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The influence of depositional environment on the abundance of microplastic pollution on beaches in the Bristol Channel, UK

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ABSTRACT

Microplastic is a ubiquitous environmental contaminant, but large gaps still exist in our knowledge of its distribution. We conducted a detailed assessment of the extent and variability of microplastic pollution in the Bristol Channel, UK. Sand samples were collected between the 5th and 30th August 2017, with microplastic recovered from 15 of the 16 beaches sampled along a coastal extent of ~230 km. In total, 1446 particles of suspected microplastic were extracted using a cascade of sieves and visual identification. The most common microplastics recovered were fragments (74%) and industrial plastic pellets (13%). We used Fourier-Transform Infrared (FTIR) spectroscopy to analyse 25% of recovered particles, 96.5% of which were confirmed as plastic, with polyethylene (61%) and polypropylene (26%) the most common polymers. Our analysis of local beach environments indicates microplastic burdens were higher on lower energy beaches with finer sediments, highlighting the importance of depositional environment in determining microplastic abundance.

1. Introduction

Driven by its versatility, low cost and durability there has been a rapid increase in the production of plastic since large-scale production began in the 1950's (GESAMP, 2015). By 2015, global plastic production was 380 million metric tons (Mt) (Geyer et al., 2017). However, plastic waste is often mismanaged and it has been estimated that every year between 4.8 and 12.7 Mt. of plastic enters the oceans (Jambeck et al., 2015). The majority of this plastic pollution is from land-based sources (Kooi et al., 2018) and enters the marine environment through inland waterways, wastewater outflows and by atmospheric transport (Bergmann et al., 2019; Dris et al., 2016). Once in the marine environment, it is thought that plastic pollution will persist for centuries (Galgani et al., 2013), gradually fragmenting as a result of physical, biological and chemical processes into microplastic (Browne et al., 2007; Cole et al., 2011). Whilst there is a range in the size definitions of nanoplastic, microplastic and the slightly larger mesoplastic (Hartmann et al., 2019), microplastics are often defined as less than 5 mm in size (Masura et al., 2015) and in this paper we refer to microplastics as plastic fragments between 1 mm and 5 mm or 1000–5000 μm. Additional sources of microplastic include synthetic clothing (De Falco et al., 2018), abrasion of car tyres (Boucher and Friot, 2017), industrial loss of pre-production plastic pellets (Di Vito et al., 2018), sewage treatment works (GESAMP, 2015) and the use of some cosmetics (Duis and Coors, 2016).

Microplastics have been reported in the digestive systems of: zooplankton (Cole et al., 2013; Frias et al., 2014), mussels destined for human consumption (Li et al., 2018), crustaceans (Murray and Cowie, 2011; Watts et al., 2014), wild caught fish (Foekema et al., 2013; Neves et al., 2015), seabirds (Wilcox et al., 2015), and large marine mammals such as seals and dolphins (Nelms et al., 2019a; Nelms et al., 2019b).

This microplastic may be consumed accidently by marine life as a result of indiscriminate feeding strategies (Fossi et al., 2014; Goldstein and Goodwin, 2013), or through active selection when microplastic is mistaken for food (Savoca et al., 2016). Microplastic can also be ingested indirectly through trophic transfer from contaminated prey (Nelms et al., 2018; Santana et al., 2017). Ingestion of microplastic has been reported as causing reduced feeding rates in langoustine (Welden and Cowie, 2016), reductions in individual and population fitness in the common goby (de Sá et al., 2015), and physical damage to the digestive system of a large range of fish (Jovanović, 2017). It has been suggested that plastic additives (Hermabessiere et al., 2017) and persistent organic pollutants that have concentrated on microplastic fragments (Hirai et al., 2011), could leach out from ingested microplastic into marine

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organisms, potentially leading to reduced health and increased mortality (Browne et al., 2013).

Despite it being widely accepted that microplastic is a ubiquitous environmental contaminant (Avio et al., 2017; Rochman, 2018), there are still significant gaps in our knowledge of the spatial and temporal distribution of microplastic pollution, and the factors which determine microplastic distribution within the marine environment (Kooi et al., 2018). For example, past research has tended to either focus on the variability of beach microplastic at spatial scales of tens of kilometres, too small to capture the influence of differing coastal environments on microplastic abundance (Browne et al., 2010; Claessens et al., 2011), or over much larger continental scales with hundreds of kilometres between sample beaches (Lots et al., 2017). Our study bridges this knowledge gap by analysing beach microplastic on a regional scale. We assess the distribution of microplastic mass and abundance (i.e. the number of microplastic particles per m^2) across a range of beach environments in the Bristol Channel, UK (i.e. which spans ~230 km), with a typical distance of 15 km between sample sites, and correlate the distribution with various environmental proxies. Microplastic pollution has not previously been extensively studied in the Bristol Channel, which,

