Marine anthropogenic litter on British beaches: A 10-year nationwide assessment using citizen science data

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HIGHLIGHTS

- Plastic is the main constituent of marine anthropogenic litter on British beaches.
- The majority of traceable items originate from land, specifically public littering.
- Clear differences in regional litter abundance were detected.
- Significant increases in some individual litter items, spanning a decade, were identified.
- Citizen science programmes are an effective tool for monitoring marine anthropogenic litter.

GRAPHICAL ABSTRACT
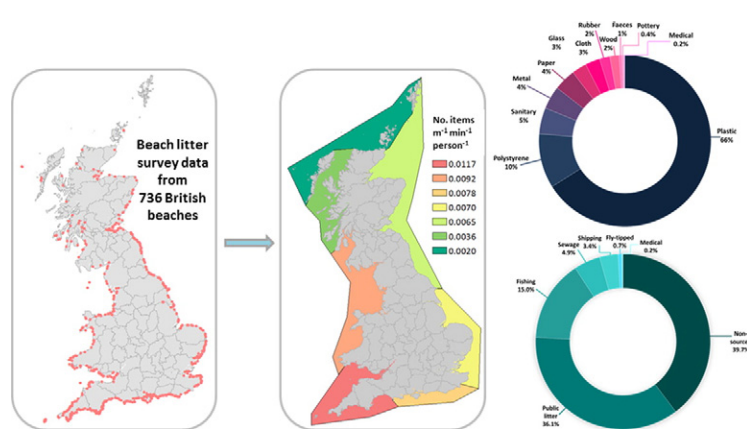
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ABSTRACT

Growing evidence suggests that anthropogenic litter, particularly plastic, represents a highly pervasive and persistent threat to global marine ecosystems. Multinational research is progressing to characterise its sources, distribution and abundance so that interventions aimed at reducing future inputs and clearing extant litter can be developed. Citizen science projects, whereby members of the public gather information, offer a low-cost method of collecting large volumes of data with considerable temporal and spatial coverage. Furthermore, such projects raise awareness of environmental issues and can lead to positive changes in behaviours and attitudes. We present data collected over a decade (2005–2014 inclusive) by Marine Conservation Society (MCS) volunteers during beach litter surveys carried along the British coastline, with the aim of increasing knowledge on the composition, spatial distribution and temporal trends of coastal debris. Unlike many citizen science projects, the MCS beach litter survey programme gathers information on the number of volunteers, duration of surveys and distances covered. This comprehensive information provides an opportunity to standardise data for variation in sampling effort among surveys, enhancing the value of outputs and robustness of findings. We found that plastic is the main constituent of anthropogenic litter on British beaches and the majority of traceable items originate from land-based sources, such as public littering. We identify the coast of the Western English Channel and Celtic Sea as

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experiencing the highest relative litter levels. Increasing trends over the 10-year time period were detected for a number of individual item categories, yet no statistically significant change in total (effort-corrected) litter was detected. We discuss the limitations of the dataset and make recommendations for future work. The study demonstrates the value of citizen science data in providing insights that would otherwise not be possible due to logistical and financial constraints of running government-funded sampling programmes on such large scales.

1. Introduction

Pollution of the marine environment by anthropogenic litter is now widely acknowledged as a significant global environmental issue requiring mitigation (Cole et al., 2011; Derraik, 2002; Vegter et al., 2014). Defined as 'any persistent, manufactured or processed material discarded, disposed of or abandoned in the marine and coastal environment', anthropogenic litter is a complex, trans-boundary and cross-sectoral concern (Hastings and Potts, 2013; UNEP, 2009). Originating from both marine- and land-based activities, the sources of debris are numerous and extensive (UNEP, 2016). Inputs from maritime activities, such as commercial and recreational fisheries and shipping, include items such as ropes, cages, nets, fishing line, plastic fish boxes, floats and buoys (Galgani et al., 2013; Moriarty et al., 2016). Items from land-based sources originate from domestic, industrial and agricultural activities (UNEP, 2009) and may enter the marine environment via a variety of pathways, including public littering, fly-tipping and poor waste management (Hastings and Potts, 2013; UNEP, 2009), transported to the sea by rivers, sewage outflows and wind (Duckett and Repaci, 2015; Galgani et al., 2013; Poeta et al., 2014; Rech et al., 2014). Anthropogenic factors, such as proximity to areas of high population density, degree of fishing effort and concentration of shipping traffic, are likely to affect the abundance and distribution of debris (Duckett and Repaci, 2015; Hoellein et al., 2015; Moriarty et al., 2016; Ribic et al., 2012). Furthermore, environmental factors, such as wind, tides, currents and coastal morphology, are influential in the distribution and accumulation of marine anthropogenic litter (Critchell et al., 2015), but are complex and their precise effects are difficult to disentangle (Browne et al., 2015).

In most cases, plastic is the main constituent of marine anthropogenic litter (Barnes et al., 2009; Derraik, 2002; Poeta et al., 2014; Schulz et al., 2015; UNEP, 2009). This is due partly to its expanding popularity as a consumer product, and its high durability and persistence within the marine environment (Andrady, 2015; Barnes et al., 2009; Jambeck et al., 2015). This synthetic material does not biodegrade but only fragments into smaller pieces (Sigler, 2014). Whilst near the sea-surface or on a beach, plastic is photo-degraded by solar ultraviolet (UV) radiation (Andrady, 2015). Once weakened, larger macro-plastics are fragmented by wave action and physical abrasion, eventually becoming micro-plastics (typically defined as items <5 mm in size; Andrady, 2011; Barnes et al., 2009). Additionally, some plastics that are produced specifically to be of a small size, such as pre-production pellets (nurdles) and polystyrene beads, microbeads from cosmetics and microfibers released during the washing of textiles, enter the marine environment directly through spills or sewerage systems (Browne et al., 2011; Cole et al., 2011; UNEP, 2009). Due to their low-density, many types of plastic are buoyant, which enables transport around global oceans via wind and current driven surface circulation, dispersing them over large distances far from their site of origin. This makes it challenging to identify their sources and implement focused management activities (Barnes et al., 2009).

Persistent marine debris, including plastics, has a range of environmental, economic and social impacts (UNEP, 2016). For biodiversity, detrimental effects include ingestion of both macro- and micro-debris (Cole et al., 2013; Lusher et al., 2015; Nelms et al., 2016; Vegter et al., 2014); entanglement in netting, sheet plastic and packing materials (Bentivegna, 1995; Chatto, 1995; Votier et al., 2011); habitat degradation and alteration by smothering (Carson et al., 2011; Richards and

Beger, 2011) and transport of invasive species (Kiessling et al., 2015). Furthermore, plastics are susceptible to the adsorption of hydrophobic contaminants (Teuten et al., 2007), such as heavy metals and polychlorinated biphenyls (PCBs), from the surrounding seawater (Endo et al., 2005; Rochman et al., 2014). If ingested, these toxic compounds, and others incorporated during production (such as plasticizers), may be released into biological tissue, potentially causing cryptic, sub-lethal effects for the organism (Batel et al., 2016; Laing et al., 2016).

