently been introduced in plastic litter research [7,17]. We calculated the diversity indices based on three categorization methods: (i) litter categories as defined by OSPAR, (ii) size-based and (iii) weight-based categories (Section 2.6, Table S3). The Shannon diversity index, which accounts for both richness in abundance and evenness, was calculated as:

$$H = -\Sigma_S^{i=0} p_i \ln(p_i) \tag{1}$$

where H is the Shannon-Wiener diversity, S the richness (the total number of species, here: different plastic categories observed) and *pi* the relative proportion of the i^{th} species [60]. Evenness (E) was calculated as:

$$\mathrm{E} = H/\ln(\mathrm{S}) \tag{2}$$

The composition of plastic litter was further studied by calculating the relative contribution of litter groups (litter categories, size and weight classes) to the total weight and abundance of plastic litter and this was visualized using pie charts.

2.3. *Temporal trends*

We investigated the existence of a temporal trend in the total amount of plastic litter (observed per survey) over time throughout our entire study area, by creating a generalized linear mixed-effect model (GLMM) using the lmer function of the *lme4* package [6]. We modelled total plastic counts and total weight (simulated as described in Section 2.6) as a function of numeric date. Beach ID was included as a random factor, because the data from different dates from the same beach cannot be treated as independent. We fitted a Poisson distribution to the count data and a gaussian distribution for the total plastic weights (simulated as described in 2.6). The assumption of normality was validated using Normal Q-Q plots and checking the residuals.

Next, we investigated temporal trends on individual beaches, by modelling the total amount of plastics observed per survey using generalized linear models (GLM) as a function of time (numeric date). We applied a GLM to the data per beach, with the criterium that only beaches were included with a minimum of 20 different survey dates spread over at least 5 different years. This resulted in a subset of 80 beaches. We modelled both total litter counts and simulated total litter weights (Section 2.6) on these beaches, hence generating a total of 160 GLMs: for each beach one for weight and one for count. Similar to the GLMM, we fitted Poisson and gaussian distributions to count and continuous data respectively.

Finally, we investigated the temporal trends for a subset of beaches in more detail by visualizing them in boxplots. We did this for all beaches which had been sampled at least once every year over the period 2001–2020, which was the case for five beaches. Based on the boxplots and GLM results from these beaches, we studied their temporal trends in amount of plastic in terms of both the total item count and total weight (grams), and additionally calculated the mean item weight as a measure for the (in)stability of the plastic litter composition over time.

2.4. *Spatial patterns*

To check the existence of spatial gradients in plastic litter diversity and amount, we tested for the presence of spatial autocorrelation, using the Moran.I function from the *ape* package [11,42,55]. The amount of plastic was studied in terms of both counts and total weight, and the relative composition of different litter types was represented by richness and diversity (Shannon-H′, Section 2.3). To minimize temporal effects, data was analysed per year. We analysed various subsets of countries in more detail for one focal year, to investigate the effect of excluding extreme outliers such as Spitsbergen, Greenland and Iceland. These Arctic beaches are known to be relatively less polluted, located relatively isolated, and in the North, which is likely to have strong influence on the spatial autocorrelation.

To investigate whether individual beaches show unique patterns in plastics - as characterized by total plastic litter amounts and diversity indices - and/or if individual beaches have (dis)similar changes over time, we modelled these variables using regression models. We tested if these response variables are significantly explained by beach ID, year and/or the interaction effect between ID and year. Only beaches with survey data from at least 15 different years and at most one year in between surveys, were included. Because the residuals from a fitted generalised linear model (GLM) were not normally distributed, we fitted a General Additive Model (GAMs) to the data using the *mgcv* package [62], supplemented by an ANOVA. For richness and abundance, based on count data, a Poisson distribution was applied. For total weight (simulated, Section 2.6), diversity and evenness, a gaussian distribution was chosen.

For all statistical analyses, a p-value of <0.05 was used as criterion for statistical significance.

2.5. *Plastic litter composition*

We performed multivariate analyses to investigate the level of variation in the composition of plastic litter on beaches, based on composition in terms of the 75 OSPAR categories. First, detrended correspondent analyses (DCA) was performed with the *vegan* package in R, to select the type of model for further analyses [14]. This analysis was based on raw count data, where rows are unique observations, and columns are plastic types. Zero-observations (22 out of the 4480 surveys) were excluded from this DCA and following multivariate analyses, as the row sum of all categories must be larger than zero. Because the DCA resulted in gradient lengths of 3.8 of the first axis and 4.4 of the second axis, we used unimodal models: correspondence analyses (CA) and canonical correspondent analyses (CCA).

To investigate which plastic categories contribute most to the observed variation, CA was performed using the package *FactoMineR* in R [33]. Figures were made using the package *factoextra* [26]. Next, CCA was performed to test if and how temporal and spatial variables explain the observed variance in the plastic litter compositions. We tested the effect of space by incorporating the coordinates of each observation, but we also took into account country and region and beach ID as factors. To account for temporal trends, we included the numeric date and year of each survey and month as an additional factor. We started with the full model and performed backward selection based on the variance inflation factors (VIF) of the variables, using the vif.cca function from the *vegan* package and adhering to a VIF threshold of 20 [14]. Based hereon, we had to remove numeric date, region and country from the model. Finally, we performed backward selection of the remaining variables based on their statistical significance, by performing an ANOVA test via the ordiR2step function (*vegan* package) [14]. To visualize the results, ordination plots were generated using the ordiplot and ordihull functions from the vegan package [14].

