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Marine litter arrived: Distribution and potential sources on an unpopulated atoll in the Seaflower Biosphere Reserve, Caribbean Sea

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ABSTRACT

The Albuquerque atoll was studied as a representative natural laboratory to explore the role of sea-based sources of marine litter. This work aimed to identify the small-scale spatial distribution of marine litter (i.e., plastic, glass, paper, and others) as well as to explore the connectivity among the atoll habitats (sand beach, water surface, and reef) to give insights of potential sources of marine litter (> 5 cm), mainly plastics. Marine litter was dominated by plastic items, as expected, with an average value of 0.5 items/m^2. Large microplastics (1–5 mm) were also sampled on beaches with an average value of 90 particles/m^2. In the atoll inner lagoon, marine litter was also composed by plastic, mainly fragments (average 0.059 items/m^3). The predominance of plastic fragments on both the sea surface and beaches of the atoll makes inferences on sources limited. However, o fishing activities and sea-based sources might be relevant since local sources are very limited.

1. Introduction

One of the most widespread and long-lasting recent changes on the Earth's surface is the accumulation and fragmentation of plastic marine litter. In a few decades, as plastic production has grown exponentially since the 1950s, it has accumulated in measurable amounts in terrestrial and oceanic environments (Barnes et al., 2009; Brown and Takada, 2017). As a consequence, plastics are protagonists among other marine litter 'species' (e.g., paper, metal, glass). A recent study estimated that 192 coastal countries generated 275 million metric tons of plastic waste only in a year (the base year 2010), and significant amounts (4.8–12.7 million metric tons) have reached the oceans from land-based sources (e.g., rivers, sewage, street runoff) during that period (Jambeck et al., 2015). Despite efforts to prevent and reduce litter at sea, there is evidence that the problem persists and continues to grow.

Insular habitats are therefore also polluted by marine litter, which act as their temporary or final sinks. This includes islands in a range of protection status under regional, national, and international legislations. For example, the Tern Island in the Northwestern Hawaiian Islands, one of the most remote archipelagos in the world, is part of the Papahānaumokuākea Marine National Monument and is therefore under restrict legislation and has very limited human occupation (as well as limited local sources of marine litter). However, the region faces chronic problems associated with marine litter from sea-based sources (i.e., boats, aquaculture, shipping) (Agustin et al., 2015). The studies on islands with special legal status, such as Biosphere Reserves, have also reported threats associated with marine litter. In the Galapagos Biosphere Reserve, Ecuador (Mestanza et al., 2019) and the Juan Fernández Archipelago Biosphere Reserve, Chile (Hidalgo-Ruz et al., 2018) for example, both island-based and marine-based sources were reported, illustrating how marine litter is widespread over a range of geographical latitudes in the sea.

Islands in the Caribbean Sea are no exception (see literature reviews by Ivar do Sul and Costa, 2007; Monteiro et al., 2018). Marine litter, especially macro (> 5 mm) and microplastics (< 5 mm), has been recorded mainly in touristic islands, including the island of San Andrés (Colombia) (Portz et al., 2018), which is a part of the Seaflower Biosphere Reserve (Fig. 1A), that also includes some of the most isolated coral reefs in the Southwestern Caribbean (Sánchez et al., 2019).

