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Coastal dunes as a sink and secondary source of marine plastics: A study at Perran Beach, southwest England

Turner, Andrew

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3 **Coastal dunes as a sink and secondary source of marine plastics: A**
4 **study at Perran Beach, southwest England**
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6 Andrew Turner*¹, Sara L. Amos¹ and Tracey Williams²

7
8 ¹School of Geography, Earth and Environmental Sciences,

9 University of Plymouth

10 Drake Circus

11 Plymouth PL4 8AA, UK

12 aturner@plymouth.ac.uk

13
14 ²The Lost At Sea Project

15 Old Bridge House

16 Porth Bean Road

17 Newquay TR7 3LU, UK

18
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Abstract

Plastic food packaging and containers ($n=263$) have been retrieved from the scarped foredunes at Perran Beach, SW England, following a storm surge. Samples displayed evidence of cracking, scratching, discolouration, staining and hydroxyl and carbonyl stretching, but legible text indicating their origin, dates of manufacture/expiration, packaging codes and logos, coupled with online product searches, allowed 25 food packets and 87 containers to be aged. Estimates of food packaging age spanned a 43-year period (1975-2018), with a median age of 25 years, while estimates for containers spanned 57 years (1962-2019), with a median age of 19 years. Plastic derived from local littering and offshore sources appears to be trapped within the foredunes for years to decades and subsequently released as “fresh” beach litter following surges sufficient to effect scarping. Dunal systems may act as significant reservoirs of historical plastics and play a critical role in their recycling and retention in the coastal zone.

Keywords: coastal dunes; historical plastic litter; food packaging; bottles; storm surge

1. Introduction

The coastal environment is a hotspot for the accumulation of litter because it is subject to a plethora of both land-based and marine sources of waste (Moore et al., 2001; Schulz et al., 2015; Nelms et al., 2020). The foreshores and backshores of sandy beaches in particular have been the focus of many scientific surveys, temporal and spatial monitoring programmes and clean-up operations, largely because of the adverse aesthetic and economic impacts of plastic litter on tourism and recreation (Ballance et al., 2000; Krelling et al., 2017; Arabi and Nahman, 2020), but additionally, and for sanitary or medical waste, direct risks to human health (Galgani et al., 2010).

Despite being integral components and morphological structures of the beach profile, dune complexes have received far less attention in respect of littering. Moreover, studies thus far have reported only on litter lying at or near the dune surface, with the following observations and inferences (Poeta et al., 2014; Rangel-Buitrago et al., 2018; Šilc et al., 2018; Andrioli et al., 2020; Andrioli et al., 2021; Mo et al., 2021). Thus, tourism appears to be the largest contributor to the surficial dunal litter pool and plastic is the most common type of material. Litter is more abundant on the foredunes (closest to the backshore) than on the secondary dunes or upper beach, an effect that can be attributed to the transport of low density litter from the beach by onshore winds and the entrapment of material within foredunes by vegetation. Organised cleaning of beaches, coupled with the lack of systematic cleaning across the dunes may also exaggerate this gradient.

Foredunes are particularly dynamic features that act as a significant sink and secondary source of sediment and that are highly susceptible to erosion, overwash and scarping during storm surges (Pye and Blott, 2008, Nordstrom, 2014). It is hypothesised, therefore, that foredunes also act as a dynamic reservoir and regulator of litter in the coastal zone, and in particular litter like plastic that is pervasive and persistent. To this end, we sample plastic litter within the foredunes backing a large sandy beach in southwest England where wind, wave climate and sediment transport, accumulation and erosion are routinely monitored. We select plastic from distinctly different sources (in situ littering and material derived, directly or indirectly, from offshore) that is exposed immediately after foredunes have undergone scarping and examine samples for visible, microscopic and chemical indicators of age, origin and weathering. More generally, the role of dunal systems in storing and supplying plastic and the potential timescales involved in these processes are addressed.