Subsequently, we investigated to what extent the observed spatiotemporal variation is caused by differences in the (total) plastic litter abundance. In other words, we want to know whether the relative contribution of different plastics is more similar in time and space than their absolute abundances. The same CCA procedure was followed, based on relative plastic litter compositions. Here, the relative contribution of each category to the total number of plastic items observed was calculated, per survey. We compared the explanatory power of the included variables to the results from the initial, count based CCA.

Finally, complementing the CCAs, we investigated how similar the plastic litter composition is on different beaches, by calculating the Bray-Curtis distance, a measure for (dis)similarity, using the vegdist function from the *vegan* package [14]. We calculated this statistic based on the mean abundance per OSPAR category per beach per year, in order to correct for differences in the number of surveys performed per beach. Similar to the CCA, we calculated this based on both absolute and relative plastic abundances. Because observations from different years cannot be considered independent, we calculated the similarity for each year. Results were visualized using histograms and boxplots. If the relative composition of beach plastic litter reveals to be relatively similar over space and time, this allows us to define generic item size and weight frequency distributions applicable for the entire study region.

2.6. *Simulating weight and size*

We established mean, lower and upper limits to characterize the size and weight range of each plastic litter category (Table S1). These ranges were established using the descriptions provided by the OSPAR beach litter monitoring guidelines [61], by actual weighing, measuring and online research. To minimize observer bias, five experts provided their findings on the measurement ranges for each of the 75 categories (Fig. S7), which were combined using weighted averages. Four out of the five contributing experts had hands-on experience with beach litter monitoring surveys.

We subsequently used these ranges for converting the observed number of plastic items to simulate the total weight of plastics in grams (per category, per survey): enabling us to investigate the total amount of plastic litter and relative composition, in terms of total plastic litter weight. The observed weight ranges were used to compose a triangular density distribution for each of the 75 plastic litter categories, using the rtriangle function from the *triangle* package [8]. The plastic litter weight was simulated per category and per observation, by drawing n samples from the triangular distribution of a focal plastic category, where n is the number of items of that category observed during a focal survey. Subsequently, the total weight of plastic litter per survey could be calculated, as well as the relative contribution of each category to the total litter weight, which were used subsequently for spatiotemporal analyses. To investigate plastic composition in terms of size and weight diversity (to calculate diversity indices based on these physical characteristics-based categories), we re-categorized the OSPAR litter categories into arbitrary size and weight classes, based on the attributed means for size and weight per OSPAR litter category.

Finally, based on the observation that the relative composition of beach plastic litter is relatively constant in space and time (Section 3.3), we were able to construct generic PDFs for the composition of beach plastic litter in terms of item weights and sizes. To simulate a frequency distribution for the occurrence of plastic items of different weights and sizes on continuous scales, we used a protocol similar to one for continuous distributions for microplastics described by Kooi & Koelmans [31]. Here, the triangular distributions are combined with the weighted average relative occurrences (fractions) per plastic litter category, based on which Monte Carlo simulations were run. We ran 10^6 iterations to generate PDFs for beached macroplastic, hence taking $n \times 10^6$ random samples from the triangular size and weight distributions of each category, where n is the relative occurrence of the focal category. We fitted a mixture of multivariate normal distributions to the resulting size and weight distributions, using the normalmixEM function from the *mixtools* package [9].

