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Spatio-temporal variability of beached macro-litter on remote islands of the North Atlantic

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ABSTRACT

Marine litter has been identified as one of the major environmental problems that oceans are currently facing. Worldwide efforts are being made to reduce the input of litter into the oceans, and projects aimed at monitoring their quantities are key to evaluate their success. This study, provide baseline information on the quantities of marine litter found on 42 beaches spread throughout the nine islands of the Azores archipelago, North Atlantic Ocean. A total of 31,439 items were collected throughout the archipelago with an average density of 0.62 ± 0.15 macro-litter items m^{-2}. Of this litter 87% were plastic and its majority (67%) plastic fragments. Six beaches were further monitored every three months for two years. Substrate type and wind exposure were important factors for explaining patterns of litter deposition. Our results highlight that marine litter have the tendency to accumulate in remote islands of the North Atlantic Ocean.

1. Introduction

Marine anthropogenic litter is one of the most pervasive environmental pollution problems that the oceans are currently facing, affecting directly and indirectly all marine ecosystems (Galloway and Lewis, 2016). Among the wide diversity of litter items found in the oceans, plastic is by far the most abundant and concerning material (GEF, 2012). Due to their physicochemical properties, plastic materials are suitable for a wide range of industrial and medical applications worldwide. However, when not properly disposed, they remain in the environment for long periods of time, eventually causing harmful effects to marine biota (Bergmann et al., 2015). The negative effects of marine litter are well known and include entanglement, a phenomenon that has been reported in 243 different species of marine organisms (Gall and Thompson, 2015) and ingestion, that has been documented in a wide variety of marine wildlife, from planktonic organisms up to baleen whales (Gall and Thompson, 2015).

Recent estimates suggest that ~8 million metric tons of plastic waste reach the oceans each year (Jambeck et al., 2015), and this figure will probably continue to increase as research into this field also progresses. A recent study by Lebreton et al. (2018), shows evidences that the extent of plastic accumulation in the Great Pacific Garbage Patch in the North Pacific Ocean has been rapidly increasing. Furthermore, the northern hemisphere has historically been reporting higher marine pollution accumulation rates than southern hemisphere areas (Galgani et al., 2015; Eriksen et al., 2014; Van Sebille et al., 2015).

Marine litter has been described as ubiquitous and has been found in every compartment of the marine realm, including the coastal zone, floating at the sea surface and in the water column, deposited on the seabed and even in the Arctic sea ice (Barnes et al., 2009; Obbard et al., 2014; Pham et al., 2014; Woodall et al., 2014; Peeken et al., 2018).

Small and isolated islands, such as the case of the Azores archipelago, are not immune to this global problem, and could potentially act as important sinks for marine anthropogenic litter in the open ocean (Lavers and Bond, 2017; Lebreton et al., 2018). At the moment, there are only a few studies conducted in the Azores archipelago that focus on marine anthropogenic litter, particularly on coastal accumulation (Pieper et al., 2015), seafloor deposition and accumulation (Pham et al., 2013; Rodríguez and Pham, 2017) and impacts on sea turtles (Pham

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et al., 2017).

Beach surveys provide an important way to assess the abundance and sources of plastic pollution in the environment while also serving as a management tool to evaluate the efficiency of policies targeted at reducing their input into the oceans. Additionally, information collected by beach monitoring programs can facilitate EU member countries to assess their progress towards a "Good Environmental Status" (GES) under the framework of the Descriptor 10 "Properties and quantities of marine litter do not cause harm to the coastal and marine environment" of the Marine Strategy Framework Directive (MSFD).

Even with the efforts of organised clean-up actions conducted by different non-governmental organizations and local municipalities, information regarding deposition factors, quantities, and seasonal trends of coastal marine litter in the archipelago is still scarce, and this study aims to fill in knowledge gaps for this region.

In order to provide a detailed characterisation of litter on beaches of the Azores archipelago, this work aims to (1) provide a snapshot of the quantity of marine litter present in 42 different beaches across the nine islands; (2) assess seasonal variability in litter deposition across the archipelago; (3) provide insight on the potential factors that influence litter deposition.

2. Materials and methods

2.1. Study area and selected beaches

The Azores archipelago, located in the middle of the North Atlantic Ocean, consists of nine volcanic islands disposed in three separate groups (Eastern Group, Central Group and Western Group) (Fig. 1). The exceptional relevance of this archipelago is directly linked to the extension of the Portuguese Exclusive Economic Zone (EEZ; 953,633 km^2), and to the environmental and socio-economic importance of this region to Portugal.

The present study focused on 42 beaches that are spread throughout the nine islands and that present a different set of characteristics (detailed descriptions of each beach can be found as supplementary material (Table S1)). The locations included different types of substrate (sandy ($n = 19$), rocky ($n = 9$) and gravel ($n = 14$)), level of accessibility, presence/absence of artificial walls, width, length and orientation.

