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The role of kelp in the transport and fate of negatively buoyant marine plastic

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Abstract

We report observations of negatively buoyant plastics washed up on the shores of a beach in southwest England in association with deposits of kelp. Items retrieved included polyethylene terephthalate (PET) bottle fragments, polyvinyl chloride toys, electrical casings and construction plastics, polycarbonate goggles, carcass tags, pot rubber, fishing float fragments and PET textiles, with an upper estimate of 36 tonnes of plastic deposited during a single kelp beaching event. It appears that after kelp becomes detached from the bed during strong winds or tides or through senescence, biological debris becomes associated with or acts to transport benthic plastic landwards through entrainment, entanglement and rafting and, sometimes, attachment to the holdfast. Observations provide evidence of significant local and regional ecological transportation of plastics in temperate coastal environments that is not driven directly or solely by buoyancy, and afford a convenient, non-invasive insight into the makeup of plastic that is encountered in the benthic environment.

Keywords: plastic litter; kelp; Laminariales; beaches; density; coastal zone

1. Introduction

Subtidal kelps are fast-growing seaweeds that dominate wave-exposed rocky and boulder shores in temperate and sub-polar regions (Steneck et al., 2002; Hannah and Cowie, 2009). Kelp beds and forests support high primary and secondary productivity, provide habitats for a diversity of organisms, including commercially important species, and influence light levels, water flow and sedimentation rates (Smale et al., 2013).

Detachment of kelp from the substrata can be caused by strong tides or intense wave activity (Krumhansl and Scheibling, 2012; López et al., 2019), with detritus subsequently depositing in local intertidal zones, accumulating in embayments or rafting farther afield (Krumhansl and Scheibling, 2012; Waters and Craw, 2017). It has been estimated that about 2.5% of kelp biomass is cast on beaches where it is subject to fragmentation, dehydration, decomposition, consumption by detritivores and microbes and burial and, depending on tidal conditions, return offshore (Colombini et al., 2000; Colombini and Chelazzi, 2003).

Around the rocky reefs of the UK, subtidal kelps are dominated by brown macroalgae up to 3 m in length belonging to the Laminariales. These consist of a holdfast, stipe and divided or undivided blade, and include *Laminaria hyperborea*, *Laminaria digitata*, *Saccharina latissima*, *Sacchorhiza polyschides* and *Himanthalia elongate* (Hannah and Cowie, 2009; Burrows et al., 2014). Sublittoral kelp beds and forests are encountered from the low water mark to depths of up to 35 m along more than 19,000 km of the coastline (Smale et al., 2013), with the precise makeup of communities dependent on a variety of factors, such as wave exposure, depth, turbidity, temperature and the abundance and type of grazers (Burrows et al., 2014).

In the UK, large accumulations of beach-cast kelp are sometimes considered as a nuisance or a health hazard because of the proliferation of kelp flies, the emission of hydrogen sulphide gas by anaerobic bacteria and the retention of faecal pathogens (Hannah and Cowie, 2009). An additional environmental concern with beach-cast kelp, however, is its association with litter. This has been mentioned in the literature (Colombini et al., 2003; Hannah and Cowie, 2009) but, thus far, has not undergone investigation or characterisation. The purpose of this study, therefore, was to examine the nature and type of plastic litter washed up with beach-cast biogenic detritus in order to understand the origin and transport of this material and whether its behaviour in the littoral zone can be linked directly to the life-cycle of kelp. For sampling and observations, we selected an accessible location in southwest England where significant kelp deposits containing visible items and fragments of plastic regularly appear.

2. Methods

2.1. Study site

Porth Beach (~ 200 m in length and ~ 500 m wide) is a west-facing sandy cove in the county of Cornwall, UK, that is backed by rocky cliffs to the north and south and an elevated road and embankment to the east (Figure 1). The hydrography and climatology of the region have been reviewed by Uncles and Stephens (2007). Briefly, climate is cool temperate and winds are predominantly westerly and south-westerly, with frequent gales and storms and a significant wave height exceeded for 10% of the year of between 2.5 and 3 m. Tidal currents are considerable (the maximum tidal range at Porth is 8 m) and are able to mix the water column, resuspend silt and mobilise sand and gravel, with net sand transport in a south-westerly direction.