Marine and coastal ecosystems are important economically, through industries such as fisheries and tourism, and socially, i.e. benefits to health and well-being (Martínez et al., 2007; White et al., 2014). The presence of anthropogenic litter, however, can diminish these returns. For example, in the United Kingdom (UK), the economic cost to fisheries is estimated at £10 million per year (e.g. repair of gear damaged by debris, time lost due to removal and repairs) and local authorities spend approximately £15 million annually on the removal of beach litter (Hastings and Potts, 2013; Mouat et al., 2010; Newman et al., 2015). The aesthetic impact of anthropogenic litter has implications for tourism and human well-being. For example, 85% of 1000 residents and tourists said they would not visit a beach with an excess of two litter items per metre (Ballance et al., 2000; Hastings and Potts, 2013), and Tudor and Williams (2006) reported that beach choice was more strongly determined by clean, litter-free sand and seawater than by safety. Wyles et al. (2015) found that the restorative psychological benefits ordinarily experienced by people visiting the coast were undermined by the presence of litter.

To understand the scale of the marine anthropogenic litter problem and inform the development of effective management strategies, it is necessary to conduct monitoring programmes that follow trends in levels of pollution as well as identify pathways and sources (Critchell and Lambrechts, 2016; Rosevelt et al., 2013; Schulz et al., 2015). In the European Union (EU), such monitoring is required of member states by the Marine Strategy Framework Directive which aims to achieve Good Environmental Status (GES) of EU marine waters by 2020 (Moriarty et al., 2016; MSFD GES Technical Subgroup on Marine Litter, 2011). Beach litter surveys are a well-known technique for gathering information on the status of anthropogenic litter, both for the beaches themselves, and as an indicator for the wider marine environment (Ribic et al., 2012). OSPAR (The Convention for the Protection of the Marine Environment of the North-East Atlantic) has been monitoring 50 indicator beaches (located within six OSPAR regions in the North-East Atlantic) using a standardised protocol since 1998. These beaches are surveyed four times a year (at three month intervals) and the number of litter items per 100 m of coastline recorded (OSPAR, 2010). Such endeavours, however, require considerable time and resources to collect meaningful and robust data. Volunteers are often recruited to carry out beach litter surveys and their involvement as *citizen scientists* can be instrumental in the generation of large, long-term datasets which may otherwise not be feasible due to logistical or financial constraints (Duckett and Repaci, 2015; Hidalgo-Ruz and Thiel, 2015, 2013). The inclusion of people of all ages from a broad social spectrum reduces the time and cost of sampling, raises awareness of environmental issues within the wider community and may lead to positive changes in behaviours and attitudes (Wyles et al., 2016). The information generated can be used to develop practical solutions at local, regional and potentially even global scales (Browne et al., 2015; Munari et al., 2015; Ribic

et al., 2012; Rosevelt et al., 2013; van der Velde et al., 2016). The results of very few (non-research focussed) beach litter programmes reach peer-reviewed scientific journals (Browne et al., 2015). This may be due to logistical or administrative constraints but is also likely related to limitations in some citizen science projects, such as lack of information on survey effort, the absence of standard methods to ensure comparability among surveys and lack of links between non-governmental organisations (NGOs) and academic institutions (Duckett and Repaci, 2015; Hidalgo-Ruz and Thiel, 2015). With appropriately designed sampling protocols (for example, prior standardisation of survey effort) and rigorous analyses it becomes possible to ameliorate some of these concerns (Duckett and Repaci, 2015; Hidalgo-Ruz and Thiel, 2015; van der Velde et al., 2016).

Each year, the Marine Conservation Society (MCS) – a UK-based charity focused on improving marine stewardship and public engagement – runs a national volunteer beach litter surveying programme around the British coastline. In this study we analysed 10 years of beach litter data collected during the period 2005–2014 (inclusive). The aims of this study were to: 1) determine composition of litter (by item category, material, pathway and origin); 2) investigate spatial patterns (on a regional scale) 3) explore temporal trends in abundance of overall litter and individual item categories and 4) based on findings, produce recommendations for future work with the aim of enhancing the field of marine litter research and public engagement.

2. Materials and methods

2.1. Study region

Along the eastern and southern borders of Britain are the North Sea and the English Channel. The former is a semi-enclosed shelf-sea, surrounded by seven countries (Britain, France, Belgium, Netherlands, Germany, Denmark and Norway) and connected to the Atlantic Ocean through the English Channel to the south and the Norwegian sea to the north (Huthnance, 1991). Along the western border are the Celtic Seas, which fringe the western coastlines of Scotland and England and the entirety of Wales. This region contains oceanic water from the North Atlantic which enters from the south and west and predominantly moves northwards (http://www.ospar.org/convention/the-north-east-atlantic/iii; last accessed 8 August 2016). The prevailing wind direction is from the south-west, with considerable seasonal and regional variability in speed and direction.

2.2. Beach litter surveys

Data on marine anthropogenic litter were collected by MCS volunteers between January 2005 and December 2014 (inclusive) from 736 beaches located throughout Britain, in England, Scotland and Wales (see Fig. 1). For the purposes of regional analysis, beaches were assigned to one of seven Regional Seas areas, as designated by the Joint Nature Conservation Committee (JNCC; UK) based on biogeographical characteristics (http://jncc.defra.gov.uk/page-1612; last accessed 8 August 2016). These are; Northern North Sea (NNS), Southern North Sea (SNS), Eastern English Channel (EEC), Western English Channel and Celtic Sea (WECCS), Irish Sea (IS), Minches and West Scotland (MWS), Scottish Continental Shelf (SCS; Fig. 1).

The number of beach litter surveys fluctuated annually and per month (recorded as counts of beaches surveyed per year from 2005 to 2014 and per month respectively; Fig. 2a and Fig. S1) and among regions (recorded as counts of surveys per Regional Sea across study period; Fig. 2b). The number of volunteer participants and duration of surveys also varied among years (recorded as counts of volunteers and hours spent surveying respectively per year from 2005 to 2014; Fig. 2c and d), as did the frequency of surveys per beach and intervals between surveys.
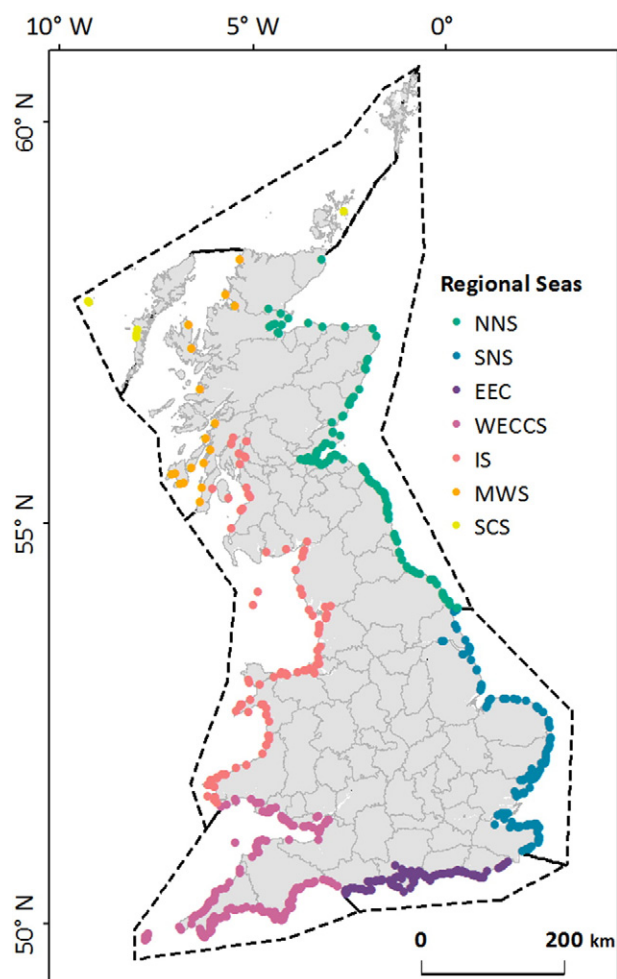
Fig. 1. Distribution of survey beaches – coloured symbols correspond to relevant Regional Seas designation (NNS = Northern North Sea; SNS = Southern North Sea; EEC = Eastern English Channel; WECCS = Western English Channel and Celtic Sea; IS = Irish Sea; MWS = Minches and West Scotland; SCS = Scottish Continental Shelf).