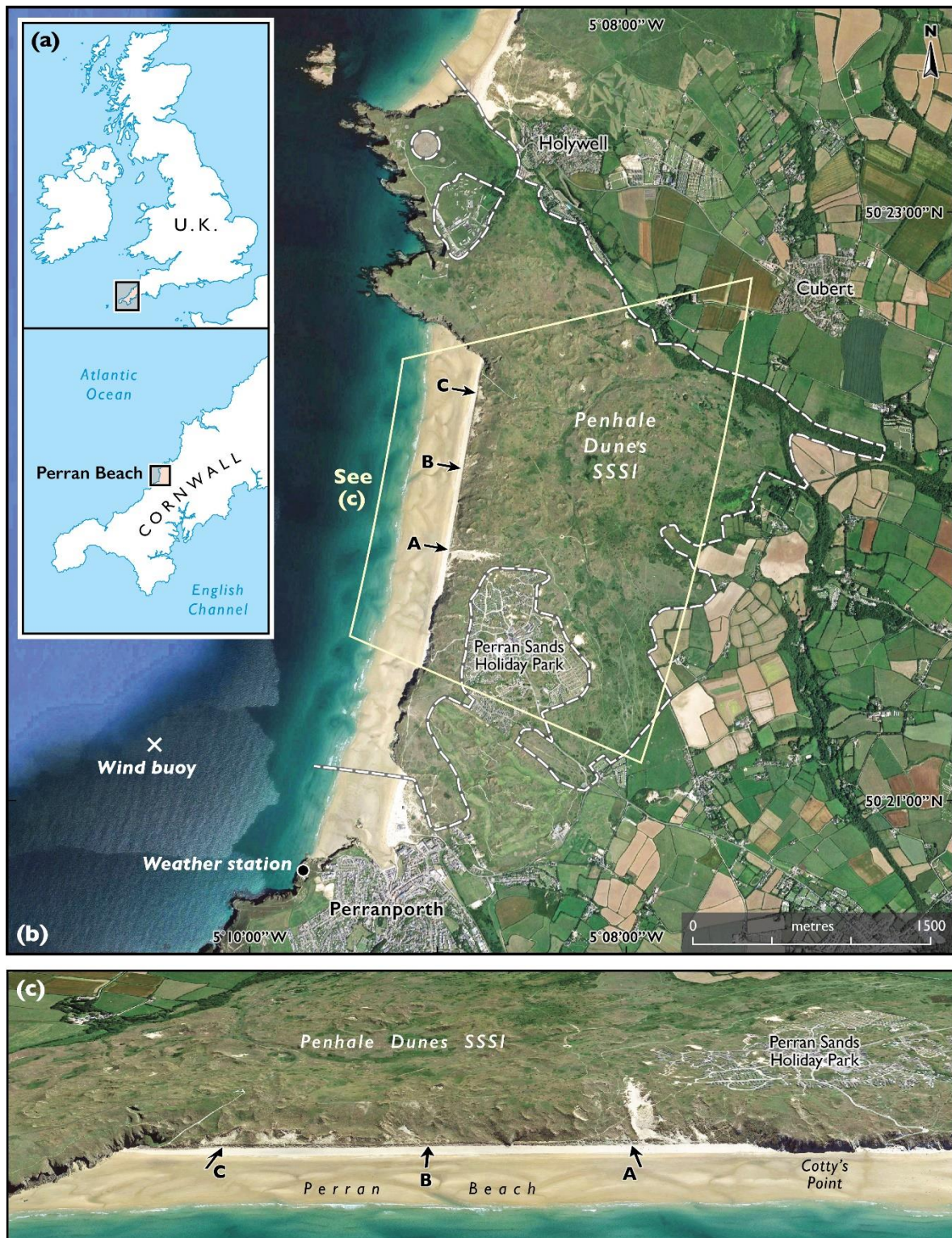
2. Methods

Study area

Perran Beach (or Perran Sands) is a WNW facing, 400-m wide, macrotidal beach on the north coast of Cornwall, UK (Figure 1). The dissipative beach is characterised by a relatively low gradient and fine-to-medium sand (average grain size = 0.3 mm), and wave climate is dominated by energetic Atlantic swell from the W and WNW (Masselink et al., 2015). Average significant wave height (H_s) and peak period (T_p) are 1.6 m and 10-11 s, respectively, but extreme storms can generate waves in excess of $H_s = 8$ m and $T_p = 19$ s (Valiente et al., 2020).

The beach is backed by sand dunes that are part of the Penhale Dunes Site of Special Scientific Interest and Special Area of Conservation (SAC) (Figure 1). The extensive calcareous dunal system of 622 hectares stretches 4 km along the coast and extends 1.6 km inland and has a maximum elevation of nearly 50 m (Joint Nature Conservation Committee, 2015). Large dune fields like this are thought to have begun forming 5-6,000 years ago due to the sediment released from retreating glaciers (Pye et al., 2007). An abandoned oratory and church indicate that accretion was occurring here until the 19th century, but presently most of the system consists of fixed secondary dune fields, with only dunes towards the seaward edge still active.

The beach and dunes are a popular tourist destination, with the town of Perranporth situated to the south, Perran Sands Holiday Park occupying part of the southern dunal system (Figure 1), and numerous interconnected footpaths crossing the complex. Beyond the SAC, land is primarily used for agriculture and cattle grazing (Rowland et al., 2017), while offshore the Bristol Channel is a busy shipping lane with an average of up to 100 vessels per week reported for the main route in 2017 (MMO, 2017).