All beaches are regularly visited by tourists during the summer and only a few are commonly frequented during the winter. As a result, in the summer, most beaches are regularly cleaned by municipalities while during the winter litter removal is far less frequent. Beaches with clean-ups occurring all year-round include Porto Pim, Prainha de Angra and Praia das Milícias. Beaches only cleaned during the summer (and occasionally in the winter) include Conceição, São Mateus, Prainha de Vitória, São Lourenço, Água de Alto, Calhau da Areia, Praia dos Moinhos, Santa Barbara, Praia da Areia, Calheta. The remaining beaches are cleaned either sporadically or are very rarely cleaned.

In order to minimise bias that could be caused by beach clean-ups, all responsible entities were contacted one month prior the surveys (January 2016), to inquire about all cleaning activities on site and to ensure no removal of marine litter took place. This action was only performed during our initial large-scale survey (see details below) that took place between February and March 2016 (not all the municipalities were able to stop their cleaning activities).

2.2. Survey design and methodology

An initial survey was designed to cover the whole archipelago and included 42 beaches. Those beaches were sampled on a single occasion between February and March 2016 while a sub-sample ($n = 6$) was subsequently monitored using the same methodology over a period of 24 months, once every three months (Table S1).

The beaches selected for the seasonal monitoring were all sandy beaches with a reduced cleaning activity and were located in all three groups of islands (Fig. 1).

For each beach, a fixed 100 m (whenever possible) section was delimited, covering the whole area between the water line to the beach

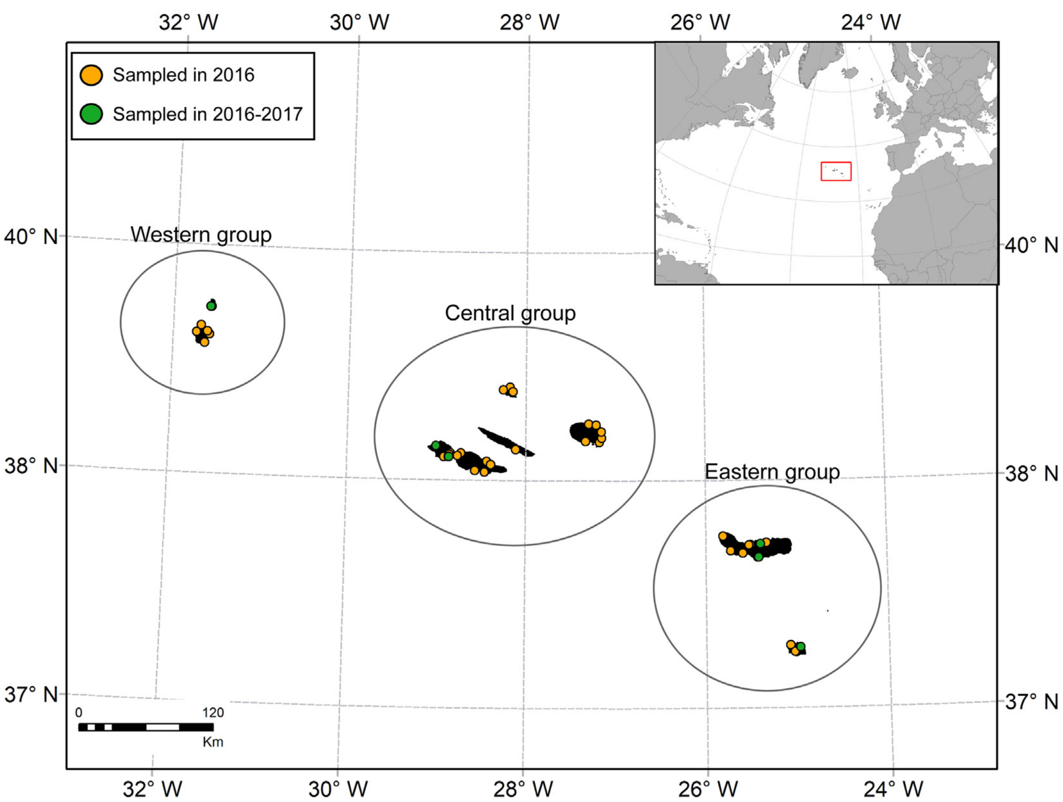

Fig. 1. Location of the selected beaches spread throughout the different islands of the Azores archipelago, subdivided into three main groups.

