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Small scale habitat effects on anthropogenic litter material and sources in a coastal lagoon system

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ABSTRACT

Anthropogenic litter is ubiquitous throughout marine ecosystems, but its abundance and distribution are driven by complex interactions of distinct environmental factors and thus can be extremely heterogeneous. Here we compare the extent of anthropogenic litter pollution at a sheltered lagoon habitat and nearby open coast sites. Monthly surveys over a period of five months showed that both the types and sources of litter always differed significantly between lagoon and open coast sites. Pollution within the lagoon was mainly land-derived and was largely made up of construction materials (70% to 95%). At open coast sites, construction materials represented a minor portion of pollution (4% to 12%) while plastics were the most abundant (82% to 95%). We show that stranded anthropogenic litter in adjacent marine habitats can differ significantly and stress the importance of sampling at appropriate spatial scales to gain realistic insights into the sources of pollution.

1. Introduction

Contamination of the marine environment by anthropogenic litter is widely acknowledged as a significant threat to natural ecosystems, their functioning and the services they provide to humans worldwide (de Souza Machado et al., 2018; Gall and Thompson, 2015; Haward, 2018; Rochman et al., 2013; Windsor et al., 2019). Indeed, it has been recognized by the European Commission as one of the 11 Descriptors of the Marine Strategy Framework Directive (European Parliament, 2008).

Marine anthropogenic litter is mainly composed of items made of paper, metal, wood and textiles (Gall and Thompson, 2015; OSPAR, 2010). Although litter enters the sea from both the land and at-sea sources, nearly 80% of ML is derived from land-based activities (EC JRC, 2013). Depending on its density, the majority of debris sinks to the seabed, while the rest drifts with the wind and currents and is deposited along the coast, where much will fragment over time (Turrell, 2018). Among these forms of litter, plastic items are the most harmful and common, comprising 61 to 87% (Barboza et al., 2019). Jambeck et al. (2015) found that every year approximately 4.8 to 12.7 million metric tons of plastic waste enter the oceans.The continuing rise in production of plastic (Giacovelli, 2018; PlasticsEurope, 2019) and its resistance to degradation in combination with inadequate waste management, has caused plastic waste to accumulate in the environment at increasing rates even in the most remote locations (Barnes et al., 2010; Bergmann and Klages, 2012).

The ubiquitous occurrence of plastic waste in the environment has raised much concern and resulted in numerous studies assessing the threat it poses globally. In the marine environment, the impacts of plastic pollution through ingestion and entanglement of marine fauna, ranging from zooplankton to cetaceans, seabirds and marine reptiles, are well documented (Gall and Thompson, 2015). In addition to the physical effects of ingested plastics (e.g., damage to locomotory, respiratory or digestive organs), toxicity also arises from leaching contaminants that were either added during plastic production (e.g., monomers and plastic additives) or adsorbed from the surrounding environment. Our limited but growing understanding of the insidious effects of the toxicity of leachates from plastic waste has highlighted several deleterious impacts including carcinogenesis, endocrine disruption, anomalous embryonic development and even impairment of behavioural vigilance and predator avoidance (e.g., Law, 2017; Seuront, 2018; Trotter et al., 2019).

The sources of anthropogenic litter are extensive, including a wide range of marine- and land-based activities, and litter can be transported to marine environments via a variety of pathways (Nelms et al., 2017). Litter originating from maritime activities, such as fisheries and shipping, generally represents a lower, yet conspicuous, portion. The majority of litter has land-based sources including domestic, industrial and agricultural activities and, typically, enters the sea via rivers, sewage

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networks and wind (Barnes et al., 2009; Nelms et al., 2017). The amount of litter increases in proximity to sewage outfalls, large densities of people and commercial activity (Browne et al., 2011; Browne et al., 2010), although the impact on remote areas has increased significantly over the last few decades (e.g., Heskett et al., 2012; Lavers and Bond, 2017). Generally, marine litter concentrations are higher within closed or semi-closed seas such as the Caribbean Sea (Siung-Chang, 1997) and the Mediterranean Sea (Cózar et al., 2015). Several studies have described large-scale accumulation areas of pelagic litter in the oceans corresponding to each of the subtropical gyres located at either side of the Equator (e.g., Borja and Elliott, 2013; Law et al., 2010). Taken together, these studies have highlighted how deposition dynamics of marine litter can vary significantly at different spatial and temporal scales, driven by complex interactions of prevailing winds, ocean currents and, coastal geography and demography (Barnes et al., 2009; Thompson et al., 2009). The patchiness of marine anthropogenic waste emphasises the need for consistent sampling to allow comparison across sites and through time for a comprehensive understanding of the factors driving the distribution and accumulation of marine litter, the identification of sources of pollution and effective management strategies. Recent interest in the study of contamination of anthropogenic litter in marine ecosystems has focused on sandy beaches, estuarine and sub-tidal habitats (e.g., Barnes et al., 2009), while few studies have examined coastal lagoons (Abidli et al., 2017; Vianello et al., 2013; Visne and Bat, 2016). Critically, there are very few direct comparisons of contamination between lagoons and adjacent open coast sites (Martellini et al., 2018).

Here, we evaluate the temporal dynamics of anthropogenic litter pollution at a sheltered lagoon in southern Portugal and assess whether lagoon sites, which are considered largely retention systems, differ markedly in the distribution, density and composition of accumulated litter from nearby open coast sites.