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89 Figure 1. (a) Location of Perran Beach in the UK, (b) an aerial image the beach and Penhale Dunes, and (c)
 90 an elevated view of the beach and dunes from offshore. The area outlined by the broken line represents
 91 the extent of Penhale Dunes Site of Special Scientific Interest and Special Area of Conservation, and the
 92 black arrows show the locations of the beach-dune profiles (A), (B), and (C). Plastic litter was collected
 93 from the foredunes between transects (A) and (C).

Plymouth Coastal Observatory data

Since 2007, aerial imagery and weather, wave and topographic data have been collected along the SW coast of the UK by Plymouth Coastal Observatory (PCO) as part of the Southwest Strategic Regional Coastal Monitoring Programme (<https://southwest.coastalmonitoring.org/>). At the locations shown in Figure 1, wind speed and direction recorded between January 2011 and March 2020 were used to generate a wind rose and wave height and direction recorded between January 2007 and December 2019 were used to produce a wave rose. Recent foredune evolution in the region where litter was collected was evaluated by comparing real-time kinematic global positioning data (accurate to ± 30 mm) recorded during April 2007 or February 2008 and March 2020 at transects intersecting (A), (B) and (C) in Figure 1, and high-resolution (10 cm) aerial photographs of the region captured in May 2013 and May 2017.

Plastic collection and characterisation

Following a period of high spring tides and storms that had caused dune cliffing (9th to 15th March, 2020), beach litter that was protruding or had fallen from the seaward edge of the foredunes between transects (A) and (C) was collected by hand (Figure 2). Because of their abundance, ease of identification and, in most cases, visible signage, the focus of the present study was on containers and food packaging. Items were photographed and characterised according to size, shape, colour, legible printed or embossed codes, text or symbols, country of origin (and language used), original use, and evidence and degree of weathering, fouling or sand scratching. Information used to age samples included expiry dates, competition dates, UN packaging codes (required for the transportation of hazardous materials; GOV.UK, 2012), currency stated and the presence of a Resin Identification Code (introduced in 1988; ASTM, 2020). Internet searches of products, patents and trademarks (e.g., <https://www.gov.uk/search-for-trademark>) were employed to date brands, logos or other information used on products over specific time periods.



Figure 2. Plastic litter revealed within the scarped coastal foredunes at Perran Beach following the storm in March 2020.

Microscopy and infrared analysis

The weathering of selected containers and samples of food packaging was assessed by Fourier Transform Infrared (FTIR) spectrometry and scanning electron microscopy (SEM). For FTIR analysis, offcuts of a few mm in size were prepared using a stainless steel scalpel before being and cleaned with isopropyl alcohol. The outer and inner surfaces of each offcut were scanned sixteen times in the range 4000 to 400 cm^{-1} and at a resolution of 4 cm^{-1} using a Bruker Vertex 70 attenuated total reflection spectrometer. The outer and inner surface morphology of separate offcuts was examined using a JEOL JSM-6610 SEM operated with an accelerating voltage of 15 kV and in a low vacuum mode.

3. Results

3.1. Long-term wind and wave climate and changes in beach-dune profiles

Wind and wave roses derived from PCO data are shown for Perran Beach in Figure 3. Thus, between 2011 and 2020, average winds are dominated by strong WSW and W components, and lower wind speeds ($1\text{--}5\text{ m s}^{-1}$) are associated with southerly and easterly winds. Between 2007 and 2019, waves whose significant heights range from < 1 to $> 5\text{ m s}^{-1}$ are predominantly from the W and WNW.

During the week of plastic sampling from the foredunes, maximum wave height (H_m) and wind speed peaked at 7.9 m and 25 m s^{-1} , respectively. In the month preceding sampling, three storms surpassed the storm alert threshold where the wave height should, statistically, only be exceeded four times per year and conditions are strong enough to move significant volumes of sediment (PCO, 2020).

