2024-01

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https://pearl.plymouth.ac.uk/handle/10026.1/22299

10.1016/j.scitotenv.2023.168535
Science of The Total Environment
Elsevier BV

Science of the Total Environment 909 (2024) 168535

Contents lists available at ScienceDirect

Science of the Total Environment

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

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Microplastic transport and deposition in a beach-dune system (Saunton Sands-Braunton Burrows, southwest England)

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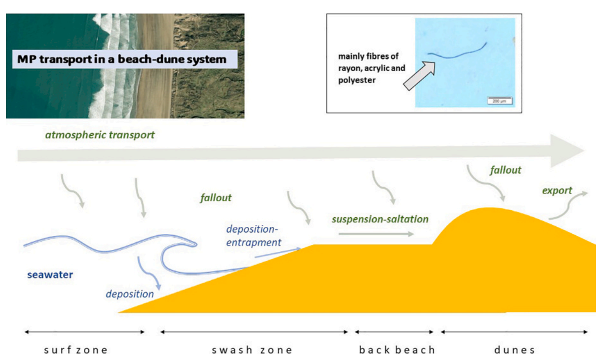
HIGHLIGHTS

- Microplastics (MPs) determined in sediments from beach transects and dunes in SW England.
- MPs mainly <1 mm fibres and concentrations range from ~40 to 560 MP kg^{-1} dry weight.
- Significant relationship between MP concentration and percentage of very fine sand
- Results suggest MP deposition from diffuse, offshore source and capture within interstitial spaces of sand.
- Sand dunes do not preferentially accumulate or act as a landward barrier of MPs.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Kevin V. Thomas

Keywords:
Fibres
Rayon
Anthropogenic
Deposition
Aeolian
Grain size

ABSTRACT

Although microplastics (MPs) are ubiquitous contaminants that have been extensively studied in the marine setting, there remain gaps in our understanding of their transport and fate in the coastal zone. In this study, MPs isolated from surface sediments sampled from a large beach-dune complex in southwest England have been quantified and characterised. Concentrations above a detectable size limit of 30 to 50 μm ranged from about 40 to 560 MP kg^{-1} dry weight but, despite local sources of plastics such as an estuary and seasonal tourism, there were no significant differences in median concentrations between different orthogonal foreshore transects and the dunes or according to zonal location on the beach. The majority of MPs were black and blue fibres of <1 mm in length that were constructed of polymers of density > 1 g cm^{-3} (e.g., rayon, polyester, acrylic). A significant correlation was found between MP concentration and the proportion of very fine sand (100 to 250 μm) but relationships with other granulometric or compositional markers of sediment (e.g., volume-weighted mean diameter, circularity, calcium content) were not evident. An association of MP concentration with very fine sand was attributed to similar particle depositional characteristics and the entrapment of fibres within small interstitial spaces. Overall, the observations reflect the wavelaid and windlaid deposition of MPs from a diffuse, offshore source, and, despite their role as accumulators of particles from the foreshore, dunes do not appear to act as a landward barrier of MPs.

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https://doi.org/10.1016/j.scitotenv.2023.168535
Received 14 August 2023; Received in revised form 31 October 2023; Accepted 10 November 2023
Available online 17 November 2023

1. Introduction

Microplastics (MPs), consisting of primary particles or secondary fragments of plastic of <5 mm in size, are ubiquitous environmental contaminants. This reflects the wide and diverse usage of plastic as a material, coupled with, one the one hand, its durability and inertness, and on the other hand, its propensity to fragment (Barnes et al., 2009; Chamas et al., 2020; Hale et al., 2020). Although the marine environment is the ultimate receptor and, through weathering, generator of MPs, the precise sources, transport, behaviour and impacts of these particles are complex and not fully understood.

MPs have been studied extensively on coastal beaches because they are accessible, close to many land-based and maritime sources, and often harbour visible accumulations of meso- and macroplastic litter. However, observations are sometimes inconsistent and inconclusive, partly because of environmental and morphological differences, but often because different sampling designs, means of sample processing and format or units of data presentation are adopted. For example, many studies focus on spatial (and often large-scale) sampling from one or more wrack lines (Esiukova, 2017; Lots et al., 2017; Schröder et al., 2021; Wilson et al., 2021) whereas others seek to evaluate MP distribution by zonation (including the swash zone, surf zone and backshore; Leibezeit and Dubaish, 2012; Mathalon and Hill, 2014; Prata et al., 2020; Rahman et al., 2020). From an experimental perspective, the use of various solutions for separation means that abundance or distribution by polymer type are not always comparable (Besley et al., 2017;

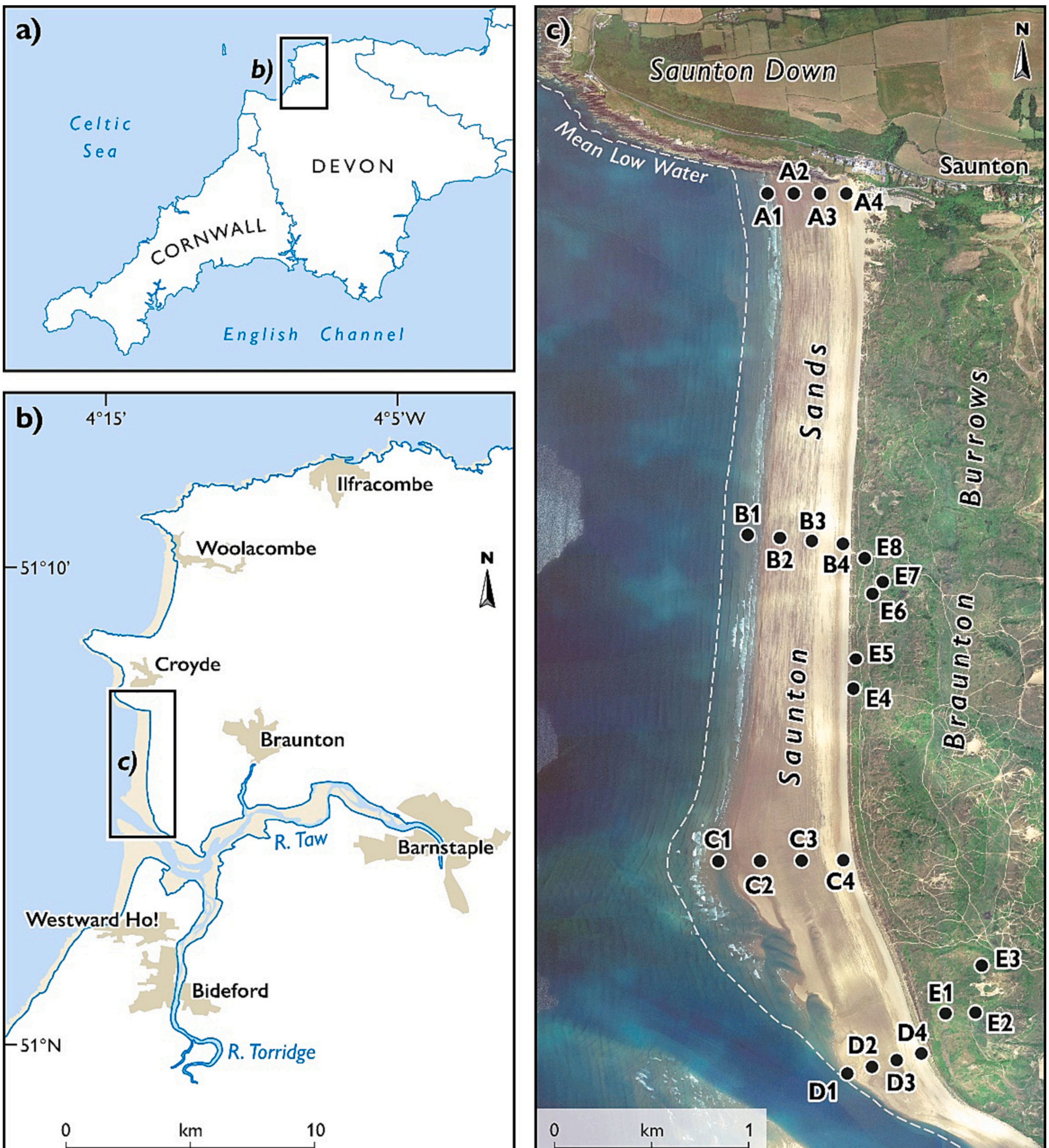

Fig. 1. Saunton Sands and Braunton Burrows, southwest England, and sampling locations along the four beach transects (A to D) and in the dunal system (E).