2. Methodology

The Ria Formosa lagoon is a mesotidal system located in southern Portugal and is framed by two peninsulas and five islands. The triangularly-shaped multi-inlet barrier island system extends for over 55 km along the coast, expanding to a maximum distance of 6 km from the mainland. It is connected to the ocean through six tidal inlets. Tides are semi-diurnal with amplitudes ranging from 3.5 m to 1.3 m (Águas, 1986). The circulation of water inside the lagoon is mostly driven by the tide, with very limited freshwater input and no evidence of haline or thermal stratification (Salles et al., 2005). The area is classified as a Natural Park and has high ecological and socio-economic significance. It sustains a variety of diverse habitats, including sand dunes, saltmarshes, and foundation species such as seagrasses, and is used for various human activities including tourism and clam farming.

To assess the effects of habitat on litter pollution on the intertidal shore of Ria Formosa barrier islands, lagoon sites (−L; i.e. within the coastal lagoon of Ria Formosa) and open coast sites (-O; i.e. facing the open sea) were selected ($n = 3$; Fig. 1). All sites were surveyed monthly over a period five months (from January to May 2016).

Litter assessment followed a standing-stock procedure (Lippiatt et al., 2013; Opfer et al., 2012). At each site, a fixed 200 m alongshore section was selected. Within these 200 m, vertical transects (n = 3) of 20 m width were randomly selected once a month during spring tide (tidal height of ≤1 m) (Lippiatt et al., 2013). In each transect, the surveyor followed the walking pattern described by Opfer et al. (2012). The litter collected was classified by material (Ceramic, Glass, Metal, Plastic, Paper, Other), source (Construction, Domestic, Fishing, Tobacco, Food Package, Hygiene/Medical, Undifferentiated) and size (5 mm ≤ *meso* < 20 mm, 20 mm ≤ macro < 100 mm and mega ≥100 mm; Barnes et al., 2009). Cement blocks were excluded from the analysis due to difficulty in assessing them in the field.

2.1. Data analyses

To test whether habitat or sampling month had an effect on patterns of litter accumulation, two datasets were created. One set included data grouped by material and one with the data grouped by source. For each dataset, a three-way multivariate analysis (PERMANOVA) was performed with habitat (O or L) as a fixed factor, site (3 levels) as a random factor nested within habitat, month as an orthogonal fixed factor and abundance by source or by type of material as the dependent variables. Bray–Curtis dissimilarity matrices were used for square root transformed multivariate measures. Post hoc comparisons were performed using pair-wise tests and applying Bonferroni correction (Anderson, 2005). To assess homogeneity of variances, permutation tests of multivariate dispersion (PERMDISP; Anderson, 2004) were used, while the SIMPER procedure was used (Clarke, 1993) to identify the percentage contribution (%) that each variable made to the between-sites Bray-Curtis dissimilarities. The cut off for low contributions was 50% of cumulative percentage of average dissimilarity between sites.

To visualize the datasets, a series of principal coordinate analyses (PCO) based on the Bray–Curtis similarity resemblance matrices were performed. Analyses were performed using PRIMER 6.1.15 & PERMANOVA+ 1.0.5 software (Anderson et al., 2008).

3. Results

A total of 249,232 litter items were encountered across all standing-stock surveys (Fig. 1). Litter was most abundant in L1 (9.10 ± 2.051 items per m^2), and least abundant in O1 (0.125 ± 0.016 items per m^2; Fig. 1S; Fig. 2S). Overall, ceramic items accounted for the vast majority of litter items at lagoon sites (66% to 91%), while at open coast sites plastic was the most predominant class of item recorded (82% to 95%). Across all sites, most litter items belonged to the smallest size categories (*meso*: 19% to 62%, macro:29% to 62%). Across all levels (exposure, site, month), most of the litter on the open coast had an undifferentiated source. Within the identifiable sources of litter, construction (O: 4% to 12%; L:70% to 95%), food package (O:12% to 24%; L: 1% to 9%), fishing (O: 18% to 30%; L: 1% to 4%) and tobacco (O: 1% to 8%; L: 0%) were the most abundant. Primary plastic was only found once in Ria Formosa (O2 in May, 11 pellets).

Overall, Habitat had a significant effect on the abundance of litter when grouped by material (PERMANOVA: $F(1,60) = 9.488$; p (MC) = 0.0017), while month did not ($F(4,60) = 1.465$; p (MC) = 0.1951). There was an effect of the nested factor site ($F(4,60) = 19.190$; p(MC) = 0.0001) with all lagoon sites being statistically different from one another (L3, L2: $t(2) = 4.56$; $p = 0.0001$; L3, L1: $t(2) = 8.20$; $p = 0.0001$; L2, L1: $t(2) = 7.98$; $p = 0.0001$). For the open coast sites, one comparison (O2 vs O1) was not significant (O3, O2: $t(2) = 1.88$; $p = 0.02$; O3, O1: $t(2) = 2.72$; $p = 0.0005$; O2, O1: $t(2) = 1.38$; $p = 0.1275$). Multivariate dispersion was homogeneous for the factor exposure ((PERMDISP: $F(1,88) = 2.99$, p(perm) = 0.113) and month ($F(4,85) = 0.08$, p(perm) = 0.99) but not for the factor site ($F(5,84) = 8.44$, p(perm) = 0.0001) indicating that the significant effect of site detected in the PERMANOVA could also be due to differences in the dispersion of the data for this term. However, Principal Coordinate Analysis was coherent with the results of the PERMANOVA (Fig. 2A), showing clear segregation between lagoon and open coast sites. Replicates within each site tended to cluster together on the PCO. The cluster formed by all lagoon sites was more dispersed than the cluster of open coast sites, which suggests that litter material is more dissimilar among lagoon sites than among open coast sites.