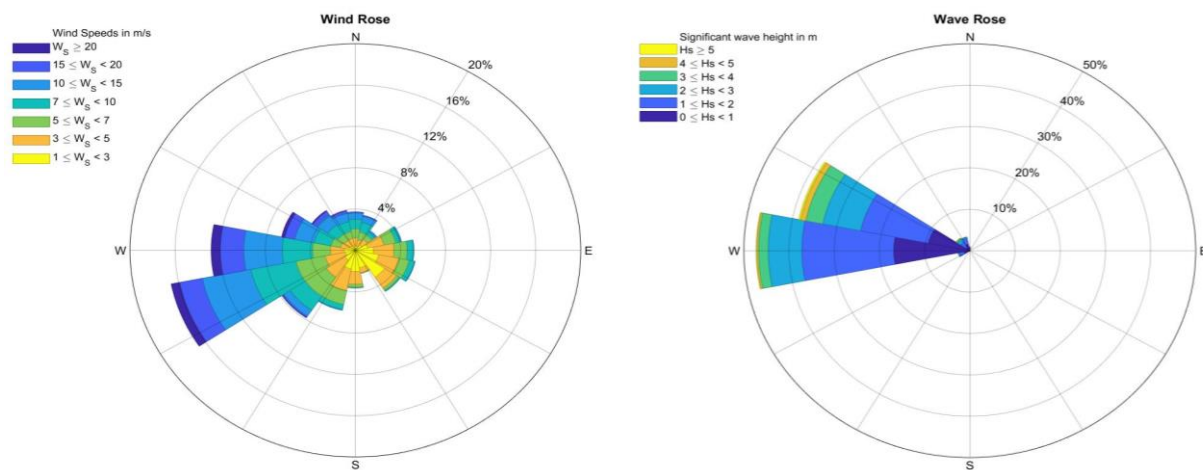


Figure 3. Roses showing average wind speed and direction and significant wave height and direction at Perran Beach, UK. Wind data collected between January 2011 and March 2020 and wave data collected between January 2007 and December 2019.

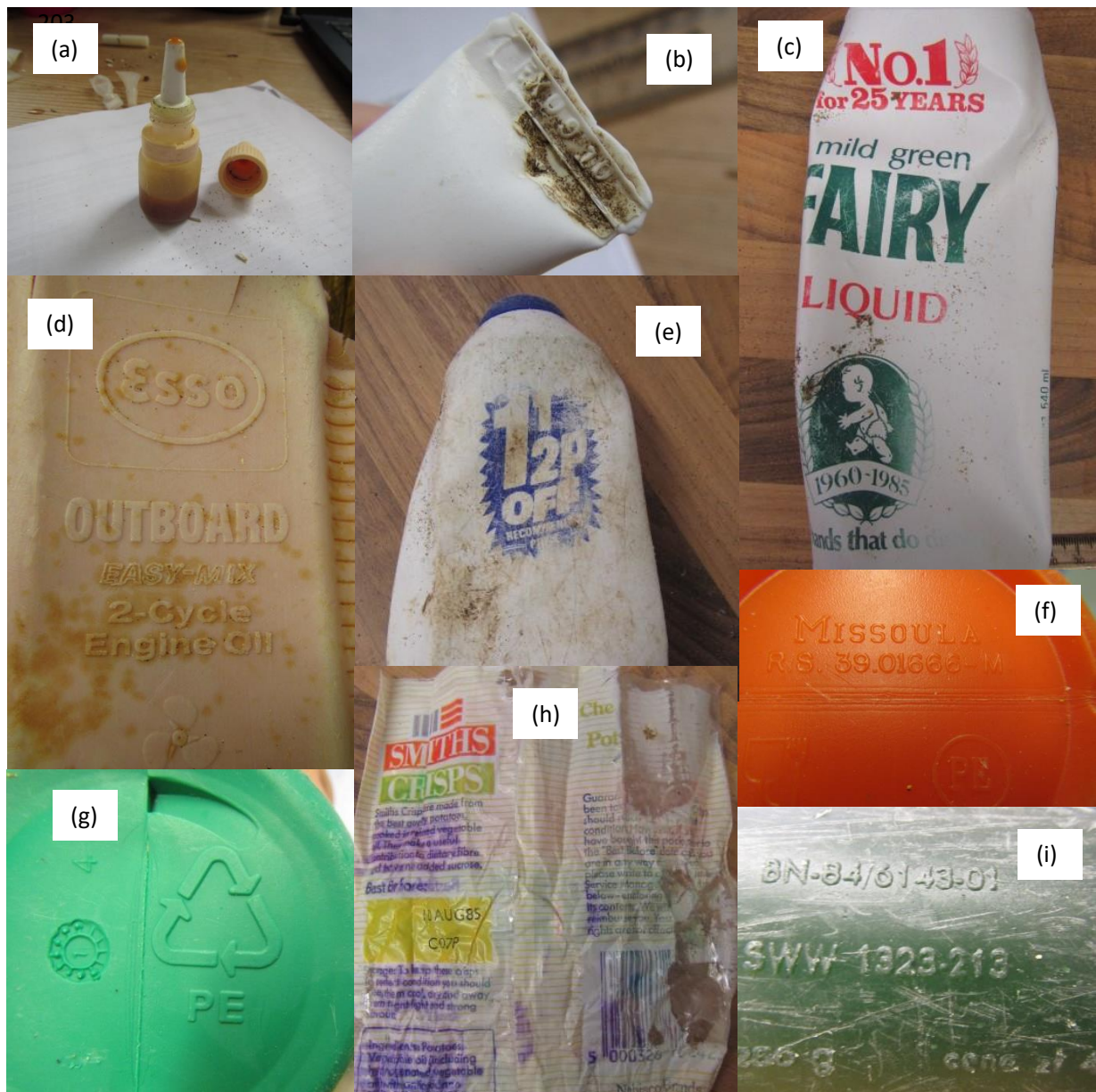
A comparison of beach-foredune profiles for 2007 or 2008 and 2020 revealed little net change in cross sectional area at location (A), but net losses of about 72 and 69 m^2 , respectively, or about 7 and 8% of total area or volume, respectively, at locations (B) and (C). A comparison of aerial images captured between 2013 and 2017 confirmed net erosion in the foredunes, with accompanying retreat of between 5 and 10 m .