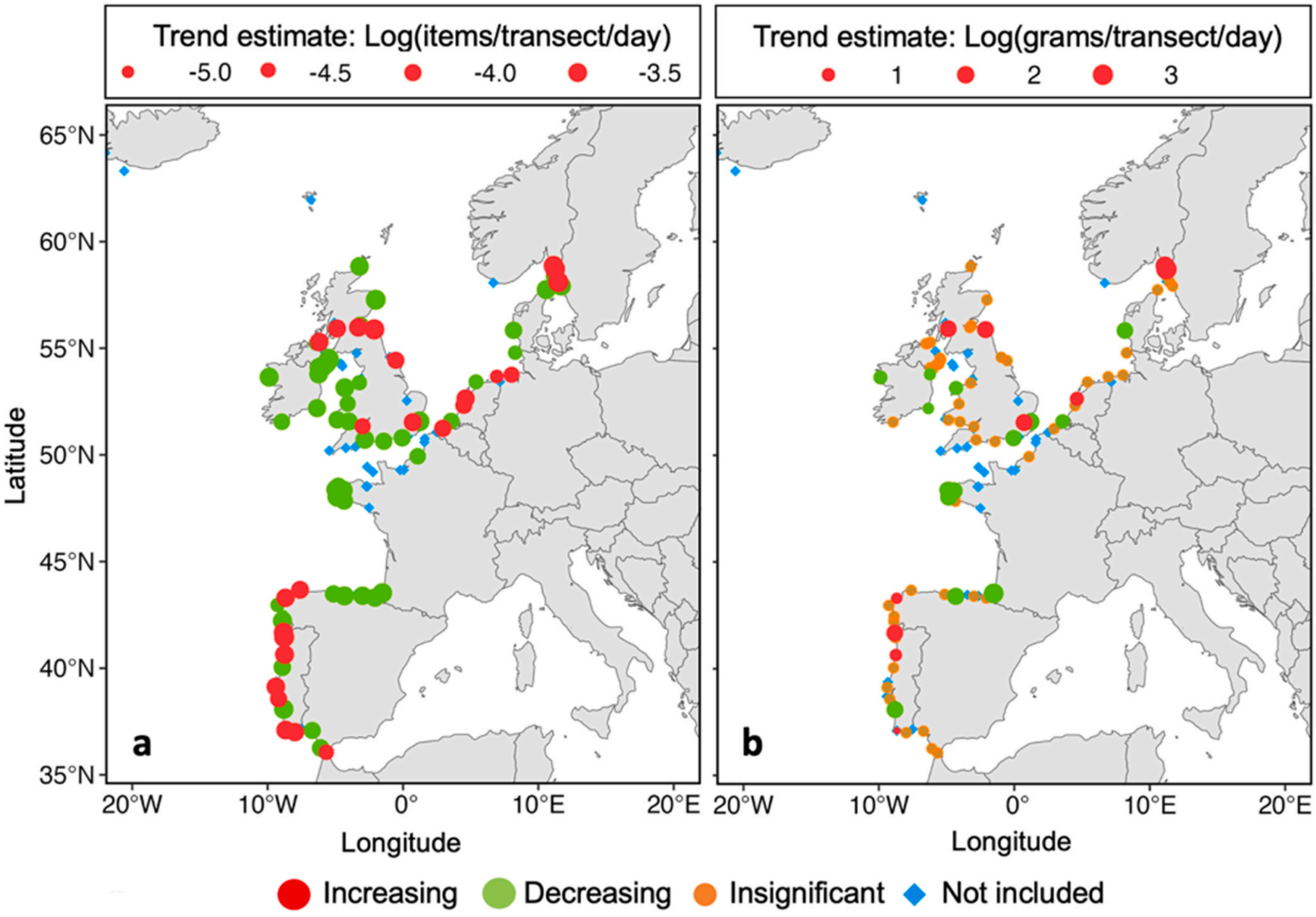

Fig. 1. Map of the temporal trends for individual beaches resulting from the GLM, based on (a) total plastic litter abundance (number of items) and (b) total plastic litter weight. Red colored values indicate a positive trend (increase in macro-plastic litter), green colored circles indicate a negative trend (decrease in macro-plastic litter). Only beaches with a minimum of 20 different survey dates spread over at least 5 different years were included.

3. Results and discussion

3.1. Explorative analyses

In total, data from 4480 beach litter monitoring surveys were included in our study, covering a total of 218 beaches (Fig. 1, S1). The maximum number of observations for one beach was 93, whereas there were 10 beaches that had only been monitored once. The mean number of items over all observations was 727. Median concentrations for individual beaches range between 0 (beach surveyed once) and 16378 pieces (surveyed six times). The single highest observed number of items on a beach was 223179 in 2017 in Edsvik (Sweden), which was also the beach with the highest median. Plastic litter diversity ranged between 0 and 3.5, with a mean value of 2.1. Richness values ranged 0–62 and had a mean of 23, representing the number of unique OSPAR categories from which litter items were observed. The mean Evenness was 0.7, which indicates relatively homogeneous abundances of litter items from different categories.

3.2. Temporal trends

The average increase in abundance was estimated at 1.00 ± 1.00 (SE) total plastic items per beach transect per year, which is a small but statistically significant positive trend (t-value $= 3.83$, $p = 1.0 \times 10^{-4}$; GLMM model; log-transformed data). For the total weight of plastic litter, a similar significant positive trend was found, where plastic litter increases with 51.29 ± 10.27 (SE) grams per transect per day (t-value $=$ 4.99, $p < 2 \times 10^{-16}$ GLMM model; untransformed data). It is remarkable that we can find these trends in the dataset, since we included all observations also when only one sample was available for a focal beach.

Out of the 80 beaches for which temporal trends were investigated with a GLM (sampled in at least 5 different years and a total of at least 20 surveys), 78 were found to have a significant trend ($p < 0.05$) regarding plastic abundance based on the count data and all 80 revealed significant ($p < 0.05$) trends based on total weight. In all cases we adhered to $p < 0.05$. Based on median plastic counts, 27 beaches revealed positive and 51 revealed negative temporal trends (Fig. 1a). Positive, significant trends vary between 4.24×10^{-6} and 1.08×10^{-3} items/transect/day, negative trends between -7.27×10^{-4} and -8.6×10^{-6} items/transect/day ($p < 0.05$). At this rate, it would take 2.5–645 years for one additional item to be added, and between 4 and 317 years to remove one, to the median number of plastic litter items found along a 100-m beach survey transect.

