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Investigating the distribution and regional occurrence of anthropogenic litter in English marine protected areas using 25 years of citizen-science beach clean data[☆]

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Marine Protected Areas (MPAs) are designated to enable the management of damaging activities within a discrete spatial area, and can be effective at reducing the associated impacts, including habitat loss and over-exploitation. Such sites, however, may be exposed to the potential impacts from broader scale pressures, such as anthropogenic litter, due to its diffuse nature and lack of constraint by legislative and/or political boundaries. Plastic, a large component of litter, is of particular concern, due to increasing evidence of its potential to cause ecological and socio-economic damage. The presence of sensitive marine features may mean that some MPAs are at greater potential risk from the impacts of plastic pollution than some non-protected sites. Understanding the abundance, distribution and composition of litter along coastlines is important for designing and implementing effective management strategies. Gathering such data, however, can be expensive and time-consuming but litter survey programmes that enlist citizen scientists are often able to resolve many of the logistical or financial constraints. Here, we examine data collected over 25-years (1994–2018), by Marine Conservation Society volunteers, for spatial patterns in relation to the English MPA network, with the aim of highlighting key sources of litter and identifying management priority areas. We found that MPAs in southeast (Kent) and southwest (Cornwall and Devon) England have the highest densities of shore-based litter. Plastic is the main material constituent and public littering the most common identifiable source. Items attributed to fishing activities were most prevalent in southwest MPAs and sewage related debris was highest in MPAs near large rivers and estuaries, indicating localised accumulation. When comparing inside and outside of MPAs, we found no difference in litter density, demonstrating the need for wider policy intervention at local, national and international scales to reduce the amount of litter.

1. Introduction

Increasing human exploitation of global marine environments has exerted significant and expanding detrimental impacts upon species and habitats (Crain et al., 2008; Halpern et al., 2015). Anthropogenic stressors such as climate change, over-exploitation and pollution have led to widespread habitat degradation and loss of biodiversity (Halpern et al., 2015; Parsons et al., 2014). Marine Protected Areas (MPAs) are increasingly being established in an effort to combat these declines and meet global conservation targets (Ban et al., 2017). MPAs are spatially defined and managed, through legal or other effective means, to provide long-term protection and conservation of nature (Day et al., 2012). In addition to protecting marine habitats and species to meet conservation aims, maintaining a biologically healthy coastal environment has socio-economic benefits (Elliott et al., 2018; White et al., 2014).

In the UK, a variety of MPAs exist, each with differing conservation objectives. These include Marine Conservation Zones

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(MCZs), Nature Conservation Marine Protected Areas (Scotland only), Special Area of Conservation with marine components (SACs), Specially Protected Areas (SPAs) and candidate Special Area of Conservation/Sites of Community Importance (cSAC/SCI). MCZs can be designated anywhere in English and Welsh territorial and UK offshore waters, and are designed to protect a range of nationally important marine wildlife, habitats, geology and geomorphology. SACs are strictly protected sites (habitat types and species) designated under the European Commission's Habitats Directive. SPAs with marine components are sites with qualifying Birds Directive Annex I species or regularly occurring migratory species that are dependent on the marine environment (http://archive.jncc.gov.uk/page-4549; last accessed 07 January 2020). cSAC/SCIs are Candidate SAC sites that have been submitted to the European Commission, but not yet formally adopted or Sites of Community Importance sites that have been adopted by the European Commission but not yet formally designated by the government of each country (https://jncc.gov.uk/our-work/special-areas-of-conservation-overview/; last accessed 07 January 2020).

The number and area of MPAs in the UK has grown in recent years - from 2% of UK seas in 2008 (Rush and Solandt, 2017) to 25% ($n = 355$) in 2019 (https://jncc.gov.uk/our-work/uk-marine-protected-area-network-statistics/; last accessed 02 March 2020). The management of these sites, which is driven by legislation and policy, is dependent on the provision of scientific evidence detailing the issues they may face (Rush and Solandt, 2017). Whilst MPAs can be effective in the management of discrete localised pressures, such sites may also be subject to wider range pressures, such as climate change, non-native species, and diffuse pollution.

Marine anthropogenic litter, which is defined as 'any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment' (UNEP, 2005) is one such concern. Its rapid increase in abundance along rivers, coastlines and in the wider marine ecosystem has resulted in litter becoming one of the most conspicuous marine pollution issues (Jefferson et al., 2014; Lippiatt et al., 2013). Marine anthropogenic litter originates from a variety of sources, including shipping, commercial and recreational fishing, aquaculture, sewage, agriculture and industry, poor waste management and public littering (Nelms et al., 2017; Watts et al., 2017). Inputs to marine ecosystems from these sources can vary regionally due to factors, such as proximity to areas of high population density, degree of fishing effort and concentration of shipping traffic (Duckett et al., 2015; Hoellein et al., 2015; Moriarty et al., 2016). Additionally, the distribution and accumulation of litter is influenced by environmental factors, such as wind, tides, currents, terrestrial hydrology and coastal morphology (Critchell and Lambrechts, 2016).

Plastic pollution, a large component of litter found in the marine environment (*ca*. 70% by frequency; Nelms et al., 2017), is of particular concern, due to the increasing evidence of its potential to cause ecological and socio-economic impacts, such as entanglement (Duncan et al., 2017), ingestion and the associated increased risk of exposure to chemical contaminants (Alexiadou et al., 2019; Tanaka et al., 2013), smothering and abrasion, spread of invasive species (Gregory, 2009), and detrimental effects on human health and well-being (Beaumont et al., 2019). Despite their statutory designated status and legal protection from discrete threats, MPAs may be exposed to the potential impacts of plastic pollution, due to its diffuse nature and lack of constraint by legislative and/or political boundaries. In addition, the presence of sensitive marine features may mean they are more at risk than some non-protected sites.