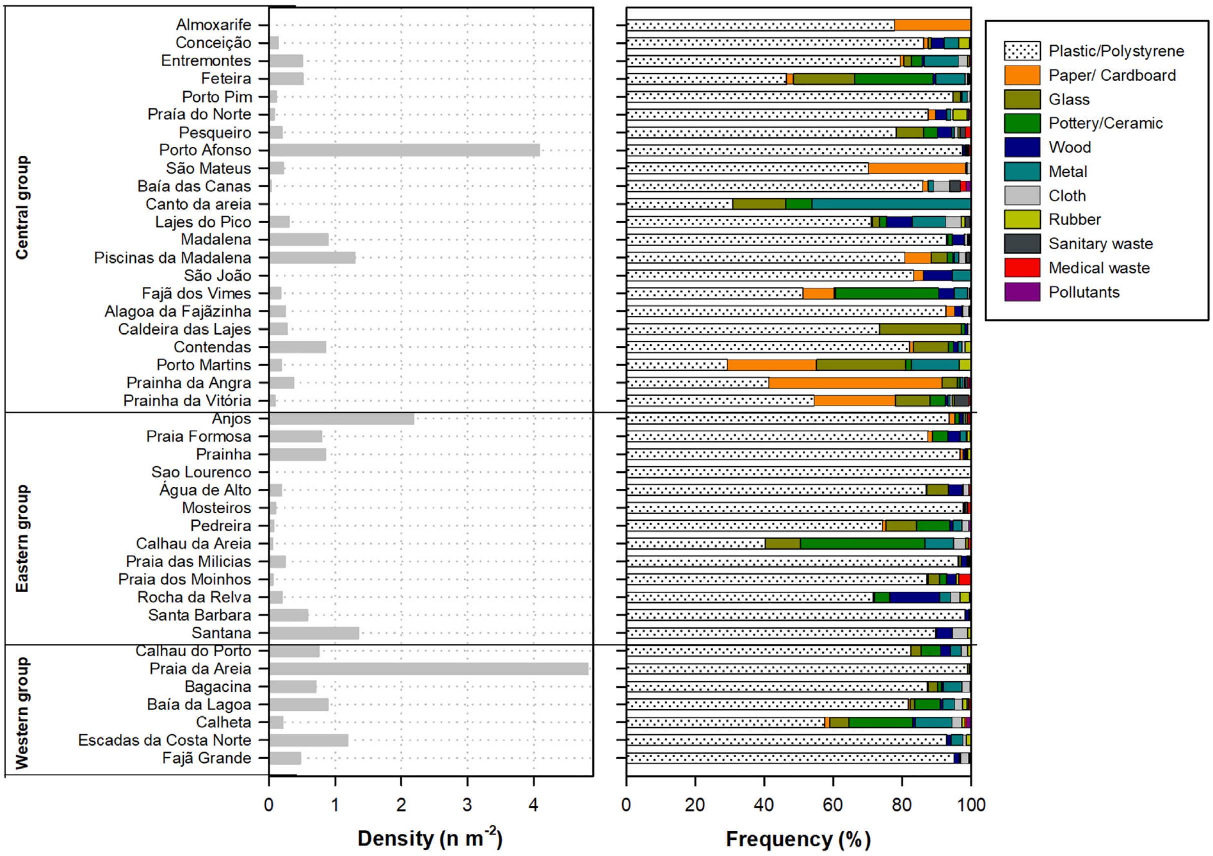

Fig. 2. Litter density (n m^{-2}) (left panel) along with the frequency of materials (%) (right panel) for each beach surveyed between February and March 2016.

backshore (i.e. start of coastal dunes). Sampling was always performed at low tide. Each surveyor monitored a small strip of approximately 2–3 m, recording all macro-litter items (> 2.0 cm in the longest dimension) within the 112 different categories (e.g. plastic bottles, multilayer containers, cans, rubber gloves, etc.) defined by the "Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area" (OSPAR, 2010).

After reaching the 100 m monitoring area limits, surveyors made a turn and proceeded to the next strip. This procedure was repeated until the sea line was reached, and the entire sampling area was covered. At the end of the survey, whenever possible, all litter items were weighed and removed from the beach. Once on site, information regarding weather conditions, beach width and proximity to urban areas or anthropogenic activities was registered. The area sampled varied between 316 m^2 (Porto Martins, Terceira) to a maximum of 6468 m^2 for Praia dos Moinhos in São Miguel (Table S1).

2.3. Data analysis

Litter density was computed for each beach and season. We further classified the 112 different items according to the type of material/category ($n = 11$) (plastic/polystyrene, paper/cardboard, metal, cloth, glass, pottery/ceramics, rubber, medical waste, sanitary waste, machined wood and other pollutants) following OSPAR (2010).