3.2. Characteristics and ages of plastic litter

A total of 263 plastic items were retrieved from the scarped foredunes for further study, comprising 80 rigid and 156 flexible containers and 27 food wrappers (and exemplified in Figure 4). Containers consisted of cylindrical, conical and rectangular bottles, vials, tubes, ampoules and syringes ranging from 10 mL to 5 L in capacity that had been used for the storage or dispensing of drinks, food, cleaning products, solvents, oils, pharmaceuticals, cosmetics, glues and laboratory reagents, while food packaging was dominated by individual crisp packets ($n = 24$). The country of manufacture of the containers was ascertained in 52 cases, with 32 from Europe (including seven from the UK and Ireland and 24 from countries having an Atlantic, North Sea or Baltic coast), eleven from North America and nine from Asia, while all but one food wrapper was manufactured in the UK. Resin identification codes visible on 29 containers indicated the following distribution: polyethylene terephthalate = 5; high density polyethylene = 19; low density polyethylene = 3; polypropylene = 2.

All but two samples exhibited visible evidence of sand-scratching and about one third of the containers were discoloured on the outside (through colour-fading or yellowing). Food packaging was always folded or tied when sampled, with some tearing and fragmentation usually evident, whereas about one half of the containers revealed visible damage that ranged from denting and cracking to rust marks, oil stains and glue-like marks and, in one case, deformation by burning. Two rectangular bottles exhibited visible indications of biofouling; specifically, one displayed the residue of what appeared to be a goose barnacle while the other displayed a network of tube worm casts on one face. Caps or lids were present on about one half of the containers, with most threaded ones being readily unscrewed and all but two (metal caps) constructed of plastic. Unscrewing caps revealed that 46 containers had remains of their liquid (or, in one case, powdered) contents, whereas most containers without caps contained deposits of sand.

Figure 4: A selection of containers and a crisp packet sampled from the scarped foredunes at Perran Beach. (a) A dispensing bottle with part of its original contents remaining; (b) the end of a tube exhibiting oil-staining and revealing an expiry date; (c) a detergent bottle displaying an anniversary year; (d) a discoloured (faded) oil can with staining; (e) a table salt bottle advertising a discount of 1½ pence (½ pence was introduced in 1971 and withdrawn in 1984); (f) the base of a bottle constructed of polyethylene but pre-dating resin identification codes; (g) the base of a bottle constructed of polyethylene and embossed with a code; (h) a crisp packet with a best before date of August 1985; (i) product information on the side of a bottle exhibiting significant scratching.



A total of 87 containers and 25 food packets was aged according to the information written on the product or available online, and the distributions of their mean ages are shown in Figure 5. Here, the mean age is derived from either the precise year stated or established for the product or the average of two years spanning the time period of production (and with median uncertainties of ± 6 years and ± 1.5 years for containers and food packaging, respectively). An implicit assumption, therefore, is that the date of manufacture is representative of the time of disposal. Mean container age spanned a 57-year period (1962 to 2019), with a median value of 19 years, and mean food packaging age spanned a 43-year period (1975 to 2018), with a median value of 25 years. There was no clear correlation between age of sample and condition; rather, samples of a similar age usually exhibited variable integrities and degrees of scratching, staining and colour fading.