Understanding the abundance, distribution and composition of litter along coastlines is key to determining the status of the marine environment as a whole and can be instrumental in designing and implementing effective management strategies aimed at reducing future inputs. Beach litter surveys are a well-known technique for gathering such information (Bravo et al., 2009; Nelms et al., 2017; Schulz et al., 2015; Watts et al., 2017). For example, the prevalence of some single-use plastic items on beaches has recently resulted in the implementation of legislation to regulate their use by a number of national and international governments (e.g. carrier bags, cutlery, plates, straws, cotton bud sticks, balloon sticks, oxo-degradable plastics and food containers and expanded polystyrene cups; EU Commission, 2018). Although this measure may help to combat the issue, a combination of actions is required to reduce the presence of plastic pollution in the environment (Wyles et al., 2019a). Large, long-term datasets can be used to provide evidence and inform management strategies but considerable time and resources are required to collect meaningful data, which have the temporal and spatial coverage to enable the detection of trends in abundance and patterns in distribution (Nelms et al., 2017; Schulz et al., 2015; Watts et al., 2017). Litter survey programmes that enlist volunteers - or *citizen scientists* – to collect data are able to resolve many of the logistical or financial constraints that may otherwise be encountered by studies using paid personnel (Duckett et al., 2015; Hidalgo-Ruz and Thiel, 2015; Nelms et al., 2017). One such project is the UK Marine Conservation Society (MCS) Great British Beach Clean (formally Beachwatch) programme, which has been conducting beach cleans and collecting litter data at a national scale since 1994. Here, we examine this 25-year dataset (1994–2018) for spatial patterns and temporal trends in relation to the English coastal MPA network, with the aim of highlighting key sources of litter and identifying management priority areas.

2. Materials and methods

2.1. Litter data collection methods

2.1.1. Beach surveys

Data on marine anthropogenic litter were collected by MCS volunteers in September of each year as part of the Great British Beach Clean programme, between 1994 and 2018 from 2378 beach clean surveys in England (Fig. 1a; data from Scotland and Wales were omitted). To collect these data, volunteers walked between the back of the beach and the strand-line, loosely adhering to a line transect (parallel to the strand-line), searching for litter. Visual identification guides were provided to ensure accurate recording of litter items by volunteers. Gathered items of litter were first assigned to item categories that were further classified into seven source categories (i.e. non-sourced, public litter, fishing, sewage, shipping, fly tipped, medical; see Supplementary Material Fig. S1 and Tables S1 and 2). Upon completion of a survey, all litter items recorded were summed, validated by a survey coordinator and subjected to further quality control by MCS. All collected litter was removed from the beach.

2.2. Data analysis methods

2.2.1. Effort correction

In recent years, 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, particularly in the initial years of the beach clean programme. In addition, there was no prior standardisation of the number of volunteers or time spent searching (duration). Previous investigation of the data found significant positive linear relationships between the number of litter items surveyed and these three variables relating to effort (see Nelms et al., 2017). These factors were

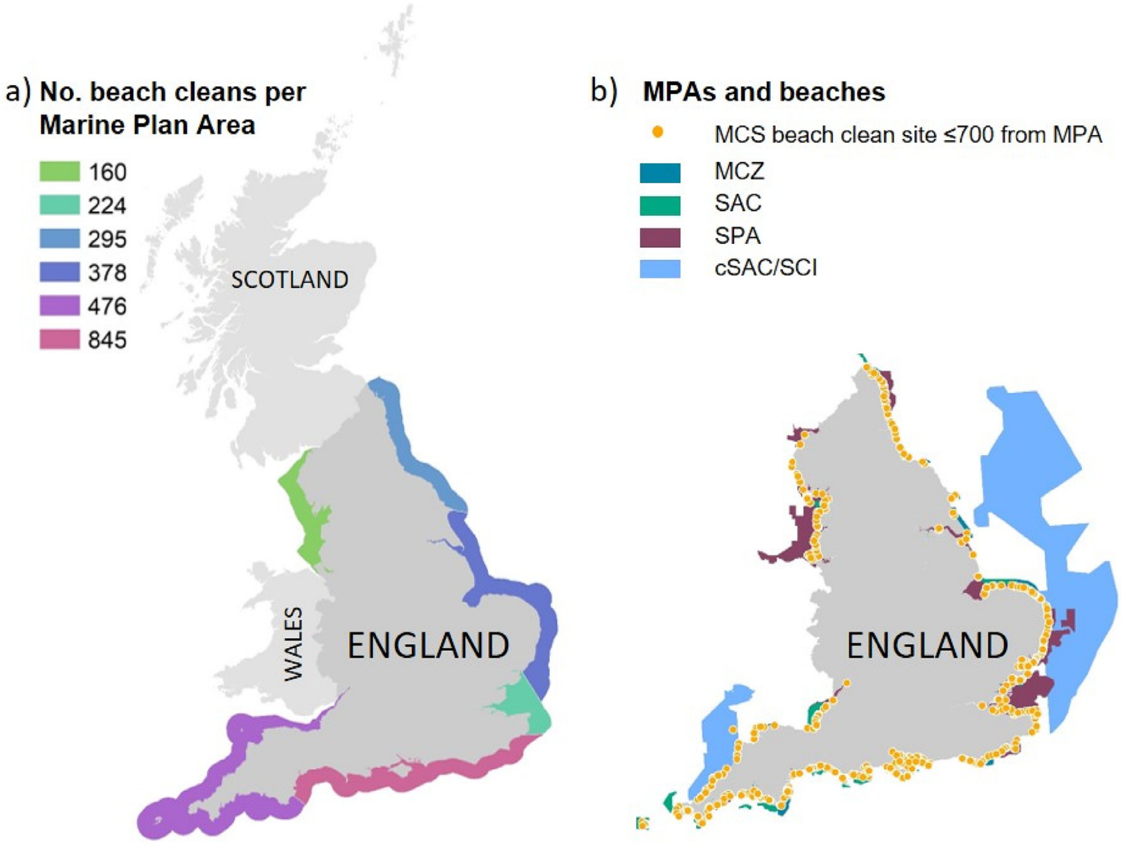

Fig. 1. Beach clean effort and coastal MPA Network. Maps displaying the a) Number of beach cleans in England per Marine Plan Area as designated by the Maritime Management Organisation (MMO; Northwest = 160, Southeast = 224, Northeast = 295, East = 378, Southwest = 476, South = 845) and b) MPAs (MCZ; Marine Conservation Zone, SAC; Special Area of Conservation with marine components, SPA; Specially Protected Area, cSAC/SCI; candidate Special Area of Conservation/Site of Community Importance) and the locations of MCS beaches occurring within 700 m of these (orange points; n = 646 beaches). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

recorded, however, allowing for retrospective calculation of survey effort to facilitate among site comparison.