Variation in litter composition between substrate type, island groups, orientation and season factors was tested for significance using a non-parametric test ANOSIM (Analysis of similarity) in PRIMER v6 software. Bray-Curtis similarity was calculated on log (x + 1) transformation of the percentage contribution of litter type for each grouping factors settings, across the entire data set. A similarity percentage analysis (SIMPER) was used to identify the litter contributing to similarities or dissimilarities between factors. Because the data did not follow a Gaussian distribution nor had homogeneous variances, a non-parametric Kruskal-Wallis test was performed, followed by post-hoc pairwise comparisons (Dunn's test) in order to investigate differences in litter density between substrate type, islands and island groups. Statistical analyses were performed using R statistical software. The significance level (α) considered was $\alpha = 0.05$. Statistically relevant differences are considered when p-value < 0.05.

2.4. Relative exposure index

Additionally, we explored the potential role of wind speed and direction to explain the accumulation of litter items on our surveyed sites. A Relative Exposure Index (REI) was computed based on Garcon et al. (2010). A total of 4 wind directions determined by beach orientation were analysed per site per sampling period:

$$REI = \sum_{i=1}^{4} \frac{ViPiFi}{100}.$$

where Vi is the mean monthly wind speed (km h^{-1}) in particular directions categorized in equal compass increments; Pi is the percentage frequency at which the wind blew from the ith compass direction; and Fi is the fetch distance (km). Fetch lengths ≥ 100 km were all set to 100 km. Data on wind speed and direction for each location were obtained from the Global Forecast Model (GFS) with a 0.25 degree resolution, produced by the National Center for Environmental Prediction/National Weather Service/NOAA/U.S.

(https://doi.org/10.5065/D65D8PWK)

3. Results

3.1. Density and spatial distribution

In our first survey, we collected a total of 31,439 items throughout the 42 beaches. The number of recovered items varied between 9 items in Almoxarife (Faial) to a maximum of 5895 items in Praia da Areia (Corvo). Average litter density throughout the archipelago was 0.62 ± 0.15 items m^{-2} (± SE), ranging between 0.01 Almoxarife (Faial) to 4.81 items m^{-2} Praia da Areia (Corvo) (Fig. 2).

Five beaches presented very low densities (< 0.05 items m^{-2}): São João (Pico), Canto da Areia (Pico), Baía das Canas (Pico), Almoxarife (Faial) and São Lourenço (Santa Maria). The beaches presenting highest density of litter (> 1 item m^{-2}) were Escadas da Costa Norte (Flores), Madalena (Pico), Santana (São Miguel), Anjos (Santa Maria), Porto Afonso (Graciosa) and Praia da Areia (Corvo).

No significant differences were found between litter densities for each group of islands (H = 5.5; $p = 0.06$) or between individual islands (H = 11.2; $p = 0.18$). However, we found significant differences in litter densities between substrate types (H = 15.8; $p < 0.001$). Litter density was significantly higher for gravel beaches in comparison to rocky and sandy beaches (Fig. 3). Principal coordinate analysis (PCoA) showed that relative composition of plastic items was proportionally similar for gravel and rocky beaches but different on sandy beaches (Fig. 4). SIMPER results suggested that dissimilarities on litter composition between rock, gravel and sand were mostly driven by the size of plastic fragments. For rocky and gravel beaches, plastic/polystyrene fragments between 2.5 and 50 cm were more prevalent. In opposition, plastic/polystyrene fragments between 2.1 and 2.5 cm were predominant in sandy beaches while larger fragments (found to be more frequent in gravel and rocky shores) were far less abundant on sandy beaches. Non-parametrical analysis ANOSIM did not demonstrate significant differences in litter composition between groups of islands (R: −0.01, $p = 0.49$) or between beach orientation (R: 0.06, $p = 0.13$).

The two beaches with highest densities of litter were southwest orientated (Fig. 5A). Although other factors related to orientation, could be responsible for higher litter densities, this azimuth corresponds to the most frequent wind direction in the Azores between 2016 and 2017 (Fig. 5B and Fig. S1).

3.2. Litter items: composition and materials

From all litter items collected, 87% were made from plastic/polystyrene, followed by paper/cardboard (3%), glass (3%), and others (7%), which included metal, wood (machined), clothes, rubber and

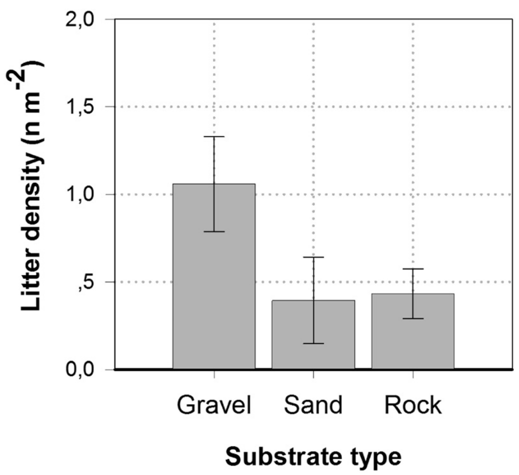

Fig. 3. Average litter density per substrate type for 42 beaches sampled in the Azores archipelago. Error bars represent standard error.