2.2. Observations and sampling

New deposits of kelp at Porth Beach were visited from September 2017 to October 2019 on sixteen occasions, with the evolution and life-span of some deposits ascertained by regular, and often daily, re-visitations. The date, tidal range and the maximum wind speed and average wind direction reported for the day on which each deposit was first observed are shown in Table 1. Also shown is the maximum daily wind speed and its average direction for the five days directly preceding each visit. Accumulations were accessed around low tide and plastic (including articles and fragments of synthetic rubber) visible to the naked eye at or just below the surface and at or near the full length of the seaward edge was retrieved and photographed. The type of polymer was noted where the resin identification code or any other relevant indicator was evident, and the buoyancy of selected washed-dried, whole objects or offcuts thereof in seawater at room temperature was noted in a clear container.

3. Results

Accumulations of kelp were variable in size and location in the intertidal zone but were most frequently encountered as mats of up to 400 m in length, several tens of m in width and up to 1 m in depth backed up along the northern, rocky boundary of the beach where incoming seawater meets freshwater issuing from a small stream (Figure 1). Detritus consisted of a heterogeneous assortment of the remains of whole individuals or components (blades, stipe or holdfast) of various *Laminaria*, with remnants of other intertidal and subtidal macroalgae, that were dominated by fucoids but with significant contributions from rhodophytes, and the soft coral, *Eunicella verrucosa*. The deposition of beach-cast kelp occurred in all seasons, over a range of tidal conditions and during or after winds originating from all directions and of variable maximum speeds (Table 1). Residence time on the beach ranged from a single tidal cycle for smaller accumulations to several days for larger deposits.

Figure 2 provides an indication of the relative abundance and variety of plastic that was typically visible at the surface of the kelp deposits. Overall, tens of thousands of pieces of plastic were retrieved from beach-cast kelp deposits for inspection, with over a thousand pieces sampled from single kelp accumulations that were visited on several occasions after successive tidal incursions had exposed or redistributed the litter. The size of plastic detected ranged from pot rubber strips up to 4 m in length to clothing buttons of a few mm in diameter, although we note that textiles and drying, perishing rubber are likely to represent significant, indirect and localised sources of much smaller microplastics and microfibers. Most rigid materials were also usually smooth and rounded and some contained fouled calcareous casts of keel worms and skeletons of bryozoans.

Table 2 categorises plastics according to usage or appearance, along with specific examples of items that were commonly observed either as whole objects or distinctive fragments. Also shown are the most likely sources and types of polymer for each category. Sources identified are littering on land, on beaches and at sea, spillages from ships transporting new products or material for recycling, abandonment of, for example, electronic and fishing gear at sea, accidental loss on beaches or at sea, and inputs of municipal waste to the marine environment via rivers or collapsing coastal landfill sites, and source attribution was based on the matrix scoring system given in Tudor and Williams (2004). Polymer type was ascertained from any relevant signage or was deduced from the materials most commonly employed in the manufacture of such items.

It was difficult to make quantitative assessments of plastic abundance or type because of the heterogeneity of litter, the tendency of smaller pieces to evade detection and settle through the deposits, entanglement of rope, line and rubber strips by kelp fragments, encapsulation of plastics below the surface by a thick matting of detritus, and specific interactions with kelp fragments (as described below). Nevertheless, based on material retrieved, the most common category of plastic on a number basis (and exceeding 50% of samples collected or visible in most cases) was food and drink, which was dominated by fragments of clear (or less frequently, coloured) polyethylene terephthalate (PET) bottles. The seaward edge of one large accumulation of beach-cast kelp that was re-visited on several occasions yielded over 1000 bottle pieces. Remains ranged from small pieces of the body or bottom to whole bottles with multiple punctures, and many fragments that included the shoulder and neck had the polyethylene cap and/or collar still attached and intact (Figure 3a). Also commonly encountered were plastics associated with fishing activities, and in particular fragments of colourful, impact-modified, moulded trawl, gill and net floats that appeared to be constructed of polystyrene or acrylonitrile butadiene styrene (ABS) (Figure 3b) and strips of rubber used on lobster pots (Figure 3c). Significant among remaining samples that were identifiable were swimming goggles and masks that are typically constructed of clear polycarbonate (Figure 3d), footwear, including beach shoes and remains of diving flippers made from polyester or rubber (Figure 3e), items or remains of polyester-based clothing (including beachwear; Figure 3f) and ABS- or polyvinyl chloride- (PVC-) based toys and sports equipment.

Distinctly lacking from our surveys, however, were low-density foamed plastics or polyolefin-based samples that are commonly found deposited around the high water strandline in the absence of beach-cast kelp. These include fragments of expanded and extruded polystyrene, and polyethylene and polypropylene-based pre-production pellets, pens, fishing beads, sand moulds, biobeads, rawl plugs, screw caps, cotton buds, straws, crate strapping, containers, cartridges, nozzles, bottle tops and packaging (Turner and Solman, 2016; Fok et al., 2017).