Following the method described by Nelms et al. (2017), data (i.e. counts of items) were standardised to account for variations in effort among beach litter surveys using the equation; where C = total count (no. items); L = survey linear distance (m); D = survey duration (mins); V = number of volunteers (people):

$$A = \frac{C}{LDV}$$

The unit of the adjusted count (A) was *number of items collected per metre per minute per person* (number of items m^{-1} min^{-1} $person^{-1}$). The adjustment facilitated comparison of litter density among beaches irrespective of volunteer effort.

2.2.2. Linking Marine Protected Areas to beach clean sites

Boundary maps for MPAs (MCZ, SAC; SPA, cSAC/SCI) in England were obtained from Natural England - the statutory body responsible for providing conservation advice for all MPAs within English territorial waters - and spatially queried with respect to MCS beach clean sites using ArcMap 10.3.1 (https://naturalengland-defra.opendata.arcgis.com last accessed 03 September 2019). Beach clean sites were considered within MPAs if they occurred less than 700 m from an MPA boundary. This approach ensured that beach clean sites located within close proximity of MPAs were not inappropriately discounted. The distance of 700 m was determined by examining the distribution of distances formed between beach clean sites and MPAs, and using expert rationale (Supplementary Material Fig. S2). The resulting list of MPA sites and locations of beach cleans was examined by Natural England marine specialists to ensure only appropriate locations were included. Consequently, litter data from 1836 beach cleans that took place on 646 beaches were recorded within or near 112 MPAs between the period 1994 and 2018 (mean number of beach cleans per MPA ± 1SD = 26 ± 28; Fig. 1b and Supplementary Material Table S3), representing 76% of all beach cleans in England (753 km of coastline). The number of beach cleans that took place outside of an MPA, or >700 m from an MPA boundary, and hence excluded, was 542 on 205 beaches (Supplementary Material Fig. S3). The mean annual number of beach cleans (±SD), occurring inside or within 700 m of MPAs, around the English coastline, was 116 ± 29 (range: 67–181 beach cleans per year).

2.3. Litter density

2.3.1. Survey beaches and MPAs

Using effort-corrected litter abundance data, the mean number of items m^{-1} min^{-1} $person^{-1}$ was calculated for each beach clean site and for each MPA across all years. These data were analysed within ArcMap and a symbology of coloured points/polygons developed to illustrate litter density (using quantiles) for each beach/MPA (dark green ≤ 25th percentile, light green = 25th - 50th percentile, amber = 50th – 75th percentile, red ≥75th percentile).

2.3.2. *Comparing litter density inside and outside of MPAs*

A Generalised Linear Mixed Model (GLMM) was used to investigate whether the density of recorded litter (number of items m^{-1} min^{-1} $person^{-1}$) was influenced by the location of the beach clean in relation to the MPA boundary - either inside ($\leq$700 m from an MPA), or outside (>700 m from an MPA; 'lme4' package for R; R Core Team, 2019). Beach-specific identification numbers were used as a random effect in the model to account for the variable number of repeated observations of beaches through time. The normality of the dependent variable (i.e. effort corrected litter density) was assessed using a Q-Q plot and determined to be non-normal. Data were therefore log-transformed (log10) and further assessed (Q-Q plot), which confirmed a satisfactory transformation. Model selection was based on Akaike's Information Criterion (AIC) and *p*-value, where the model with lowest AIC score was deemed the most reliable. The null hypothesis was rejected if $p \leq 0.05$.

2.4. *Comparing litter density by MPA type*

Differences in litter density among the four MPA types (i.e. MPA, cSAC/SCI, SAC and SPA) were explored using a GLMM following similar procedures as above.

2.5. *Litter sources and materials*

Litter items were categorised by source (i.e. non-sourced, public litter, fishing, sewage, shipping, fly-tipped and medical; Supplementary Material Table S1) and material (i.e. plastic, rubber, cloth, metal, medical, sanitary, faeces, paper, wood, glass and pottery; Supplementary Material Table S2). The number of items was enumerated for each source type and corrected for effort using the method outlined in the *Effort correction* section (2.2.1) above. With respect to material, this analysis was repeated for plastic only due to its persistence and omnipresence within the marine environment and potential to cause harm.

2.5.1. *Proportion*

The overall composition of litter by source and material was examined by calculating the proportion for each using effort-corrected data from all sites combined.

2.5.2. *Spatial abundance*

To examine the data for spatial patterns in litter abundance, the mean number of items m^{-1} min^{-1} $person^{-1}$ was calculated for each beach clean site (across the number of years each site was surveyed within the 1994–2018 time-period) for each source/material per MPA site and explored in the spatial analysis software, ArcMap.

2.6. *Temporal trends in litter abundance*

Temporal trends in litter abundance were investigated using GLMMs for four MPAs where survey data were collected for each year in the 25-year time-period (1994–2018). These were Beachy Head West MCZ, Humber Estuary SPA, Lyme Bay and Torbay SAC and Northumbria Coast SPA; Supplementary Material Table S4). Additionally, 15 MPAs with data in every year of a 10-year period (2009–2018) were similarly investigated using the same statistical framework (Supplementary Material Table S5).