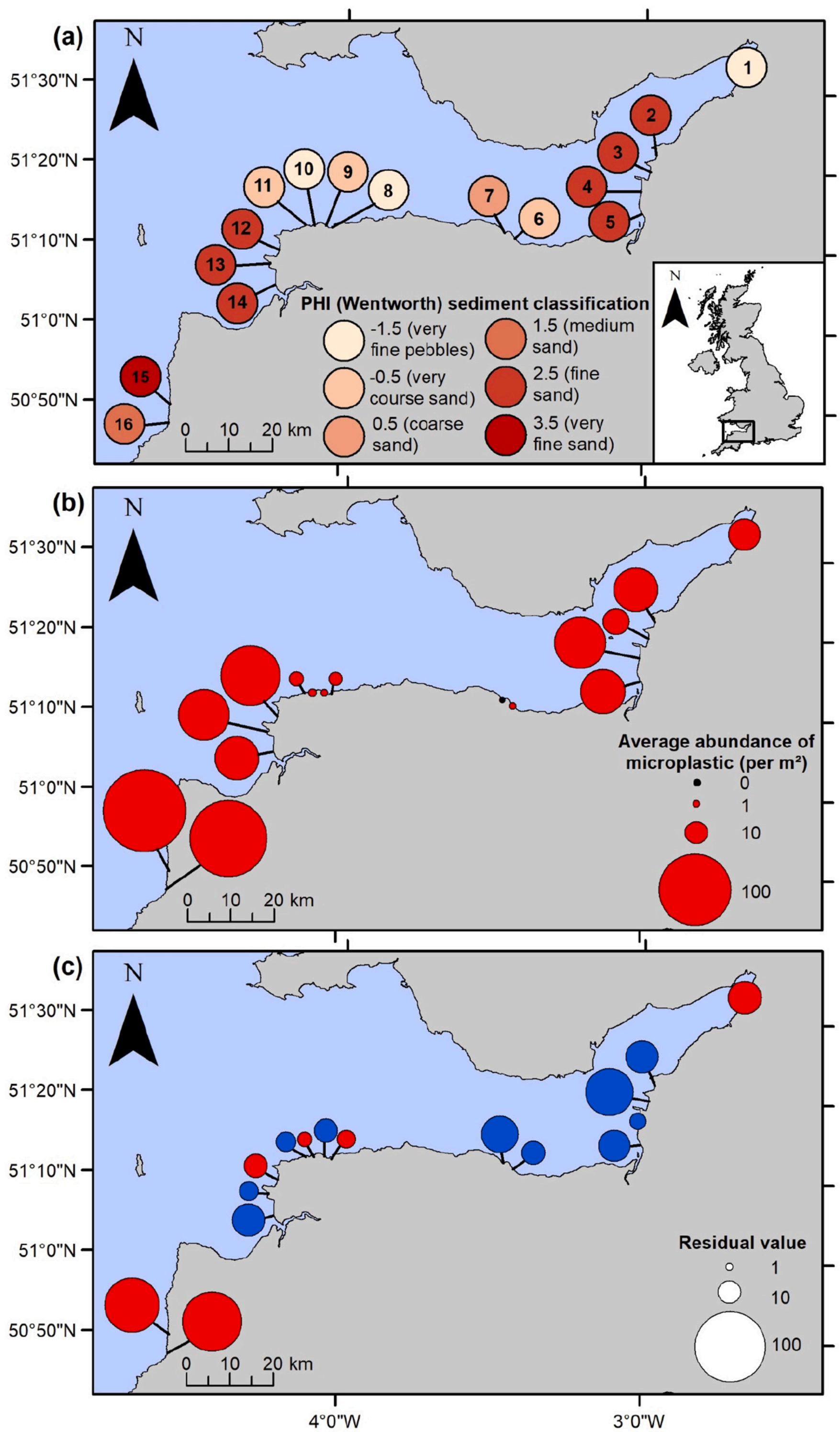

Fig. 1. Maps showing: **(a)** The beaches sampled for microplastic pollution within the Bristol Channel and their corresponding sediment grain size at the high tide mark, on the Krumbein PHI (and Wentworth) sediment classification scale. Beaches sampled were: 1–Severn Beach, 2-Sand Bay, 3-Weston-super-Mare, 4-Brean, 5-Burnham on sea, 6-Dunster, 7-Minehead, 8-Combe Martin, 9-Combe Martin (Broadsands Beach), 10-Ilfracombe (Hele Bay), 11-Ilfracombe, 12-Woolacombe Bay, 13-Croyde, 14-Saunton, 15-Bude, 16-Widemouth Bay. Inset shows location of Bristol Channel. **(b)** The beach-averaged abundance of (1–5 mm) microplastic per m2 found in the top 2 cm of surface sediment. **(c)** The residual microplastic abundance values of each beach based on sediment grain size. Red (blue) circles represent beaches with more (less) microplastic present than expected. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

combined with the region's varied geological, oceanographic and human coastal environment, make it the ideal study site to forge new insights into the factors that influence marine microplastic distribution on regional scales.

2. Methodology

2.1. Microplastic sample collection locations

In total, 16 beaches across ~230 km of the southern coast of the Bristol Channel, were sampled for microplastic pollution (Fig. 1a and Supplementary Tables 1 & 2). Beaches were deemed suitable for sampling if the sediment at the high tide area consisted of sediment fractions smaller than and inclusive of very fine pebbles, as classified on the Wentworth scale, and equivalent to higher than negative 2 on the Krumbein PHI scale (USGS, 2006). Beaches with larger sediment proved difficult to press the quadrat into the sediment and gain an accurate measurement of the top 2 cm. All beaches were sampled between the 5th and 30th August 2017, during which there were no significant weather events (Met Office, 2019). Each beach was also sampled within 3 h of high tide to minimise disruption to the study from wind and beach users.

At each beach, ten samples were taken at 5, 15, 25, 35, 45, 55, 65, 75, 85 and 95% of beach length. The total lengths of each beach and the subsequent intervals between replicate samples for each beach are noted in Supplementary Table 1. Whilst variation in the interval distance between samples at different beaches could lead to small scale hotspots of microplastic accumulation being more likely to be missed at longer beaches than smaller beaches, it does ensure that equal numbers of samples are collected at each beach and that the total beach, including the beach periphery, was sampled. The more sheltered areas of beaches, that are protected to some degree from wave action, such as beach edges have been shown to experience higher abundances of 1–5 mm microplastic than more exposed areas of the beach and we wanted to capture this accumulation (Bissen and Chawchai, 2020; Pinheiro et al., 2019). Each sample consisted of the top 2 cm of sand from an area defined by a 25 cm by 25 cm wooden quadrat, centred on the most recent high tide line. A metal trowel was used to remove sand from the quadrat and sand samples were stored in brand new airtight sample bags. At our chosen size fraction any contamination from the sample bag would be clearly visible when compared to weathered microplastic.

2.2. Microplastic extraction and beach categorisation

In the laboratory: cotton lab coats were worn, samples were placed into foil trays and covered at all times when in the lab but not being actively sieved, and sieving was conducted in a fume cupboard to reduce the likelihood of airborne contamination (Lusher et al., 2017). Samples were placed overnight in a drying oven at 75 °C before being dry sieved through a cascade of two stainless steel sieves, with mesh sizes of 5 mm and 1 mm, respectively. Sieving was conducted in a horizontal side to side motion rather than a vertical up and down motion and checks were made around the sieve after each sample was processed for potential escaped plastics and none were identified. All material trapped on top of the 1 mm sieve was systematically visually analysed for potential microplastic. The vast majority of microplastic particles were clearly distinguishable as a result of their distinct, unnatural colouration. However, for particles where there was uncertainty as to whether the particle was plastic or lithic, the particle was dropped into a beaker of freshwater and further examined under a dissection microscope. Particles that floated or sunk slowly, lacked a cellular structure, and were a homogeneous colour (and a uniform thickness in the case of threads), were counted as being microplastic (Hidalgo-Ruz et al., 2012). Particles that sank rapidly and did not display any characteristics of microplastic when viewed under a microscope were determined to be lithic.

Once extracted from the sand samples, the microplastic recovered from each beach was categorised into one of six categories, as shown in Supplementary Table 3, allowing for comparison with other studies (van Franeker et al., 2016). Microplastic particles from each category at each beach were then counted and weighed. A specimen from each of the 10 samples collected at each beach were qualitatively assessed, along with field notes and pictures to assign the high tide sediment found at each beach a Wentworth size term descriptor e.g. 'fine sand' (Wentworth, 1922). Wentworth size terms were then converted to a beach-mean Krumbein PHI value (Krumbein, 1938) for quantitative analysis using the USGS 2006 comparison chart (USGS, 2006). Throughout the paper therefore sediment type is quantified using the Krumbein PHI sediment value. For example, on the Krumbein PHI scale, a value of −1.5 represents very fine pebbles and a value of 3.5 represents very fine sand on the Wentworth scale.