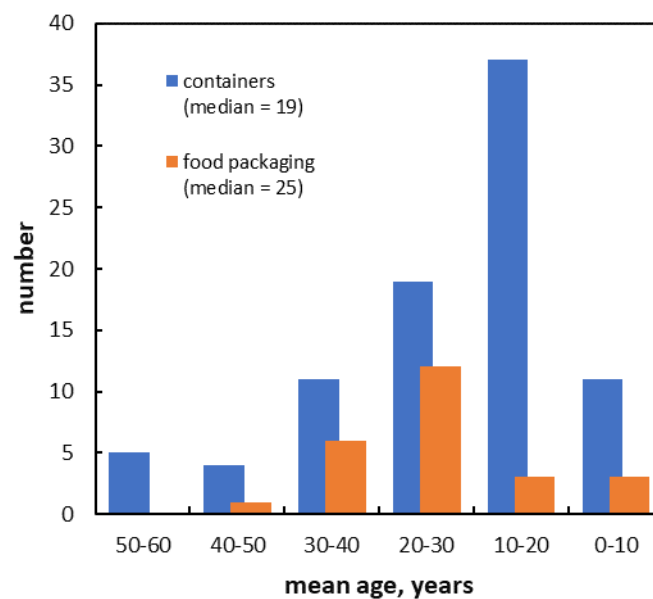


Figure 5: Frequency distributions the ages of containers and food packaging retrieved from the foredunes at Perran Beach.

3.3. Microscopic and chemical signs of plastic weathering

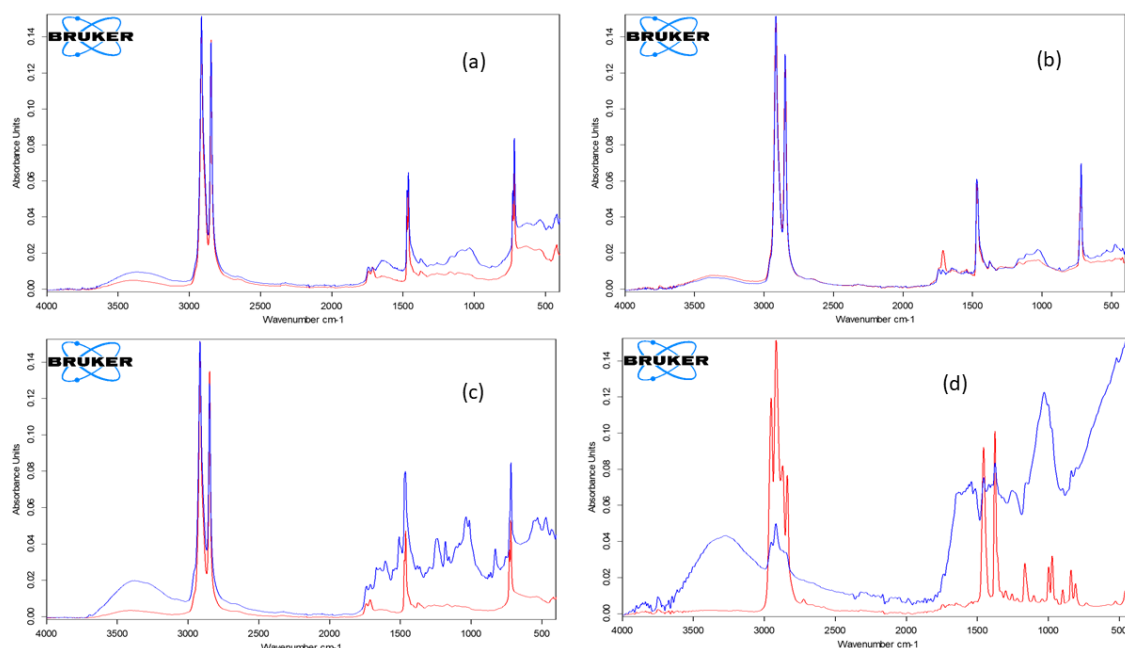


Figure 6: FTIR spectra of the inner and outer surfaces (in red and blue, respectively) of the body (a) and threaded lid wall (b) of a polyethylene bottle (illustrated in Figure 4e), (c) the body of a polyethylene bottle (illustrated in Figure 4c), and (d) a polypropylene crisp packet.

Figure 6 shows the FTIR spectra for the inner and outer surfaces of four components of three plastic samples retrieved from the scarpd foredunes at Perran Beach. Spectra in Figures 6a to 6c correspond to polyethylene and the spectra in Figure 6d corresponds to polypropylene. However, all sample spectra exhibit additional peaks or effects consistent with degradation, including a broad peak centred around 3300 cm^{-1} indicative of hydroxyl stretching absorption and a more distinctive peak at 1715 cm^{-1} indicative of carbonyl stretching. While the spectra in Figure 6b (the loosely fitting threaded lid of a bottle) are almost identical, reflecting almost equal exposure of the inner and outer surfaces, those in remaining samples exhibit clear differences that are most significant in Figure 6d (a crisp packet).