As above, model selection was based on AIC score and *p*-value, where the model with lowest AIC score was deemed the most reliable.

3. Results

3.1. *Litter density*

3.1.1. *Survey beaches and MPAs*

Litter density was spatially heterogeneous on beaches across the English coastal MPA network, though clusters of beaches with high litter densities can be observed in the southeast (Thames estuary area), southwest (Devon and Cornwall), and the northwest (Liverpool; Fig. 2a). MPA sites with the highest mean number of items m^{-1} min^{-1} $person^{-1}$ present on the shoreline were Thames Estuary and Marshes SPA (0.0156; 1 survey only in 2009), Land's End and Cape Bank SAC (0.0117; IQR = 0.0026–0.0045) and Mersey Narrows and North Wirral Foreshore SPA (0.0107; IQR = 0.0066–0.0096; Fig. 2b and Supplementary Material Table S6).

3.1.2. *Comparing litter density inside and outside of MPAs*

Litter density was not influenced by beach clean site location in relation to being inside or outside MPAs; removing this classification during model selection had no significant effect (GLMM; *p*-value = 0.28) and the model without the inside or outside variable was the best fit for the data (lowest AIC score; null model = 4517.282; alternative model = 4522.788). The median number of items m^{-1} min^{-1} $person^{-1}$ for beach clean sites inside ($\leq$700 m from MPA boundary) and outside (>700 m from MPA boundary) were 0.0022 and 0.0020 respectively (Fig. 3a).

3.1.3. *By MPA type*

Litter density was not influenced by MPA type; removing this classification during model selection had no significant effect (GLMM; *p*-value = 0.52) and the model without the MPA type variable was the best fit (lowest AIC score). There was little variation in the median number of items m^{-1} min^{-1} $person^{-1}$ between MPA types (SACs; 0.0025, MCZs; 0.0023, SPAs; 0.0019, cSAC/SCI; 0.0014; Fig. 3b).

3.2. *Sources and materials of litter recorded inside MPAs*

3.2.1. *Proportion*

Items with no discernible source (i.e. non-sourced) were the main component (40.2%) of litter on beaches in or near English MPAs, 76.6% of which was plastic. This was followed by items from public littering (36.9%), fishing (12.6%), sewage (6.7%), shipping (3.1%), fly-tipped (0.4%) and medical (0.2%) litter (Fig. 4a).

Plastic was the most common material described (68.4%), then paper (6.4%), sanitary (5.5%), rubber (5.4%), metal (5.3%), glass (3.7%), wood (2.4%), cloth (2.0%), pottery (0.5%), medical and faeces (both 0.1%; Fig. 4b).

3.2.2. *Spatial abundance*

MPAs experiencing the highest litter densities varied for each source. Land's End and Cape Bank SAC had the highest levels of non-sourced items (0.00734 items m^{-1} min^{-1} $person^{-1}$), Thames Estuary and Marshes SPA had the highest levels of items from public littering (0.00778 items m^{-1} min^{-1} $person^{-1}$) and Mounts Bay MCZ encountered the highest levels of items relating to fishing activity (0.00689 items m^{-1} min^{-1} $person^{-1}$; see Supplementary Material Table S6 for more information). The spatial distribution of litter from sources that constitute more than 10% of the total litter composition (i.e. non-sourced, public litter, fishing) is shown in Fig. 5a–c. Maps for the remaining sources (<10% of litter composition; sewage, shipping, fly tipped and medical) can be found in Supplementary Material Fig. S4.

The MPAs experiencing the highest densities of plastic were Thames Estuary and Marshes SPA, Mounts Bay MCZ and Land's End

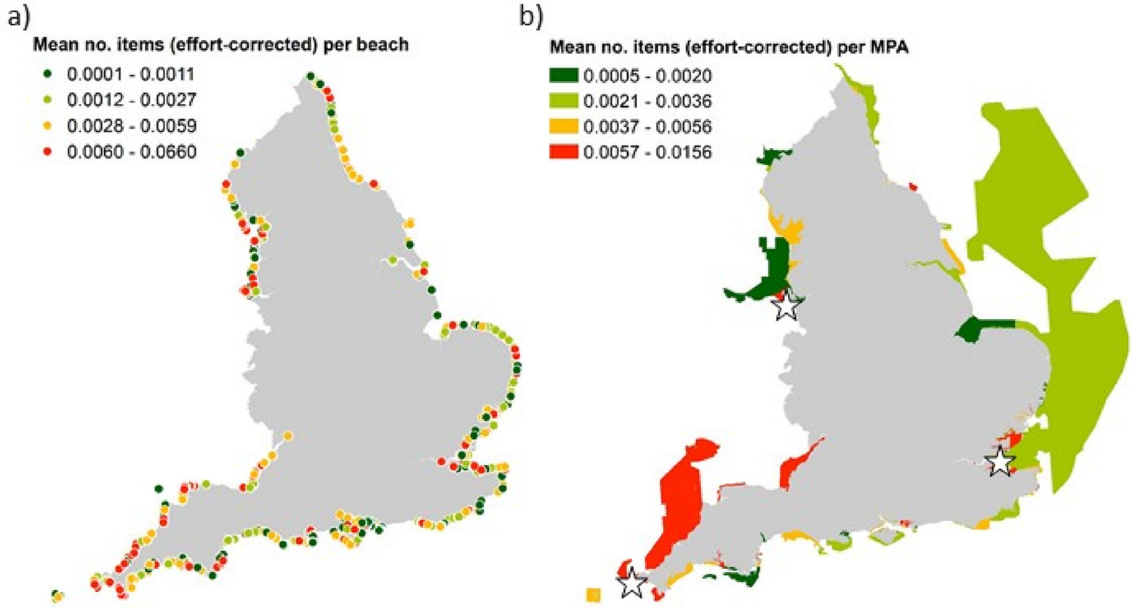

Fig. 2. Litter density at beach clean sites and within the English MPA network. Maps show mean number of shore-based items m^{-1} min^{-1} $person^{-1}$ for each a) beach (coloured points) and b) MPA (coloured polygons). Locations of the three MPAs with the highest mean number of items m^{-1} min^{-1} $person^{-1}$ (Thames Estuary and Marshes SPA, Land's End and Cape Bank SAC and Mersey Narrows and North Wirral Foreshore SPA) are indicated by empty white stars. Where MPAs overlap, those with higher levels of litter are display ordered above those with lower levels (red = highest, dark green = lowest). MPAs with small spatial extents may not be visible at this scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