Survey best practice instructions indicated that a 100 m survey should be undertaken. Given the nature of the project, however, and the desire for volunteers to survey and clear longer stretches of beaches, surveys were frequently longer in distance. In addition, there was no prior standardisation of the number of volunteers or time spent searching (duration). These factors were recorded, however, allowing for the variation in effort among surveys to be calculated and subsequently used to standardise data gathered. The number of participants was variable (range: 1–945 people per survey, mean ± SD = 12.3 ± 22.4 people, median = 8 people, IQR = 3–15 people) as was survey duration (range: 10 min–8 h, mean ± SD = 1.71 ± 0.95 h, median = 1.5 h, IQR = 1–2 h) and survey distance covered (range: 1 m–7.5 km, mean ± SD = 432 ± 662 m, median = 140 m, IQR = 100–500 m; see Supplementary Material Fig. S2.). Various methods of outlier removal were investigated but it was preferred that all data collected were utilised.

To collect the data, volunteers would walk between the back of the beach and the strand-line, loosely adhering to a linear transect (parallel to the strand-line), searching for litter. Litter identification guides were provided to ensure accurate recording of items by volunteers. In addition, face to face training was offered to beach survey organisers, enabling them to support the volunteers in following the protocol. Gathered items of litter were assigned to one of 101 item categories that could be further classified into 12 material groups (plastic, polystyrene, rubber, cloth, metal, medical, sanitary, faeces, paper, wood, glass, pottery/ceramic; see Supplementary Material Table S1). These
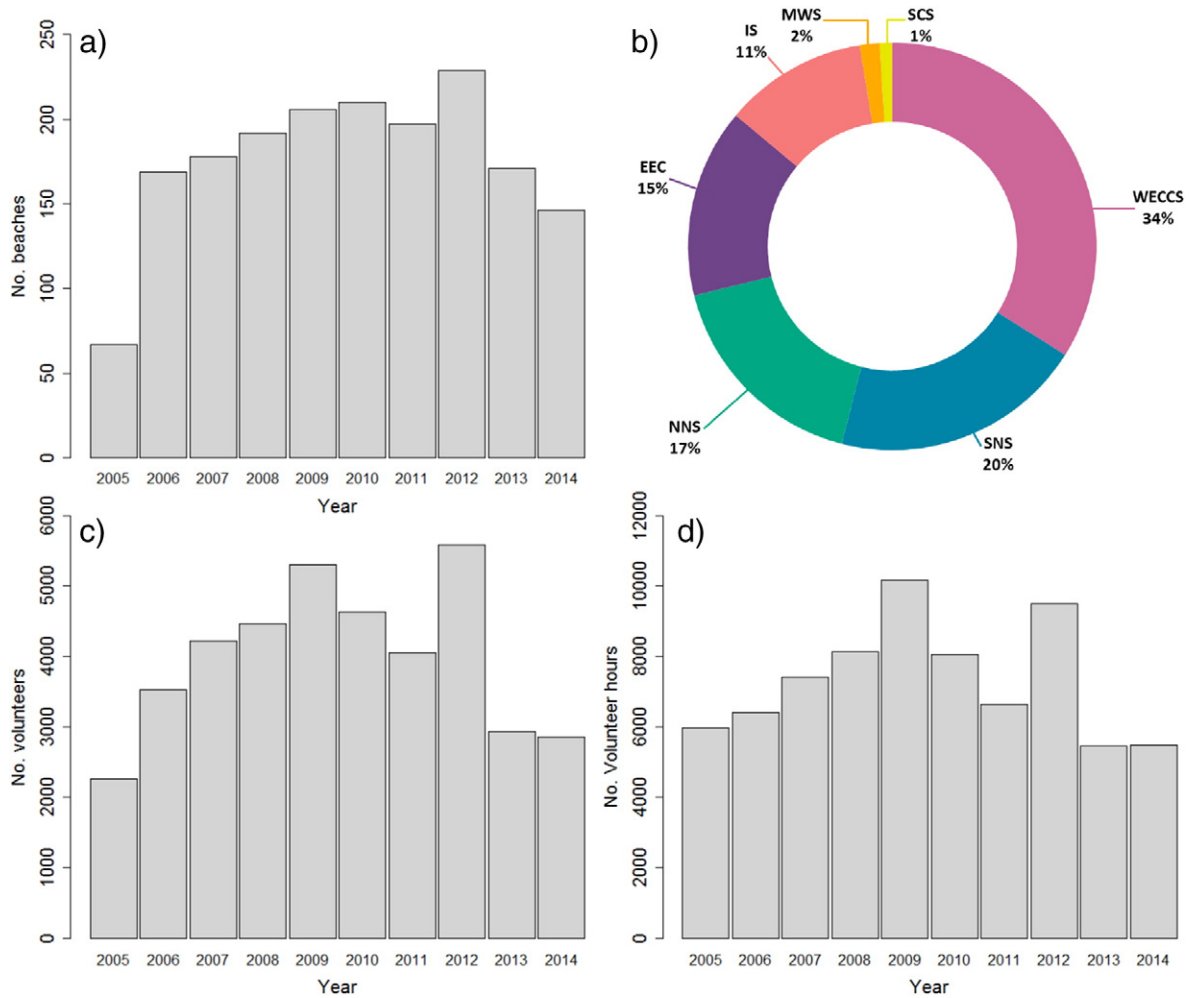
Fig. 2. a) Number of beaches surveyed per year (of $n = 736$ investigated); b) Proportion of effort (number of surveys) per Regional Sea (NNS = Northern North Sea; SNS = Southern North Sea; EEC = Eastern English Channel; WECCS = Western English Channel and Celtic Sea; IS = Irish Sea; MWS = Minches and West Scotland; SCS = Scottish Continental Shelf); c) Number of volunteer participants per year; d) Number of volunteer hours spent surveying per year.

classifications were pre-determined by MCS. Upon completion of a survey, all anthropogenic litter items recorded were summed, validated by a survey coordinator and subjected to further quality control by MCS. All collected litter items were removed from the beach.