Coppock et al., 2017). Inferences about the sources and transport of beached MPs (e.g., deposition, retention, resuspension) are also difficult to make where little or no information is provided about sediment grain size distribution or composition (Lots et al., 2017; Bridson et al., 2020; Kumar and Varghese, 2021; Tsukada et al., 2021).

In the present study, and to improve our understanding of the transport of MPs in the coastal setting, we examine the distribution and characteristics (size, shape, colour, polymer type) of MPs in conjunction with the physical and geochemical characteristics of sediment along orthogonal transects of a large, sandy beach in southwest England. We also extend the study into the adjacent dunal system, an aeolian landscape where, more generally, plastic litter is known to be trapped and buried (Turner et al., 2021; Andriolo and Gonçalves, 2022) but very little information exists on MPs (Leibezeit and Dubaish, 2012; Costello and Ebert, 2020). Given that sediment in dunes is subject to different transport pathways than sediment deposited in the foreshore (Hallin et al., 2019), we hypothesise that the concentrations and characteristics of MPs in these two settings will be different and that any differences will afford an insight into the transport and retention of MPs within and across the coastal zone.

2. Methods

2.1. Study site

Saunton Sands (Fig. 1) is a popular beach for tourists and surfers in North Devon, SW England. The beach is characterised by a high tidal range (4 to 7 m), low gradient and fine, quartz-dominated sand (Scott et al., 2007). Extending over five km in length from Saunton Down Headland in the north to the mouth of the Taw-Torridge Estuary in the south, the width of the beach varies and can reach 1.5 km during spring tides (Sarre, 1988). Inland of Saunton Sands is Braunton Burrows, an 1800-acre sand dune system (up to 1.5 km wide and with a maximum elevation of 30 m) that is the second largest in the UK and at the core of the UNESCO North Devon Biosphere (Abesser et al., 2017).

The coastline at Saunton Sands is at an oblique angle to incoming westerly waves and this causes a drift alignment in which a northerly longshore current augments the tidal gyre and transports sediment northwards (Pethick, 2007). Comprising predominantly short period waves that are primarily generated by storms and Atlantic swells, the beach has no intense rip current systems and a subdued intertidal morphology (Scott et al., 2007). The dominant winds for sand transport capacity are directed 4° south of west and essentially perpendicular to the shoreline (Greenwood, 1978). Consequently, sediment deposition in the region is thought to occur through wave-current interactions in the foreshore and wind action in the backshore and dunes (Greenwood, 1978; Scott et al., 2007).

2.2. Sampling

Sampling was carried out within about one hour either side of low water during dry and calm conditions outside of the tourist season (23rd January 2023). Beach sediment was collected at four locations spaced equally (1, just above the low water line, 2 and 3, two intertidal positions, and 4, the high water line) along four orthogonal foreshore transects (A to D) of Saunton Sands (Fig. 1). At each location, surface sediment was collected to a depth of 2 cm (Chubarenko et al., 2018; Costello and Ebert, 2020) and within a 10 cm by 10 cm stainless steel quadrat using a stainless steel spoon, with samples transferred to and stored in a series of 5 cm-diameter by 7 cm-high, screw-capped aluminium containers.

Because of constraints on access, transects could not be continued directly into the dunes. Here, therefore, eight sediment samples (E1 to E8) were taken as above at unvegetated locations of the fore dunes and hind dunes where entry was possible and permissible (and between beach transects B and C, and C and D) within 500 m from the backshore of the beach (Fig. 1).

2.3. Sample preparation and density separation

With the container lids loosened, samples were dried in an oven at 40 °C for up to a week. Large items of debris (mainly vegetative and in the dune samples) were manually removed using stainless-steel tweezers before samples were weighed on a Sartorius ME215P balance.

The approach for isolating MPs was similar to that described by Coppock et al. (2017). Thus, approximately 50 g of each dried sediment sample was added to a custom-built, clear, ~ 400 mL (250 mm high, internal diameter ~ 4.3 cm) polyvinyl chloride (PVC) column, fitted with flexi-PVC tubing at about 5 cm from the base and 10 cm from the top and fixed to a square PVC base-plate. About 300 mL of zinc chloride solution, prepared by dissolution of 98 % + anhydrous $ZnCl_2$ (Thermo Scientific) in distilled deionised water and with a measured specific gravity of ~1.50, was added to each tube, before the sediment was thoroughly stirred with a stainless-steel rod. The inner surfaces of the tubes in the headspace were washed with $ZnCl_2$ solution to remove any adherent material and the contents left overnight. Material floating and suspended at or near the surface was carefully decanted through the upper flexi tube, along with $ZnCl_2$ solution used to subsequently wash the resulting headspace surfaces, before being vacuum-filtered through individual 47-mm diameter Whatman 541 filter papers (pore size = 22 μm) housed in a clamped, glass filtration kit (Keene and Turner, 2023). Filters were transferred to foil-covered aluminium trays and dried in the oven at 40 °C for about 30 min.

2.4. Identification and classification of microplastics

Filters were inspected under a Nikon SMZ800 or Leica S9i stereo-microscope at a magnification of 55 X with the aid of stainless-steel tweezers and microplastics were identified according to methods and criteria outlined by MERI (2019). Specifically, particles that exhibited flexibility, homogeneity in colour and equal thickness throughout, with no organic or cellular structure evident were assumed to be microplastic. Suspected microplastics were photographed with a scale bar using an Olympus SC30 camera with Olympus Stream software (Nikon SMZ800) or Leica LASX imaging software (Leica S9i) and were further classified according to shape (fibre, fragment, pellet), colour and size (diameter or length; < 1 mm versus >1 mm, and with a size limit of detection of 30 to 50 μm depending on shape). All particles considered were subsequently transferred to numbered cover slips with the aid of tweezers or the wetted tip of a sable 000 paint brush.

2.5. FTIR analysis

The polymeric makeup of about 20 % of suspected microplastics, encompassing all transects (including the dunes) and shapes, and ranging in size from about 200 to 1000 μm, was determined by Fourier transform-infrared (FTIR) spectroscopy. Individually, particles were relocated from the cover slips to a 2 mm-diameter Specac DC2 diamond compression cell using stainless steel tweezers or a wetted paint brush. Here, they were flattened before being transferred to a Bruker Vertex 70 μ-FTIR spectrometer connected to a Hyperion 100 microscope. Absorbance spectra were acquired through 32 scans between wavenumbers of 4000 cm^{-1} and 600 cm^{-1} using Bruker OPUS 7.5 software. Sample spectra were compared with spectra from a variety of Bruker and third-party polymer and material libraries (including Bruker ATR-FTIR polymer vol. 1 to 4, BPAD S01, MERCK S01 and KMIW ATR-IR), with a hit quality >65 % accepted as a positive identification.