Based on total plastic litter weight, we observed significant temporal trends on 24 of the selected beaches. Here, we found 10 beaches that have a significant positive, and 14 beaches that have a significant negative trend in their (simulated) total plastic litter weight (Fig. 1b). Significant positive trends vary between 37.10 and 58.87 g/transect/day, significant negative trends between -5.47 and -828.84 g/transect/day ($p < 0.05$). Hence, on beaches with significant positive trends, every 17–27 days one kilogram of plastic is added to the median total plastic litter weight observed along a 100-m transect. On beaches with significant negative trends, plastic litter is removed from the median total weight per transect at a pace of one kilogram per 1–183 days.

Beaches that were observed to have a significantly increasing trend in plastic litter counts, seem clustered in space (Fig. 1a), being in Sweden, the Northern part of the UK and on Spanish and Portuguese coasts along the Atlantic Ocean. Clusters with decreasing trends are found along the Bay of Biscay, in Denmark and in Southern beaches of the UK and Ireland. Interestingly, beaches along the Bay of Biscay (French and Northern Spanish coast) and influx of the English Channel all showed decreasing trends.

When further investigating long-term trends for the five beaches that were surveyed each year (Fig. 2), no clear, consistent temporal patterns were observed. This is in agreement with the results of previous studies on the temporal plastic litter trends performed along the North Sea coast [46,47] and United Kingdom [59]. In Saltburn and Sand Bay, there appears to be consistently more plastic litter compared to the other three beaches, both in terms of total abundance and total weight. For these two beaches, we see that the relative amount of plastic is slightly lower based on weight, and major peaks are somewhat dampened.

Mean item weight (grams) over time was visualized, serving as a rough measure for plastic litter composition in terms of item size and weight (Fig. 2). High mean weights indicate that relatively many large plastic items (e.g. buoys, fishing gear, tyres) and/or relatively few small items (e.g. bottle caps, cigarette stubs, bottles) were found. At Saltburn and Sand Bay beach, stable mean weights were observed over the long-term, whereas for the remaining beaches major fluctuations were found. Interestingly, the mean item weight seems to become more stable and more similar on all beaches from 2011 onwards.

Putting these temporal trend results in perspective is difficult, as long-term plastic beach litter studies are not particularly abundant [57]. However, a single long-term study previously performed within the OSPAR maritime area (with 25-years of data), found increasing plastic litter counts at 26 beaches, and decreasing trends at 16 out of 112 studied beaches [46]. This positive/negative ratio deviates from our results, as we detect almost double as much beaches with negative plastic litter abundance trends compared to positive trends. They concluded the absence of any “systematic spatial patterns or long term trends” [46]. Similarly, our results do not reveal patterns or temporal trends that are consistent over the entire study area. However, we did observe some clustering, which could suggest the presence of small-scale patterns, hence we do not reject the possibility of spatial patterns.

The GLMs revealed significant ($p < 0.05$) positive trends (increasing number of plastic litter items) at Baldaio (2.79×10^{-4} items/transect/day, SE$=8.36 \times 10^{-6}$), Bergen (3.58×10^{-4} items/transect/day), SE$= 5.83 \times 10^{-6}$, Sand Bay (5.05×10^{-5} items/transect/day, SE$=1.74 \times 10^{-6}$) and Saltburn (8.43×10^{-5}items/transect/day, SE$=8.43 \times 10^{-5}$). Based on total plastic weight, significant ($p < 0.05$) positive trends were observed at Baldaio (6.54 g/transect/day, SE=1.39), Bergen (16.81 g/transect/day, SE=4.48) and Saltburn (46.92 g/transect/day, SE=18.51).

3.3. Spatial patterns

Based on the complete dataset, we observed significant spatial autocorrelation for plastic litter counts, weight, richness and diversity (Table S4), which suggests the presence of spatial gradients. However, after removing the Arctic beaches (Iceland, Spitsbergen, Greenland), spatial autocorrelation was no longer significant for richness. This indicates that the spatial correlation in richness is caused by lower richness values in the Arctic seas compared to those in the rest of Europe. This is not surprising, as Arctic beaches are known to have lower plastic pollution levels compared to continental Europe [25,35]. The spatial autocorrelation for total plastic litter count and weight were caused by higher levels of abundance on Sweden’s beaches, as there is no spatial autocorrelation once all Swedish beaches are removed. The high plastic litter abundances in Sweden (Fig. 1, S1) can be explained from oceanic currents and streams; both a major branch of the North Atlantic current and coastal streams coming from Dutch, German and Danish coasts, are directed towards the small bay between Sweden and Denmark [38,54,56]. In addition, the high ship traffic and fishing intensity in the North Sea are known to be a major source of plastic pollution. As a result, much of the plastic litter in the North Sea may end up on Swedish and Danish coasts [38,56]. Hence, we conclude there is no statistically sound, significant spatial gradient in the diversity and amount of beach plastic litter within continental Europe.