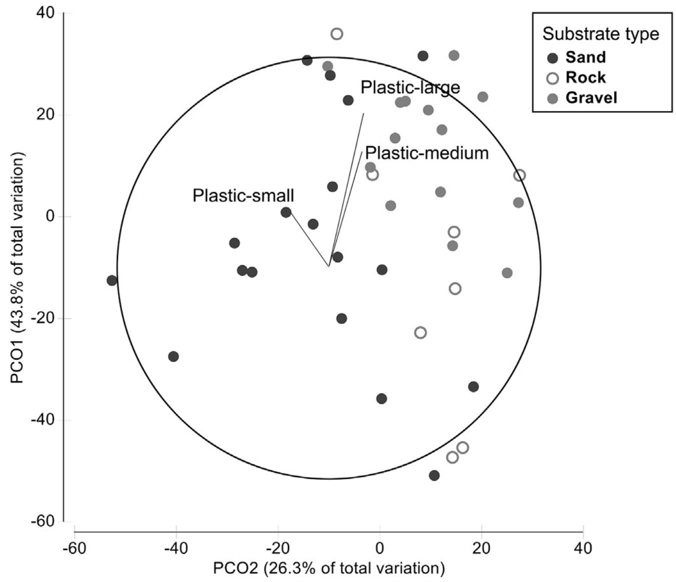

Fig. 4. Principal coordinate analysis (PCoA) of fragments sizes for beaches with different substrate types. Blue lines show the plastic size material (Plastic-small 2.1–2.5 cm, Plastic-medium 2.5_50 cm, Plastic-large > 50 cm) that drives dissimilarities between substrate types.

pottery/ceramic (Fig. 6A). Within plastic items (Fig. 6B), the largest fraction of items (37.6%) was plastic fragments ranging from 2.5 to 50 cm, followed by smaller fragments (2.1–2.5 cm; 26%). Other relevant items included pieces of strings, bottle caps, bottles, shoes or bags (Fig. 6B). Larger plastic pieces (> 50 cm) represented only 3.3% of the litter collected.

3.3. Seasonal monitoring

The six beaches monitored throughout the 24 months period showed high variability in litter density (Fig. 7). Although not entirely consistent throughout the study sites, Autumn was the period with highest densities of litter. During the two-years, a total of 12,741 items were collected. Fig. 7 shows the amount of accumulated litter in relation to the Relative Exposure Index (REI). Higher litter density following an increase in REI was especially evident for Praia do Norte (Faial), São Lourenço (Santa Maria), and Pedreira (São Miguel).

From all litter items collected throughout the 24 months, 90% were plastic/polystyrene items, followed by pottery/ceramic (3.2%), glass (2.3%), metal (1.1%) and other item types (3.4%), which included paper, wood, textile, and medical waste. Within the plastic items category, fragments ranging from 2.1 to 2.5 represented the largest fraction (51.6%), followed by large fragments 2.5 to 50 cm (17.83%). Fig. 8 displays the main type of materials found for the different seasons in the six sandy beaches, highlighting that plastic fragments where the dominating litter items for most of the seasons with the exception of two beaches (Calhau da Areia and Almoxarife) which displayed a higher variability of item typology throughout the entire period with an almost constant proportion of similar materials in Calhau da Areia during the study (Fig. 8).

Non-parametrical analysis ANOSIM showed no statistically significant differences in litter composition between groups of islands (R:0.08, $p = 0.07$); beach orientation (R: −0.03, $p = 0.66$), season (R: 0.05, $p = 0.12$) or beaches (R: 0.32 $p = 0.06$)