Ceramic was the main contributory to dissimilarities between habitats (SIMPER: 55%). Plastic contributed to most of the dissimilarity among open coast sites (39–53%), while ceramics contributed to most of the dissimilarity among lagoon sites (37–62%).

Overall, Habitat (PERMANOVA: $F(1,60) = 7.033$; p(MC) = 0.0065) had a significant effect on the abundance of litter when grouped by

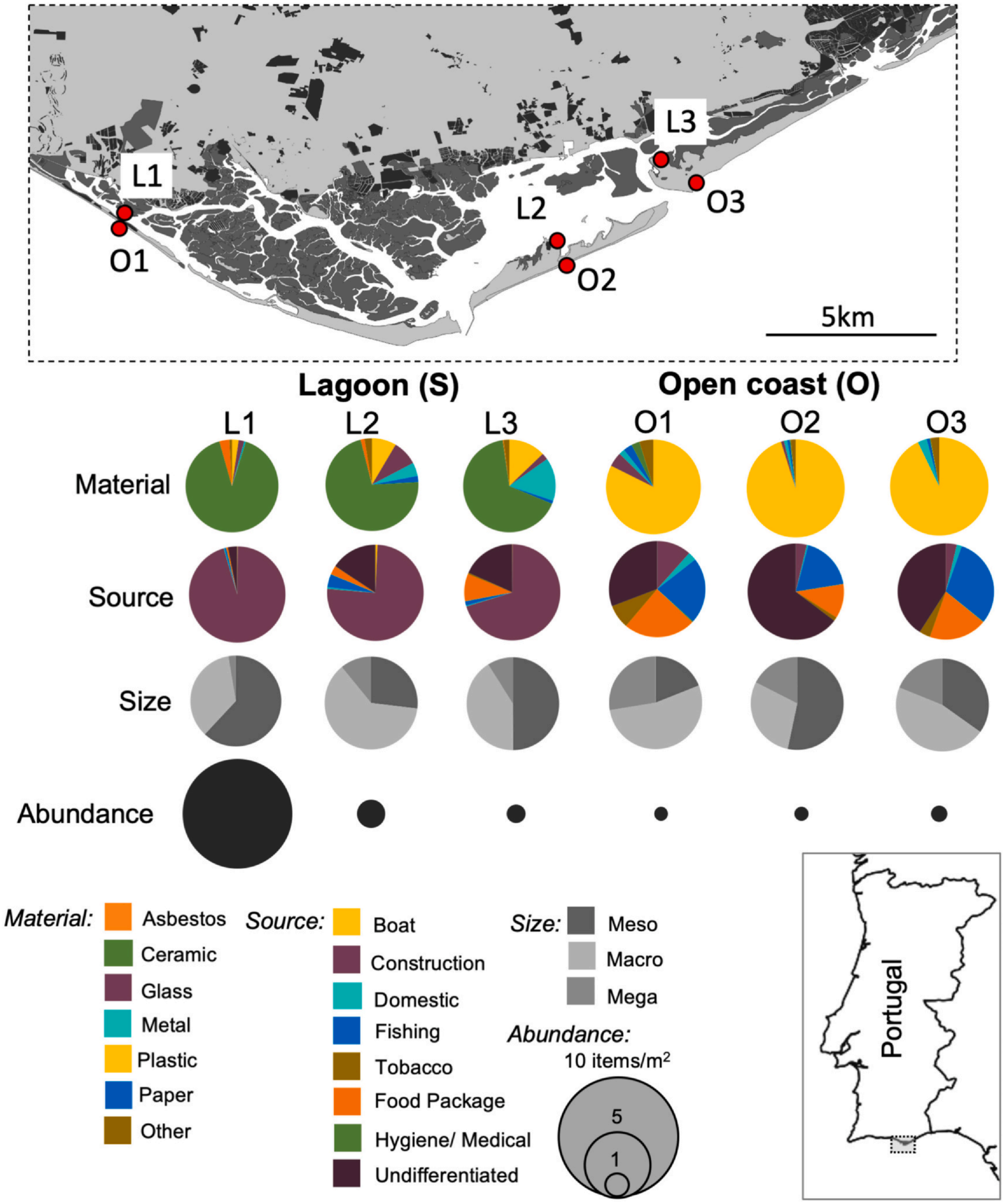

Fig. 1. Study area and overall results. Proportion of each material, source and size are described by colour coded pies per each site. Sampling sites full names: Praia de Faro lagoon site (L1) and open coast site (O1); Armona lagoon site (L3) and open coast site (O3); Culatra lagoon site (L2) and open coast site (O2).

source, while Month did not show a significant effect ($F(4,60) = 1.262$; $p(MC) = 0.269$). The nested factor, site, had a significant effect ($F(4,60) = 24.071$; $p(MC) = 0.0001$), with all pairs of sites being statistically different from each other within the levels of the factor Habitat (pairwise comparison: L1, L2: $t(2) = 8.60, p = 0.0001$; L1, L3: $t(2) = 8.77$, $p = 0.0001$; L2, L3: $t(2) = 4.5$, $p = 0.0001$; O1, O2: $t(2) = 1.88, p = 0.013$; O1, O3: $t(2) = 2.51, p = 0.0021$; O2, O3: $t(2) = 2.37, p = 0.0045$).