Small-scale patterns in plastic abundance and diversity (diversity indices, Section 2.2) were investigated by regression modelling, where abundance and diversity were modelled as a function of year and beach ID. The results revealed significant contributions of beach ID alone and the interaction effect of ID and decimal year to GAMs for total plastic

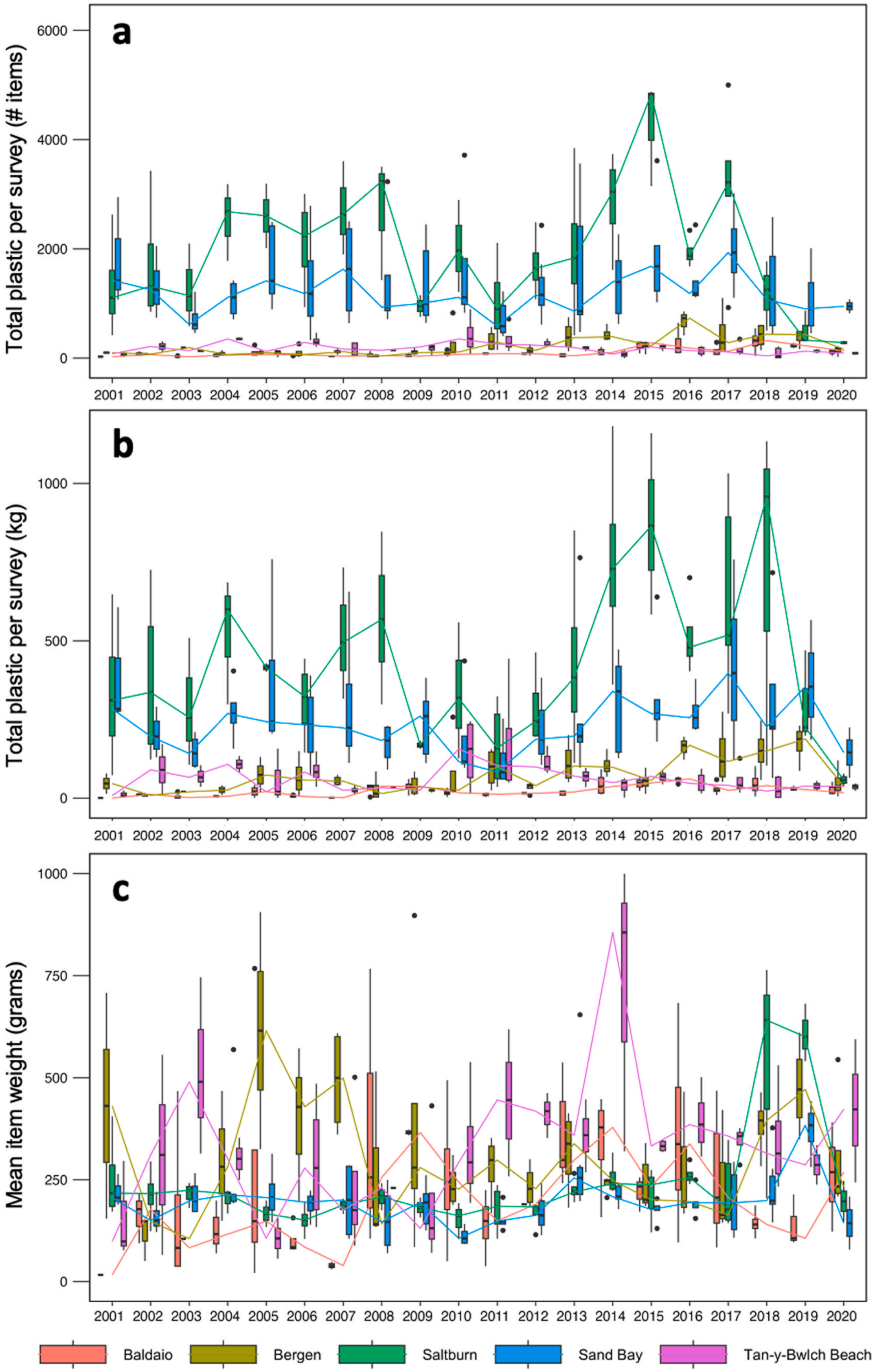

Fig. 2. Time series for beaches sampled each year, showing (a) the abundance of plastic litter in number of items, (b) total plastic weight (kg) and (c) the mean item weight (grams), per beach per survey. The boxplots show the variation between different sampling periods (usually sampled in 4 periods). The lines show the median value and assumes linear interpolation between the years.

counts and weight, as well as for all diversity indices, except richness (Table S2). Similarly, the diversity and evenness values that were based on arbitrary weight- and size-based groups, were significantly explained by both ID and the interaction effect between ID and numeric date (Table S3). This indicates that individual beaches have unique plastic abundances, diversity, richness and evenness, as well as unique responses of these variables to temporal variation. Unique patterns on individual beaches can be explained by selective trapping processes that act on a local scale (further discussed in Section 3.4) [13,23,39]. For total plastic weight and the H-values based on size- and weight-classes, decimal year alone was also significant, revealing the existence of a temporal effect that is independent of beach ID. Year not significantly contributing to the GAMs for the total number of items and diversity indices based on the OSPAR categories, shows that there is no temporal trend for these values that is consistent at the majority of the studied beaches. This is in line with the GLM(M) results. Although this is the first long-term study on a continental scale, our results are consistent with the conclusions of previous long-term studies within the United Kingdom [37,59], where beaches showed varying amounts of litter over time without the existence of a consistent trend.

3.4. Plastic litter composition

The CA results show that 19.9% of the variation in plastic litter compositions on beaches is explained by the first two dimensions (Fig. S2). The categories ‘other sanitary’, ‘plastic string’, ‘other medical’, (sanitary) ‘towels’ and ‘buds’ have a significant contribution to the first dimension (Fig. S3). Significant contributions to the second dimension come from (plastic) ‘string’, ‘other sanitary’, ‘buds’, ‘cigarette stubs’ and ‘caps’. Hence, these are the most dominantly varying plastic litter categories within our data.