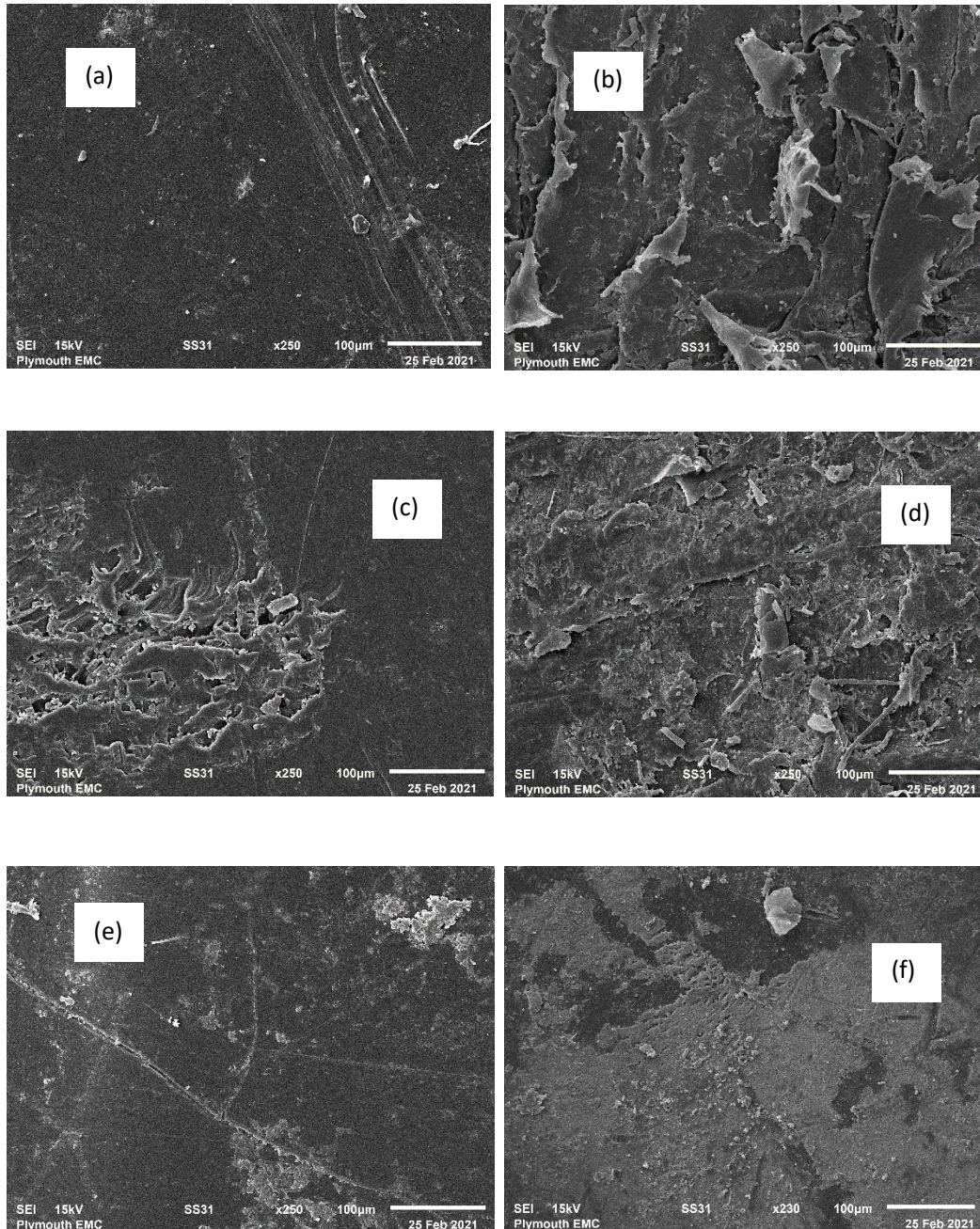


Figure 7: SEM images of the inner and outer surfaces of the samples referred to in Figures 6a (a and b; polyethylene bottle), 6c (c and d; polyethylene bottle) and 6d (e and f; polypropylene crisp packet).

Electron microscope images of the inner and outer surfaces of the three samples referred to in Figure 6 are presented in Figure 7. The inner surfaces of the samples exhibit some degradation (e.g., fractures, pits, fractures, scratches) and contamination by extraneous material. However, in each case the outer surface exhibits more substantive physical weathering, photo-oxidation and contamination, with greater roughness and irregularity and either extensive flaking (b and d) or chemical fouling (f).