4. Discussion

The plastic samples retrieved from beach-cast kelp are a heterogeneous assortment of fragments and articles whose most important sources appear to be related to offshore fishing and littering and accidental loss, both at sea and onshore, with a smaller contribution arising from municipal waste. Samples also display a range of ages, with online searches of branded sunglasses, toothbrushes and toys and documented, regional spillages of cargo revealing a manufacturing period spanning more than sixty years. Significantly, however, from a physical perspective and as ascertained from visible indicators (including resin codes and calcareous fouling), typical polymer applications and empirical observations, the majority of samples appear to be constructed of plastics (and synthetic rubbers) that are denser than seawater. Exceptions here included polyolefin-based fishing ropes and beads visibly entangled with the biomass and low density plastics combined with denser materials as composites (e.g. polyethylene-aluminium laminate drink pouches).

In the marine environment, plastics whose inherent density, ρ, is lower than seawater ($\rho \sim 1.025$ g cm^{-3} for local coastal water) are predicted to exist in suspension or become beached along the strandline of the littoral zone, and include polyethylene and polypropylene ($\rho = 0.9$-1.0 g cm^{-3}) and foamed polystyrene ($\rho = < 0.1$ g cm^{-3}). In contrast, plastics whose density is greater than seawater, including polyester-PET ($\rho \sim 1.4$ g cm^{-3}), polycarbonate ($\rho \sim 1.2$ g cm^{-3}), PVC ($\rho \sim 1.4$ g cm^{-3}) and polyamide ($\rho \sim 1.2$ g cm^{-3}) are predicted to sink and settle on the seafloor. This simple concept of fractionation is generally borne out by observations of the presence and distribution of different types of plastics in marine settings (Munari et al., 2017; Erni-Cassola, 2019; Schonlau et al., 2020) and is a key component of plastic modelling in the coastal zone (Critchell and Lambrechts, 2016; Collins and Hermes, 2019). Contrary to these studies, however, our observations suggest that negatively buoyant plastics have been transported from the sub-littoral zone throughout a depth range supporting kelp beds and forests (up to 35 m; Smale et al., 2016) to the intertidal zone.

An upper-estimate of the mass of negatively buoyant plastic beached by a single casting of kelp at the location under study can be gained for a 400 m long, 15 m wide and 0.5 m deep deposit, similar to that shown in Figure 2. Thus, the volume of this deposit of 3000 m^3 is equivalent to a mass of 720,000 kg of material if a porosity (or air space) of 80% and a density of 1.2 g cm^{-3} are assumed. A relative abundance of plastic in the casting of 5% therefore yields a mass of plastic deposited of about 36,000 kg. This is comparable with remotely sensed estimates of low density (e.g. polystyrene foam and polyethylene) plastic debris on southeast Pacific beaches of a similar size to Porth that are known to act as accumulators of more buoyant oceanic debris (up to about 20,000 kg; Acuña-Ruz et al., 2018). Although our estimate is subject to uncertainties and temporal variation, it nevertheless illustrates that significant quantities of relatively dense plastic can be deposited on beaches in association with biogenic debris.

What is unclear is how such plastics become beach-cast with kelp, and whether kelp itself plays a direct role in the onshore transportation of plastic. Thus, it is possible that kelp and plastic are associated because both components are carried onshore with winds or currents of a suitably favourable speed or direction, with a pre-requisite of preceding conditions that are sufficiently turbulent to defoliate kelp and detach macroalgae from the substrate. In the current context, however, it is difficult to define the precise hydrographic or meteorological conditions from the data provided in Table 1. The transport of plastic could be facilitated by kelp that is either positively buoyant or negatively buoyant if it becomes entangled or entrained amongst the fragments, fronds and stipes of detached individuals. In some large species of kelp, the blades have greater buoyancy than the holdfasts because of the presence of gas bubbles or gas-filled pneumatocysts in the former (Thiel and Gutow, 2005) and, once detached, individuals could also act to increase drag on the seafloor and 'sweep' plastic items as bedload in the direction of travel. This process is akin to the physical abrasion of the understorey of communities of *L. digitata* that is engendered by the long flexible stipe and finger-like blades of the alga (Burrows et al., 2014).