2.3. Data preparation and effort correction

Significant linear relationships were determined between the number of litter items surveyed and three variables relating to effort (linear model(s): distance ($F_{1, 3058} = 8.6491$, $p = 0.003$); duration ($F_{1, 3058} = 165$, $p \leq 0.001$); number of volunteers ($F_{1, 3058} = 634$, $p \leq 0.001$)). Data (i.e. counts of items) were standardised to account for variations in effort among beach litter surveys using Eq. (1); where C = total count (no. items); L = survey linear distance (m); D = survey duration (mins); V = number of volunteers (people):

$$A = \frac{C}{L(DV)} \tag{1}$$

The unit of the adjusted count (A) was *items collected per metre per minute per person* (number of items m^{-1} min^{-1} person^{-1}). It was therefore possible to investigate differences in litter density among beaches irrespective of varying volunteer effort.

2.4. Descriptive statistics

Using our standardised counts (number of items m^{-1} min^{-1} person^{-1}), the proportion (as number of items independent of mass or volume) of each litter item category ($n = 101$) and material group ($n = 12$) was calculated for all survey events and for each Regional Sea area. Where possible, items were attributed to a pathway (non-sourced, public litter, fishing, sewage, shipping, fly-tipped, medical) based on MCS classifications (see Supplementary Material Table S2) and, where possible, assigned as originating from either land- or marine-based activities (see Supplementary Material Table S3). Where litter items could not be assigned to either of these origin groups they were deemed non-sourced.

2.5. Spatial analyses

For each beach and Regional Sea area, the mean number of items m^{-1} min^{-1} person^{-1} across the study period (2005–2014) was calculated for total litter and three types of litter of interest - food and drink packaging, fishing gear and wet wipes, chosen as they represent the three major pathways – public littering, fishing and sewage respectively. The former two types are assemblages of related items, whereas wet wipes are a stand-alone individual item category (see Supplementary Material Table S4). Beaches and regions were then ranked based on their mean standardised count values, from high to low. Annual mean

estimates of standardised counts (for total litter) were also subject to spatial analysis using Moran's I clustering in ArcMap 10.2.2 (ESRI, 2014) – a technique which identifies statistically significant areas of litter presence and absence.

2.6. Temporal analyses

Generalised Linear Mixed Models (GLMMs) were used to examine temporal patterns in the abundance of total litter (standardised counts for all beaches), individual item categories (20 most common plus three additional item categories of interest). Analyses were undertaken in the statistical computing software, R (GLMM; 'lme4' package for R; R Development Core Team, 2015). Beach-specific identification numbers were used as a random effect in the model to account for the variation in survey frequency among beaches. Season and region were incorporated within the GLMM as fixed effects in addition to year. The normality of the dependent variable was assessed using a Q-Q plot and determined to be non-normal. As such, the data were log-transformed (log10) and further assessed using a second Q-Q, which confirmed a satisfactory transformation ('car' and 'MASS' packages for R; R development Core Team, 2015). Statistical significance was set at a probability level (α) of 0.05. To deal with multiple testing of individual item categories ($n = 23$), a Bonferroni correction was applied and the probability threshold adjusted to <0.0021 (α/n). Seasons were defined as; spring (March, April, May), summer (June, July, August), autumn (September, October, November), winter (December, January, February).

3. Results

3.1. Descriptive statistics

Anthropogenic litter was recorded during all beach litter surveys ($n = 3245$) and a total of 2,376,541 items were collected from 1402 km of cumulative surveyed coastline, with volunteers contributing 73,167 h (equivalent to ~25 years of continuous surveying (365 days a year) by a single person working 8 h per day). Mean abundance across all beaches was 0.0085 items m^{-1} min^{-1} $person^{-1}$, with a maximum of 0.3297 items m^{-1} min^{-1} $person^{-1}$. This is equivalent to 51 items and 1978 items respectively, based on a survey carried out over 100 m for 1 h by one volunteer. Large plastic fragments (>25 mm) was the most frequently recorded item category, representing 13% of all litter items, followed by small plastic fragments (<25 mm) at 10% (Table 1 for 20 most common item categories).

Table 1
Twenty most common item categories by proportion.

Item category	Proportion
Plastic fragments (large; >2.5 cm)	0.13
Plastic fragments (small; <2.5 cm)	0.10
Plastic caps	0.07
Polystyrene (small; <50 cm)	0.07
Crisp packets	0.06
Fishing net (small; <50 cm)	0.05
Plastic string	0.05
Plastic drinks bottles	0.04
Cotton buds	0.03
Fishing line	0.03
Cigarette stubs	0.03
Plastic cutlery	0.02
Glass fragments	0.02
Cloth pieces	0.02
Plastic bags	0.02
Polystyrene foam	0.02
Metal Drinks can	0.02
Plastic rope	0.01
Fishing net (large; >50 cm)	0.01
Wood pieces	0.01

Of the 12 material groups, plastic was the most dominant (66%), with expanded polystyrene and sanitary items representing 10% and 5% respectively (Fig. 3a).

The Scottish Continental Shelf (SCS) exhibited the highest proportion of plastic (83%) in beach litter surveys whilst the neighbouring region of Minches and West Scotland (MWS) exhibited the lowest (52%; Fig. 4a). The Northern North Sea (NNS) experienced the highest proportion of polystyrene (14%) and sanitary items (7%; Fig. 4b and c). In contrast, the Scottish Continental Shelf region reported the lowest proportions for both (3% and 0.2% respectively; Fig. 4b and c).

After non-sourced items (40%), public littering represented the most common pathway (36%), followed by fishing (15%), sewage (5%), shipping (3%), fly-tipping (0.7%) and medical (0.2%; Fig. 3b). Of items that could be attributed to an origin, 42% derived from land-based sources, such as littering (e.g. food packaging) and sewage (e.g. sanitary items), and 18% from marine-based activities, such as fishing and shipping. The remaining 40% consisted of items that could not be definitively assigned to either source category (e.g. fragments of various materials and generic items whose origin could either be from land- or marine-based sources). The Southern North Sea, Northern North Sea and Irish Sea encountered the highest proportion of litter from land-based activities (50%) and the Scottish Continental Shelf the lowest (20%; Fig. 5a). This region (SCS) experienced the greatest proportion of litter attributed to marine-based activities (40%; Fig. 5b). There was little variation in the proportion of non-sourced items among the regions (35–40%; Fig. 5c).

3.2. Spatial analyses

The five most affected beaches (mean number of items m^{-1} min^{-1} $person^{-1} > 0.1$) were heterogeneously distributed across Britain within four of the seven Regional Seas. Clustering analysis (Moran's I) revealed five areas where adjacent beaches share similar high levels of litter abundance, in Kent, Hampshire, Cornwall and the Bristol Channel (Lundy Island; Supplementary Material Fig. S3). Variations in regional mean abundances were evident, indicating significant differences among the Regional Seas (one-way ANOVA, $F_{6,3238} = 37.95$, $p < 0.001$; Fig. 6).