4. Discussion

Studies that have reported litter visible at the surface of coastal dunes generally conclude that, because of the action of onshore winds and beach cleans, plastics are more abundant on the foredunes than on secondary dunes or the upper beach (Poeta et al., 2014; Rangel-Buitrago et al., 2018). The present investigation, however, appears to be the first to document the occurrence and storage of plastics within the dunal structure itself. Here, it is possible that the presence of plastic deposits modify the dunal environment and habitat. For instance, Carson et al. (2011) showed that the presence of plastic changes the physical properties of sand by increasing permeability and decreasing heat transfer, and suggested that these modifications may have consequent ecological and geochemical impacts. Menicagli et al. (2020) buried fragments of plastic bags in shifting Mediterranean dunes to a depth of 10 cm and demonstrated that plastic litter could impair dune plant development and survival and modify the long-term accretion and stability of dunal sediment.

Food packaging encountered within the foredunes at Perran Beach is likely to have local and in situ origins from littering (Tudor and Williams, 2004; do Sul et al., 2011). However, the wide uses and origins of the containers encountered, coupled with residues of chemical and biological fouling, suggest that the majority of these plastics are derived from offshore. Sources may be either direct, through spillages or loss at sea, for example, or indirect and a consequence of the poor management or littering of land-based plastics that are carried in to the marine environment via rivers and storm runoff. Poor, local management of waste in the present study was exemplified by a high incidence of syringes recovered from the foredunes that had been used for intra-mammary injections and that are believed to be derived from local dairy farms.

Westerly waves and onshore winds (Figure 3) transport containers and packaging to the back beach where, eventually, they become incorporated into the dunal system with beach sediment. It is unclear how far plastic is transported landwards but presumably this is dependent on the size and mass of the material, and whether the dunal system is undergoing landward migration and accretion or erosion. Under conditions sufficient to scarp the foredunes, including the storm surge in March 2020, plastic will be re-exposed, initially appearing as fresh inputs of litter to the back beach. Subsequently, the fate of

plastic may be similar to that of eroded sediment in being redistributed amongst the dunal system with wash-over, dune slumps and blowouts or removed and transported offshore (Abanades et al., 2014).

By analogy, Williams and Tudor (2001) demonstrated that much of the litter observed on a cobble beach in South Wales was buried and re-emerged or underwent “exhumation” following certain weather and tidal conditions. Exhumation resulted in what appeared to be fresh inputs of litter but effectively reflected the internal recycling of material. Williams and Tudor (2001) reported beach burial-exhumation events over periods of a few weeks, but in dunal systems our observations suggest that this process may take place over decadal timescales (up to at least 60 years). While the outer surfaces of the plastics in the present study demonstrate weathering, including photo-oxidation (Figures 7b and d) and presumably arising from exposure to sunlight while at sea or beached, burial is likely to shield material from further deterioration, or at least reduce the rate of degradation. Regardless of their age, for example, the containers retrieved from the foredunes of Perran Beach are mostly in reasonable to good condition, with many containing traces or significant quantities of their original products, while the printing on food packets dating back to the 1970s-80s was still clearly visible.

More generally, our observations support the assertions made by Lebreton et al. (2019) that the coastal zone acts to trap and filter marine litter and delay its transport to offshore oceanic waters. The authors refer to historical plastics being stranded and buried on beaches and settling and resurfacing (though buoyancy changes) in coastal waters, and suggest that the formation of microplastics occurs principally through the degradation of legacy macroplastics. Lebreton et al. (2019) also argue that a time lag of years to decades may account for discrepancies between estimates of plastic production and disposal and the mass of plastic floating in the ocean. In the present study, we provide direct evidence of the coastal zone retaining historical plastics and demonstrate that dunal systems have a critical role to play in storage, preservation and secondary supply.

As reservoirs and secondary sources of historic and legacy plastics, foredunes also bear similarities with poorly engineered or managed landfills along eroding coastlines (Pope et al., 2011; Brand and Spencer, 2019). Inputs of plastic may be gradual and continuous as cliffs or dunes retreat or erode, and as recent evidence suggests for the foredunes at Perran Beach (Figure 5), or acute and abrupt during more specific events, such as the storm encountered in March 2020. Significantly, inputs of plastic and other waste from both sources are predicted to increase in the future through climate change and anthropogenic activities. Regarding foredunes, coastal developments and defences, rising sea levels and increased storm activities are likely to enhance sediment erosion (Feagin et al., 2005; Nordstrom, 2014), while changes in temperature and precipitation are predicted to impact dune stability through shifts in dune vegetation and species composition (Nordstrom, 2014). The role of dunes and any consequences of climate change should also be factored into models of plastic transport and accumulation in the coastal zone (Critchell and Lambrechts, 2016).

332

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