By analogy, a recent study found that fibres of the seagrass, *Posidonia oceanica*, intertwined into balls (aegagropilae) and recovered from Mediterranean beaches had up to about 1500 (micro-) plastic items per kg of plant material and that the polymers identified were mainly negatively buoyant (including PET, polyamide and PVC; Sanchez-Vidal et al., 2021). It was suggested that shallow, coastal seagrass meadows are able to trap sinking plastics and subsequently package them into fibrous aggregates during the erosion of leaf sheafs, with resulting aegagropilae transported onshore during stormy conditions. As with kelp, seagrass appears to provide an ecosystem service by buffering, trapping and redistributing high density plastics in the coastal environment.

Our observations also reveal that kelp and plastic may interact with each other in situ more actively and persistently than physical intertwining and entrainment. For example, Figure 4 shows the threaded neck of a green-dyed PET bottle around the stipe of *L. digitata* and a golf ball (consisting of a thermoplastic cover over a solid rubber core) attached to the rhizoids of the holdfast of *L. hyperborea*. Experiments aimed at studying hatchery-reared macroalgal juveniles have demonstrated that certain plastics are suitable substrates for bioadhesion (Kerrison et al., 2019) but the latter of our observations appear to be the first to document thigmotactic attachment in the environment. The implications of this association are that kelp may be more prone to become detached or dislodged than when bound to a hard, rocky substrate, or, conversely, kelp may act to stabilise loosely deposited plastic on the seafloor.

Beach-cast kelp will eventually be removed from the intertidal zone through a variety of processes. For example, biomass will gradually disappear through degradation, consumption and, if buried by sand, anaerobic decomposition. Accumulations in some cases may also be disposed of by intervention (e.g. beach cleaning), but if deposited on or around a neap tide, spring tides are likely to resuspend unprocessed material in the water column or at the bed and return it offshore (Hannah and Cowie, 2009; Krumhansl and Scheibling, 2012). The rather short residence times of kelp on Porth beach (~ days) and lack of systematic intervention suggest that hydrodynamic processes are likely to be the most significant removal mechanism in the current study.

The subsequent transport and fate of plastic washed up with kelp may or may not be associated with that of the biomass. Thus, some smaller plastics could undergo burial with fragments of kelp while items becoming detached from assemblages may be dispersed elsewhere. For relatively dense kelps or components thereof (e.g. stipes), encapsulated plastic may retreat offshore with the biomass, while for relatively low density kelps or components thereof (e.g. blades), kelp and associated plastic may be resuspended by tidal action and rafted offshore. The latter mechanism affords a means by which plastic may be biologically dispersed and deposited far further from its point of origin than would be predicted from physical (i.e. density) considerations alone. By analogy, rafts of bull kelp, *Durvillaea antarctica*, retrieved from beaches of south-eastern New Zealand revealed geogenic debris on many holdfasts that had travelled more than 100 km in the Southern Ocean (Waters and Craw, 2017). Since deposition of kelp on beaches represents less than half of the amount that is eroded and detached at sea (Colombini and Chelazzi, 2003), rafting without beaching (for instance, during offshore winds) could represent a more significant, general dispersal mechanism of dense plastic.

In summary, negatively buoyant plastics, like bottle fragments, textiles, fishing gear and electronic housings, exhibit a physical association with beach-cast kelp in the coastal zone of rocky, temperate environments, highlighting an additional means by which coastal plants are able to interact with marine plastics (Poeta et al., 2017; Battisti et al., 2020; Sanchez-Vidal et al., 2021). Clearly, modelling of plastic behaviour in the coastal setting should not rely on density considerations alone but factor in onshore ecologically-assisted transport and dispersal of bedload. Beach-cast deposits of kelp also provide a convenient and accessible medium in which to study this type of plastic litter without incurring the costs and difficulties associated with in situ benthic surveys.

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Table 1: Dates on which beach-cast kelp deposits were first observed, along with the tidal range (from the first low water to first high water), maximum wind speed (v_{max}) and average wind direction. Also shown are the maximum daily wind speed reported for the five days previous to the date shown (v_{max} 5-day) along with the average direction of this wind.

accumulation	date	tidal range, m	v_{max}, mph	direction	v_{max} 5-day, mph	direction
1	28/09/2017	2.6	16	139	18.4	116
2	10/10/2017	5.8	16	232	19.6	296
3	27/02/2018	4.9	13	60	18	99
4	11/03/2018	2.1	17	101	22	261
5	27/03/2018	3.9	22	272	16	205
6	08/04/2018	2.5	9	19	21	306
7	16/09/2018	3.7	13	191	15	358
8	12/12/2018	4.5	16	124	38	268
9	26/12/2018	6.4	8	118	23	255
10	25/01/2019	6.6	15	292	26	328
11	10/02/2019	4.9	30	291	33	208
12	17/04/2019	6.1	16	102	29	117
13	30/05/2019	3.8	14	246	21	286
14	31/07/2019	5.9	15	270	28	306
15	26/08/2019	3.1	10	333	16	123
16	22/10/2019	2.9	8	126	21	245