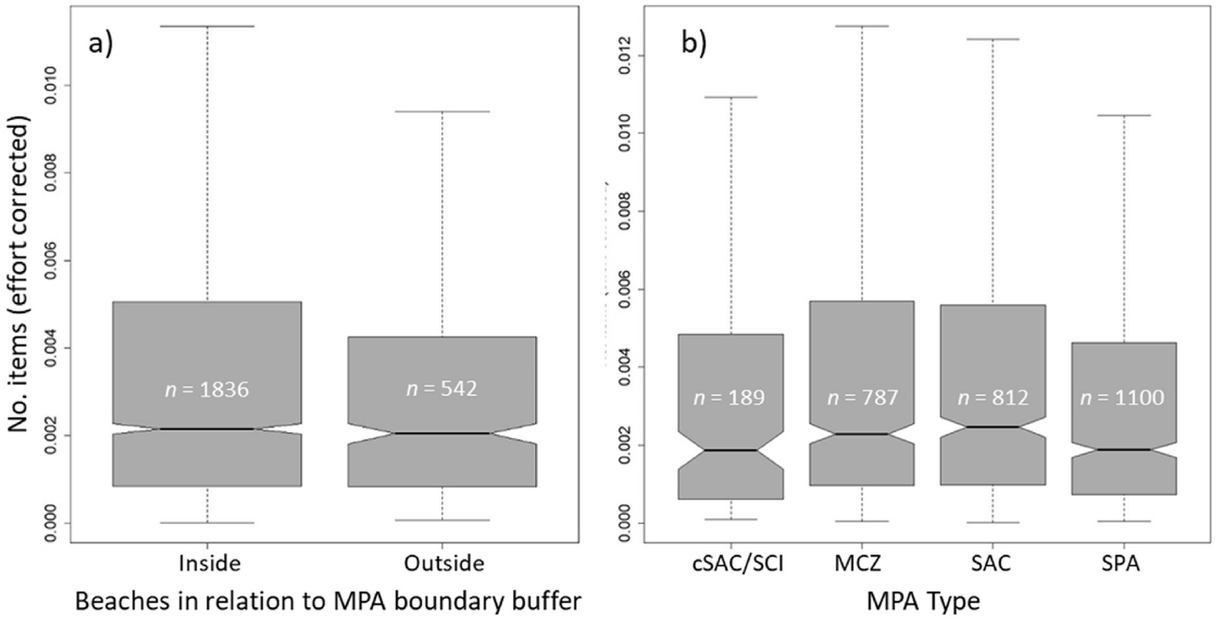

Fig. 3. Beach litter density inside & outside of MPAs and among MPA types. Box and whisker plots describing the number of items (effort-corrected) collected on beaches in relation to a) the MPA boundary − Inside (≤700 m from MPA boundary) or Outside (>700 m from MPA boundary); b) MPA type (cSAC/SCI, MCZ, SAC and SPA). *n* = number of beach cleans per category. The horizontal black lines represent median values the box depicts the first and third quartiles and whiskers illustrate the minimum and maximum values.

and Cape Bank SAC at 0.0128, 0.0096 and 0.0093 items m^{-1} min^{-1} $person^{-1}$ respectively (Fig. 6).

3.3. Temporal trends in litter abundance

No statistically significant temporal trends in the density of litter for the 25-year or 10-year duration analyses were detected (Supplementary Material Tables S7 and S8). Although significant *p*-values ($p < 0.05$) were reported for two MPAs (Northumbria Coast SPA; 25 years, and Humber Estuary SPA; 10 years), the null models had lower AIC scores and were therefore deemed more appropriate.

4. Discussion

Anthropogenic litter, particularly plastic pollution, represents a growing ecological and socio-economic issue which has the