Multivariate dispersion was not homogenous between the levels of the factor Habitat ($F(1,88) = 6.61$, $p(perm) = 0.0178$) or among levels of the factor Site ($F(5,84) = 6.93, p = 0.0003$). This indicates that the significant effect of the factors Site and Habitat detected in the PERMANOVA could have been due to differences in the dispersion of the data. Month had a homogeneous multivariate dispersion (PERMDISP: $F(4,85) = 0.10, p = 0.989$). However, Principal Coordinate Analysis was coherent with the results of the PERMANOVA (PCO; Fig. 2B). There was clear segregation between lagoon and open coast sites; the cluster formed by lagoon sites were clearly segregated while in the cluster of open coast sites several overlapped, suggesting that litter source was more dissimilar among lagoon sites than among open coast sites. Replicates within each site clustered together in the PCO.

When data were grouped by source, construction was the main contributor to the dissimilarity between habitats (SIMPER: 64%). Dissimilarity of source abundance within the lagoon group was mostly explained by construction (43%–75%) while within the open coast group dissimilarity was mostly explained by undifferentiated debris (27%–31%) and fishing (17%–22%).

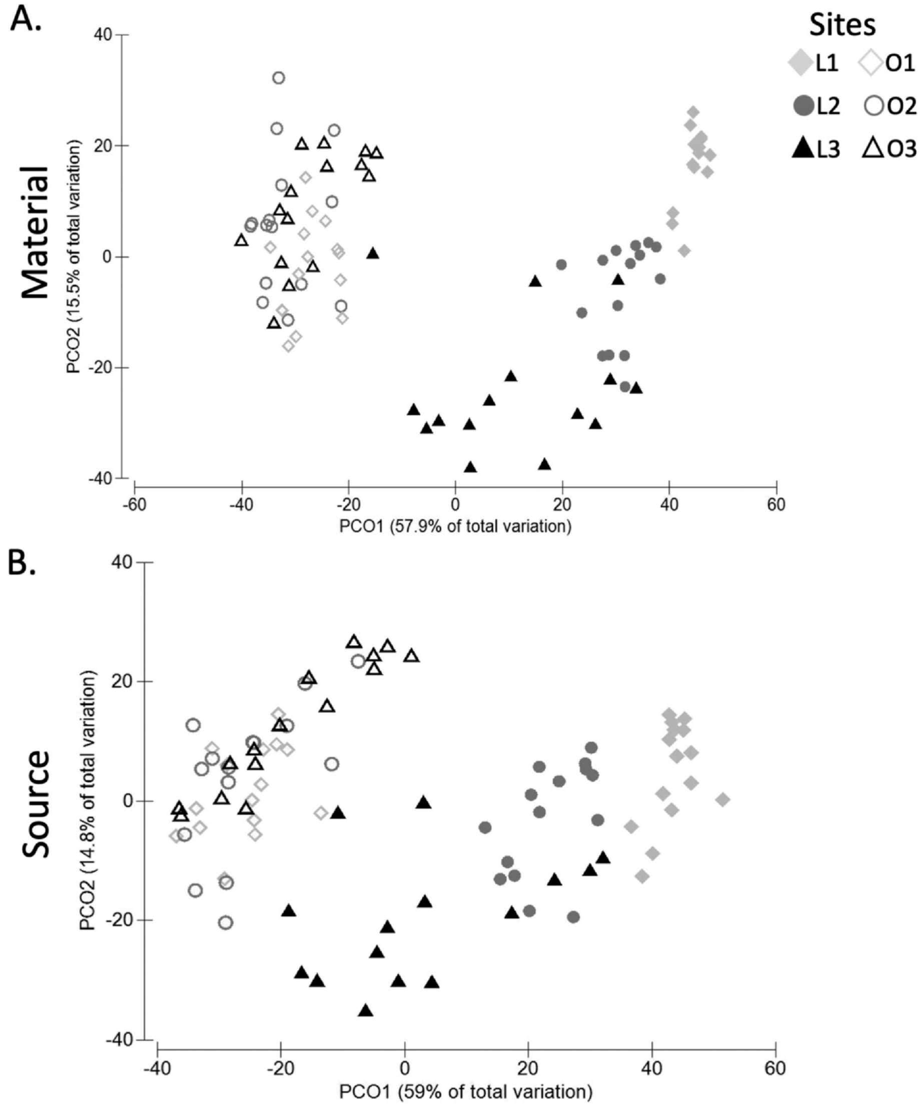

Fig. 2. Principal coordinate analysis (PCO) panel based on a Bray – Curtis similarity resemblance matrix on square root transformed data of Ria Formosa debris grouped by material (A) and by debris source (B). Open coast sites are depicted with hollow symbol and lagoon sites with solid symbols.