The Western English Channel and Celtic Sea exhibited the greatest mean abundance of 0.012 items m^{-1} min^{-1} $person^{-1}$ whilst the Scottish Continental Shelf exhibited the smallest of 0.002 items m^{-1} min^{-1} $person^{-1}$ (Fig. 7a). The Western English Channel and Celtic Sea exhibited the highest mean abundance of both food and drink packaging and fishing gear (0.0027 and 0.0015 and items m^{-1} min^{-1} $person^{-1}$ respectively; Fig. 7b and c). The Southern North Sea exhibited the highest mean abundance of wet wipes (0.0001 items m^{-1} min^{-1} $person^{-1}$; Fig. 7d)

3.3. Temporal analyses

3.3.1. Seasonal variation

The overall abundance of litter was not significantly affected by season (one-way ANOVA, $F_{3,3241} = 1.21$, $p \geq 0.05$). Nor was there a significant seasonal effect on the abundance of litter from land-based sources (one-way ANOVA, $F_{3,3241} = 0.13$, $p \geq 0.05$) or marine-based sources (one-way ANOVA, $F_{3,3241} = 1.13$, $p \geq 0.05$).

3.3.2. Long-term trends

Analysis of the long-term trends using GLMMs indicated that the standardised litter abundance (number items m^{-1} min^{-1} $person^{-1}$) did not change significantly over the study period (2005–2014); removing Year from the model had no significant effect, p-value = 0.39. This analysis was repeated to investigate long-term trends in abundance of the 20 most common item categories as well as balloons, wet wipes and plastic food packaging due to concerns for their environmental impact. Six of these items experienced a significant increase - small plastic fragments (2.3 fold; i.e. from 0.00011 to 0.00037 number items m^{-1} min^{-1} $person^{-1}$ over 10 years); plastic food packaging (1.0
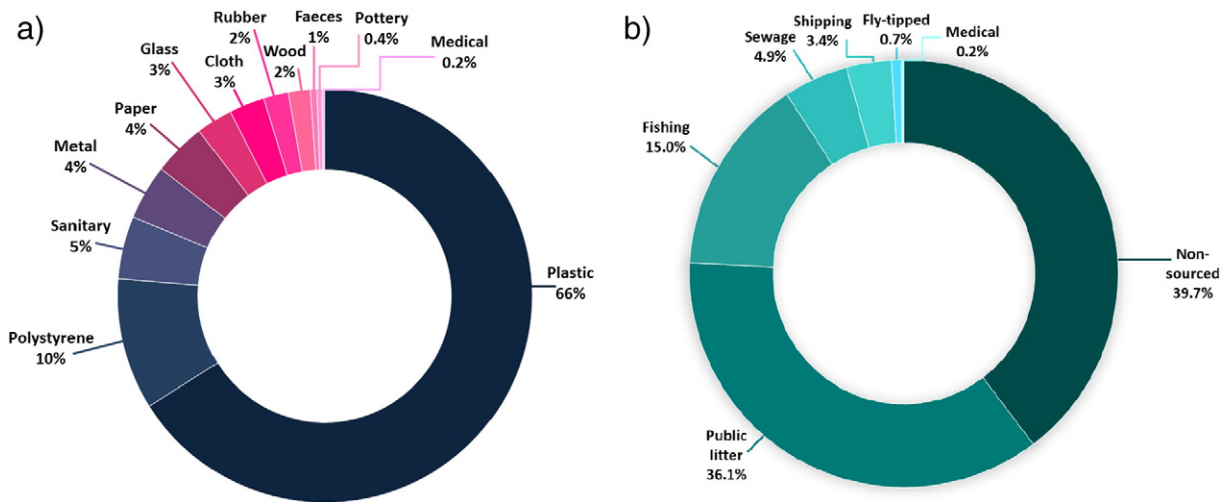
Fig. 3. Composition of marine anthropogenic litter across all beaches surveyed as proportions by a) material and b) pathway.

fold); wet wipes (0.9 fold); polystyrene foam (0.7 fold); balloons (0.6 fold); large fishing net (0.5 fold) - whilst the remaining items exhibited no significant temporal trend (Table 2).

4. Discussion

4.1. Descriptive statistics

Given their durability, it is perhaps unsurprising that items made from synthetic materials comprise a large proportion of anthropogenic litter. Large and small plastic fragments are generated by the degradation of larger items, and so they represent the accumulated remains of many years of waste. They will be broken down further by UV photodegradation and wave action until they become micro-plastics, small synthetic particles that can be ingested by a range of organisms, including zooplankton, commercial fish species and other sea foods consumed by humans, and marine megafauna (Besseling et al., 2015; Cole et al., 2013; Neves et al., 2015; Rochman et al., 2015). The Scottish Continental Shelf experienced the highest proportion of plastic whilst its neighbouring region, Minches and West Scotland exhibited the lowest. Due to its remote location, it is likely that the former is exposed to inputs

from fairly uniform sources, mainly fisheries and floating debris from other countries within the north Atlantic. This is further highlighted by the fact that the region (SCS) also exhibited the greatest proportion of litter attributed to marine-based activities. Over a third of total litter originates from public littering, indicating that land-based inputs are likely key sources of marine anthropogenic litter. These results correspond with those from previous studies in other areas, such as the Mediterranean Sea, the Great Lakes (USA) and the SE Pacific, though the proportions vary (Bravo et al., 2009; Hidalgo-Ruz and Thiel, 2013; Hoellein et al., 2015; Munari et al., 2015; Topçu et al., 2013).

4.2. Spatial patterns

Although the most affected beaches were heterogeneously distributed across Britain, there were strong differences among the regions and the Western English Channel and Celtic Sea exhibited the highest mean abundance of litter from both land and sea. This may be due to a number of reasons, such as the presence of large cities and discharging rivers (Swansea, Cardiff, Newport, Bristol, Plymouth; River Severn), high levels of fishing effort (Lee et al., 2010; Witt and Godley, 2007), the world's third busiest shipping route - the English Channel - and input from the
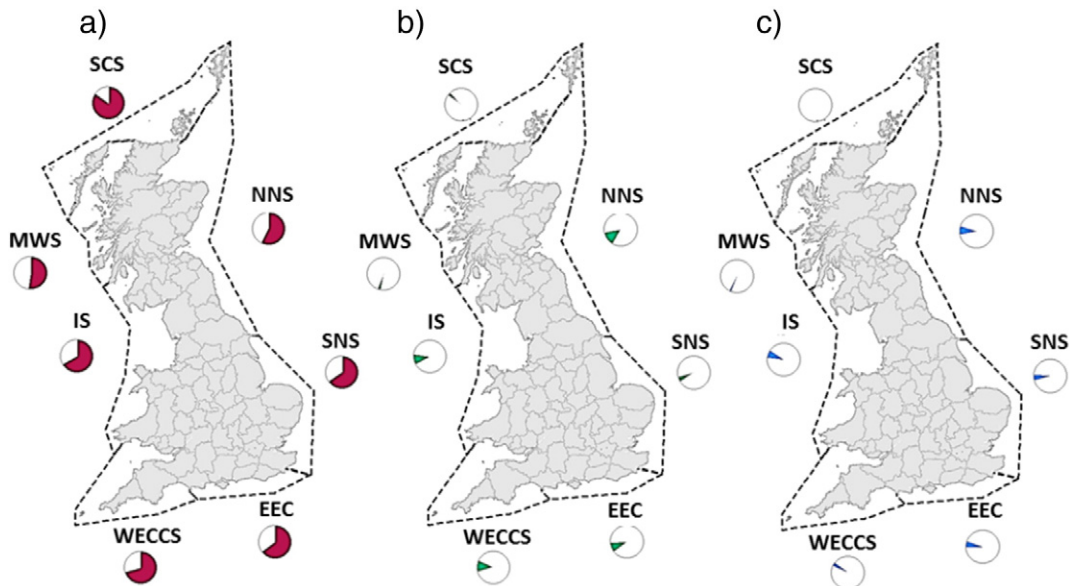