2.6. Cleanliness and quality control

With the exception of the PVC settling columns, samples were in contact with metal or glass surfaces only. Laboratory operators wore white laboratory coats constructed of 50 % cotton-50 % polyester and non-latex nitrile gloves, and before filters were manipulated or inspected or individual particles were transferred to or from coverslips, local working surfaces were cleaned with 70 % ethanol. Filters arising from the direct filtration of $ZnCl_2$ solution ($n = 4$) and the processing of $ZnCl_2$ solution in the absence of sediment ($n = 4$) revealed no particulate contamination from the reagents but an average of two fibres resulting from the microplastic separation procedure.

2.7. Sediment characterisation

For particle size analysis, approximately 2 to 3 g of sediment was mixed with a small amount of distilled water in a 50 mL glass beaker and transferred to a 10 mL glass test tube. Size distribution was measured by laser diffraction using a Malvern Mastersizer 2000 coupled with a Hydro 2000G dispersion module. Specifically, the instrument returned volume-weighted mean particle diameter (μm), mean circularity (μm), and the percentages of very coarse (1000 to 2000 μm), coarse (500 to 1000 μm), medium (250 to 500 μm), fine (125 to 250 μm) and very fine (63 to 125 μm) sand.

The elemental content of sediment was determined by X-ray fluorescence (XRF) spectrometry. Here, about 5 g of each sample were transferred to individual polyethylene XRF sample cups (Chemplex series 1400; 21-mm internal diameter, 20 mm depth) that were collar-sealed with 3.6 μm SpectraCertified Mylar polyester film. Measurements were made using a Niton XL3t GOLDD+ XRF spectrometer housed in a laboratory test stand for 60 s in a mining-soils mode (Turner and Taylor, 2018). Analysis of a certified reference material (stream sediment GBW07301a; Institute of Geophysical and Geochemical Exploration, Langfang, China) returned elemental concentrations that were within 5 to 20 % of certified values.

2.8. Statistics

Statistical analysis was performed using the open-source programming software, RStudio (2022.07.2 Build 576), and Microsoft Excel 2016. Differences were determined using either an independent (two-sample) *t*-test or a Mann-Whitney *U* test, or one-way ANOVA or a Kruskal-Wallis test, after variables had been tested for normality using the Shapiro-Wilk normality test. Pearson's moment correlation analysis was performed with an implicit assumption of normal distributions.

3. Results

3.1. Sediment characteristics

Fig. 2 summarises the grain size distribution and circularity of surface sediment from the four beach transects (A to D) and the dune system (E). Here and elsewhere, data displayed a combination of normal and non-normal distributions but the mean is always shown as a measure of central tendency.

Mean grain circularity was greatest in the dunes and statistically greater than circularity at beach transects A and C, and (volume-weighted) mean grain size was significantly greater (with a greater proportion of coarse sand and a smaller proportion of fine sand) along the most northerly beach transect (A). There were no significant differences in mean grain size or circularity with respect to tidal position on the beach although we note that very coarse sand was only present in the intertidal zone. Within the dunes, we note a significantly higher particle diameter and greater proportion of coarser sand towards the south (E1 to E3; 283 ± 9.3 μm and 5.44 ± 0.89 %, respectively) compared with more northerly locations (E4 to E8; 200 ± 9.4 μm and 0.01 ± 0.02 %, respectively).

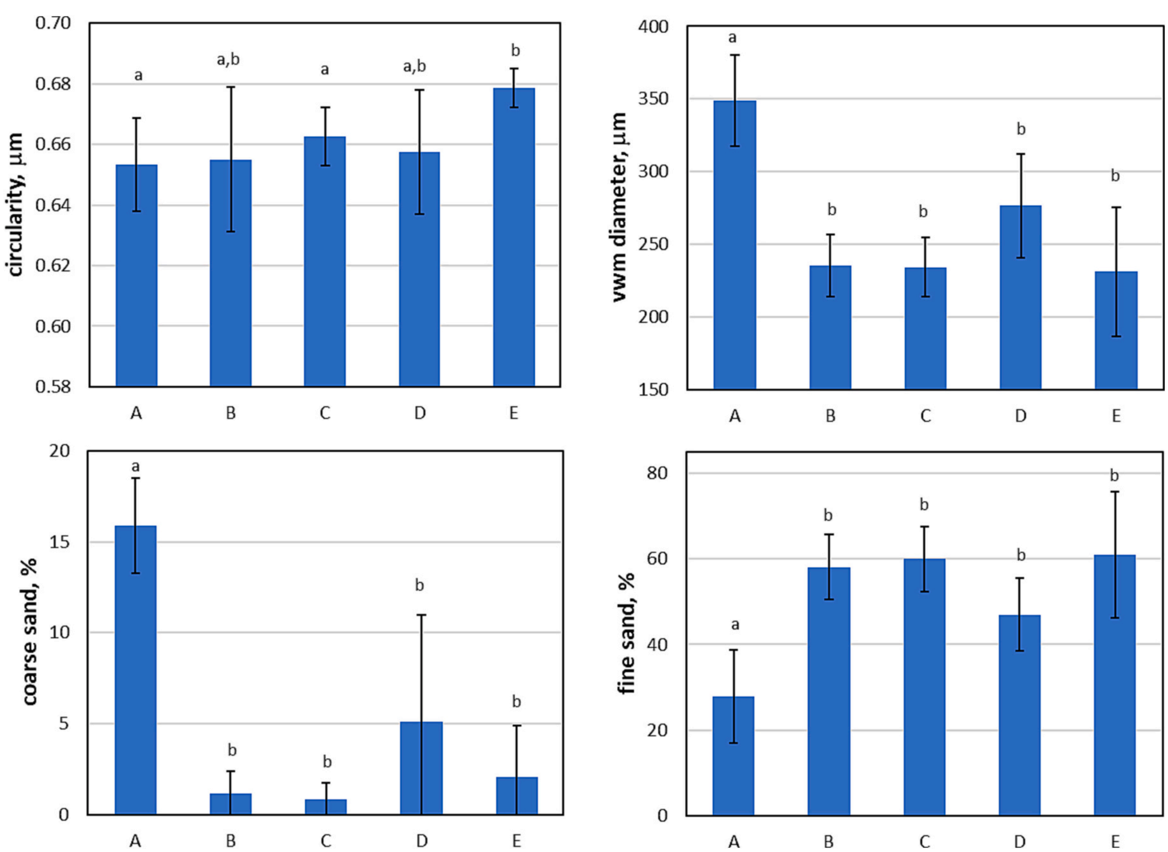

Fig. 2. A summary of grain size distribution and shape (as circularity) of sediments among the four beach transects (A to D) and in the dunes (E) (vwm = volume-weighted mean). Errors are standard deviations about the mean of four (A to D) or eight (E) samples and different, lower-case letters above bars denote significant differences ($p < 0.05$) according to one-way ANOVA or a Kruskal-Wallis test (coarse sand only).

Fig. 3 shows the concentrations of selected elements as proxies for anthropogenic influence (As), marine biological cycling (Ba), calcium carbonate and the presence of shell material (Ca), and grain size and surface area (Fe). Among these elements, there were significant differences in mean concentrations of As and Ba between two beach transects (B and D and A and D, respectively) and the median concentration of Ca (used for statistical testing based on a non-normal distribution and more widely dispersed data) was significantly greater in the dunal system than in beach transect A. No significant differences were observed in elemental concentrations with respect to tidal position.