Ordnance Survey (2020) maps were used to measure beach width, defined as the distance between mean low water and mean high water, and satellite images (Google Maps, 2020) were used to calculate the distance along the coast from sample beach to the nearest harbour. These satellite images were also used alongside observations from sampling trips to order each beach in a touristic infrastructure index from most to least amount of tourism infrastructure present, similar to the land-based sources index used by Bissen and Chawchai (2020). The index we use takes into account the presence and quantity of: shops, restaurants, takeaways, beach car parks, hotels, campsites, caravan parks, piers, amusement facilities, and other relevant touristic infrastructure present in the vicinity of the beach.

2.3. FTIR analysis

After the microplastic had been extracted, 25% or 20 pieces of suspected microplastic, whichever was higher, from each beach location were randomly selected for further analysis using Fourier-Transform Infrared (FTIR) spectroscopy (Perkin Elmer Spectrum 2 ATR FT-IR system) with polymer libraries used as in (D'Souza et al., 2020). In total 402 of the collected particles were analysed. The resulting spectra were compared to a number of polymer libraries using Spectrum™ (Perkin Elmer). Only readings with a confidence level of 70% or greater (Lusher et al., 2013), and a reliable spectrum after visual inspection (Nelms et al., 2018), were accepted as a match. Samples below this confidence level were classified as 'unknown'.

2.4. Analysis of microplastic distribution

To investigate the factors that determine the abundance of microplastic pollution on beaches in the Bristol Channel, the sediment type of each beach, a proxy for the type of depositional environment, was correlated with the beach-averaged microplastic abundance and mass. The strength of possible correlations was assessed using a Spearman's replicate bootstrap correlation (Core Team, 2018, Version 3.4.1): beach averaged data points were resampled 1000 times, with two randomly selected sites removed each time, before computing the correlation. Correlation coefficients, r, are quoted in the text with error bars in brackets that represent the 5–95% confidence interval limits from the resultant probability distribution of 1000 correlation values. We also provide the probability value, p.

The sediment grain size, Ss, as defined on the Krumbein PHI scale was found to be linearly related to the beach averaged microplastic abundance, M_A, such that $M_A = m\ Ss + c$, where m and c are the computed gradient and intercept, respectively. To assess the deviation of each beach from this simple relationship, residual values of microplastic abundance were also computed (i.e. the difference between the observed microplastic abundance and that predicted from the sediment grain size using the deduced linear relationship).

3. Results

3.1. Beach sediment type

The grain size of sediment at the high tide line varies across the Bristol Channel. Finer sediments, represented by higher Krumbein PHI values were found on study beaches from Sand Bay to Burnham-on-Sea (sites 2–5) and from Woolacombe Bay to Widemouth Bay (sites 12–16). It was also found that sediment on the generally more exposed north facing study beaches between Dunster and Ilfracombe (sites 6–11), and the west facing Severn Beach (site 1) were categorised by lower Krumbein PHI Values, representing larger grained sediment at the high tide line (Fig. 1a).

3.2. The makeup of microplastic pollution in the Bristol Channel

Of a total of 160 sand samples, suspected microplastic particles were recovered from 99 samples, with 1446 particles recovered in total. The distribution of microplastic found across the study region is shown in Fig. 1b. Microplastic was recovered from 15 of the 16 beaches sampled with only Minehead (site 7) having no microplastic present. Those beaches that had microplastic present were found to have beach mean values of between 0.8 (± 1.0) and 132.8 (± 66.0) particles of microplastic per m^2, with the greatest density of microplastic being found at Bude (site 15). Most of the microplastic particles recovered from samples in this study were fragments, making up 74% of the total microplastic pieces recovered (Fig. 2a). Industrial plastic pellets were also found in significant numbers across the study area (13 out of 16 sites) and made up 13% of the total microplastic particles recovered. The density of industrial pellets was highest at Sand Bay (site 2), Croyde (site 13) and Widemouth Bay (site 16). (Supplementary Table 2).

Of the 402 suspected microplastic particles selected for FTIR analysis, 96.5% were confirmed to be plastic, with 3% ($n = 12$) of suspected microplastic particles being too degraded to provide reliable spectra and 0.5% ($n = 2$) of tested samples most likely being a non plastic material, such as charcoal. The high percentage of confirmed microplastic particles from the FTIR analysis supports the visual inspection techniques performed on the full sample collection as robust. The FTIR analysis indicated that the most common polymers found across the study area were polyethylene (61%) and polypropylene (26%) (Fig. 2b). In addition, a total of seven pellets were identified as ethylene propylene diene monomer (EPDM) in the form of industrial plastic pellets, all sourced from Severn Beach (site 1) and Weston super Mare (site 3) in the estuary area of the River Severn at the northern extent of the study region.

3.3. The spatial distribution of microplastic pollution in the Bristol Channel

Some interesting patterns in the distribution of microplastic pollution on beaches in the Bristol Channel are apparent (Fig. 1b). The centre of the study area, where the coastline is broadly orientated East – West, had noticeably low microplastic abundance. By comparison, high microplastic abundance was found on the Northern and Southern ends of the Bristol Channel, where the coastline is generally North – South orientated. The distribution of microplastic mass across the Bristol Channel showed very similar patterns (not shown). Moreover, a significant positive correlation was found between the average abundance of microplastic particles found per m^2 (on each beach) and the Krumbein PHI sediment value, with $r = 0.71$ (0.36, 0.87) and $p = 0.002$ (Supplementary Fig. 1). This relationship indicates that the smaller the sediment grain size of the beach, the higher the number of microplastic particles that were recovered. Similarly, a significant relationship was found with average microplastic mass per m^2 and sediment value, with $r = 0.70$, (0.34, 0.89) and $p = 0.003$. On the other hand, we found no significant correlation between average abundance of microplastic particles found per m^2 (on each beach) and: beach width, beach length (and thus sampling interval), position on our touristic infrastructure index and distance to the nearest harbour.

4. Discussion

4.1. Microplastic pollution is widespread within the Bristol Channel

Microplastic was found on all except one of the beaches sampled, providing compelling evidence that microplastic pollution is widespread in the Bristol Channel, supporting other studies that have found microplastic pollution, of a range of size fractions, to be present in beach sediments (Claessens et al., 2011; Graca et al., 2017; Stolte et al., 2015), coastal wetlands (Lourenço et al., 2017), surface waters (Gallagher et al., 2016; Kanhai et al., 2017) and on the sea floor (Ling et al., 2017; Van Cauwenberghe et al., 2013). By recording zero microplastics in 38% of our samples, across multiple beaches, we are confident any contamination such as from lab based airborne sources, is minimal. No sample bag plastic was recorded in the FTIR analysis.

The majority (74%) of microplastic particles recovered from our samples were found to be fragments, suggesting that the majority of microplastic pollution on beaches in the Bristol Channel, results from the breakdown of larger macroplastic pollution. This finding highlights the importance of preventing plastic litter from entering the marine environment and of initiatives such as coastal beach cleans that remove larger items from the marine and coastal environment.