Fig. 4. Regional proportions of three most collected materials a) Plastic b) Polystyrene c) Sanitary.
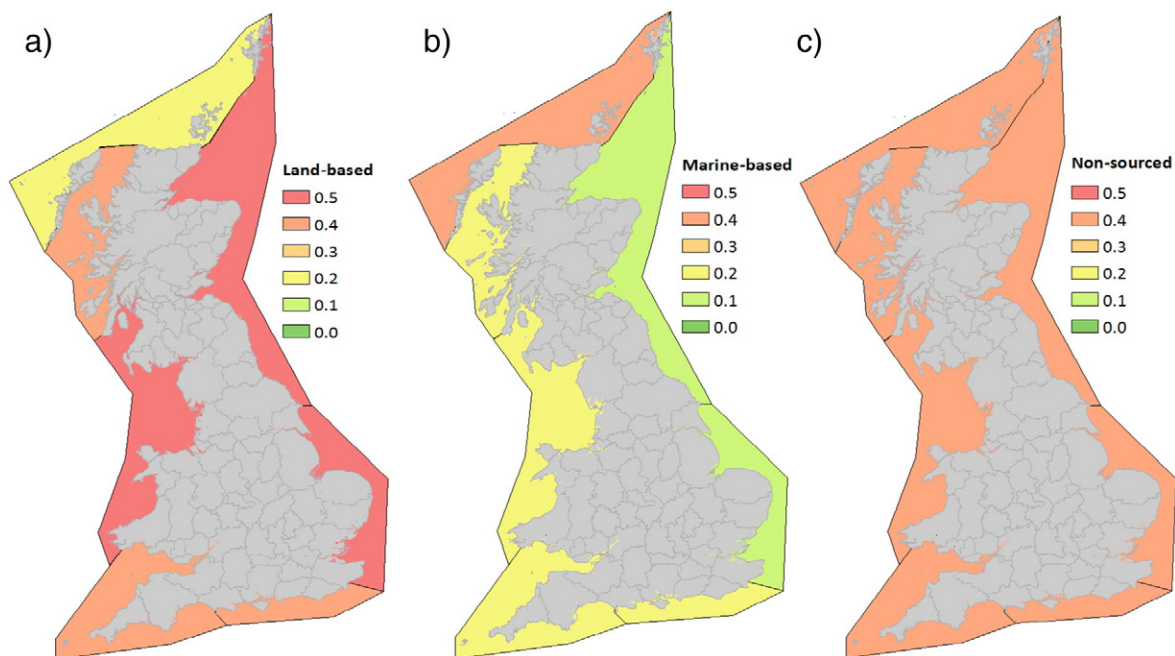
Fig. 5. Distribution-maps showing regional proportions of litter from a) land-based activities b) marine-based activities and c) non-sourced items.

wider Atlantic Ocean (wind and currents). In addition, this region represents a popular tourist destination, particularly during the summer months. The south west of England attracts the highest number of domestic tourists of all UK regions (Smith, 2010) and it is estimated that approximately five million visits are made to Cornwall alone each year (South West Research Company, 2010). This high density of beach-users likely contributes to the observed levels of anthropogenic litter.

4.3. Temporal trends

There was an absence of a temporal trend in the overall abundance of marine anthropogenic litter through the 10-year dataset. This lack of change may be due to a number of reasons. Firstly, the amount of litter may have indeed changed little over the 10-year period. Secondly, it may be that the time-period is insufficient to statistically reveal small

Fig. 6. Regional differences in log corrected litter abundance (WECCS = Western English Channel and Celtic Sea; IS = Irish Sea; EEC = Eastern English Channel; SNS = Southern North Sea; NNS = Northern North Sea; MWS = Minches and West Scotland; SCS = Scottish Continental Shelf).

changes within a variable system. For example, one study surmised that some sampling regimes are unlikely to detect a ≤30% change within 25 years but a 40%–50% change may be detected in 10–15 years (Moriarty et al., 2016). Thirdly, it is possible that the methodological constraints, such as the need for effort correction, and variability within the system (due to the multitude of inputs and extensive transportation of debris by currents and wind) dilute the statistical signal (Ryan et al., 2009; Schulz et al., 2015). Finally, the extent of litter removal by volunteers and local authorities may be large enough to limit the accumulation of debris and effectively prevent its escalation (Hoellein et al., 2015), but insufficient to make detectable improvements. Further work is required to better understand these factors.