Table 2: Categorisation, sources, examples and polymeric construction of plastics retrieved from beach-cast kelp deposits at Porth, Cornwall. Sources: Ab = abandoned; Li = litter; Lo = lost; Mu = municipal; Sp = spillage. Polymers: ABS = acrylonitrile butadiene styrene; CA = cellulose acetate; PA = polyamide; PC = polycarbonate; PE = polyethylene; PET = polyethylene terephthalate (polyester); PS = polystyrene; PMMA = Poly(methyl methacrylate); PVC = polyvinyl chloride; R = synthetic rubber.

Category	Sources	Examples	Polymers
Plumbing and construction	Mu,Sp	pipes, adaptors, hosing, seals, gaskets, nuts, bolts, screws, cable ties, hooks	PA, PC, PVC, R
Textiles	Ab,Lo,Sp	clothing, swimwear, carpet offcuts, parasols, bodyboard covers	PA, PET
Toys	Lo,Mu,Sp	figures, whistles, party toys, inflatables, Lego, dog toys	ABS, PVC
Maritime sports	Lo	surf board screws, diving fins, goggles, masks	PC, R
Electronic	Sp,Lo	cable-wire insulation, plug sockets, radio and computer casings, keyboard keys	ABS, PS
Food and drink	Li,Lo	water bottles, drink pouches, single-use cutlery, snack spreaders, mugs and plates, jar seals, ice cream spoons	PE, PET, PS
Cosmetic and health	Lo,Mu	combs, dentures, toothbrush heads, razor handles, spectacles, sunglasses, medical lancets	CA, PA, PMM, PS
Fishing	Ab,Li,Lo	carcass tags, rope, fishing line, fishing float fragments, pot rubber, gloves, laminated card	ABS, PA, PE, PET, PS, R
Eyewear, footwear, accessories	Lo	beach shoes, spectacles, costume jewellery, sunglasses, zips, buttons, hair-bands and ties, buckles	ABS, PC, PET, PMMA
Unidentifiable objects and fragments	Ab,Li,Lo,Mu,Sp		various

Figure 1: Porth Beach, showing local bathymetry and approximate locations of beach-cast kelp.

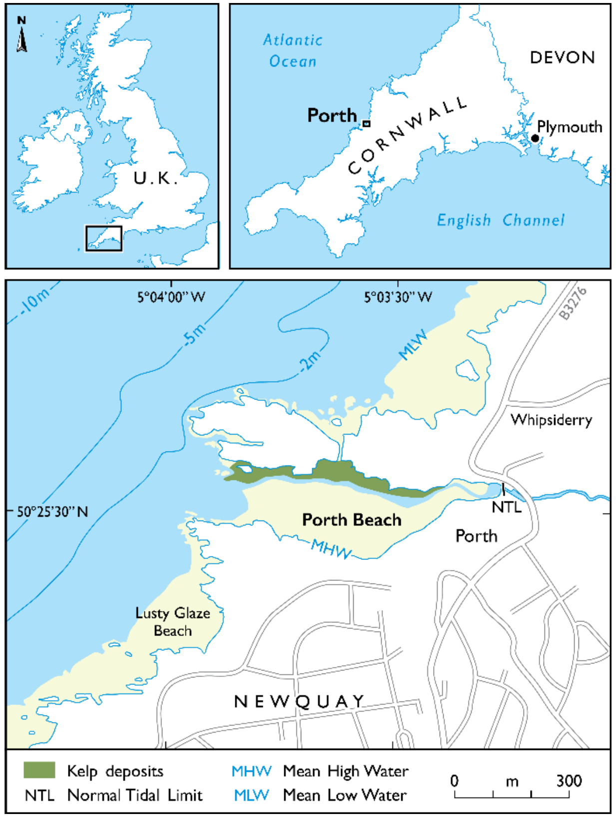

Figure 2: Beach-cast kelp on the northern edge of Porth Beach.

Figure 3: A selection of plastic articles and fragments retrieved from beach-cast kelp on Porth Beach. (a) PET bottle fragments, (b) fishing float fragments, some of which have visible encrustations of keel worm casts; (c) pot rubber strips; (d) goggles and masks; (e) footwear; (f) clothing.

Figure 4: The neck of a PET bottle around the lower stipe of *L. hyperborea* and a golf ball attached to the holdfast of *L. digitata*.