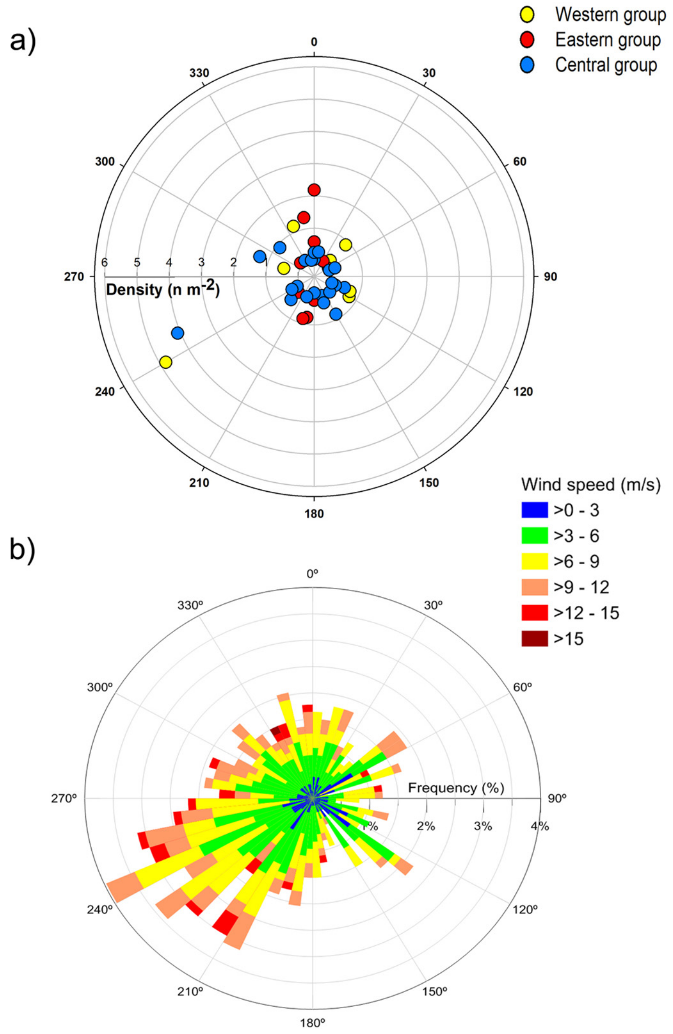

Fig. 5. a) Azimuths with litter density ($n\,m^{-2}$) for the 42 beaches sampled between February and March 2016 and b) stacked wind rose displaying wind speed strength categories (m/s) and frequency (%) of dominating wind direction in the Azores (data for 2016-2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

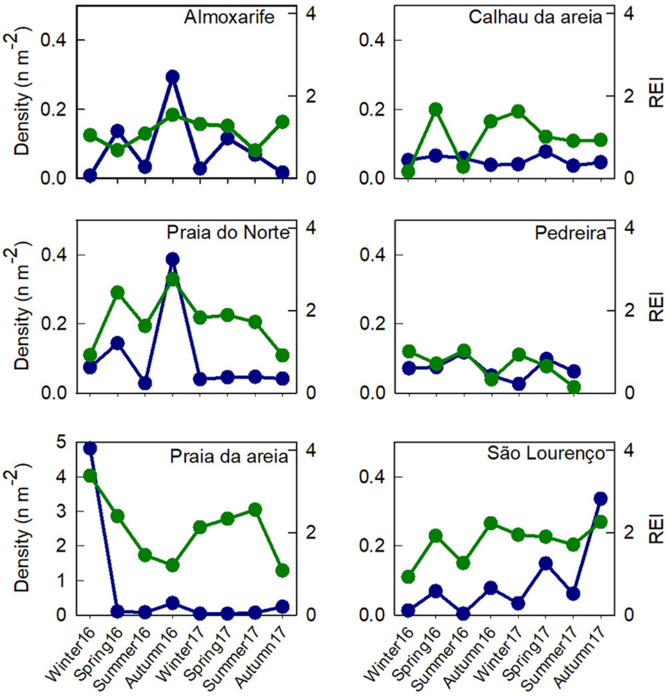

Fig. 7. Litter density ($n\,m^{-2}$) and Relative Exposure Index (REI) in six sandy beaches monitored between 2016 and 2017. Density represented by blue lines and REI by green lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Litter densities

This study revealed that marine litter is ubiquitous and highly variable along the coastline of the Azores archipelago. Some segments of the coastline were found to have low litter densities (< 0.05 items m^{-2}) whilst other sampled areas had higher densities, reaching up to 5 items m^{-2}. The beach with highest litter density (Praia da Areia) was located on the smallest island (Corvo), far away from any urban center and with the smallest population of the archipelago (approximately of 400 inhabitants). The other beach with a high litter density (4 items m^{-2}) is also located in an isolated area on Graciosa island (~5000 inhabitants). The densities on these sites were comparable to the average quantities found in highly polluted beaches in some Caribbean Islands (Schmuck et al., 2017) and on recreational beaches in Uruguay (Lozoya et al., 2016) which are far more populated and touristic than the Azores. Such high densities may be partly explained by exceptional adverse weather conditions (strong storms) prior to sampling, together with the fact that both beaches are in semi-enclosed bay and are subject to only sporadic cleaning efforts. Thus, the amount of litter items found in these sites likely represent long periods of accumulation. In addition, both beaches have a southwest orientation, which matches the prevalent wind direction in the archipelago. Studies on the residence of macroplastics in islands have mentioned the importance of how currents and winds influence the accumulation of