3.2. Number, concentration and characteristics of microplastics

A total of 332 suspected MPs were identified microscopically from the surface samples collected in the present study, with examples illustrated in Fig. 4. The majority of suspected MPs were fibres ($n = 323$), with the remainder largely consisting of clear or translucent fragments. Numbers normalised on a dry sediment weight basis are summarised in Fig. 6. Concentrations in individual samples varied from about 40 MP kg^{-1} at C1 to 560 MP kg^{-1} within the dunes but in the majority of cases ($n = 16$) concentrations ranged from 160 to 450 MP kg^{-1}. MP concentrations were variable within the beach transects and the dunal system and no statistical differences were observed between the different transects and the dune samples. However, there was a significantly greater concentration of MPs in the northern dune samples (E4 to E8) compared with those to the south (E1 to E3). A breakdown of MPs by size (as percentage < 1 mm) and colour, also shown in Fig. 6, revealed that distributions were similar, with the majority of MPs < 1 mm in length and colours dominated by black and blue, throughout the region.

3.3. Relationships between microplastic concentration and sediment granulometry and composition

Correlation analysis was performed among the variables reported above (and for all samples); namely, concentrations of MPs by number and size in dry sediment, sediment diameter, circularity and size distribution, and As, Ba, Ca and Fe contents. Statistically significant positive and negative relationships were found between various sediment size fractions, and significant positive relationships were observed between Fe and the percentage of very fine sand, Ca and the percentage of coarse sand, Ba and the percentage of fine sand, and As and Fe concentrations in sediment. However, the only significant relationship involving MPs and sediment was a positive correlation between concentration in sediment on a dry weight basis and the percentage of very fine sand (Fig. 5). A closer inspection of the data by sample location revealed that the strength of the relationship was strongest in the dunes and beach transect C.

3.4. Composition of suspected microplastics

FTIR returned a positive identification for 64 out of 70 suspected MPs analysed, with the results shown in Table 1 and sample and matching library spectra exemplified in Fig. 7. The majority of particles were identified as cellulosic, with a closer examination of the spectra (and in particular the 3000 to 3700 cm^{-1} region) and microscopic images suggesting that the semi-synthetic material, rayon, was most important but that cotton fibres were also present. The remaining particles identified were synthetic and petroleum-based and limited to four polymer types. Regardless of their construction, a common and significant

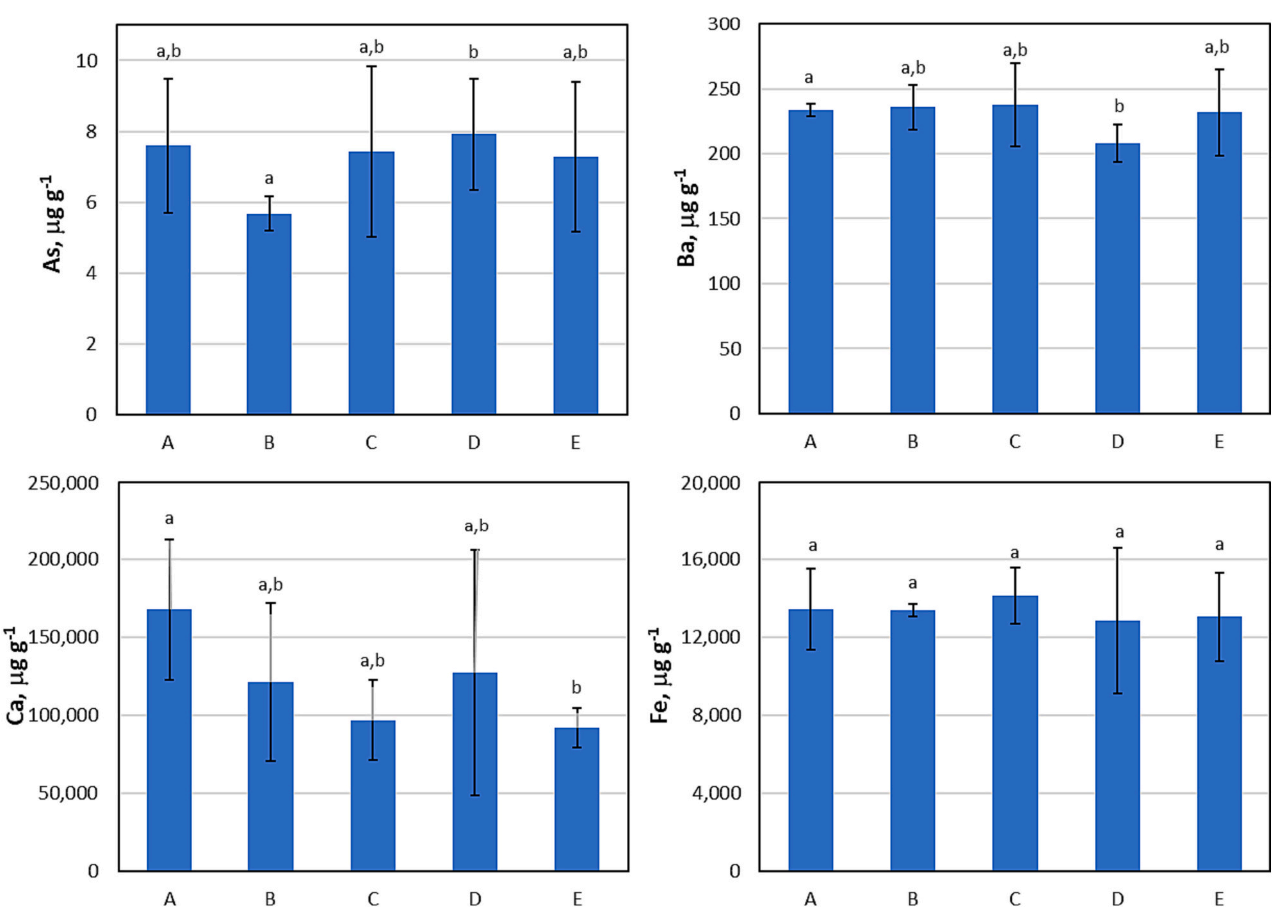

Fig. 3. A summary of the concentrations of selected elements in sediments among the four beach transects (A to D) and in the dunes (E). Errors are standard deviations about the mean of four (A to D) or eight (E) samples and different, lower-case letters above bars denote significant differences ($p < 0.05$) according to one-way ANOVA or a Kruskal-Wallis test (Ca only).