To test how much of the total observed variation in plastic compositions on beaches can be explained by space and time, CCA was performed. After omitting explanatory variables with high (>20) VIF values, only beach ID, month and year remained. The results of an ANOVA showed that these three variables were significant ($p < 0.05$). Beach ID has the largest explanatory power, as it yields an adjusted R^2 value of 0.42 (42% explained). Month explains an additional 5% and year adds 4.5%. These results suggest that variation between locations is stronger than temporal variation, at least for the temporal scale of this study (20 years). Together, these variables that represent time and space explain 43.7% of the variation in the (absolute) occurrence of different OSPAR categories observed in our data.

The large explanatory power of beach ID suggests that much of the existing spatial variation in plastic litter composition is caused by local selective trapping and transport processes, depending on site-specific marine and coastal characteristics. This is in line with the results from the GAM (Section 3.1), which indicated that individual beaches have significantly unique litter abundances and diversities, as well as unique responses to temporal changes. Previous research has shown that vegetation and geomorphological, hydraulic and hydrological coastal features can strongly impact local settling rates and beach litter composition [13,16,18,22,23,34,43]. As a result, the abundance and composition of plastic on beaches is not expected to be perfectly homogeneous, even if the concentration and relative composition of plastics in the water were to be perfectly homogenous [13,16,23]. In addition, the physical properties of any plastic item can strongly affect its fate in the marine environment [13,16,22].

Although minor compared to beach ID, the contribution of month and year cannot be neglected. It is remarkable that we find a significant contribution of year by itself ($p < 0.05$). The fact that month significantly contributes to the observed variation suggests that there is seasonal variation in plastic litter composition, independent of the effect of year. This could be the result of seasonal increase in certain types of pollution, such as tourism-related litter or river outflows. But, as we used the absolute composition of plastics (number of items per category), the effect of both year and month could most simply be the result of temporal variation in litter abundance.

The absolute litter composition and abundance does however not tell us anything about the relative composition of plastic litter. We investigated if beached plastic litter can be considered “one thing”, in other words, is the relative composition of plastics in space similar throughout our entire study area? Based on the relative plastic abundances, beach ID had an adjusted R^2 of 0.27 (27.0% explained), with an additional contribution of year (2.2%). The explanatory power of month (R^2 of 0.01) was not statistically significant. Together, year and beach ID explain 28.5% of the observed variation in observed relative plastic litter compositions. Hence, 71.5% of the variation in relative plastic composition cannot be explained by the yearly, seasonal or local patterns discussed above, and remains unexplained. Comparing these results with the results from the CCA based on absolute litter abundances, the total explanatory power of the variables in the CCA decreases with ($0.437 - 0.285 / 0.437 * 100\%$) 35% when analyzing the relative compositions. This shows that 35% of the total observed variation in (absolute) plastic compositions explained by space and time, can be attributed to differences in total amount of plastic litter items.

The observed reduction in explanatory power of beach ID is in line with what would be expected based on our hypothesis that the relative composition of plastic litter is similar on different beaches. This decrease indicates that 36% of the observed variation in (absolute) plastic compositions between individual beaches is caused by differences in total plastic abundance.

It is remarkable that month does not contribute to the variation in relative litter compositions. This shows that the relative occurrence of plastic items from different categories does not strongly vary seasonally. Based hereon, we can conclude that the seasonal variation in absolute litter compositions is caused by seasonal variation in plastic litter abundance as a whole. Similarly, the contribution of year is only half as strong as based on absolute litter abundances, indicating that part of the explanatory power of year for absolute litter compositions is simply the result of temporal changes in total plastic abundance. The remaining contribution of 2.2% in explaining relative litter compositions, could be the result of a consistent increase or decrease of certain plastic types on a large spatial scale. For example, decreases in tourism-related litter over time as a result of the growing public pollution awareness. Other causes for large-scale variation in both total litter abundance as well as certain litter categories, include occasional waste dumps or the beaching of plastic items after pollution “events” (e.g. loss of ship containers). Alternatively, it might be caused by differences in weather (e.g. wind speed, wave strength) and/or water flow directions, the level of pollution of the North Atlantic current, or a combination hereof.

The observed Bray Curtis distance for absolute compositions (mean value of all beaches per year) ranged 0.73–0.82 from 2001 to 2020, with a mean of 0.76 (Fig. S6). Based on relative abundances, we found yearly mean values ranging 0.58–0.75 with a mean of 0.64, which is more similar (Fig. S6). Considering 75 different plastic litter categories were distinguished, which is quite detailed, the observed dissimilarity is quite low. Moreover, some categories have overlapping physical characteristics and/or origin, and some litter items may theoretically fit in multiple categories. Combined with the results from the CCA - which led to the conclusion that differences in the total abundance of plastics have a major effect on absolute differences in plastics compositions on different beaches – our results indicate that beach plastics compositional differences in space, are of minor importance compared to differences plastic abundances. In contrast to the frequently mentioned spatial heterogeneity of marine plastic litter abundances (e.g. [10,20,48]), the presented results suggest that despite some spatiotemporal variation, the relative composition of plastic litter items can be considered to be quite homogenous.