Temporal trends for some individual items were identified. The more than two-fold observed increase in small plastic fragments is likely a result of the perpetual break-down of larger plastic items by UV photo-degradation and wave action. As a result, the number of small plastic pieces is likely to rise exponentially into the future, especially given the current and predicted levels of plastic litter input to the marine environment. The increase in both balloons and large fishing net abundance is of concern due to the threat they pose to biodiversity, particularly seabirds, marine mammals and marine turtles, through ingestion and entanglement (Allen et al., 2012; da Silva Mendes et al., 2015; Plotkin et al., 1993). Though fishing gear is usually lost accidentally, balloons are often actively released *en masse* at public events and our results show a significant increase in the number recorded during surveys. Balloons are not currently defined as 'litter' under the UK Environmental Protection Act (EPA) 1990 whereby it is an offence to drop "or otherwise deposit" litter in a public place (Parliament of the United Kingdom, 1990). Some local authorities, however, do recognise the threat posed by balloons and have voluntarily banned releases on their property. It would seem judicious that revisions are made to the EPA that reflect these concerns and legislatively prevent such mass littering events from occurring. Wet wipes may enter the marine environment via waste water from domestic sources. Many contain plastic and so persist indefinitely, often leading to blockages within sewerage systems. It is estimated that approximately £88 million is spent in the UK annually as a result (Water UK, pers. comm., 2016). The increase reflected in our results demonstrates an urgent need for mitigation. The observed increases in other items, such as polystyrene foam and plastic food packaging, illustrates the
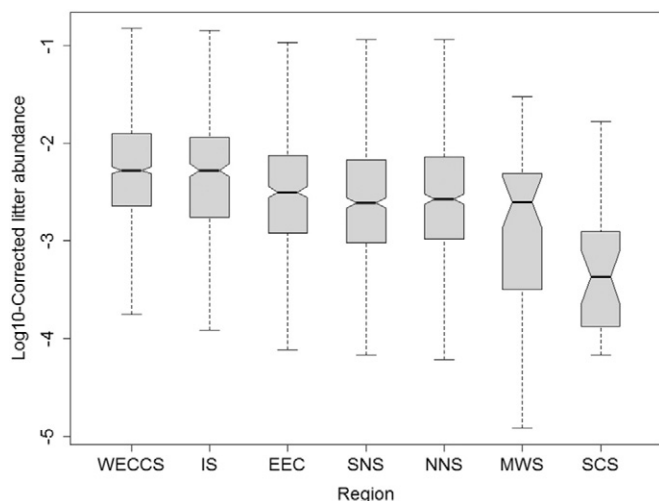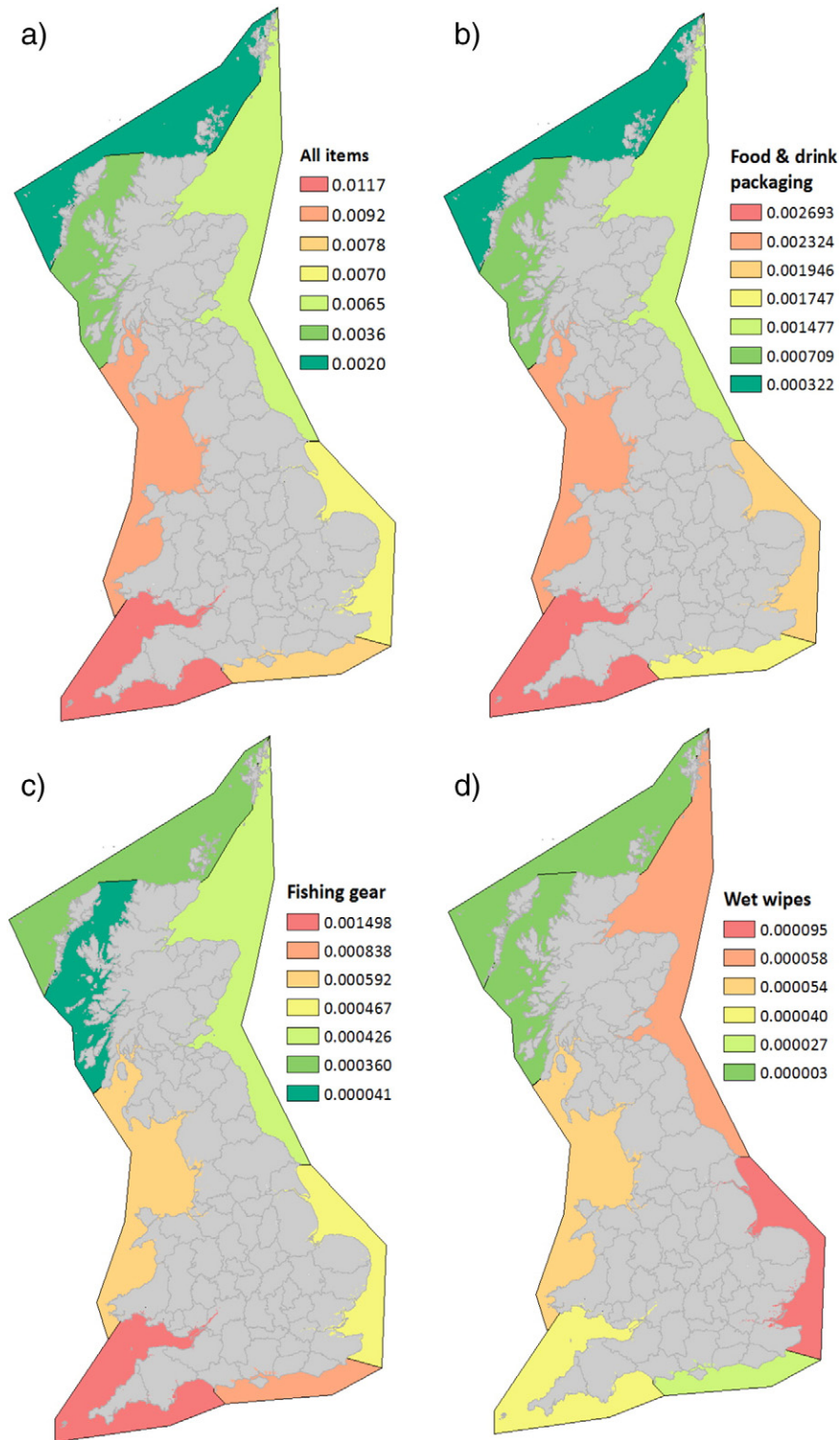
Fig. 7. Distribution-maps of regional mean number of items m^{-1} min^{-1} $person^{-1}$ for a) all litter items b) food and drink packaging c) fishing gear d) wet wipes.

need for a reduction in their inappropriate disposal as well as biodegradable alternatives to such materials, e.g. cardboard.

4.4. Recommendations for future work

Citizen science projects are valuable in terms of their ability to generate large-scale data on the distribution and abundance of marine anthropogenic litter (Hidalgo-Ruz and Thiel, 2015, 2013). Yet, we acknowledge a number of constraints that are worthy of discussion

and make recommendations for future work based on our findings. We recognise that implementing all of the recommended measures may not be logistically feasible for some beach litter programmes (due to factors such as, volunteer availability, health and safety, time and resources) but outline a series of measures based on a best-case scenario;

4.4.1. Site selection

Survey beaches were chosen by local volunteers and so it is possible that those perceived as 'dirty' or iconic, or of special environmental

Table 2
Results of long-term trend analysis using GLMMs for top 20 individual litter items plus balloons, wet wipes and plastic food packaging based on mean across all surveys.

Item	p-Value (α)	Standard error	t value	p-Value accepted following Bonferroni adjustment to significance threshold	Fold change
Plastic fragments (large; >2.5 cm)	0.0048	–	–	N	–
Plastic fragments (small; <2.5 cm)	<0.001	0.005581	10.373	Y	+2.3
Plastic caps	0.9472	–	–	N	–
Polystyrene (small; <50 cm)	0.5235	–	–	N	–
Crisp packets	0.7782	–	–	N	–
Fishing net (small; <50 cm)	0.8307	–	–	N	–
Plastic string	0.5947	–	–	N	–
Plastic drinks bottles	0.1279			N	–
Cotton bud sticks	0.0781	–	–	N	–
Fishing line	0.3836	–	–	N	–
Cigarette stubs	0.0507	–	–	N	–
Plastic cutlery	0.1959	–	–	N	–
Glass fragments	0.0800	–	–	N	–
Cloth pieces	0.0027	–	–	N	–
Plastic bags	0.5031	–	–	N	–
Polystyrene foam	0.0002	0.005993	3.703	Y	+0.7
Metal drinks can	0.6405	–	–	N	–
Plastic rope	0.3550	–	–	N	–
Fishing net (large; >50 cm)	0.0019	0.007563	3.097	Y	+0.5
Wood pieces	0.4704	–	–	N	–
Balloons	0.0005	0.005942	3.460	Y	+0.6
Wet wipes	0.0001	0.008088	3.819	Y	+0.9
Plastic food packaging	<0.001	0.005856	5.545	Y	+1.0

value (such as Sites of Special Scientific Interest; SSSIs) may be preferentially selected above other sites which have little or no debris (Browne et al., 2015). Logistical factors, such as beach accessibility and therefore ease of litter removal, may also be a selection factor. This inherent bias could be eliminated by employing a random sampling approach but would likely be constrained by volunteer availability, willingness of volunteers to visit less desirable sites and health and safety considerations at certain locations.