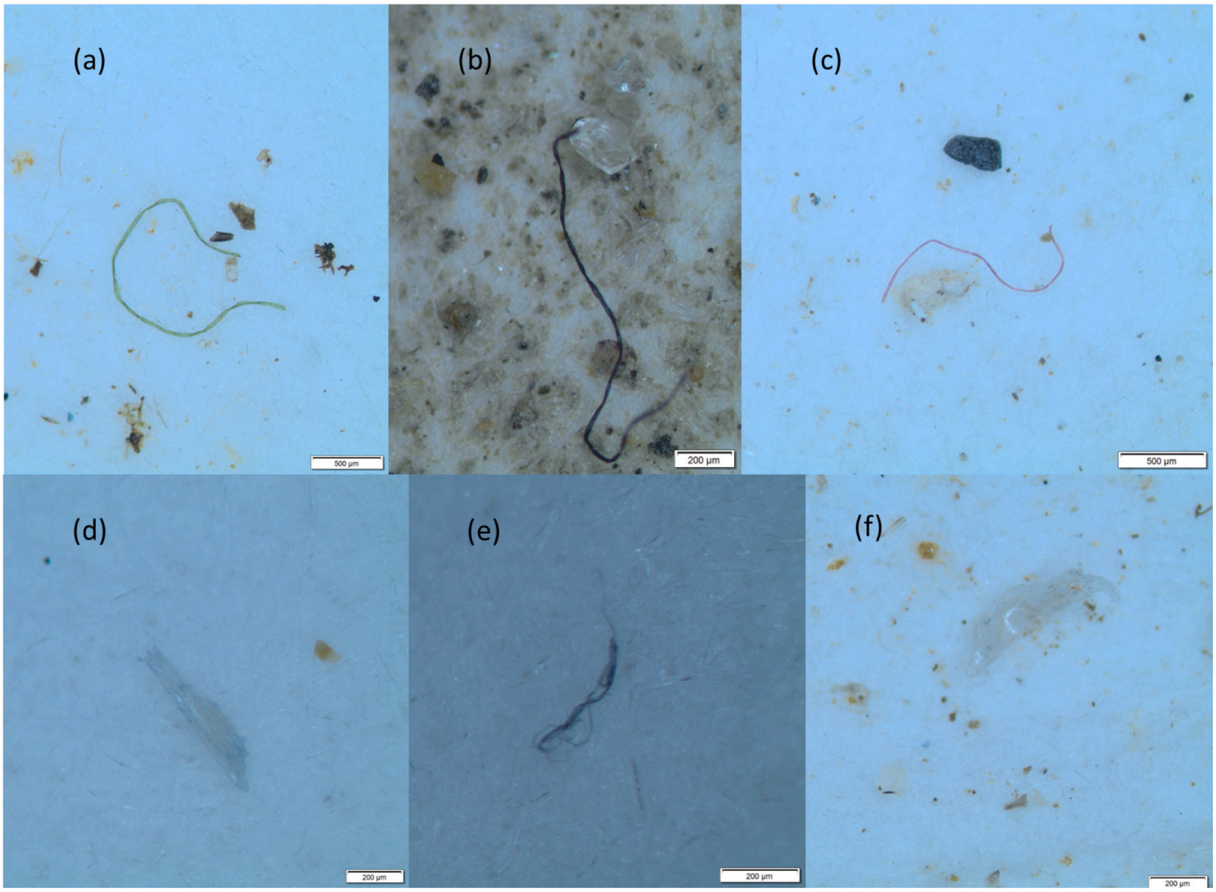

Fig. 4. A selection of fibrous and non-fibrous suspected MPs from the beach transects and dunes that had been identified and characterised microscopically. Scale bars are 200 μm (b, d, e and f) or 500 μm (a and c).

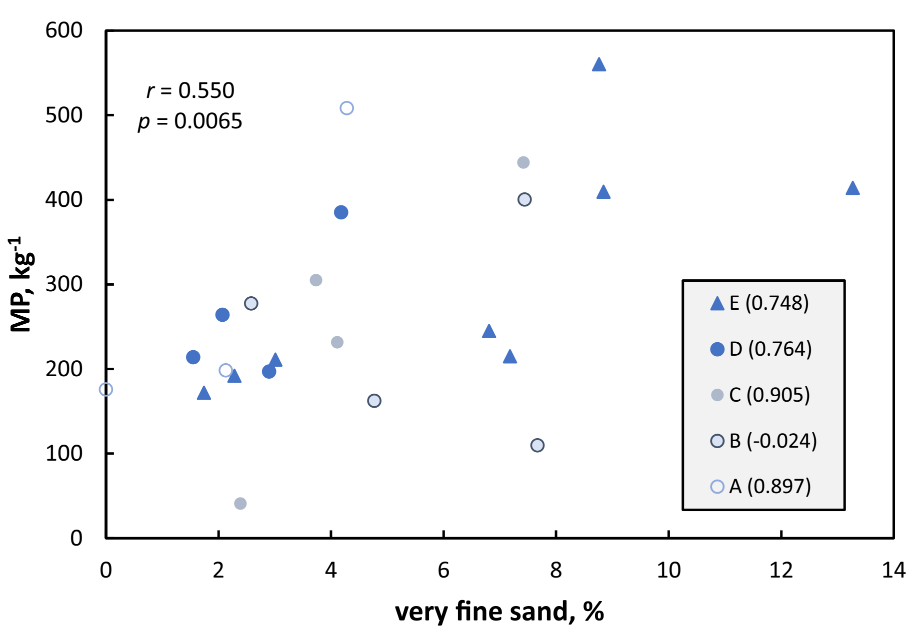

Fig. 5. Concentrations of suspected MPs per kg of dry sediment versus the percentage of very fine sand in the beach transects and dunes. Correlation coefficients are shown for the whole dataset and, in parentheses, for individual transects and the dune system.

characteristic of all suspected MPs identified by FTIR is that their densities, also shown in Table 1 based on indicative values, exceed that of seawater (about 1.02 to 1.03 g cm^{-3}).

Despite the presence of some natural, albeit anthropogenically-derived, fibres (i.e., cotton; Sillanpää and Sainio, 2017), for the purposes of the discussion below and any comparisons with the literature,

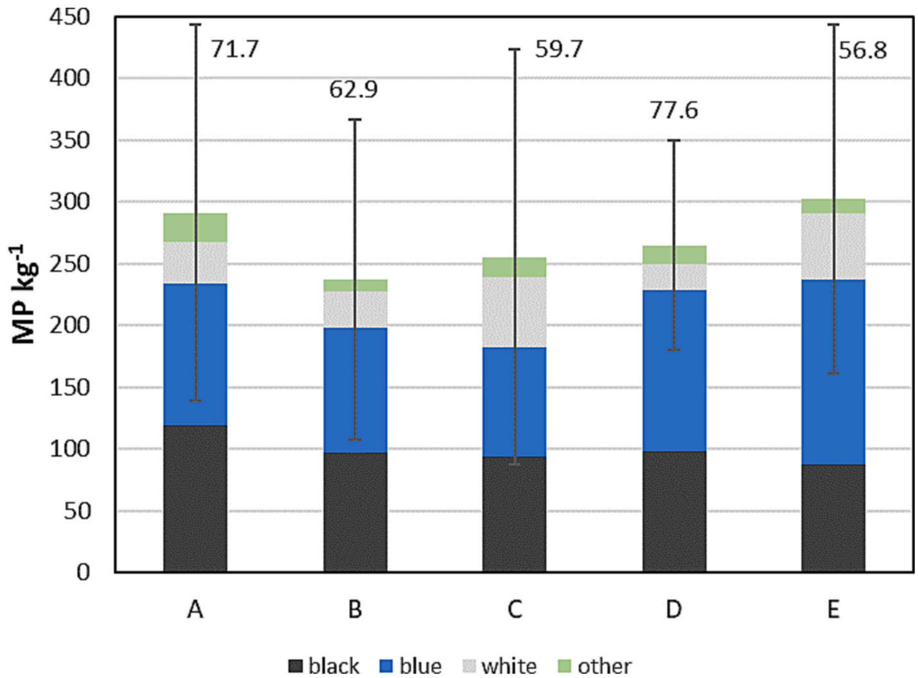

Fig. 6. Concentrations of suspected MPs per kg of dry sediment (and according to colour) for the four beach transects (A to D) and in the dunes (E). Errors are standard deviations about the mean of four (A to D) or eight (E) samples and numbers annotated are mean percentages of MPs that were < 1 mm in size. No significant differences in concentration or size were observed according to one-way ANOVA or Kruskal-Wallis tests.