4. Discussion

Coastal lagoons are among the most productive ecosystems on Earth, providing a wide range of ecosystem services and benefits (Kennish and Paerl, 2010). Because of human population growth and associated land-use alteration, coastal lagoons are under increasing threat worldwide (Webster and Harris, 2004). In particular, alteration of natural land cover to urban, industrial and agricultural development has enhanced pollution loading of streams and rivers that discharge into estuaries, degrading water quality and biotic integrity and impoverishing the value of coastal waters for recreational and commercial use. Many coastal lagoons, in particular those with restricted exchange with the adjacent ocean and relatively long water residence times, are particularly vulnerable to nutrient enrichment and litter from surface runoff and groundwater (e.g., David et al., 2019). Moreover, several climate change stressors such as rising temperatures, more frequent and extreme floods and droughts can aggravate these effects (Lloret et al., 2008). Thus, while coastal lagoons have significant ecological and economic importance, they are particularly vulnerable to the pressures exerted by human populations. Litter accumulation is influenced by both human and natural effects. For example, local activities, such as tourism and fishery, as well as shipping and industry, play important roles as sources of litter and help explain the large differences in litter accumulation among sites (Abidli et al., 2017; Bayo et al., 2019). At the same time, litter tends to accumulate in areas with less dynamic water movement such as sandbars and the inner parts of lagoons (Vianello et al., 2013) and can also be affected by vegetation type (e.g., Cozzolino et al., 2020).

Our results showed that coastal lagoon and open coast sites were significantly different in terms of the types and sources of anthropogenic litter that accumulated on them. Plastic litter was the dominant type of litter at open coast sites, but represented a much smaller portion of waste at lagoon sites where heavier materials like ceramics, glass and metal were more abundant. The largest proportion of litter items at lagoon sites originated from land-derived sources, particularly with construction as the source, mainly coming from damaged or demolished houses and shacks. It is worth noting that construction materials included asbestos; despite being illegal, this material is often used for roofing and fencing. Although paired lagoon and open coast sites were separated on scales of only 10s to 100 s m, construction materials formed a very small proportion (5–10%) of litter on the open coast. There, open coast, in addition to a large fraction of undifferentiated items, litter originating from marine-derived sources (e.g., fishing) formed an important contributed to waste composition (18% to 30%).

Knowledge about the predominant sources of litter (e.g. land- versus marine-derived) could inform management strategies and facilitate the development of measures to limit the amount of litter entering the marine environment.

Habitat differences outweighed temporal variation even when sampling sites experienced intense environmental fluctuations. For example, between the sampling events of April and May, an intense storm (waves up to 3.4 m, www.windguru.cz) severely damaged several infrastructures (mainly shacks and fishermen's houses) along the peninsulas and islands of the Ria Formosa. In addition, large quantities of sand were removed from the shore at sites on the open coast. Surprisingly, litter abundance did not show any significant differences in May, immediately after this extreme event.

In addition to a persistent habitat effect throughout the entire sampling period, our study showed that sheltered lagoon sites were less variable in terms of both litter source and material, but showed higher variation in the abundance of litter. This pattern is most likely explained by the relatively higher water retention and weaker hydrodynamics within the lagoon, leading to a high abundance of non-buoyant items. The lagoon includes salt marshes, sand flats and a network of natural and partly dredged channels. Its complex geometry, with numerous channels and straits and several inlets, makes it a substantially challenging study area (Lencart e Silva et al., 2014). High resolution models have shown that, except for isolated torrential run-off events (Newton and Mudge, 2003), the absence of significant density driven flow or relevant wind fetch, results in the tide being the main driver of hydrodynamics within the Ria Formosa and controlling its exchange with the adjacent shelf through the six inlets (Lencart e Silva et al., 2014). Importantly, the analysis of general ebb and flood currents in the Ria Formosa indicates extremely limited direct flow between its western and the eastern sides. In addition, areas located near inlets have relatively small residence times, of less than five days, for the removal of 90% of their water, whereas inner areas, may have a half residence time of over two weeks (Duarte et al., 2008). Taken together, these hydrodynamic features provide the most likely explanation for the marked differences in litter abundance between site L1 (westernmost and distant from the influence of the inlets) and the eastern sites L2 and L3, which experience significantly lower flushing times due to their vicinity to inlets. In terms of sources, as for the comparison between open coast and lagoon environments, the observed differences between the western lagoon site (L1) and those to the east (L2, L3) are probably linked to the past and ongoing house demolition in the western areas of the lagoon. Heavy constructions materials such as ceramic and metal are unlikely to be dispersed by water movement, especially at sheltered lagoon sites, and likely to be retained close to their source. The hydrodynamics of our open coast sites are largely controlled by nearshore wind, remote wind, thermohaline circulation and mesoscale features of the Gulf of Cadiz. Such sites will experience lower retention and stronger wave action, increasing the turnover of litter items through more frequent removal and higher input from other sites. In particular, plastics - the most abundant material at these exposed sites - contribute to high source variability because of their high potential for dispersal; most plastic items remain buoyant until they become waterlogged or accumulate too much epibiota to float. Across all lagoon sites, for those plastic items that could be identified, fishing and food packaging were the sources that contributed most. This reflects the conflicting uses of the Ria Formosa and, at the same time, provides key data for its management. Ria Formosa is a protected area with high ecological, social, and economical value (Nobre, 2009). It is an important migration stopover and breeding site for many birds and a key area for fisheries and shellfish production. This coastal lagoon is a Special Protection Area (SPA) and a Site of Community Importance (SCI) within the Natura2000 Network under European legislation (Birds Directive 79/409/CEE and Habitat Directive 92/43/CEE, respectively), as a Natural Park under Portuguese legislation (DL 373/87), and internationally as a RAMSAR site (no. 212). Despite its importance, Ria Formosa is subject to multiple anthropogenic influences and is situated in a region classified as very vulnerable to climate change (e.g., de Noronha Vaz et al., 2013; Guerrero-Meseguer et al., 2017; Veloso et al., 2015). For example, recent warming trends have significantly reduced the distributional range and abundance of the intertidal macroalga *Fucus vesiculosus* within Ria Formosa (Mota et al., 2015; Nicastro et al., 2013). Increasing water temperature and heatwaves have restricted the distribution of this, once dominant, key ecosystem engineer higher to the intertidal within saltgrass meadows. In addition to climate-induced stressors, anthropogenic litter is also increasingly affecting this protected area. Macroplastics are accumulating, trapped in the canopy of intertidal and subtidal seagrass and saltmarsh meadows and in nearby sediments (Cozzolino et al., 2020), with evidence of microplastic ingestion by associated infaunal species (Cozzolino et al. in revision). Mounting evidence also indicates that several aquatic-associated bird species in the Ria Formosa ingest large amounts of plastics, particularly storks and gulls (Basto et al., 2019; Nicastro et al., 2018).