3.5. Towards continuous descriptions of litter abundance and composition

Based on the presented results (Sections 3.1–3.4) we conclude that the relative composition of plastic items is relatively homogenous, at least within the OSPAR maritime region. Because the categorization method is detailed and categories are well defined, we can assume that if the relative composition in terms of the 75 categories is relatively homogeneous, the size and weight frequency distributions for plastic litter items are relatively homogenous as well. Therefore, we lastly describe the relative composition of beach plastic litter in terms of item weight and size, without separating our data into space or time-based groups. We present generic probability density functions (PDFs), describing the relative composition of beach plastic litter item size and weight in our study area (Fig. 3). For data based on counts (Fig. 3a), peaks are observed for small plastic fragments (<2.5 cm), cigarette stubs (or butts) and earbuds, while the remaining categories are blended into the two other peaks. For data based on item weights, cigarette stubs and large plastic fragments (> 50 cm) composed relatively stand-alone peaks where the other groups are blended (Fig. 3b). We fitted multivariate normal distributions on both continuous frequency distributions, composed of a mixture of seven- and eight-modal functions for size and weight respectively (Table S5).

When modelling the transport, distribution and accumulation processes of plastic litter, information on item size, shape, density and weight are of high importance. Hence, describing the physical characteristics of macroplastics, as well as describing the relative composition of plastic litter on a continuous scale, has major advantages over approaches that use arbitrary categorization methods. The presented PDFs and the mathematical descriptions of the multivariate mixture normal distributions fitted hereon (Table S5) can be implemented in amongst others plastic litter fate models and risk assessment frameworks. For example, when modelling the fate and transport of marine plastics, the size and weight of the plastic items can be probabilistically taken into account, using the mathematical description of the PDFs. Similarly, PDFs for microplastics have been developed and successfully implemented in fate models and risk assessment frameworks [1,30,31].

In this study, we attributed size and weight ranges to 75 beach litter categories (Section 2.6). We attributed the upper and lower limits in addition to a mean measurement value, to capture variation within the categories. To additionally account for stochasticity, which is especially important for the simulation of total plastic weights, a random sampling procedure was implemented (Section 2.6). With regards to all these factors, we feel it is safe to assume the established measurement ranges are accurate and our results are not sensitive to sporadic differences. Nevertheless, future work may aim to further refine and validate the presented measurement ranges and PDFs. Although laborious, we argue that future verification of the presented measurement ranges may be based on long-term and large-scale field studies, measuring the size and weight of every single plastic item collected during beach surveys, in order to capture and quantify all potential spatiotemporal variation in intraclass-variation.

The OSPAR protocol is the most detailed and comprehensive beach litter monitoring protocol available, and has been widely applied [49,61]. However, other monitoring protocols with slightly different categorization methods exist. Apart from OSPAR, the most commonly applied monitoring and categorization include the ones established by UNEP, NOAA and EA/NALG [12,2,28,40]. The implementation of various litter monitoring protocols has to date hampered the integration of plastic litter research data and has been an obstacle for global harmonization of marine plastic pollution data [2,50]. The approach presented in this study (Section 2.6) removes the necessity of selecting one of these protocols and establishing its global application for future integration of plastic litter research data. Instead, the obstacle of differences in categorization can be removed by attributing (ranges of) physical characteristics to each category (here showcased for weight and size) and subsequent application of continuous distributions, instead of categories and discrete classes, which enables the integration of all currently available marine plastic litter data. In addition to size and weight, this approach can be applied for other physical characteristics (e.g. volume, density) [31]. Moreover, PDFs can in principle span the full continuum from nano-, micro- to microplastic [1,31], on which focused research efforts are generally separated. Hence, universal application of continuous distributions (including PDFs) can support both large-scale integration of marine plastic pollution data and harmonization of research on nano-, micro- and macroplastics.

4. Implications and conclusion

We performed a comprehensive study on macroplastics in marine environments within the OSPAR maritime area, based on 20 years of beach litter data from 168 beaches collected according to the OSPAR beach litter monitoring protocol. Our results revealed significant temporal trends for 78 and 80 beaches based on the median observed number of items and median weight respectively. Of all beaches, 28