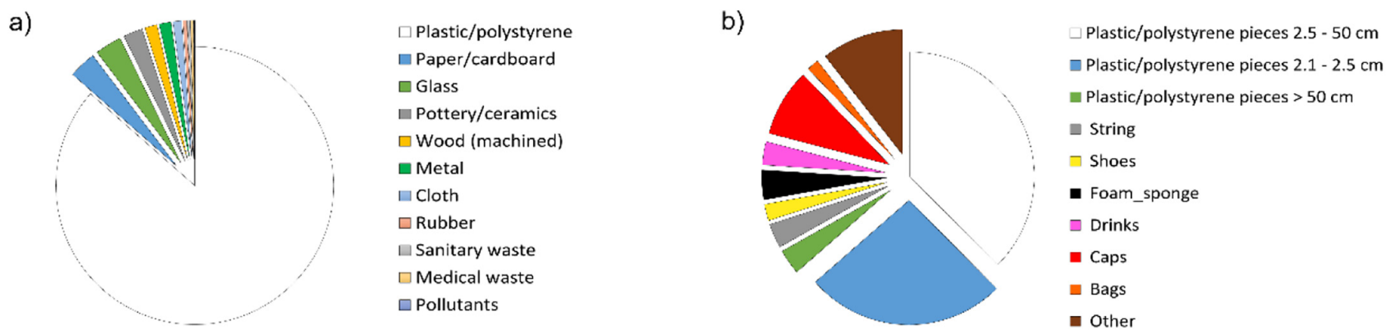

Fig. 6. Composition of litter items recovered from 42 beaches surveyed in the Azores between February and March 2016, grouped by a) frequency of materials and b) frequency of dominating items.

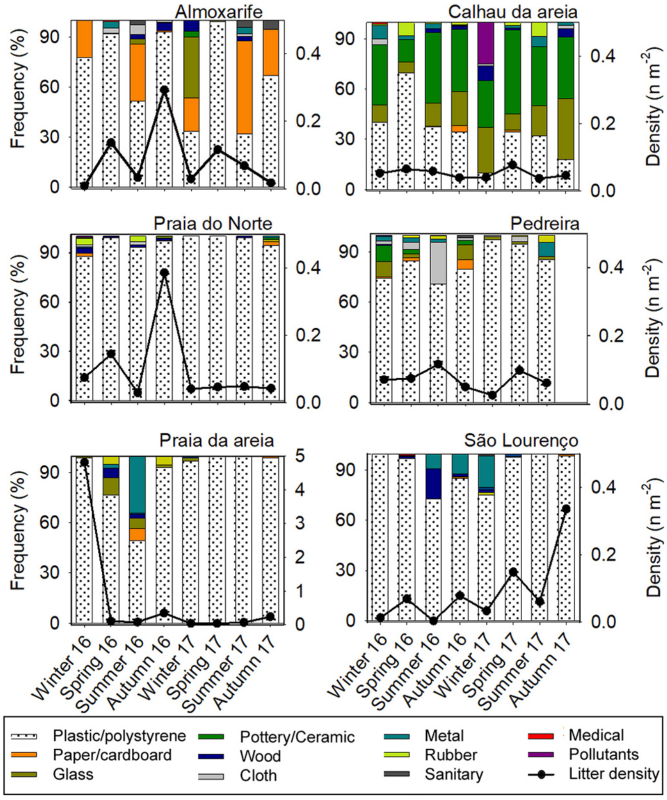

Fig. 8. Litter density (n m^{-2}) and material composition of litter recovered from six sandy beaches over two years.

macrolitter in coastal areas (Kataoka et al., 2015; Hinata et al., 2017; Kataoka et al., 2017; Monteiro et al., 2018).

Average litter density throughout the 42 beaches of the archipelago was 0.62 ± 0.15 litter items m^{-2}, which is within the levels reported for most locations around the Atlantic Ocean (Galgani et al., 2015), although slightly higher than beaches in South Georgia island (South Atlantic) (Convey et al., 2002). A recent review paper (Monteiro et al., 2018) compiling litter densities in linear meters (items m^{-1}) in oceanic islands of the Atlantic Ocean, has identified Faial island in the Azores archipelago as the island with higher litter density (4.61 items m^{-1}). Pieper et al. (2015), identified high variability of litter densities in their study (ranging from 0 to 1.94 items m^{-2}) over 6 months on two sandy beaches. Data provided in the present study provides a more extensive snapshot of the entire archipelago, highlighting differences in the abundance, size and type of litter between beaches with different substrate typology. Gravel beaches, for instance, showed higher densities compared to sandy beaches, which could be partly explained by differences in the retention capacity of the substrates. In opposition to sandy beaches, the increased terrain complexity provided by gravel may trap litter items when the tide is flowing out. For similar reasons, rocky shores were expected to promote the retention of washed litter items (Moore et al., 2001), but our results showed significantly lower litter densities. Items may be trapped between rocks and therefore unreachable, making it difficult to collect or even detect (Kuo and Huang, 2014).