The noticeable (14%) presence of industrial plastic pellets on beaches in the Bristol Channel also suggests effort should be made to

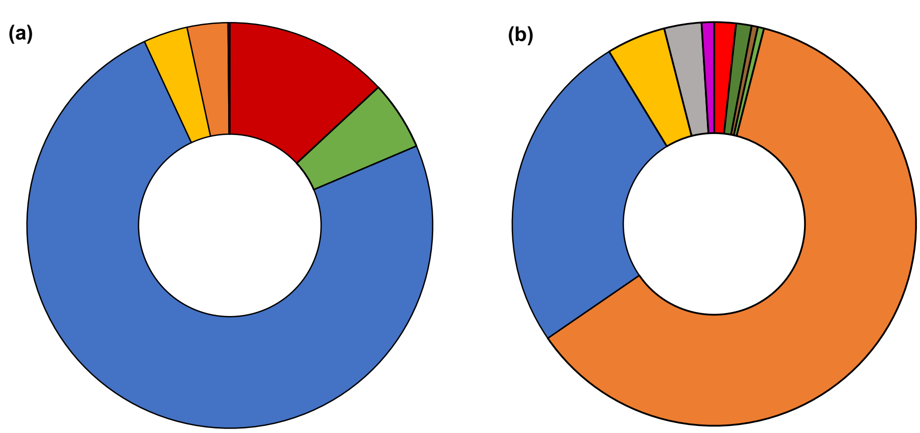

Fig. 2. **(a)** The breakdown contribution of different microplastic types to the total 1446 microplastic particles recovered from samples across the Bristol Channel and identified using visual inspection techniques. Fragments: blue 74.5%; Industrial plastic pellets: red, 13.1%; Foamed plastics: green, 5.5%; Sheet like plastic: yellow, 3.5%; Thread like plastic: orange, 3.3%; Plastic like other: purple, 0.1%. **(b)** The breakdown contributions of polymer type to the 402 samples tested using FTIR. Polyethylene: orange, 61.4%; Polypropylene: blue, 25.9%; Polystyrene: yellow, 4.7%; Unidentified: grey, 3.0%; Ethylene propylene diene monomer (EPDM): red, 1.7%; Ethyl vinyl acetate copolymer (EVA): dark green, 1.2%; Other: purple, 1%; Nylon: light green, 0.5%; Non plastic: brown, 0.5%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

understand where and how industrial pellets are entering the marine environment. Given that industrial pellets are generally deposited close to their industrial source (Karlsson et al., 2018), the higher concentrations of industrial pellets found at Sand Bay (site 2), Croyde (site 13) and Widemouth Bay (site 16), could indicate a proximity to industrial plastic pollution release. In addition, FTIR analysis revealed a concentration of industrial EPDM pellets with very similar visual appearances to each other on Severn Beach (site 1) and Weston-super-Mare (site 3), suggesting the presence of a source specifically for EPDM industrial pellets in the north of the study area.

Possible sources of industrial pellet pollution could be producers, transporters and processors of industrial pellets that do not have effective pellet loss reduction measures in place (Cole and Sherrington, 2016). The industrial area of Avonmouth for example, approximately 30 km north of Weston-super-Mare and 7 km south of Severn Beach, likely contains a number of industrial plastic pellet producers and consumers. Another possible source of industrial plastic pellet pollution is the leakage of Bio-Beads, a type of industrial plastic pellet used in some sewage treatment works. The majority of plants using Bio-Beads, including the Combe Martin plant which is within the study area (close to sites 8 and 9 in Fig. 1a), were constructed in the 1990's and 2000's and allowed sewage treatment works to have a much smaller footprint compared to conventional activated sludge systems (Cornish Plastic Pollution Coalition, 2018). These Bio-beads, can escape into the environment as a result of damage to containment mesh or from abrasion reducing the size of Bio-Beads to a level where they can fit through containing meshes (Turner et al., 2019). In our study, suspected Bio-beads made up 21% of the industrial plastic pellets we recovered.

The microplastic deposition found on beaches was heterogeneous (see standard error in Supplementary Table 2). In particular, as found in other studies, more microplastic was in general found at sheltered areas of the beach (Bissen and Chawchai, 2020; Pinheiro et al., 2019), such as the beach edges. Despite the variability within each beach, the general pattern of beach median microplastic abundances does reflect that of the beach mean abundances (see Supplementary Fig. 2). We have tested the impact of microplastic variability at each beach on our results by recomputing the correlation between beach sediment grain size and microplastic abundance, and removing the five beaches with a relative standard error (Supplementary Table 3) greater than 50%. A significant correlation between microplastic abundance and the Krumbein PHI sediment value remains ($p = 0.005$).

4.2. Factors influencing the deposition of microplastic pollution on beaches in the Bristol Channel

The striking difference between microplastic levels found along differently orientated coastlines suggests that the depositional environment is an important factor in determining microplastic accumulation (Harris, 2020). This result is reinforced by the robust quantitative evidence we provide that microplastic pollution within the Bristol Channel region is more abundant on beaches with finer grained sediment as typically associated with low energy, depositional environments (Switzer and Pile, 2015). This result supports the qualitative observations of Martins and Sobral (2011).

In contrast to our study (Browne et al., 2011; Mathalon and Hill, 2014; Urban-Malinga et al., 2020) have reported finding no significant trend between microplastic abundance and sediment grain size on beaches/estuaries studied. However, these three papers are not directly comparable to our results as they focus on identifying and documenting a significantly smaller size fraction of microplastic than we report on. Browne et al. (2010) also did not find an overall trend between microplastic abundance and the proportion of clay in sediments, which they use as an index of depositional environment, but the authors do note that considerable quantities of very dense particles of plastic >1 mm in size were found in regions with a greater deposition of fine sediment. These results lead us to tentatively suggest that sediment grain size and thus depositional environment may impact the abundance of 'larger' (i.e. >1 mm) microplastics differently to smaller microplastics with the implication that different plastic particle sizes accumulate in different locations within the beach environment. Alternatively, it could be that other factors such as proximity to waste water treatment works (Browne et al., 2011; Estahbanati and Fahrenfeld, 2016; Murphy et al., 2016) in these studies is obscuring a relationship between sediment grain size and microplastic abundance in this size fraction. Indeed, we find that outliers in our relationship between sediment grain size and microplastic abundance correspond to likely marine plastic source regions of the Severn Estuary and Atlantic Ocean.