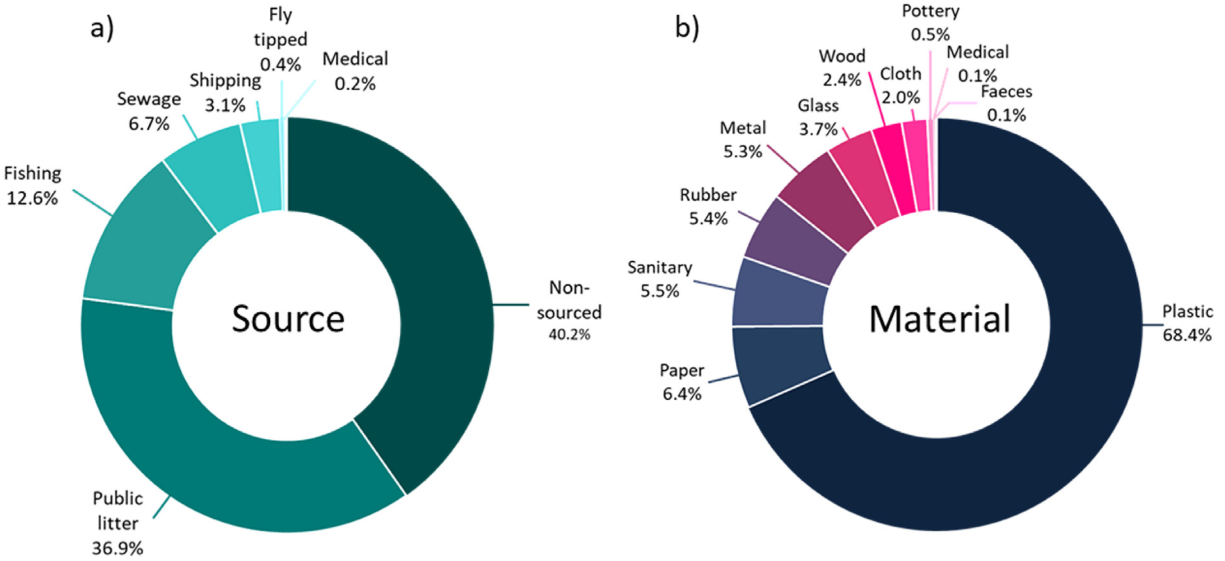

Fig. 4. Composition of shore-based litter recorded inside MPAs during beach clean surveys. Ring plots showing a) source and b) material for litter items recorded during 25 years (1994–2018) of MCS beach cleans.

potential to undermine the protection of habitats and species afforded by MPAs (Liubartseva et al., 2019). As such, key information is required to inform any additional management measures that may be required to mitigate the potential impacts of litter on these sites. Here, we used citizen-science beach clean data to assess the abundance, sources and materials of marine litter on beaches in, or near to ($\leq$700 m), English MPAs and compare the amount of litter within and outside of their boundaries.

4.1. Litter density

Though the amount of litter on individual beaches was geographically variable across the English coastal MPA network, MPAs on the coastlines of the southeast (Kent) and southwest (Cornwall and Devon) England experience higher densities of intertidal litter. In particular, the Thames Estuary and Marshes SPA had the highest mean number of items m^{-1} min^{-1} $person^{-1}$ of both total litter (0.0156) and, more specifically, plastic items (0.0128), as well as items attributed to public littering (0.00778; Supplementary Material Table S6). The mean density of total litter for the whole UK, as reported in Nelms et al. (2017), was 0.0085 items m^{-1} min^{-1} $person^{-1}$. The higher densities of total and plastic litter observed in Thames Estuary and Marshes SPA is most likely due to the area of the River Thames catchment, the local population density (i.e. proximity to Greater London) and associated number of sewage treatment works (Morritt et al., 2014).

Six of the ten MPAs experiencing the highest mean number of items m^{-1} min^{-1} $person^{-1}$ of total litter were located in the southwest (Land's End and Cape Bank SAC, Mounts Bay MCZ, Padstow Bay and Surrounds MCZ, Newquay and the Gannel MCZ, Bristol Channel Approaches/Dynesfeydd Môr Hafren cSAC/SCI and Bideford to Foreland Point MCZ). This observation may be due to several factors, such as high levels of fishing effort (Lee et al., 2010; Witt and Godley, 2007), proximity to the world's third busiest shipping route (English Channel), input from the wider Atlantic Ocean (driven by wind and currents), the presence of large cities and discharging rivers (Swansea, Cardiff, Newport, Bristol, Plymouth; River Severn), and tourist hotspots (Smith, 2010).

4.2. Inside and outside of MPAs

The lack of difference in litter density on beaches inside and outside MPAs suggests that sensitive sites may be exposed to the potential impacts of plastic pollution (e.g. entanglement, ingestion, smothering and abrasion, spread of invasive species, and detrimental effects on human health and well-being; Alexiadou et al., 2019; Beaumont et al., 2019; Duncan et al., 2017; Lamb et al., 2018). By its diffuse nature, litter in the marine environment is not constrained by legislative and/or political boundaries so action beyond MPA site management is needed to address this issue, at local, national and international levels.

4.3. By MPA type

No statistically significant differences in litter density were detected among MPA types (cSAC/SCI, MCZ, SAC, SPA). Any variation is likely due to the characteristics of the sites (e.g. geographic location, local currents and exposure, and proximity to and size of local population centres) rather than litter input as a result of the varying management actions applied to them. For example, SPAs, which are classified for rare and vulnerable birds, tend to encompass comparatively small areas and are usually coastal in their locality, yet they generally host birds during critical phases of their life-history (E.g. breeding populations).

4.4. Sources

Of the items that could be attributed to a source, more than a third (36.9%) originated from public littering. This observation, and those of the other sources (non-sourced, fishing, sewage, shipping, fly tipped and medical), corresponds with findings from previous analysis of 10-year data collected from beaches around the UK coastline by Nelms et al. (2017).

Litter items attributed to fishing activities comprised 13% overall and the southwest appears to be particularly affected, with nine of the ten most influenced MPAs occurring in this area. Watts et al. (2017) examined six years of litter data, collected from nine beaches in north Cornwall, using similar methods to those employed by MCS volunteers, and found that 32% of litter could be assigned to