On the island of San Andrés, a strong positive correlation between

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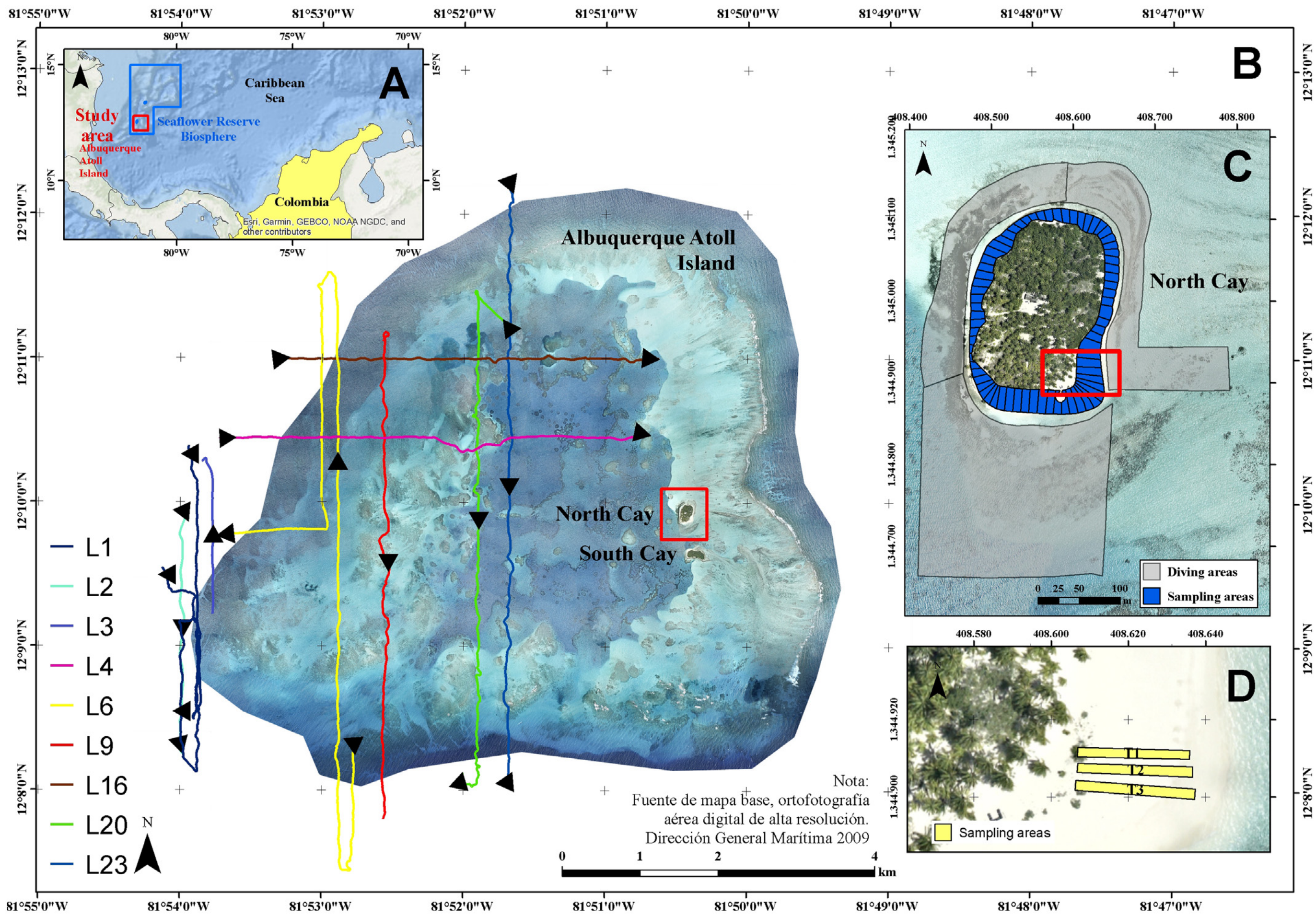

Fig. 1. (A) Location of the Albuquerque atoll and the Seaflower Biosphere Reserve in the Caribbean Sea. (B) Direction – represented by arrows – and extension of surface plankton tows (named L1 to L23). (C) Beach transects were sampled for marine litter > 5 cm quantification and qualification (blue) and diving area is sampled for benthic litter (light grey). (D) Microplastics were sampled in three transects (yellow) as representative of all the beach area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

human activities and the occurrence of plastic litter was previously reported (Portz et al., 2018), and a similar pattern was also described for other populated islands in the Atlantic Ocean (Monteiro et al., 2018). However, within the Seaflower Biosphere Reserve, there are islands where human activities are restricted, representing 'natural laboratories' for understanding the significance of surface currents on the transport of marine litter from sea-based sources at small-spatial scales. Therefore, this paper aims to identify the small-scale (< 1 km) spatial distribution of marine litter accumulation in the Albuquerque atoll, Seaflower Biosphere Reserve, Colombia (12° 10′ N, 81° 51′W). Moreover, the connectivity between habitats within the atoll (i.e., sandy beach, water surface, reef) was explored in relation to marine plastic litter within a range of sizes.

2. Materials and methods

2.1. A natural laboratory in the sea

The Seaflower Biosphere Reserve (SBR) is the largest Marine Protected Area in the Caribbean and the second in Latin-America (Guarderas et al., 2008). It comprises a variety of ecosystems that have together higher levels of biodiversity when compared with other regions in the Caribbean Sea (CCO, 2015). Its biological and ecological importance has been highlighted in the literature, for instance, regarding corals, echinoderms, fish, reptiles, and seabirds (Prato and Newball, 2015; Acero et al., 2019; Borrero-Pérez et al., 2019; Ramirez-Gallego and Barrientos-Muñoz, 2020).

The Albuquerque atoll is located about 37 km southwest of San Andrés Island (the largest island within the reserve) and 190 km east of the Nicaragua coast. It has a circular shape and about 8 km diameter in the E-W direction (CCO, 2015, Fig. 1B). The atoll is a semi-closed basin protected by a coral reef with average depths of 9 to 15 m in the inner lagoon. Two banks emerge from it, the North Cay (~412 m^2) that permanently shelters a military base from the Colombian Navy and where this study was conducted, and the South Cay, which is eventually occupied by fishermen. These sand banks are separated from each other by a shallow canal (~400 m wide) (Diaz et al., 1996).