Four of the beaches we sampled were found to have microplastic pollution levels noticeably outside the 95% confidence interval of our deduced linear relationship between sediment grain size and microplastic abundance (Supplementary Fig. 1b). Therefore, alongside depositional environment, several other factors likely influence plastic accumulation on beaches in the study region. For example, the proximity of beaches to urban and industrial activity, and the amount of beach users has been shown to impact microplastic influx rates at a range of size classes (Nel et al., 2020; Stolte et al., 2015; Munari et al., 2016). In the Bristol Channel we found no significant relationship between microplastic abundance and distance to the nearest harbour, or our tourist infrastructure index in line with Laglbauer et al. (2014). It is important to note that the relationship between tourism levels and microplastic abundance on beaches is complicated by some more touristic beaches being cleaned and/or raked by beach owners/operators. Additionally, our tourism infrastructure index is a rough measure of tourism at each beach. It would be interesting to build on this work by, for example, simultaneously surveying or estimating beach visitors or using estimates from tourism bodies or beach operators and also accounting for the size and traffic of proximal harbours. Finally, we found there to be no significant relationship between microplastic abundance and distance from Severn Beach, which is located close to the major population and industrial centres of Bristol, Avonmouth Docks, Newport, and Cardiff.

However, on accounting for variability in sediment grain size, which appears to be the dominant driver of microplastic abundance in the region. We found Severn Beach (site 1) in the north of the study area, and Bude (site 15) and Widemouth Bay (site 16) at the very south of the study region, showed considerably higher microplastic abundance than expected from the beach sediment type (Fig, 1c), suggesting that these sites may be associated with enhanced microplastic influx or proximity to microplastic sources. As such we deduce that the Severn Estuary, along with the wider Atlantic Ocean, is likely a notable source of marine microplastic. On the other hand, a cluster of negative residuals were found between Sand Bay (site 2) through to Minehead (site 7) suggesting that there may also be a regional factor causing these beaches to have lower than expected microplastic abundance.

Water currents are also known to influence the abundance of microplastic, at a range of different size classes, on beaches (Hidalgo-Ruz and Thiel, 2013; Kaberi et al., 2013; Lots et al., 2017; Nel and Froneman, 2015) and may explain a second zone of enhanced microplastic abundance located around the beaches of Bude (site 15) and Widemouth Bay (site 16) on the westward Atlantic-facing coastline. It has been documented that in the Bristol Channel both the prevailing south westerlies (HSE, 2001) and south easterly winds produce residual wind currents that flow in from the north east Atlantic, up the coast of Cornwall and Devon, past the beaches of Widemouth Bay (site 16) and Bude (site 15), before being deflected, away from the inner Bristol Channel and out towards west Wales (Uncles, 2010). The north-east Atlantic could therefore be acting as a second source for microplastic pollution in the Bristol Channel, with these residual wind driven currents acting as a microplastic transport pathway. Tidal currents could also play a role in determining microplastic abundance on beaches in the Bristol Channel. Fast localised tidal currents, are particularly prevalent between the beaches of Minehead (site 7) and Ilfracombe (site 11)

(Admiralty, 2006), coinciding with where we identified a cluster of beaches with lower residuals of microplastic abundance. It should be noted however that local tidal and wind currents themselves influence the depositional environment and thus the size of sediment occurring at a given beach (Klovan, 1966). Therefore, our residuals are likely to have accounted for, at least in part, the effect of local wind and tidal currents on microplastic abundance variability. To better determine the origin, trajectories and accumulation of microplastic debris in the Bristol Channel, a Lagrangian tracking model could be applied to the region (Critchell and Lambrechts, 2016; Delandmeter and van Sebille, 2019; Jalón-Rojas et al., 2019). Indeed, the dataset collected in this study could be used to validate such a simulation or to initialise a backcast particle tracking model.

Finally, this study was limited in sample size and time. There is an inherent variability encountered when surveying for microplastic, such that, for example, beach averaged data may be skewed by a small number of samples with particularly high microplastic abundances. Longshore drift, local winds, natural protection, and/or the raking of a beach by beach operators could lead to a large proportion of the microplastic pollution load being concentrated towards one or both ends of the beach, as we found at Sand Bay (site 2) and Widemouth Bay (site 16). Rivers flowing out across the middle of a beach may also lead to higher microplastic abundances in specific areas, as was the case at Croyde (site 13). Reassuringly, a comparison of the beach-mean and beach-median microplastic abundances collected display an overall similar pattern across the study region (Supplementary Fig. 2). Our survey does not however capture any temporal variability in microplastic accumulation on beaches, such as the influence of high-energy storm events or spring-neap tidal cycles. Additionally, the use of the Wentworth scale to quantify sediment grain size in this study is somewhat basic and in future work, a full grain size analysis should be conducted, as carried out by (Nel et al., 2020). The levels and patterns observed in our dataset do however provide an important motivation for a more comprehensive survey of microplastic accumulation in the Bristol Channel, with increased sample sizes and collection throughout the year.

5. Conclusion

This study provides the first assessment of microplastic accumulation in beach sediments across the Bristol Channel, UK, and has demonstrated that microplastic pollution is widespread across a variety of differing environments in the region. We have also shown that the majority of this pollution is secondary microplastic and provided evidence for possible sources of industrial plastic pellets, specifically EPDM industrial pellets, in the north of the Bristol Channel. Our analysis has found that sediment grain size, a proxy for depositional environment, is a significant factor in determining the abundance of microplastic pollution on beaches in the Bristol Channel. Secondary factors potentially include wind driven and tidal currents, and the proximity to microplastic production, leakage or influxes. Here we identify two likely origins of microplastic in the Bristol Channel; the urban areas of Bristol and Avonmouth in the Severn Estuary, and the wider Atlantic.

CRediT authorship contribution statement

Daniel Wilson: Conceptualisation, methodology, formal analysis, investigation, writing-review and editing, visualisation. **Brendan Godley:** Conceptualisation, resources, writing-review and editing. **Gemma Haggar:** Methodology. **David Santillo:** Resources, writing-review and editing. **Katy Sheen:** Conceptualisation, writing-review and editing, visualisation.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.111997.

References

Admiralty, 2006. Tidal Stream Atlas 2006: Bristol Channel (Lundy Island to Avonmouth), 1st ed, ISBN 9780707716367. United Kingdom Hydrographic Office.

Avio, C.G., Gorbi, S., Regoli, F., 2017. Plastics and microplastics in the oceans: from emerging pollutants to emerged threat. Mar. Environ. Res. 128, 2–11. https://doi.org/10.1016/j.marenvres.2016.05.012.

Bergmann, M., Mützel, S., Primpke, S., Tekman, M.B., Trachsel, J., Gerdts, G., 2019. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Sci. Adv. 5, eaax1157. doi:https://doi.org/10.1126/sciadv.aax1157.

Bissen, R., Chawchai, S., 2020. Microplastics on beaches along the eastern Gulf of Thailand – a preliminary study. Mar. Pollut. Bull. 157, 111345. https://doi.org/10.1016/j.marpolbul.2020.111345.

Boucher, J., Friot, D., 2017. Primary Microplastics in the Oceans: A Global Evaluation of Sources. IUCN, Gland, Switzerland. https://doi.org/10.2305/IUCN.CH.2017.01.en, 43pp.