Beach macrolitter has been investigated at several open coast sites along northeastern Atlantic shores (southern Iberia and Morocco; Velez et al., 2019). These included some sites along the southern coast of Portugal that are comparable in terms of exposure and geomorphology to those examined in our study. The area covered in the earlier study encompassed a wide latitudinal range (37°N-28°N) that is characterised by extreme differences in the sizes of coastal human populations, economic state, waste generation and management, and distance from potential land-based sources of pollution (Akkouri et al., 2019; Lazarevic et al., 2010). Despite this heterogeneity, no major differences in distribution, composition (%) and source (%) of pollution of either general litter or microplastics were detected among widely separated sites, with plastic being the most abundant littering material at all sites. This uniformity across large spatial scales highlights the significance of the distinct differences observed in our study at very much smaller scales. Open coast sites at the Ria Formosa were more similar in the composition and sources of litter to open coast sites 1000s of km away than to lagoon sites 10s to 100 s m away.

Our study adds to the abundant literature showing that anthropogenic litter is ubiquitous throughout the marine environment, but importantly highlights the strong effect of habitat on litter material and source. Recent studies have suggested that immediate and coordinated approaches combining pre- and post-production actions could limit the growing trend of environmental plastic pollution (Lau et al., 2020). However, currently, due to a lack of significant commitment to advance and improve the global plastic system from businesses, governments and the international community, plastic waste in marine habitats continues to rise globally (Kühn et al., 2015). Beyond a likely increase in abundance it is difficult to predict how plastic pollution has changed and will develop within the Ria Formosa since our survey. Baseline assessments, such as the one reported here, are not only central to the assessment of changes through time and differences among sites, they are also important to an efficient determination of management and conservation practices. Mounting evidence has debunked the notion that beach users are responsible for most litter; its place is now taken by a more complex view in which the inseparable interaction of multiple physical processes determines the abundance and nature of marine litter (Kühn et al., 2015). Our data indicate that the accumulation of litter in lagoon systems is influenced by both different human activities and different hydrodynamics than from open coast sites. Together, this results in a lower contribution of plastics and increased preponderance of heavy materials such as ceramics, glass and metal within the lagoon. Given such large differences in the nature of litter pollution, management and conservation strategies will only be effective if they are context specific and take local factors into account.

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CRediT authorship contribution statement

Nadja Velez: Data curation, Investigation, Formal analysis.

Katy R Nicastro: Conceptualization, Methodology, Resources, Formal analysis, Writing original draft.

Christopher D. McQuaid: Conceptualization, Writing - review & editing.

Gerardo I. Zardi: Conceptualization, Methodology, Supervision, Writing original draft.

Declaration of competing interest

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

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References

Abidli, S., Toumi, H., Lahbib, Y., El Menif, N.T., 2017. The first evaluation of microplastics in sediments from the complex lagoon-channel of Bizerte (northern Tunisia). Water Air Soil Pollut. 228, 262.

Águas, M., 1986. Simulação da circulação hidrodinâmica na Ria Formosa. Os sistemas lagunares do Algarve. Univ. do Algarve, Faro, pp. 78–90.

Akkouri, N., Baba, K., Simou, S., Alanssari, N., Nounah, A., 2019. The impact of recycled plastic waste in Morocco on bitumen physical and rheological properties. In: International Congress and Exhibition "Sustainable Civil Infrastructures". Springer, pp. 131–145.

Anderson, M., 2004. PERMDISP: A FORTRAN Computer Program for Permutational Analysis of Multivariate Dispersions (for any Two-Factor ANOVA Design) Using Permutation Tests. Department of Statistics, University of Auckland, New Zealand, pp. 24.

Anderson, M.J., 2005. Permutational Multivariate Analysis of Variance. Department of Statistics, University of Auckland, Auckland.

Anderson, M.J., Gorley, R.N., Clarke, K.R., 2008. PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. PRIMER-E, Plymouth, UK.

Barboza, L.G.A., Cózar, A., Gimenez, B.C.G., Barros, T.L., Kershaw, P.J., Guilhermino, L., 2019. Macroplastics pollution in the marine environment. In: Sheppard, C. (Ed.), World Seas: an Environmental Evaluation, 2nd. Academic Press, Cambridge, MA, pp. 305–328.

Barnes, D.K., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philosophical Transactions of the Royal Society of London B: Biological Sciences 364, 1985–1998.

Barnes, D.K., Walters, A., Gonçalves, L., 2010. Macroplastics at sea around Antarctica. Mar. Environ. Res. 70, 250–252.

Basto, M.N., Nicastro, K.R., Tavares, A.I., McQuaid, C.D., Casero, M., Azevedo, F., Zardi, G.I., 2019. Plastic ingestion in aquatic birds in Portugal. Mar. Pollut. Bull. 138, 19–24.