The climate in this area is classified as isomegathermal with year-round stable air temperatures (27.4 ± 1 °C) (Gómez, 2012). Predominant winds are the east-north and east-northeast Trade Winds with average speed between 4 m/s (May to October) and 7 m/s (December to July). Faster winds eventually reach the atoll during the hurricane season (May to November) as it is located within the Caribbean hurricane belt (Gómez, 2012). However, no such conditions were observed in the months when the sampling campaign was carried for this work.

The Caribbean current (< 0.5 m/s) is the predominant surface current in the area (Oey et al., 2003), which is an oligotrophic current with constant salinity (34.0–36.3) (Diaz et al., 1996). However, small-scale circulation patterns are unknown. Therefore, in order to understand circulation patterns and their potential correlation with the deposition of marine litter, waves and superficial currents were modeled (see Supplementary material).

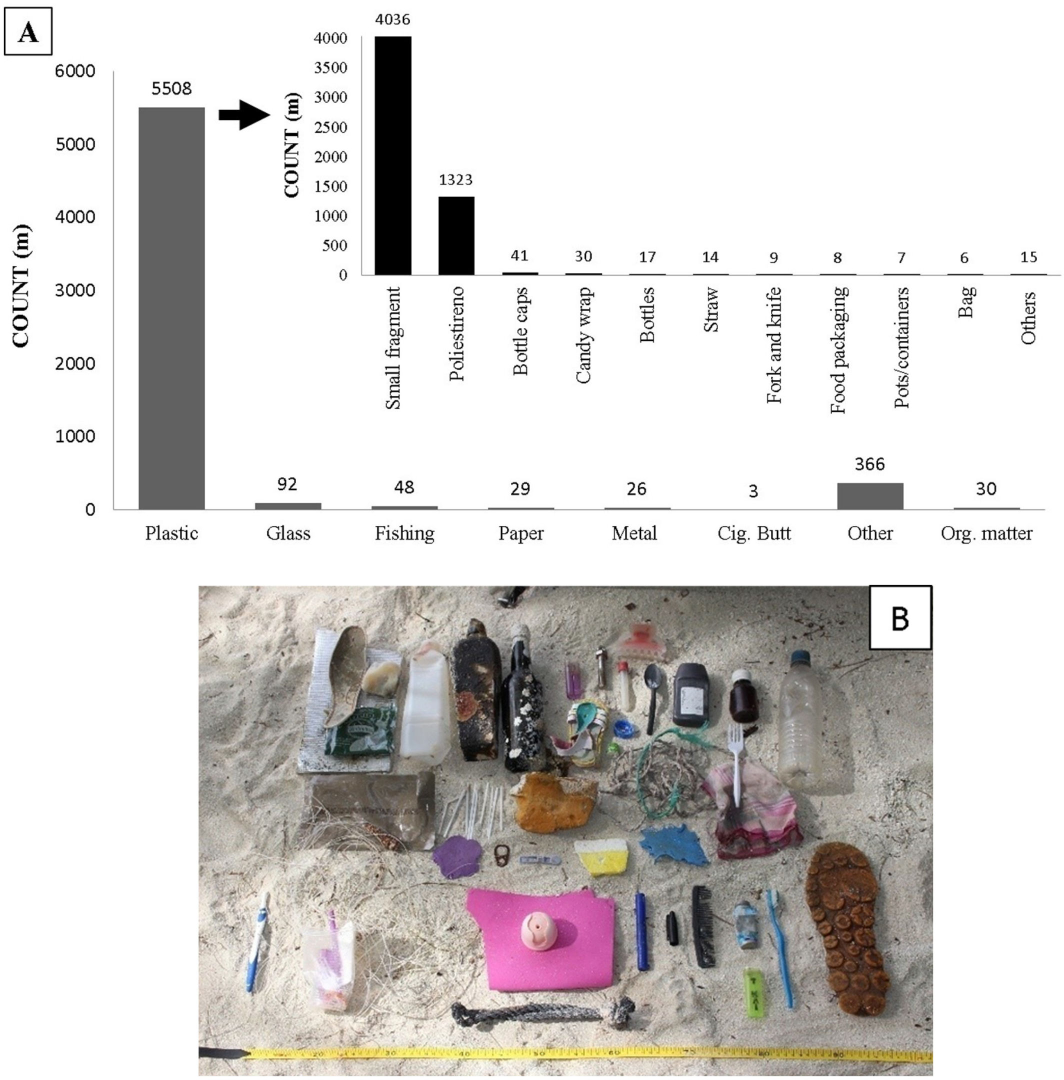

Fig. 2. (A): Types of materials and/or potential sources of marine litter > 5 cm sampled at the beach using transects (grey columns). Potential sources here are fishing-related activities. In detail (black columns), plastic items only. (B) A snapshot of the items > 5 cm sampled at the North Cay in the Albuquerque atoll.