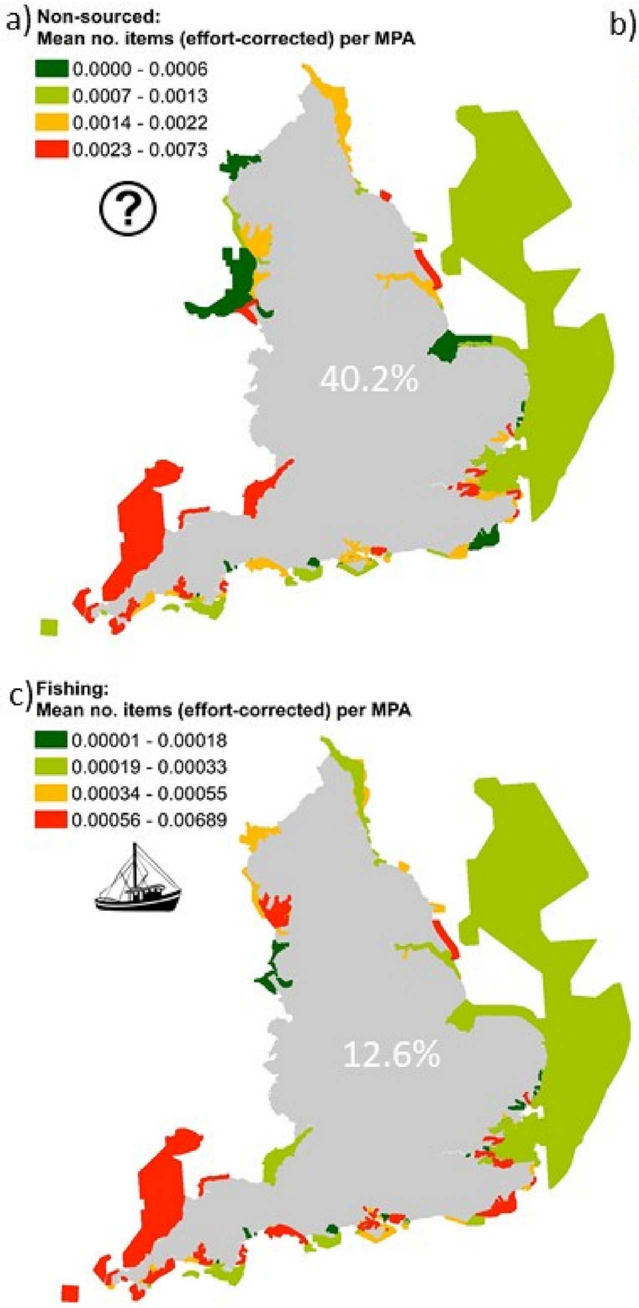

Fig. 5. Shore-based litter density occurring within English MPAs categorised by three source types. Maps showing the mean number of items m^{-1} min^{-1} $person^{-1}$ for each MPA for a) non-sourced b) public litter c) fishing. The percentages in the centre of each map pertain to the contribution of that source to the overall litter composition. See Supplementary Material Fig. S4 for the remaining sources (<10% of litter composition; sewage, shipping, fly tipped and medical).

fishing. This figure is considerably higher than the average for England determined in this study, perhaps due to the proximity of an area of relatively heavy fishing activity (Lee et al., 2010; Witt and Godley, 2007), and exposure to prevailing currents from the Atlantic. This variation demonstrates the need for management actions (i.e. greater participation in schemes such as Fishing for Litter; Wyles et al., 2019a) that are sensitive to regional nuances in litter sources.

No regional pattern for sewage related litter (7%) was detected but the MPAs with the highest levels were all estuarine and/or near the mouths of large rivers, such as the Mersey, Severn, Dee and Deben (Mersey Narrows and North Wirral Foreshore SPA, Severn Estuary SPA, Severn Estuary/Môr Hafren SAC, Dee Estuary/Aber Dyfrdwy SAC, Chichester and Langstone Harbours SPA, The Dee Estuary SPA, Ribble and Alt Estuaries SPA, Deben Estuary SPA, Mersey Estuary SPA, and Solent Maritime SAC). This observation could implicate leakage from combined sewer overflows during periods of intense rainfall, though further investigation is required. In addition, the generally lower-energy conditions of these areas may lead to greater settlement of debris onto local coasts.

These results demonstrate that locally relevant interventions and management actions should be prioritised to effectively reduce anthropogenic litter inputs into the marine environment.

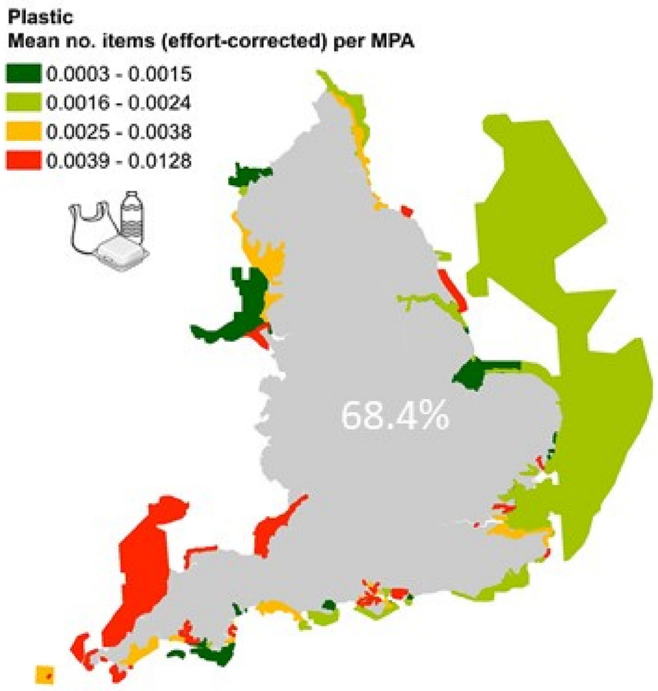

Fig. 6. Density of plastic shore-based litter occurring within English MPAs. Map showing mean number of plastic litter items m^{-1} min^{-1} $person^{-1}$ for each MPA.

4.5. *Materials*

Plastic was the most common material of items found (68.4%), similar to the result for the UK coastline (Nelms et al., 2017). It should be noted that during the 2017 study by Nelms et al. (2017), plastic and polystyrene were treated as separate categories and comprised 66% and 5% of litter respectively (71% combined). In this study, they have been combined under the term, ‘plastic’. Similarly, a study of litter on eight German beaches in the North Sea reported plastic/Styrofoam/foam rubber comprised ~74% of items (Schulz et al., 2015), which is similar to the present study. Globally, the composition of litter varies and plastic may constitute between 48 and 91% (Galgani et al., 2015). For example, the litter on beaches around the northern South China Sea is dominated by plastics and Styrofoam (95%; Lee et al., 2013).