Bayo, J., Rojo, D., Olmos, S., 2019. Abundance, morphology and chemical composition of microplastics in sand and sediments from a protected coastal area: the mar Menor lagoon (SE Spain). Environ. Pollut. 252, 1357–1366.

Bergmann, M., Klages, M., 2012. Increase of litter at the Arctic deep-sea observatory HAUSGARTEN. Mar. Pollut. Bull. 64, 2734–2741.

Borja, Á., Elliott, M., 2013. Marine monitoring during an economic crisis: the cure is worse than the disease. Mar. Pollut. Bull. 68, 1–3.

Browne, M.A., Galloway, T.S., Thompson, R.C., 2010. Spatial patterns of plastic debris along estuarine shorelines. Environmental science & technology 44, 3404–3409.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., Thompson, R., 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environmental Science & Technology 45, 9175–9179.

Clarke, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol. 18, 117–143.

Cózar, A., Sanz-Martín, M., Martí, E., González-Gordillo, J.I., Ubeda, B., Gálvez, J.Á., Irigoien, X., Duarte, C.M., 2015. Plastic accumulation in the Mediterranean sea. PLoS One 10, e0121762.

Cozzolino, L., Nicastro, K.R., Zardi, G.I., de los Santos, C.B., 2020. Species-specific plastic accumulation in the sediment and canopy of coastal vegetated habitats. Sci. Total Environ. 723, 138018.

David, M., Bailly-Comte, V., Munaron, D., Fiandrino, A., Stieglitz, T.C., 2019. Groundwater discharge to coastal streams – a significant pathway for nitrogen inputs to a hypertrophic Mediterranean coastal lagoon. Sci. Total Environ. 677, 142–155.

Duarte, P., Azevedo, B., Pereira, A., 2008. Hydrodynamic Modelling of Ria Formosa (South Coast of Portugal) with EcoDynamo.

EC JRC, 2013. European Commission, Joint Research Centre, 2013. In: MSFD Technical Subgroup on Marine Litter (TSG-ML). Guidance on Monitoring of Marine Litter in European Seas.

European Parliament, C.o.t.E.U, 2008. Directive 2008/56/EC of the European Parliament and of the council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). Off. J. Eur. Union 164, 19–40.

Gall, S.C., Thompson, R.C., 2015. The impact of debris on marine life. Mar. Pollut. Bull. 92, 170–179.

Giacovelli, C., 2018. Single-Use Plastics: A Roadmap for Sustainability.

Guerrero-Meseguer, L., Marín, A., Sanz-Lázaro, C., 2017. Future heat waves due to climate change threaten the survival of Posidonia oceanica seedlings. Environ. Pollut. 230, 40–45.

Haward, M., 2018. Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. Nat. Commun. 9, 667.

Heskett, M., Takada, H., Yamashita, R., Yuyama, M., Ito, M., Geok, Y.B., Ogata, Y., Kwan, C., Heckhausen, A., Taylor, H., Powell, T., Morishige, C., Young, D., Patterson, H., Robertson, B., Bailey, E., Mermoz, J., 2012. Measurement of persistent organic pollutants (POPs) in plastic resin pellets from remote islands: toward establishment of background concentrations for international pellet watch. Mar. Pollut. Bull. 64, 445–448.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., et al., 2015. Plastic waste inputs from land into the ocean. Science 347, 768–771.

Kennish, M.J., Paerl, H.W., 2010. Coastal Lagoons: Critical Habitats of Environmental Change. CRC Press.

Kühn, S., Rebolledo, E.L.B., van Franeker, J.A., 2015. Deleterious Effects of Litter on Marine Life, Marine Anthropogenic Litter. Springer, Cham, pp. 75–116.

Lau, W.W., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., 2020. Evaluating scenarios toward zero plastic pollution. Science. https://doi.org/10.1126/science.aba9475.

Lavers, J.L., Bond, A.L., 2017. Exceptional and rapid accumulation of anthropogenic debris on one of the world's most remote and pristine islands. Proc. Natl. Acad. Sci. 114, 6052.

Law, K.L., 2017. Plastics in the marine environment. Annu. Rev. Mar. Sci. 9, 205–229.

Law, K.L., Morét-Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic subtropical gyre. Science 329, 1185–1188.

Lazarevic, D., Aoustin, E., Buclet, N., Brandt, N., 2010. Plastic waste management in the context of a European recycling society: comparing results and uncertainties in a life cycle perspective. Resour. Conserv. Recycl. 55, 246–259.

Lencart e Silva, J.D., Lopes, C.L., Picado, A., Sousa, M.C., Dias, J.M., 2014. Tidal dispersion and flushing times in a multiple inlet lagoon. J. Coast. Res. 598–603.

Lippiatt, S., Opfer, S., Arthur, C., 2013. Marine Debris Monitoring and Assessment: Recommendations for Monitoring Debris Trends in the Marine Environment.

Lloret, J., Marín, A., Marín-Guirao, L., 2008. Is coastal lagoon eutrophication likely to be aggravated by global climate change? Estuar. Coast. Shelf Sci. 78, 403–412.

Martellini, T., Guerranti, C., Scopetani, C., Ugolini, A., Chelazzi, D., Cincinelli, A., 2018. A snapshot of microplastics in the coastal areas of the Mediterranean Sea. TrAC Trends Anal. Chem. 109, 173–179.