Browne, M.A., Galloway, T., Thompson, R., 2007. Microplastic–an emerging contaminant of potential concern? Integr. Environ. Assess. Manag. 3, 559–561. https://doi.org/10.1002/ieam.5630030412.

Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. Environ. Sci. Technol. 44, 3404–3409. https://doi.org/10.1021/es903784e.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environ. Sci. Technol. 45 (21), 9175–9179. https://doi.org/10.1021/es201811s.

Browne, M.A., Niven, S.J., Galloway, T.S., Rowland, S.J., Thompson, R.C., 2013. Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. Curr. Biol. 23, 2388–2392. https://doi.org/10.1016/j.cub.2013.10.012.

Claessens, M., De Meester, S., Van Landuyt, L., De Clerck, K., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199–2204. https://doi.org/10.1016/j.marpolbul.2011.06.030.

Cole, G., Sherrington, C., 2016. Study to Quantify Pellet Emissions in the UK. Available at https://www.eunomia.co.uk/reports-tools/study-to-quantify-pellet-emissions-in-the-uk/.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025.

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., Galloway, T.S., 2013. Microplastic ingestion by zooplankton. Environ. Sci. Technol. 47, 6646–6655. https://doi.org/10.1021/es400663f.

Core Team, R., 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available at. https://www.R-project.org.

Cornish Plastic Pollution Coalition, 2018. Bio-bead Pollution on Our Beaches. Available at http://www.ramepbc.org/CPPC_Biobead_Pollution_on_our_Beaches_2nd_Edition_July_2018.pdf.

Critchell, K., Lambrechts, J., 2016. Modelling accumulation of marine plastics in the coastal zone; what are the dominant physical processes? Estuar. Coast. Shelf Sci. 171, 111–122. https://doi.org/10.1016/j.ecss.2016.01.036.

De Falco, F., Gullo, M.P., Gentile, G., Di Pace, E., Cocca, M., Gelabert, L., Brouta-Agnésa, M., Rovira, A., Escudero, R., Villalba, R., Mossotti, R., Montarsolo, A., Gavignano, S., Tonin, C., Avella, M., 2018. Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. Environ. Pollut. 236, 916–925. https://doi.org/10.1016/j.envpol.2017.10.057.