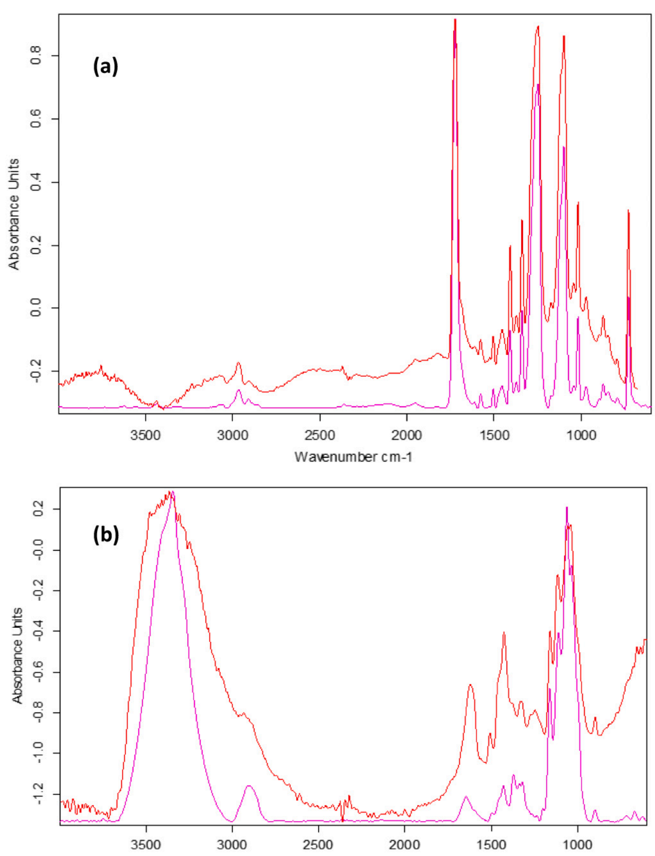

Fig. 7. Sample (red) and matching library (purple) FTIR spectra for two suspected MP fibres retrieved from the beach transects: (a) polyester and (b) rayon.

Table 1
Polymeric composition of suspected MPs (by number) from the beach transects (A to D) and dune system (E), along with indicative densities of polymers identified.

Polymer	A,B,C,D	E	Density, g cm^{-3}
Cellulosic (mainly rayon)	34	17	1.52
Acrylic	6	1	1.18
Polyester	2	1	1.38
Polyvinyl chloride	1	1	1.38
Polyamide	1	0	1.14

we hereafter refer to MPs rather than suspected MPs. We also implicitly assume, therefore, that particles unidentified by FTIR (because of a low hit rate or lacking a suitable match in the spectral databases) are polymeric based on the visual criteria employed during microscopic analysis.

4. Discussion

4.1. Comparison with previous studies of beached MPs

Making quantitative comparisons of the concentrations and distributions of MPs reported in the present study with published data can be problematic because different sampling strategies and means of MP processing are adopted (Besley et al., 2017; Coppock et al., 2017). For instance, sampling is often restricted to the high-water line where MPs are presumed to be deposited (Lots et al., 2017; Piñon-Colin et al., 2018; Jaubet et al., 2021; Wilson et al., 2021; Banik et al., 2022), while many studies employ a solution to isolate MPs whose density is lower than that of at least one polymer shown in Table 1 (Stolte et al., 2015; Piñon-Colin et al., 2018; Pervez et al., 2020; Jaubet et al., 2021). Nevertheless, MP concentrations determined for surface samples at Saunton Sands are the same order of magnitude as concentrations reported in many other beach studies (Chubarenko et al., 2018; Piñon-Colin et al., 2018; Kumar and Varghese, 2021; Yaranel et al., 2021; Ben-Haddad et al., 2022), and the colours and principal (fibrous) shape encountered at Saunton are consistent with characteristics observed elsewhere (Nel and Froneman, 2015; Lots et al., 2017; Pervez et al., 2020; Banik et al., 2022).

Despite the wide occurrence of MPs in beach sediment, however, relatively little is known about the processes and mechanisms governing their transport and deposition. To this end, it has been recommended that studies both address the zonation of beached MPs and factor in sediment granulometry (Vermeiren et al., 2021). Where zonation has been considered, little if any differences in MP concentrations are observed (Leibezeit and Dubaish, 2012; Besley et al., 2017). However, where granulometry has been determined, a relationship between MP concentration and some measure of beach sediment grain size is reported when either data from multiple, regional beaches are pooled (Leibezeit and Dubaish, 2012; Jaubet et al., 2021; Marquez Mendes et al., 2021; Ben-Haddad et al., 2022; Rangel-Buitrago et al., 2022) or multiple measurements from different areas of a single beach are considered (Banik et al., 2022).

4.2. Sources of sediment and MPs at the study site

The principal differences in grain size and composition of surface samples collected from Saunton Sands and Braunton Burrows are a distinctly coarser fraction of grains towards the northern end of the beach and a more circular population in the dunal system. The former may be attributed to the addition of new sediment to the beach from the cliffs of Saunton Down Headland and selective transport by littoral drift away from this source (Greenwood, 1978). The latter is explained by the wind being able to pick up and transport rounder grains relative to more angular particles and, although this is often associated with a lower calcareous (shell) content and higher heavy mineral content (Shepard and Young, 1961), with the exception of Ca there is no evidence of such elemental sorting in the present study. Aside from these differences, our results suggest that wave-laid and wind-laid deposits are broadly similar in terms of granulometry and composition.

MPs have very different (and more distal) primary sources to coastal sediment. The relatively thin fibres observed here, for example, are likely derived from consumer textiles for clothing and furnishings rather than fishing gear (where filaments of higher strengths and denier counts are generally employed; Ramos, 1999; Turner, 2017) and are emitted to the atmosphere and aquatic environment during their production, use, laundering and disposal (Murphy et al., 2016; Almroth et al., 2017). With onshore waves and prevailing winds and no clear gradient in MP characteristics or abundance away from the Taw-Torridge Estuary (with 135 sewage treatment works in its combined catchment; South West Water, 2022), the main source of MPs at the study site would appear to be offshore, and delivered via both the ocean and dry and wet atmospheric fallout. Similar signatures of MPs in terms of size, colour, shape and polymeric composition throughout the region are consistent with a single, diffuse source and little or no sorting after fallout or deposition.

4.3. Mechanisms of MP deposition in the foreshore

With respect to the foreshore, and aside from ubiquitous atmospheric fallout, the nature, extent and location of MP deposition (i.e., wavelaid deposition) will, to a significant extent, be controlled by local energy conditions and particle settling velocity. The settling velocity of fibres, with a high aspect ratio, depends on a number of factors related to particle characteristics and settling orientation but empirical measurements of various polyester fibres (density = 1.38 g cm^{-3}) of 1 to 4 mm in length range from 0.1 to 0.55 mm s^{-1} in freshwater (Nguyen et al., 2022). This range is equivalent to Stokesian settling velocities of spherical quartz particles (density = 2.65 g cm^{-3}) of about 10 to 25 μm in diameter, or below the size range measured for sand in the present study. It is possible that MP deposition is accelerated through turbulent vortices or interactions with denser sand particles or other debris (Ruiz et al., 2004; Maggi, 2013). However, observations made in controlled laboratory studies by Waldschläger and Schüttrumpf (2020) suggest that MPs, and in particular those of a fibrous nature, are preferentially retained by the interstitial spaces between sand grains. The latter effect may also explain why thicker fibres derived from fishing activities and more rounded pellets or angular secondary fragments were not observed at our study site, and may partly account for the relationship between MP concentration in the foreshore and the percentage of very fine sediment. Thus, as well as reflecting low energy depositional environments, very fine sediments might be associated with interstitial spaces that are highly favourable for the entrapment of microfibres.

4.4. MP transport to the dunes

One of the key findings of the present study was similar concentrations and characteristics (colour, size and polymeric makeup) of MPs in surface samples from the dunal system and beach transects, in spite of different modes of sand transport (wind versus wave, respectively). Higher accumulations of unspecified or larger MPs (as pellets) and other plastic items of litter have been reported in dunes compared with the foreshore, partly because particle trapping is facilitated by dune morphology and vegetation (Leibezeit and Dubaish, 2012; Moreira et al., 2016; Calderisi et al., 2023; Corti et al., 2023), but little information exists on fibrous MPs in this respect.