Mota, C.F., Engelen, A.H., Serrão, E.A., Pearson, G.A., 2015. Some don't like it hot: microhabitat-dependent thermal and water stresses in a trailing edge population. Funct. Ecol. 29, 640–649.

Nelms, S.E., Coombes, C., Foster, L.C., Galloway, T.S., Godley, B.J., Lindeque, P.K., Witt, M.J., 2017. Marine anthropogenic litter on British beaches: a 10-year nationwide assessment using citizen science data. Sci. Total Environ. 579, 1399–1409.

Newton, A., Mudge, S.M., 2003. Temperature and salinity regimes in a shallow, mesotidal lagoon, the Ria Formosa, Portugal. Estuar. Coast. Shelf Sci. 57, 73–85.

Nicastro, K.R., Zardi, G.I., Teixeira, S., Neiva, J., Serrao, E.A., Pearson, G.A., 2013. Shift happens: trailing edge contraction associated with recent warming trends threatens a distinct genetic lineage in the marine macroalga *Fucus vesiculosus*. BMC Biol. 11, 6.

Nicastro, K.R., Lo Savio, R., McQuaid, C.D., Madeira, P., Valbusa, U., Azevedo, F., Casero, M., Lourenço, C., Zardi, G.I., 2018. Plastic ingestion in aquatic-associated bird species in southern Portugal. Mar. Pollut. Bull. 126, 413–418.

Nobre, A.M., 2009. An ecological and economic assessment Methodology for coastal ecosystem management. Environ. Manag. 44, 185–204.

de Noronha Vaz, E., Walczynska, A., Nijkamp, P., 2013. Regional challenges in tourist wetland systems: an integrated approach to the Ria Formosa in the Algarve, Portugal. Reg. Environ. Chang. 13, 33–42.

Opfer, S., Arthur, C., Lippiatt, S., 2012. NOAA Marine Debris Shoreline Survey Field Guide. US National Oceanic and Atmospheric Administration Marine Debris Program.

OSPAR, 2010. The OSPAR System of Ecological Quality Objectives for the North Sea: A Contribution to OSPAR's Quality Status Report 2010, OSPAR Publication 404/ 2009. , En Rijkswaterstaat VenW, Rijswijk. OSPAR Commission London, Rijkswaterstaat VenW, Rijswijk, pp. 16 (Update 2010).

PlasticsEurope, 2019. In: EuPC, P.a (Ed.), Plastics – The Facts 2018. Plastic Europe, Bruxelles.

Rochman, C.M., Browne, M.A., Halpern, B.S., Hentschel, B.T., Hoh, E., Karapanagioti, H.K., Rios-Mendoza, L.M., Takada, H., Teh, S., Thompson, R.C., 2013. Classify plastic waste as hazardous. Nature 494, 169–171.

Salles, P., Voulgaris, G., Aubrey, D.G., 2005. Contribution of nonlinear mechanisms in the persistence of multiple tidal inlet systems. Estuar. Coast. Shelf Sci. 65, 475–491.

Seuront, L., 2018. Microplastic leachates impair behavioural vigilance and predator avoidance in a temperate intertidal gastropod. Biol. Lett. 14, 20180453.
Siung-Chang, A., 1997. A review of marine pollution issues in the Caribbean. Environ. Geochem. Health 19, 45–55.
de Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S., Rillig, M.C., 2018. Microplastics as an emerging threat to terrestrial ecosystems. Glob. Chang. Biol. 24, 1405–1416.
Thompson, R.C., Swan, S.H., Moore, C.J., vom Saal, F.S., 2009. Our plastic age. Philosophical Transactions of the Royal Society B: Biological Sciences 364, 1973–1976.
Trotter, B., Ramsperger, A.F.R.M., Raab, P., Haberstroh, J., Laforsch, C., 2019. Plastic waste interferes with chemical communication in aquatic ecosystems. Sci. Rep. 9, 5889.
Turrell, W.R., 2018. A simple model of wind-blown tidal strandlines: how marine litter is deposited on a mid-latitude, macro-tidal shelf sea beach. Mar. Pollut. Bull. 137, 315–330.
Velez, N., Zardi, G.I., Lo Savio, R., McQuaid, C.D., Valbusa, U., Sabour, B., Nicastro, K.R., 2019. A baseline assessment of beach macrolitter and microplastics along northeastern Atlantic shores. Mar. Pollut. Bull. 149, 110649.
Veloso, N., Cruz, P., Carvalho, H., da Silva, M.M., 2015. Monitoring urban storm water: facing climate changes in a Mediterranean coastal city. WIT Trans. Ecol. Environ. 194, 93–103.
Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Da Ros, L., 2013. Microplastic particles in sediments of lagoon of Venice, Italy: first observations on occurrence, spatial patterns and identification. Estuar. Coast. Shelf Sci. 130, 54–61.
Visne, A., Bat, L., 2016. Plastic pollution in Sinop Sarikum lagoon coast in the southern Black Sea. Rapp Comm Int Mer Médit 41.
Webster, I.T., Harris, G.P., 2004. Anthropogenic impacts on the ecosystems of coastal lagoons: modelling fundamental biogeochemical processes and management implications. Mar. Freshw. Res. 55, 67–78.
Windsor, F.M., Durance, I., Horton, A.A., Thompson, R.C., Tyler, C.R., Ormerod, S.J., 2019. A catchment-scale perspective of plastic pollution. Glob. Chang. Biol. 25, 1207–1221.