4.4.2. Survey protocol

Though data adjustment is a useful method of retrospectively correcting for variation in survey effort, the use of standardised survey protocol based on OSPAR's Guidelines is optimal (OSPAR, 2010). In particular, efforts should be made to use the same sampling unit (repeated sampling of same 100 m section of beach) for each survey as this would likely reduce variation within dataset. We also recommend that a standard number of volunteers (e.g. 2) survey the 100 m section for a set amount of time to ensure the degree of effort is consistent across surveys. Following this, any remaining litter may be removed using a non-standardised method. In addition, as some litter items may be less numerous but larger in size (i.e. fishing nets) it may advantageous to record item mass as well as frequency where possible. This would also enhance the potential to compare survey results with those of similar studies (Ryan et al., 2009) but likely be constrained by availability of resources.

4.4.3. Area surveyed

Although it was possible to adjust the data to account for variation in survey distance, the effective width of the transects was not always recorded and so the total area covered was unknown. Such information would enhance the reliability of abundance estimates and make comparisons among surveys more feasible. de Araújo et al. (2006) found that the diversity of item categories detected was related to sampling transect area and the number of categories significantly increased with transect width but stabilised from 15 to 20 m onwards. As such, it would seem pertinent to standardise width or at the very least, record it so that retrospective adjustment can be applied.

4.4.4. Disparities among volunteers

Statistically, survey participants were treated uniformly, but in reality they likely differed in their personal effort and ability to search for, collect and categorise litter. These disparities may be affected by factors, such as age. For example, young children may present difficulties when distinguishing among the various material types, particularly for smaller items (Hidalgo-Ruz and Thiel, 2013). Illustrative guides are a useful tool for minimising this potential source of error (Eastman et al., 2014; Hidalgo-Ruz and Thiel, 2013). Further investigation is required to better understand how factors, such as age and gender, affect the types and amount of litter gathered and recorded. In addition, we recommend that survey leaders, where possible, undergo training prior to the event taking place as in Hoellein et al. (2015).

4.4.5. Sightability bias

Volunteers may be more or less likely to detect, gather and record certain items of litter due to known or subconscious preference. For example, items with a recognisable purpose, such as a plastic drinks bottle, may be more likely to be seen than generic items, such as fragments of plastic or pieces of glass. Quantitative methods, such as detectability trials whereby beach litter composition before and after cleaning is compared, are required to investigate the presence of detectability bias and correct for it if necessary. In addition, marine anthropogenic litter items not easily detectable by the naked eye, such as microplastics, may be under-recorded.

4.4.6. Accumulation rates and long-term trends

The intervals between beach cleans, carried out either by NGOs or local authorities, were not standardised and so litter removal varied temporally (Hoellein et al., 2015). For example, depending on ownership, bathing beaches may be subjected to regular (daily or weekly) cleaning during the tourist season but receive little litter management during the winter months. As a result, it is likely that the detectability of re-accumulation rates, and therefore trends in overall abundance within our dataset, was diminished (Smith and Markic, 2013). For this reason, OSPAR (2010) guidelines state that monitoring beaches should 'ideally not be subject to any other litter collection activities'. Although frequent sampling of all beaches to monitor accumulation rates would not be feasible due to the considerable amount of effort and resources required, a sub-sample of indicator beaches could be rigorously examined to infer patterns within the wider system. This would involve an initial beach clean to remove all litter followed by regular sampling (e.g. once a month) to record and remove any new items, as suggested by Ryan et al. (2009). This type of fine-scale sampling can provide insights in to local patterns and cycles. For a more broad-scale impression, some beach litter survey programmes, such as the MCS *Great British*

Beach Clean, opt to survey at the same time each year. This method enhances inter-annual comparability and would be more sensitive in generating insights into long-term trends. Information on the rates of litter removal by local authorities and other bodies would further enhance understanding of re-accumulation.

4.4.7. Origins and pathways

In our study we were able to broadly assign litter items to originating from either land- or marine-derived sources based on their perceived original purpose. To better understand how litter arrives on beaches, it would be useful to differentiate between items that have previously entered the marine environment and re-stranded, and those directly deposited from land-based sources, for example, poor waste management or littering (Smith and Markic, 2013). Quantitative information on the various pathways could inform management recommendations and facilitate the development of measures to restrict the amount of litter entering the marine environment. For example, beaches that experience high levels of tourism, may also experience high concentrations of items attributable to direct public littering. In such cases, efforts to increase awareness and provide appropriate and convenient waste disposal facilities may provide a suitable solution. Conversely, beaches with high use may experience lower levels of litter due to more frequent cleaning (Bravo et al., 2009).

For monitoring purposes, we recommend that beach litter recording forms include the facility to document which pathway - directly deposited or re-stranded having spent time at sea – each item has taken. Pictorial guidance notes may assist volunteers in allocating items to the appropriate pathway. This may be constrained by the willingness of volunteers to undertake surveys once they reach a certain level of complexity and effort, as well as the ability to offer training to maintain consistency of recording of pathways.

4.5. Value of citizen science

The data analysed in this study were collected by volunteers of varying age and background, including school children and community groups. Their involvement as citizen-scientists is of considerable value; firstly, it enabled the removal of over two million (2,376,541) items of anthropogenic litter from British beaches. Second, it greatly reduced the cost of sampling. For example, if every volunteer hour (total = 73,167) was charged at National Living Wage (£7.20 as of 1 April 2016; UK), data collection would have cost ~£500,000 in salaries. Thirdly, activities such as beach cleans and litter surveys can enhance public appreciation of environmental issues, potentially leading to positive changes in behaviours and attitudes (Wyles et al., 2016). This is particularly important given that social viewpoints have a significant impact on littering behaviour and the acceptance of measures to reduce it (UNEP, 2016). Beach cleans are also associated with higher levels of marine awareness, demonstrating their educational value (Wyles et al., 2016). Lastly and crucially, citizen science programmes can also be instrumental in the generation of large, insightful datasets with broad temporal and spatial coverage - we analysed data collected by MCS volunteers during beach litter surveys in every month of the year for 10 years, around much of the British coastline.

5. Conclusion

In summary, our results demonstrate how organised citizen science programmes that adopt a defined sampling approach and record effort can be effective for monitoring marine anthropogenic litter. Volunteer-led beach cleans and litter surveys facilitate the removal of large quantities of litter from marine and coastal environments, reduce the cost of sampling, enhance public awareness of environmental issues and generate insightful data, all of which are necessary for addressing the complex problem of marine anthropogenic litter pollution. Ultimately though, the most efficacious and economic solution is to minimise and eventually prevent the release of anthropogenic waste into the marine environment by reducing our consumption and inappropriate disposal of synthetic and persistent materials, such as plastic.

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