de Sá, L.C., Luís, L.G., Guilhermino, L., 2015. Effects of microplastics on juveniles of the common goby (*Pomatoschistus microps*): confusion with prey, reduction of the predatory performance and efficiency, and possible influence of developmental conditions. Environ. Pollut. 196, 359–362. https://doi.org/10.1016/j.envpol.2014.10.026.
Delandmeter, P., van Sebille, E., 2019. The parcels v2.0 Lagrangian framework: new field interpolation schemes. Geosci. Model Dev. 12, 3571–3584. https://doi.org/10.5194/gmd-12-3571-2019.
Di Vito, S., Zampetti, G., Sighicelli, M., Carpentieri, S., Pietrelli, L., 2018. Assessment of Microplastics Marine Pollution from an Environmental NGO's Point of View: The First Study About the Widespread Presence of Plastic Pellets Along the Italian Coast, in Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea. Springer, Cham, pp. 47–52. https://doi.org/10.1007/978-3-319-71279-6_7.
Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104, 290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006.
D'Souza, J.M., Windsor, F.M., Santillo, D., Ormerod, S.J., 2020. Food web transfer of plastics to an apex riverine predator. Glob. Chang. Biol. 00, 1–12. https://doi.org/10.1111/gcb.15139.
Duis, K., Coors, A., 2016. Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. Environ. Sci. Eur. 28, 2. https://doi.org/10.1186/s12302-015-0069-y.
Estahbanati, S., Fahrenfeld, N.L., 2016. Influence of wastewater treatment plant discharges on microplastic concentrations in surface water. Chemosphere 162, 277–284. https://doi.org/10.1016/j.chemosphere.2016.07.083.
Foekema, E.M., De Gruijter, C., Mergia, M.T., Van Franeker, J.A., Murk, A.J., Koelmans, A.A., 2013. Plastic in north sea fish. Environ. Sci. Technol. 47, 8818–8824. https://doi.org/10.1021/es400931b.
Fossi, M.C., Coppola, D., Baini, M., Giannetti, M., Guerranti, C., Marsili, L., Panti, C., de Sabata, E., Clò, S., 2014. Large filter feeding marine organisms as indicators of microplastic in the pelagic environment: the case studies of the Mediterranean basking shark (*Cetorhinus maximus*) and fin whale (*Balaenoptera physalus*). Mar. Environ. Res. 100, 17–24. https://doi.org/10.1016/j.marenvres.2014.02.002.
Frias, J.P.G.L., Otero, V., Sobral, P., 2014. Evidence of microplastics in samples of zooplankton from Portuguese coastal waters. Mar. Environ. Res. 95, 89–95. https://doi.org/10.1016/j.marenvres.2014.01.001.
Galgani, F., Hanke, G., Werner, S., De Vrees, L., 2013. Marine litter within the European marine strategy framework directive. ICES J. Mar. Sci. 70, 1055–1064. https://doi.org/10.1093/icesjms/fst122.
Gallagher, A., Rees, A., Rowe, R., Stevens, J., Wright, P., 2016. Microplastics in the Solent estuarine complex, UK: an initial assessment. Mar. Pollut. Bull. 102, 243–249. https://doi.org/10.1016/j.marpolbul.2015.04.002.
GESAMP, 2015. "Sources, fate and effects of microplastics in the marine environment: a global assessment", (Kershaw, P. J., ed.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud GESAMP. No 90, 96p. Available at: https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/pdf/GESAMP_microplastics%20full%20study.pdf.
Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782 https://doi.org/10.1126/sciadv.1700782.
Goldstein, M.C., Goodwin, D.S., 2013. Gooseneck barnacles (*Lepas spp.*) ingest microplastic debris in the north Pacific subtropical gyre. PeerJ 1:e184 doi:https://doi.org/10.7717/peerj.184.
Google Maps, 2020. Sattelite Imagery. Accessed through. https://www.google.co.uk/maps/@51.1303521,-3.9097413,118061m/data=!3m1!1e3.
Graca, B., Szewc, K., Zakrzewska, D., Dołęga, A., Szczerbowska-Boruchowska, M., 2017. Sources and fate of microplastics in marine and beach sediments of the southern Baltic Sea—a preliminary study. Environ. Sci. Pollut. Res. 24, 7650–7661. https://doi.org/10.1007/s11356-017-8419-5.
Harris, P.T., 2020. The fate of microplastic in marine sedimentary environments: a review and synthesis. Marine Pollution Bulletin. Elsevier Ltd. 158, 111398. https://doi.org/10.1016/j.marpolbul.2020.111398.
Hartmann, N.B., Hüffer, T., Thompson, R.C., Hassellöv, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N. P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. 53 (3), 1039–1047. https://doi.org/10.1021/acs.est.8b05297.
Hermabessiere, L., Dehaut, A., Paul-Pont, I., Lacroix, C., Jezequel, R., Soudant, P., Duflos, G., 2017. Occurrence and effects of plastic additives on marine environments and organisms: a review. Chemosphere 182, 781–793. https://doi.org/10.1016/J.CHEMOSPHERE.2017.05.096.
Hidalgo-Ruz, V., Thiel, M., 2013. Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project. Mar. Environ. Res. 87–88, 12–18. https://doi.org/10.1016/j.marenvres.2013.02.015.
Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075. https://doi.org/10.1021/es2031505.
Hirai, H., Takada, H., Ogata, Y., Yamashita, R., Mizukawa, K., Saha, M., Kwan, C., Moore, C., Gray, H., Laursen, D., Zettler, E.R., Farrington, J.W., Reddy, C.M., Peacock, E.E., Ward, M.W., 2011. Organic micropollutants in marine plastics debris from the open ocean and remote and urban beaches. Mar. Pollut. Bull. 62, 1683–1692. https://doi.org/10.1016/J.MARPOLBUL.2011.06.004.
HSE Health & Safety Executive, 2001. Wind and wave frequency distributions for sites around the British Isles. Available at: https://www.hse.gov.uk/research/otopdf/2001/oto01030.pdf.
Jalón-Rojas, I., Wang, X.H., Fredj, E., 2019. A 3D numerical model to track marine plastic debris (TrackMPD): sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes. Mar. Pollut. Bull. 141, 256–272. https://doi.org/10.1016/j.marpolbul.2019.02.052.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science. 347, 768–771. https://doi.org/10.1017/CBO9781107415386.010.
Jovanović, B., 2017. Ingestion of microplastics by fish and its potential consequences from a physical perspective. Integr. Environ. Assess. Manag. 13, 510–515. https://doi.org/10.1002/ieam.1913.
Kaberi, H., Zeri, C., Mousdis, G., Papadopoulos, A., and Streftaris, N., 2013. Microplastics along the shoreline of a Greek island (Kea isl., Aegean Sea): types and densities in relation to beach orientation, characteristics and proximity to sources. In Proceedings of the 4th International Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE) and SECOTOX Conference. Mykonos Island, Greece. June 24–28, 2013. Available at: https://www.academia.edu/18842238/Microplastics_along_the_shoreline_of_a_Greek_island_Kea_isl_Aegean_Sea_types_and_densities_in_relation_to_beach_orientation_characteristics_and_proximity_to_sources.
Kanhai, L.D.K., Officer, R., Lyashevska, O., Thompson, R.C., O'Connor, I., 2017. Microplastic abundance, distribution and composition along a latitudinal gradient in the Atlantic Ocean. Mar. Pollut. Bull. 115, 307–314. https://doi.org/10.1016/j.marpolbul.2016.12.025.
Karlsson, T.M., Arneborg, L., Broström, G., Almroth, B.C., Gipperth, L., Hassellöv, M., 2018. The unaccountability case of plastic pellet pollution. Mar. Pollut. Bull. 129, 52–60. https://doi.org/10.1016/j.marpolbul.2018.01.041.
Klovan, J.E., 1966. The use of factor analysis in determining depositional environments from grain-size distributions. SEPM J. Sediment. Res. 36, 115–125. https://doi.org/10.1306/74d7141a-2b21-11d7-8648000102c1865d.
Kooi, M., Besseling, E., Kroeze, C., van Wenzel, A.P., Koelmans, A.A., 2018. Modeling the fate and transport of plastic debris in freshwaters: review and guidance, in: Handbook of Environmental Chemistry. Springer, Cham, pp. 125–152. https://doi.org/10.1007/978-3-319-61615-5_7.
Krumbein, W.C., 1938. Size frequency distributions of sediments and the normal phi curve. SEPM J. Sediment. Res. Vol. 8, 84–90. https://doi.org/10.1306/D4269008-2B26-11D7-8648000102C1865D.
Laglbauer, B.J.L., Franco-Santos, R.M., Andreu-Cazenave, M., Brunelli, L., Papadatou, M., Palatinus, A., Grego, M., Deprez, T., 2014. Macrodebris and microplastics from beaches in Slovenia. Mar. Pollut. Bull. 89 (1–2), 356–366. https://doi.org/10.1016/j.marpolbul.2014.09.036.
Li, J., Green, C., Reynolds, A., Shi, H., Rotchell, J.M., 2018. Microplastics in mussels sampled from coastal waters and supermarkets in the United Kingdom. Environ. Pollut. 241, 35–44. https://doi.org/10.1016/j.envpol.2018.05.038.
Ling, S.D., Sinclair, M., Levi, C.J., Reeves, S.E., Edgar, G.J., 2017. Ubiquity of microplastics in coastal seafloor sediments. Mar. Pollut. Bull. 121, 104–110. https://doi.org/10.1016/j.marpolbul.2017.05.038.
Lots, F.A.E., Behrens, P., Vijver, M.G., Horton, A.A., Bosker, T., 2017. A large-scale investigation of microplastic contamination: abundance and characteristics of microplastics in European beach sediment. Mar. Pollut. Bull. 123, 219–226. https://doi.org/10.1016/j.marpolbul.2017.08.057.
Lourenço, P.M., Serra-Gonçalves, C., Ferreira, J.L., Catry, T., Granadeiro, J.P., 2017. Plastic and other microfibers in sediments, macroinvertebrates and shorebirds from three intertidal wetlands of southern Europe and west Africa. Environ. Pollut. 231, 123–133. https://doi.org/10.1016/j.envpol.2017.07.103.
Lusher, A.L., McHugh, M., Thompson, R.C., 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Mar. Pollut. Bull. 67, 94–99. https://doi.org/10.1016/j.marpolbul.2012.11.028.
Lusher, A.L., Welden, N.A., Sobral, P., Cole, M., 2017. Sampling, isolating and identifying microplastics ingested by fish and invertebrates. Analytical Methods. Royal Society of Chemistry. 9, 1346–1360. https://doi.org/10.1039/C6AY02415G.
Martins, J., Sobral, P., 2011. Plastic marine debris on the Portuguese coastline: a matter of size? Mar. Pollut. Bull. 62, 2649–2653. https://doi.org/10.1016/J.MARPOLBUL.2011.09.028.
Masura, J., et al., 2015. Laboratory methods for the analysis of microplastics in the marine environment: recommendations for quantifying synthetic particles in waters and sediments. NOAA Technical Memorandum NOS-OR&R-48. Available at: https://repository.library.noaa.gov/view/noaa/10296.
Mathalon, A., Hill, P., 2014. Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. Mar. Pollut. Bull. 81 (1), 69–79. https://doi.org/10.1016/j.marpolbul.2014.02.018.
Met Office, 2019. Past Weather Events - Met Office [WWW Document]. URL https://www.metoffice.gov.uk/weather/learn-about/past-uk-weather-events#y2017 (accessed 10.31.19).
Munari, C., Corbau, C., Simeoni, U., Mistri, M., 2016. Marine litter on Mediterranean shores: analysis of composition, spatial distribution and sources in north-western Adriatic beaches. Waste Manag. 49, 483–490. https://doi.org/10.1016/j.wasman.2015.12.010.
Murphy, F., Ewins, C., Carbonnier, F., Quinn, B., 2016. Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. Environ. Sci. Technol. 50 (11), 5800–5808. https://doi.org/10.1021/acs.est.5b05416.
Murray, F., Cowie, P.R., 2011. Plastic contamination in the decapod crustacean *Nephrops norvegicus* (Linnaeus, 1758). Mar. Pollut. Bull. 62, 1207–1217. https://doi.org/10.1016/j.marpolbul.2011.03.032.
Nel, H.A., Froneman, P.W., 2015. A quantitative analysis of microplastic pollution along the south-eastern coastline of South Africa. Mar. Pollut. Bull. 101, 274–279. https://doi.org/10.1016/j.marpolbul.2015.09.043.