Particles, including MPs and other light debris, are transferred from the foreshore to the dunes by consistent onshore winds when intertidal foreshore sediment dries out, and, specifically, via saltation and in suspension (Baas and Sherman, 2006; Houser, 2009; Costello and Ebert, 2020). Because of their relatively low densities and aerodynamic diameters, fibrous MPs are entrained more readily from the foreshore than fine sand particles, at least in the absence of appreciable moisture in the surface layer (Abbasi et al., 2023). Greater landward transport of fibrous MPs and the persistent and direct atmospheric deposition of MPs in the dunal system (compared with a foreshore that is subject to cyclical inundation and the constraints of MP settlement and erosive forces) suggests a greater propensity for fibrous MP accumulation in the dunes. However, MP fibres are also predicted to be more readily entrained and redistributed landwards or exported from the dunal system than sand. Similar MP signatures in the foreshore and dunes can, therefore, be explained by an equilibrium in which their greater, relative rate of input to the dunes is balanced by their greater, relative rate of export.

4.5. General implications

The present study is one of very few that has considered the zonal distribution of MPs on a beach and, as far as we are aware, the first to extend zonation to a dunal system. Despite different modes of particle transport between the foreshore and dunes, and a potentially significant source of MPs from an estuarine complex to the south, MP concentrations and characteristics (size, shape, polymer type and density) are similar in surface sands throughout the region. This observation is consistent with a general, diffuse (and offshore) source of MPs, rather than specific sources related to treated wastewater, commercial fishing and tourism, for example, and the propensity of MPs, and in particular those of a fibrous nature, to undergo relatively rapid, long-range atmospheric transport (Abbasi et al., 2021; Evangeliou et al., 2022). Agreement with concentrations, distributions and characteristics of beached MPs in the literature also suggests that the atmosphere may act as the most important (secondary) source of MPs in the marine setting in many cases rather than local, point sources.

Despite similar distributions of MPs throughout the study site, and in accordance with previous studies, there is evidence of an inverse relationship between MP concentration and sediment grain size. This may be related to both depositional similarities between very fine sand and fibrous MPs and the control of grain size distribution on the interstitial space able to trap MPs. What is less clear, however, is whether MPs that are too small to evade detection by standard microscopy are captured by coastal sediment. On the one hand, evidence suggests an increase in particle number with decreasing size in the marine environment (Zheng et al., 2021), but on the other hand interstitial spaces might be too large to accommodate smaller fibres.

With respect to coastal sand dunes, our findings suggest that, unlike the case for meso- and macroplastic litter (Turner et al., 2021; Andriolo and Gonçalves, 2022), they do not act as net accumulators of MPs, nor do they appear to retard their landward transport. Rather, they appear to act as non-selective, transient reservoirs of (mainly) fibrous MPs derived from the adjacent foreshore or through direct atmospheric deposition. Clearly, confirmation of these assertions and a better understanding of the role of sand dunes in capturing, storing and transferring MPs more generally would require further study, including field experiments and measurements of (dated) depth distributions.

CRediT authorship contribution statement

Rachael J. Anderson: Conceptualization, Investigation, Formal analysis, Writing – original draft. **Andrew Turner:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

We thank Christie Estates for granting permission to carry out sampling at Braunton Burrows and Michaela Parish for assistance with sampling. We are grateful to Jodie Fisher, Jamie Quinn, Billy Simmonds and Rich Hartley (all University of Plymouth) for technical assistance.