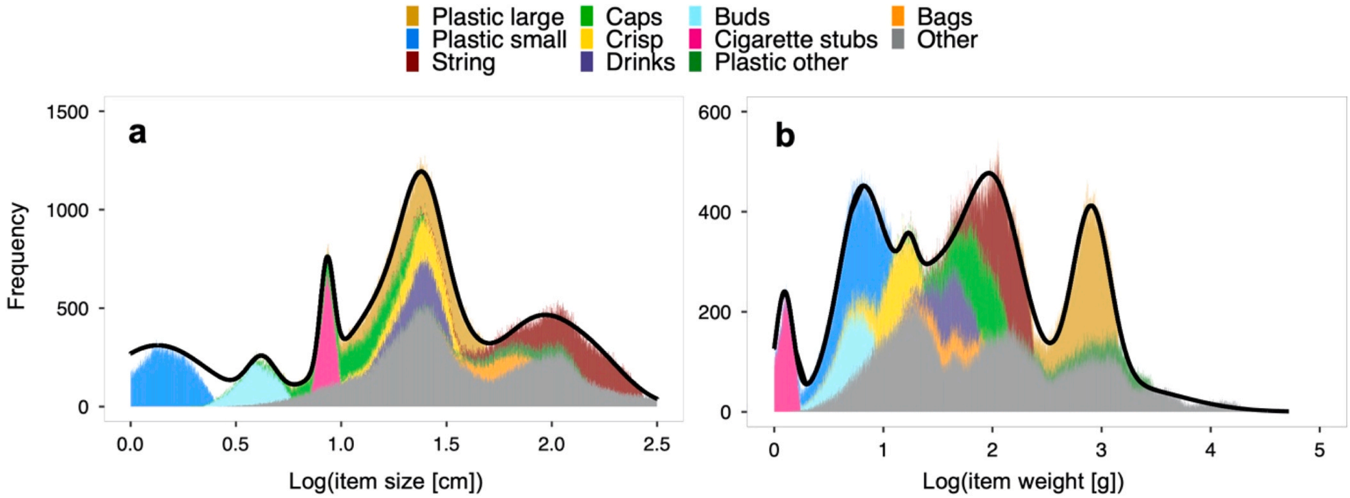

Fig. 3. Probability density functions describing the relative frequency of the (a) sizes and (b) weights of individual plastic litter items, based on the relative abundance of plastic litter categories as observed throughout the entire study area, combined with 10^6 Monte-Carlo simulations (Section 2.6). The ten relatively most abundant plastic categories have been colored individually, the other 65 are grouped into “Other”. Black line shows the fitted mixture of k multivariate normal distributions, where k = 8 for item size and k = 7 for item weight (fitted model parameters provided in Table S5).

revealed an increasing median number of plastic litter items, and 34 beaches an increasing median total plastic litter weight. Whilst no temporal change in plastic abundance was revealed that was consistent throughout the entire study area, similar compositional changes over time were observed for multiple beaches. Seasonal compositional variations were not observed in relative abundances of different plastic categories, suggesting that seasonal variations are predominantly differences in total plastic amounts. Similarly, our results reveal that a large part of the observed spatial variation in plastic litter composition is caused by variations in total plastic abundance. We showed that although the amount of plastic litter is highly variable in space, the relative composition of different plastic litter types is quite similar for beaches across Europe. Finally, we show that on a large spatial scale, beach macro-plastic litter composition can be modelled using one probability density function.

In this study, we provided a simple yet effective method for studying plastic litter size and weight when only count data is available. This broadens the range of future applications for beach litter monitoring data collected according to existing monitoring protocols. Moreover, the presented approach serves as a tool to support the comparison and integration of plastic litter data that is collected according to different categorization or monitoring protocols.

We presented generic probability density functions, describing the relative composition of beach plastic litter item size and weight on continuous scales, which can be implemented in amongst others plastic litter fate models and risk assessment frameworks and have advantages over approaches that use arbitrary categorization methods. For example, when modelling the fate of plastic, size and weight of the plastic items can be taken into account probabilistically by using the mathematical description of the PDFs, similarly as done with PDFs for microplastics [1,31,32]. Together, the presented count-to-weight conversion method and the continuous frequency distributions can bridge the gap between common beach litter monitoring data and marine plastic modelling studies.

We would like to stress that the approach we have adopted in this study, like any other model, has inherent limitations. In our methodology, we estimated the weights of plastic litter items based on their weights in mint conditions. To account for the variability and uncertainty in these weights, we used triangular distributions, while the possible fragmentation products of these items were accommodated by the OSPAR categories 'plastic fragments small/large/very large'. The advantage of this prospective approach is its efficiency, as it does not require labour-intensive and expensive field campaigns. However, a drawback of this approach is that the assumed weights and their distributions remain estimations, albeit well-motivated. To enhance the robustness of our approach, we plan to validate the distributions provided here with in situ data describing beach litter sizes and weights in future work. Such validation will help verify these estimations and increase the reliability of our findings.

Environmental Implication

Plastic litter is a diverse material, is one of the most common hazardous materials on Earth, and causes animal deaths. Thus, it is important to assess the spatiotemporal trends and take this diversity into account. Here we analyze 20 years of monitoring data on beached plastic litter. We introduce a novel method to convert monitoring data based on the number of plastic items into data in terms of the weight and size of the litter. We demonstrate significant positive trends in litter abundance and introduce new probability density functions that quantify the multidimensionality of litter. This will facilitate risk assessment.

Funding

This research did not receive any specific grants or funding from agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Anne Grundlehner: conceptualization, methodology, software, formal analysis, investigation, visualization, writing (original draft); **Noël Diepens**: conceptualization, writing (review & editing); **Theo Linders:** Formal analysis, writing (review & editing); **Edwin Peeters**: formal analysis, writing (review & editing); **Albert Koelmans:** conceptualization, supervision, writing (review & editing).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank Merel Kooi for her contributions to this work. We also want to thank the OSPAR Commission for providing publicly available monitoring data. Thank you to all those who engaged in beach clean-up and litter surveys.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2023.131984.

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