Nel, H.A., Sambrook Smith, G.H., Harmer, R., Sykes, R., Schneidewind, U., Lynch, I., Krause, S., 2020. Citizen science reveals microplastic hotspots within tidal estuaries and the remote Scilly Islands, United Kingdom. Mar. Pollut. Bull. 161, 111776. https://doi.org/10.1016/j.marpolbul.2020.111776.
Nelms, S.E., Galloway, T.S., Godley, B.J., Jarvis, D.S., Lindeque, P.K., 2018. Investigating microplastic trophic transfer in marine top predators. Environ. Pollut. 238, 999–1007. https://doi.org/10.1016/j.envpol.2018.02.016.
Nelms, S.E., Barnett, J., Brownlow, A., Davison, N.J., Deaville, R., Galloway, T.S., Lindeque, P.K., Santillo, D., Godley, B.J., 2019a. Microplastics in marine mammals stranded around the British coast: ubiquitous but transitory? Sci. Rep. 9, 1075. https://doi.org/10.1038/s41598-018-37428-3.
Nelms, Sarah E., Parry, H.E., Bennett, K.A., Galloway, T.S., Godley, B.J., Santillo, D., Lindeque, P.K., 2019b. What goes in, must come out: combining scat-based molecular diet analysis and quantification of ingested microplastics in a marine top predator. Methods Ecol. Evol. 10, 1712–1722. https://doi.org/10.1111/2041-210x.13271.
Neves, D., Sobral, P., Ferreira, J.L., Pereira, T., 2015. Ingestion of microplastics by commercial fish off the Portuguese coast. Mar. Pollut. Bull. 101, 119–126. https://doi.org/10.1016/j.marpolbul.2015.11.008.
Ordnance Survey 2020. Accessed through: https://www.bing.com/maps/.
Pinheiro, L.M., Monteiro, R.C.P., Ivar do Sul, J.A., Costa, M.F., 2019. Do beachrocks affect microplastic deposition on the strandline of sandy beaches? Mar. Pollut. Bull. 141 (569–572), 569–572. https://doi.org/10.1016/j.marpolbul.2019.03.010.
Rochman, C.M., 2018. Microplastics research-from sink to source. Science. 360, 28–29. https://doi.org/10.1126/science.aar7734.
Santana, M.F.M., Moreira, F.T., Turra, A., 2017. Trophic transference of microplastics under a low exposure scenario: insights on the likelihood of particle cascading along marine food-webs. Mar. Pollut. Bull. 121, 154–159. https://doi.org/10.1016/j.marpolbul.2017.05.061.
Savoca, M.S., Wohlfeil, M.E., Ebeler, S.E., Nevitt, G.A., 2016. Marine plastic debris emits a keystone infochemical for olfactory foraging seabirds. Sci. Adv. 2, e1600395 https://doi.org/10.1126/sciadv.1600395.
Stolte, A., Forster, S., Gerdts, G., Schubert, H., 2015. Microplastic concentrations in beach sediments along the German Baltic coast. Mar. Pollut. Bull. 99, 216–229. https://doi.org/10.1016/j.marpolbul.2015.07.022.
Switzer, A.D., Pile, J., 2015. Grain size analysis. In: Long, A., Horton, B. (Eds.), Shennan, I. Handbook of Sea Level Research, Wiley Blackwell, pp. 331–346.
Turner, A., Wallerstein, C., Arnold, R., 2019. Identification, origin and characteristics of bio-bead microplastics from beaches in western Europe. Sci. Total Environ. 664, 938–947. https://doi.org/10.1016/j.scitotenv.2019.01.281.
Uncles, R.J., 2010. Physical properties and processes in the Bristol Channel and Severn Estuary. Mar. Pollut. Bull. 61, 5–20. https://doi.org/10.1016/J.MARPOLBUL.2009.12.010.
United States Geological Service (USGS) 2006. Sediment Comparison Chart. Available at: https://pubs.usgs.gov/of/2006/1195/htmldocs/images/chart.pdf.
Urban-Malinga, B., Zalewski, M., Jakubowska, A., Wodzinowski, T., Malinga, M., Pałys, B., Dąbrowska, A., 2020. Microplastics on sandy beaches of the southern Baltic Sea. Mar. Pollut. Bull. 155, 111170. https://doi.org/10.1016/j.marpolbul.2020.111170.
Van Cauwenberghe, L., Vanreusel, A., Mees, J., Janssen, C.R., 2013. Microplastic pollution in deep-sea sediments. Environ. Pollut. 182, 495–499. https://doi.org/10.1016/j.envpol.2013.08.013.
van Franeker, J.A., Kuhn, S., Bravo Rebolledo, E.L., 2016. Fulmar litter EcoQO monitoring in the Netherlands – update 2015. Wageningen Marine Research Report C091/16, RWS Centrale Informatievoorziening BM 16.12. Available at: doi: 10.13140/RG.2.2.31383.16803.
Watts, A.J.R., Lewis, C., Goodhead, R.M., Beckett, S.J., Moger, J., Tyler, C.R., Galloway, T.S., 2014. Uptake and retention of microplastics by the shore crab *Carcinus maenas*. 48, 8823–8830. doi:https://doi.org/10.1021/es501090e.
Welden, N.A.C., Cowie, P.R., 2016. Long-term microplastic retention causes reduced body condition in the langoustine, *Nephrops norvegicus*. Environ. Pollut. 218, 895–900. https://doi.org/10.1016/j.envpol.2016.08.020.
Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. The Journal of Geology 30 (5), 377–392. https://doi.org/10.1086/622910.
Wilcox, C., Van Sebille, E., Hardesty, B.D., 2015. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc. Natl. Acad. Sci. U. S. A. 112, 11899–11904. https://doi.org/10.1073/pnas.1502108112.