References

Abbasi, S., Turner, A., Hoseini, M., Amiri, H., 2021. Microplastics in the Lut and Kavir Deserts, Iran. Environ. Sci. Technol. 55, 5993–6000.
Abbasi, S., Rezaei, M., Mina, M., Sameni, A., Oleszczuk, P., Turner, A., Ritsema, C., 2023. Entrainment and horizontal atmospheric transport of microplastics from soil. Chemosphere 322, 138150.
Abesser, C., Clarke, D., Hughes, A.G., Robins, N.S., 2017. Modelling small groundwater systems: experiences from the Braunton burrows and Ainsdale coastal dune systems, UK. J. Coast. Conserv. 21, 595–614.
Almroth, B.M.C., Åström, L., Roslund, S., Petersson, H., Johansson, M., Persson, N.K., 2017. Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. Environ. Sci. Pollut. Res. 25, 1191–1199.
Andriolo, U., Gonçalves, G., 2022. Is coastal erosion a source of marine litter pollution? Evidence of coastal dunes being a reservoir of plastics. Mar. Pollut. Bull. 174, 113307.
Baas, A.C.W., Sherman, D.J., 2006. Spatiotemporal variability of aeolian sand transport in a coastal dune environment. J. Coast. Res. 22, 1198–1205.
Banik, P., Hossain, M.B., Nur, A.A.U., Choudhury, T.R., Liba, S.I., Yu, J., Noman, M.A., Sun, J., 2022. Microplastics in sediment of Kuakata Beach, Bangladesh: occurrence, spatial distribution, and risk assessment. Front. Mar. Sci. 9, 860989.
Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. B364, 1985–1998.
Ben-Haddad, M., Abelouah, M.R., Hajji, S., Rangel-Buitrago, N., Hamadi, F., Alla, A.A., 2022. Microplastics pollution in sediments of Moroccan urban beaches: the Taghazout coast as a case study. Mar. Pollut. Bull. 180, 113765.
Besley, A., Vijver, M.G., Behrens, P., Bosker, T., 2017. A standardized method for sampling and extraction methods for quantifying microplastics in beach sand. Mar. Pollut. Bull. 114, 77–83.
Bridson, J.H., Patel, M., Lewis, A., Gaw, S., Parker, K., 2020. Microplastic contamination in Auckland (New Zealand) beach sediments. Mar. Pollut. Bull. 151, 110867.
Calderisi, G., Cogoni, D., Loni, A., Fenu, G., 2023. Difference between invasive alien and native vegetation in trapping beach litter: a focus on a typical sandy beach of W-Mediterranean Basin. Mar. Pollut. Bull. 192, 115065.
Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L., 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng. 8, 3494–3511.
Chubarenko, I.P., Esiukova, E.E., Bagaev, A.V., Bagaeva, M.A., Grave, A.N., 2018. Three-dimensional distribution of anthropogenic microparticles in the body of sandy beaches. Sci. Total Environ. 628-629, 1340–1351.
Coppock, R.L., Cole, M., Lindeque, P.K., Queirós, A.M., Galloway, T.S., 2017. A small-scale, portable method for extracting microplastics from marine sediments. Environ. Pollut. 230, 829–837.
Corti, A., La Nasa, J., Biale, G., Ceccarini, A., Manariti, A., Petri, F., Modugno, F., Castelvetro, V., 2023. Microplastic pollution in the sediments of interconnected lakebed, seabed, and seashore aquatic environments: polymer-specific total mass through the multianalytical "PISA" procedure. Anal. Bioanal. Chem. 415, 2921–2936.
Costello, J.D., Ebert, J.R., 2020. Microplastic pollutants in the coastal dunes of Lake Erie and Lake Ontario. J. Great Lakes Res. 46, 1754–1760.
Esiukova, E., 2017. Plastic pollution on the Baltic beaches of Kaliningrad region, Russia. Mar. Pollut. Bull. 114, 1072–1080.
Evangeliou, N., Tichý, O., Eckhardt, S., Zwaaftink, C.G., Brahney, J., 2022. Sources and fate of atmospheric microplastics revealed from inverse and dispersion modelling: from global emissions to deposition. J. Hazard. Mater. 432, 128585.
Greenwood, B., 1978. Spatial variability of texture over a beach-dune complex, North Devon, England. Sediment. Geol. 21, 27–44.
Hale, R.C., Seeley, M.E., La Guardia, M.J., Mai, L., Zeng, E.Y., 2020. A global perspective on microplastics. J. Geophys. Res. Oceans 125, e2018JC014719.
Hallin, C., Almström, B., Larson, M., Hanson, H., 2019. Longshore transport variability of beach face grain size: implications for dune evolution. J. Coast. Res. 35, 751–764.
Houser, C., 2009. Synchronization of transport and supply in beach-dune interaction. Prog. Phys. Geogr. 33, 733–746.
Jaubet, M.L., Hines, E., Elías, R., Garaffo, G.V., 2021. Factors driving the abundance and distribution of microplastics on sandy beaches in a Southwest Atlantic seaside resort. Mar. Environ. Res. 171, 105472.
Keene, J., Turner, A., 2023. Microplastics in coastal urban sediments: discrepancies in concentration and character revealed by different approaches to sample processing. Sci. Total Environ. 865, 161140.
Kumar, A.S., Varghese, G.K., 2021. Microplastic pollution of Calicut beach – contributing factors and possible impacts. Mar. Pollut. Bull. 169, 112492.
Leibezeit, G., Dubaish, F., 2012. Microplastics in beaches of the East Frisian Islands Spiekeroog and Kachelotplate. Bull. Environ. Contam. Toxicol. 89, 213–217.
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.
Maggi, F., 2013. The settling velocity of mineral, biomineral, and biological particles and aggregates in water. J. Geophys. Res. Oceans 118, 2118–2132.
Marquez Mendes, A., Golden, N., Bermejo, R., Morrison, L., 2021. Distribution and abundance of microplastics in coastal sediments depends on grain size and distance from sources. Mar. Pollut. Bull. 172, 112802.
Mathalon, A., Hill, P., 2014. Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. Mar. Pollut. Bull. 81, 69–79.
MERI, 2019. Guide to Microplastic Identification. Marine and Environmental. Research Institute, Blue Hill, Maine.
Moreira, F.T., Bathazar-Silva, D., Barbosa, L., Turra, A., 2016. Revealing accumulation zones of plastic pellets in sandy beaches. Environ. Pollut. 218, 313–321.
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, 5800–5808.
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.
Nguyen, T.H., Kieu-Le, T.C., Tang, F.H., Maggi, F., 2022. Controlling factors of microplastic fibre settling through a water column. Sci. Total Environ. 838, 156011.
Pervez, R., Wang, Y., Mahmood, Q., Jattack, Z., 2020. Stereomicroscopic and Fourier transform infrared (FTIR) spectroscopic characterization of the abundance, distribution and composition of microplastics in the beaches of Qingdao, China. Anal. Lett. 53, 2960–2977.
Pethick, J., 2007. The Taw-Torridge Estuaries: Geomorphology and Management. Report to Taw-Torridge Estuary Officers Group. North Devon Biosphere. Available at: https://www.northdevonbiosphere.org.uk/uploads/1/5/4/4/15448192/taw_torridge_and_approaches_coastal_evolution_study.pdf [Accessed: 16 April 2023].
Piñon-Colin, T.J., Rodriguez-Jimenez, R., Pastrana-Corral, M.A., Rogel-Hernandez, E., Wakida, F.T., 2018. Microplastics on sandy beaches of the Baja California peninsula, Mexico. Mar. Pollut. Bull. 131, 63–71.
Prata, J.C., Reis, V., Paço, A., Martins, P., Cruz, A., da Costa, J.P., Duarte, A.C., Rocha-Santos, T., 2020. Effects of spatial and seasonal factors on the characteristics and carbonyl index of (micro)plastics in a sandy beach in Aveiro, Portugal. Sci. Total Environ. 709, 135892.
Rahman, S.M.A., Robin, G.S., Momotaj, M., Uddin, J., Siddique, M.A.M., 2020. Occurrence and spatial distribution of microplastics in beach sediments of Cox's Bazar, Bangladesh. Mar. Pollut. Bull. 160, 111587.
Ramos, J.M.L., 1999. Chemical and Physical Properties of Synthetic Fibres most Commonly Used in Fishing Gear, with Reference to their Use in Cape Verde Fisheries. United Nations Fisheries Training Programme, Reykjavik.
Rangel-Buitrago, N., Rodríguez, R.D.B., Moreno, J.B., Ochoa, F.L., Neal, W., 2022. Are sediment textural parameters an "influencer" of microplastics presence in beach environments? Mar. Pollut. Bull. 184, 114125.
Ruiz, J., Macías, D., Peters, F., 2004. Turbulence increases the average settling velocity of phytoplankton cells. Proc. Nat. Acad. Sci. 101, 17720–17724.

Sarre, R.D., 1988. Evaluation of aeolian sand transport equations using intertidal zone measurements, Saunton Sands, England. Sedimentology 35, 671–679.
Schröder, K., Kossel, E., Lenz, M., 2021. Microplastic abundance in beach sediments of the Kiel Fjord, Western Baltic Sea. Environ. Sci. Pollut. Res. 28, 26515–26528.
Scott, T., Russell, P., Masselink, G., Wooler, A., Short, A., 2007. Beach rescue statistics and their relation to nearshore morphology and hazards: a case study for Southwest England. J. Coast. Res. 50, 1–6.
Shepard, F.P., Young, R., 1961. Distinguishing between beach and dune sands. J. Sediment. Petrol. 31, 196–214.
Sillanpää, M., Sainio, P., 2017. Release of polyester and cotton fibers from textiles in machine washings. Environ. Sci. Pollut. Res. 24, 19313–19321.
South West Water, 2022. Our Emerging Drainage and Wastewater Management Plan: Level 2, Draft Plan, Taw-Torridge. South West Water, Exeter, UK.
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.
Tsukada, E., Fernandes, E., Vidal, C., Salla, R.F., 2021. Beach morphodynamics and its relationship with the deposition of plastic particles: a preliminary study in southeastern Brazil. Mar. Pollut. Bull. 172, 112809.
Turner, A., 2017. In situ elemental characterisation of marine microplastics by portable XRF. Mar. Pollut. Bull. 124, 286–291.
Turner, A., Taylor, A., 2018. On site determination of trace metals in estuarine sediments by field-portable-XRF. Talanta 190, 498–506.
Turner, A., Amos, S.L., Williams, T., 2021. Coastal dunes as a sink and secondary source of marine plastics: a study at Perran Beach, Southwest England. Mar. Pollut. Bull. 173, 113133.
Vermeiren, P., Lercari, D., Muñoz, C.C., Ikejima, K., Celentano, E., Jorge-Romero, G., Defeo, O., 2021. Sediment grain size determines microplastic exposure landscapes for sandy beach macroinfauna. Environ. Pollut. 286, 117308.
Waldschläger, K., Schüttrumpf, H., 2020. Infiltration behavior of microplastic particles with different densities, sizes, and shapes - from glass spheres to natural sediments. Environ. Sci. Technol. 54, 9366–9373.
Wilson, D.R., Godley, B.J., Haggar, G.L., Santillo, D., Sheen, K.L., 2021. The influence of depositional environment on the abundance of microplastic pollution on beaches in the Bristol Channel, UK. Mar. Pollut. Bull. 164, 111997.
Yaranel, N.A., Subbiah, S., Mohanty, K., 2021. Distribution and characterization of microplastics in beach sediments from Karnataka (India) coastal environments. Mar. Pollut. Bull. 169, 112550.
Zheng, Y., Li, J., Sun, C., Cao, W., Wang, M., Jiang, F., Ju, P., 2021. Comparative study of three sampling methods for microplastics analysis in seawater. Sci. Total Environ. 765, 144495.