Eight of the ten MPAs with the highest mean number of plastic items m^{-1} min^{-1} $person^{-1}$ were located in southwest England, particularly Devon and Cornwall (Mounts Bay MCZ, Land’s End and Cape Bank SAC, Padstow Bay and Surrounds MCZ, Bristol Channel Approaches/Dynesfeydd Môr Hafren cSAC/SCI, Bideford to Foreland Point MCZ, Hartland Point to Tintagel MCZ, Newquay and the Gannel MCZ and Lizard Point SAC). This area experiences high relative densities of litter likely, in part due to its westward facing nature, and over two thirds of litter on UK beaches is plastic (Nelms et al., 2017).

4.6. *Temporal trends*

Globally, the abundance of plastic pollution within the marine environment appears to be increasing but there are strong spatial differences in the presence and direction of temporal trends (Galgani et al., 2015). For example, the lack of change in total litter density through time (25 or 10 years) in this study corresponds with results from previous 10-year analysis of British beaches (Nelms et al., 2017) and 25-year analysis of German beaches in the North Sea (Schulz et al., 2015). Elsewhere, significant increases in plastic pollution have been reported (Ryan et al., 2019; Wilcox et al., 2019).

The lack of temporal trends detected in the present study may be due to a variety of reasons. Firstly, the amount of litter may have changed little over the time-periods and the results faithfully represent the real-world situation. Secondly, the sample size and time-period may be insufficient to statistically reveal small changes within such a variable system. For example, most MPAs analysed for temporal trends had less than ten surveys per year and many only had one. Considering the large spatial extent of some MPA sites, this survey coverage may not provide an accurate whole-site assessment of litter density. A tailored sample size based on the spatial extent of each site would be a more representative method of collecting the data. Thirdly, it is possible that localised variability within the system (due to the multitude of inputs and extensive transportation of debris by currents and wind) makes the detection of overall trends, at a broader scale, challenging. For example, Watts et al. (2017) found that the direction (increase or decrease) of temporal change in litter abundances varied significantly among the three north Cornwall study areas, indicating that local factors are highly influential. Finally, the extent of litter removal by volunteers (from MCS and other non-governmental organisations) and local authorities may be significant to regulate the accumulation of litter and effectively limit its escalation but insufficient to make detectable improvements. A coordinated database with information from beach cleans conducted by groups and individuals would greatly improve our knowledge of the types and combined quantities of items removed and recorded from the coastline.

4.7. *MPA management and beach litter*

MPAs are designated to provide discrete spatial management of activities that may impair the conservation status of protected species and habitats. Our study demonstrates that MPAs are exposed to the same levels of plastic pollution as non-protected sites and further work is needed to develop effective management strategies aimed at reducing inputs of plastic pollution. A better understanding of the potential impacts on sensitive marine ecosystems is also required.

In addition to protecting marine habitats and species to meet conservation aims, maintaining a biologically healthy coastal environment has socio-economic benefits. For example, over 170 million visits are made to UK beaches annually which contributes heavily to the local and national economy (Elliott et al., 2018; White et al., 2014; www.visitbritain.org/value-tourism-england; last accessed 16 September 2019). Visits to protected natural sites around the coast have been shown to provide greater benefits for relaxation and connecting to nature but this is decreased by the presence of litter (Wyles et al., 2019b, 2015). Furthermore, as litter is considered by the public to be an indicator of an unhealthy coastal environment (Jefferson et al., 2014), its presence may alter the public perception of the condition and effectiveness of MPAs.

Protecting MPAs from plastic pollution requires measures that address the broader scale input of litter at source (Green and Johnson, 2019). For example, investment in waste management (including coastal waste) combined with education on recycling and littering has proven successful in Australia (Willis et al., 2018). Other measures, such as a Deposit Return Scheme (DRS) for single use drinks containers, action on fly tipping and inappropriate flushing, an Extended Producer Responsibility Scheme for the collection of fishing gear, and more water refill points, would also likely lead to less leakage of plastic items into the environment (Royle et al., 2019). Continued monitoring via citizen science schemes and professional surveys would be required to assess the effectiveness of these policy measures. Remedial action specific to MPA sites may be beneficial to reduce the potential impacts of plastic pollution, alongside wider measures to prevent future release into the marine environment. For example, recovery of abandoned, lost or discarded fishing gear where feasible and containment of historic coastal waste disposal sites. Citizen science diver surveys to record and remove debris from the seabed may also provide additional knowledge on marine litter distribution and help protect sensitive benthic habitats and species.

5. Conclusion

Here, we demonstrate the value of citizen science as an approach able to generate useful data on the state of the marine environment (Nelms et al., 2017; van der Velde et al., 2016). Though there are some constraints (see Nelms et al., 2017), the benefits likely outweigh the costs. To the authors' knowledge, there are no other beach clean datasets with such broad spatial coverage that span a quarter of a century. Gathering these data was only possible because input from volunteers significantly lessened the costs on time and resources usually associated with data collection on this scale. Therefore, not only do clean-ups help to remove large volumes of litter from coastlines, they can also greatly contribute to our understanding of marine anthropogenic litter (Wyles et al., 2019a). Globally, the number of citizen-science clean-up projects appears to be increasing and it is essential that we are able to harness the evidence generated by the data they collect and hold. Here, we outline methods that can be easily replicated and applied to similar projects worldwide.

Declaration of interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: SN, LE, BG, PR, JLS and MW declare no conflict of interest. HS is an employee of Natural England, a public body whose role is to advise government on nature conservation and management of MPAs, and a financial funder of this study.

CRediT authorship contribution statement

Sarah E. Nelms: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization. **Lauren Eyles:** Resources, Data curation, Writing - review & editing. **Brendan J. Godley:** Methodology, Writing - review & editing, Funding acquisition. **Peter B. Richardson:** Resources, Writing - review & editing. **Hazel Selley:** Conceptualization, Methodology, Resources, Data curation, Writing - original draft, Writing - review & editing, Funding acquisition. **Jean-Luc Solandt:** Resources, Writing - review & editing. **Matthew J. Witt:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Supervision.

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Appendix A. Supplementary data

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