Municipal and public beach clean-ups are also important factors that most likely influenced our results, especially for sandy beaches. Even though we contacted local municipalities to prevent beach cleaning prior to our surveys, it is likely that litter removal still occurred since most of these beaches have regular visitors, known to remove litter items (beachcombing). This activity alongside with impromptu beach clean-ups are becoming habitual and their unpredictability could add bias into assessments of litter deposition for sandy beaches in particular (Moore et al., 2001). Furthermore, litter abundance and typology on the coastline is known to be guided by a complex combination of various factors but also proximity to urban centres (Leite et al., 2014; Nelms et al., 2017); proximity to water streams (Wagner and Lambert, 2018); exposure to oceanic currents (Bouwnman et al., 2016), winds (Walker et al., 2006; Browne et al., 2010; Agustin et al., 2015; Schmuck et al., 2017) or beach orientation, slope and geomorphology (Critchell et al., 2015; Willis et al., 2017).

4.2. Litter composition

The predominant material collected during this study was plastic, which is the most common material found on beaches worldwide (e.g. Widmer and Hennemann, 2010; Thiel et al., 2013; Leite et al., 2014; Moriarty et al., 2016) including in oceanic islands of the Atlantic (Widmer and Hennemann, 2010; Monteiro et al., 2018) and of the Pacific (e.g. Agustin et al., 2015; Blickley et al., 2016; Ribic et al., 2012, Lavers and Bond, 2017). Plastic fragments of different sizes were the most abundant plastic items found throughout the archipelago, similarly to what was found on the beach of a remote island of the Pacific (Lavers and Bond, 2017) and on the windward beaches of Aruba in the Caribbean (De Scisciolo et al., 2016). Obviously, tracing the source of these plastic pieces is a very challenging task. However, it is fair to assume that such items entered the marine environment a long time ago and are probably not from local sources. Plastic fragments are generated by the degradation of larger items by UV photo-degradation, wave action and physical abrasion and after being transported by currents, they are known to accumulate in locations far away from their origin (Barnes et al., 2009). Plastic fragments comprise a significant portion of the litter items accumulating in oceanic gyres (Law et al., 2010; Eriksen et al., 2014) and the location of the Azores at the edge of the North Atlantic Subtropical Gyre, is very likely acting as a sink for these items. However, we cannot totally exclude that a portion of plastic fragments could also originate from the fragmentation of large items from local sources (e.g. from landfills or rivers) that remained in the area before being washed ashore.

4.3. Seasonal trends

The nine beaches that were subsequently surveyed seasonally for two consecutive years displayed a high temporal variability in litter density. Because every sampling involved the removal of all litter items from the beach, each density estimate represents litter deposition over the three-month period as opposed to standing-stock surveys (Ryan et al., 2009). For most beaches, the lowest litter input was recorded during the summer with exception of Pedreira (São Miguel). Although, these lower abundances corresponded to a decrease in relative exposure index, it is also when clean-ups are more frequent because of the elevated use of these beaches by tourists. Peaks in litter deposition occasionally corresponded to increase in the relative exposure index (REI) for some beaches but it was not consistent throughout the different locations and seasons. Previous studies found correlations between wind exposure and abundance of litter items (Walker et al., 2006) whereas other studies could not identify such a relationship (Blickley et al., 2016; Prevenios et al., 2017). Our mixed result could be indicative that some beaches are more influenced by wind exposure than others, but most importantly, they highlight that litter deposition is guided by a suite of environmental and anthropogenic factors that are not easily distinguishable with short time series.

Overall, plastic fragments were the most dominant items collected on the 6 beaches throughout the two years. Yet, litter composition displayed some minor temporal and spatial variation along the two years. As opposed to all other locations dominated by fragments, Calhau da Areia was a distinct location because of the high range of material identified during the two-years in which glass, ceramic (pottery), wood and rubber were the predominant materials in this beach.

These items are likely to result from local users, being either unintentionally abandoned and/or dumped. On Almoxarife, paper/cardboard materials are presents practically during the whole year. This could maybe due to the proximity to bars and restaurants that might increase the presence of these materials (e.g. newspapers, cigarette boxes).

5. Conclusion

This study represents a snapshot of the abundance and typology of marine litter throughout the Azores archipelago demonstrating a high spatial and seasonal variability, which reflects the patchy distribution of litter in the marine environment (Galgani et al., 2015). The predominance of unidentifiable plastic fragments suggests that the bulk of items polluting the coastline is not of local origin. Maintaining programs for monitoring beach litter will be essential to disentangle the role of environmental and anthropogenic factors responsible for the spatio-temporal patterns of litter on Azorean beaches. Such understanding will allow a more detailed assessment of sources but also act as a management tool to evaluate the success of regional and international policies aimed at reducing the input of marine litter in the Altantic Ocean.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2018.05.038.

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