2.2. Sampling strategy

The samples were collected during the IV Scientific Expedition Seaflower (October 2018), a common effort between the Colombian Ocean Commission and the Colombian Navy. In the North Cay, the military crew (11 persons) systematically removes relatively large marine litter items (> 10 cm) from sandy beaches. A cleaning campaign was conducted just before the arrival of the researchers for this research.

Marine litter survey on beaches was conducted following well-established protocols (UNEP, 2009; Galgani et al., 2013). Briefly, seventy-one 10 m wide transects were used for sampling, covering the entire circumference of the North Cay (Fig. 1C). Each transect covered the beach from the strandline to the beginning of vegetation or dunes. The items that were larger than 5 cm were then classified according to the type of material (plastic, paper, cigarette butts, glass, metal, non-anthropogenic organic matter, and others i.e., materials that do not fit into any of these material categories) and/or source (e.g., fishing related activities). Cigarette butts are made mainly of cellulose-based polymers and thus were quantified separately among the main litter categories (Fig. 2A, Araújo and Costa, 2019). Plastic items were further classified as disposable items (e.g., straws, bottles), fishing-related items (e.g., rope, floats), films (e.g., bags, wrappers), fragments, clothing (e.g., shoes), and miscellaneous items (e.g., toys, cosmetics).

Microplastics were sampled and isolated from sediments using well-established protocols (UNEP, 2009) with minor modifications. Three transects set perpendicular to the waterline were sampled along the beach (Fig. 1D). The samples were taken from the windward side of the atoll bank as representative for its entire circumference. Within each transect, 2 × 1 m quadrants were sampled at distances of 1–2 m, 7–8 m, 14–15 m, 23–24 m, and 28–29 m from the waterline, integrating a representative sample for the entire beach length. In each quadrant, only the first five centimeters of sediments were sampled. Sediments were immediately stirred for 5 min in silicone tanks filled with natural seawater; after resting, the water from the tanks was filtered through 500 μm and 60 μm sieves, while the remaining particles were stored in glass containers for further analyses. For this study, only the particles retained by the 500 μm filter are reported.

The surface water sampling was also done following a protocol previously established (Galgani et al., 2013). The samples were taken using a cylindrical plankton net (80 μm mesh, ø = 25 cm) equipped with a flowmeter. The net was set at a distance of 8 m from the boat to avoid turbulence. Tows were conducted at a speed of ~4 knots along transects with variable lengths from 2 to 10 km (Fig. 1B). Transects represent the entire navigable area in the atoll lagoon. The volume-reduced samples were stored in glass jars, and density separation was conducted following a well-established protocol (INVEMAR, 2017). The identification and quantification of microplastic particles were carried out under a stereoscopic microscope by experienced researchers (L.P and R.P.M). When the nature of a particle was unclear, individual particles were tested with 10% hydrochloric acid to differentiate carbonate particles from plastic ones. The carbonate particles immediately react to the acid and produce bubbles; this is not observed in case of plastics. Microplastic particles were reported in relation to their size and predominant color. The same procedure was applied for large microplastic particles sampled on beaches when appropriated.

Free diving was used to sample marine litter deposited on the bottom of the reef. Two divers covered the whole extent of the diving area (~80,000 m^2), and all identified items (> 5 cm) were collected for subsequent quantification and classification (Fig. 1C).

2.3. Statistical analysis

The factorial analysis of variance (one-way ANOVA) was used to determine significant differences in the amount of marine litter between windward (sector NE of the atoll bank, corresponding to transects 1–11 and 66–71, and sector SE of the atoll bank, corresponding to transects 12–29), and leeward (sector NW of the atoll bank, corresponding to transects 48–65, and sector SW of the atoll bank, corresponding to transects 30–47, Fig. S1) beaches on the atoll bank. Tukey's posthoc test was then applied to determine which differences were statistically significant ($p < 0.05$). All statistical analyses were performed using GraphPad Prism 7, California, USA.

3. Results and discussion

3.1. Characteristics of marine litter and large microplastics

This study confirms the presence of marine litter of different sizes at the Albuquerque atoll. A total of 6122 items > 5 cm was collected in the beaches at the North Cay ($N = 71$ transects) with an average of 0.5 items/m^2 (0.03–1.94 items/m^2). Large microplastics comprised heterogeneous particles with diverse shapes and colors. On the beach, a total of 679 particles were sampled. Densities were similar in all transects, with 99, 141, and 99 particles/m^2 in transects 1, 2, and 3, respectively (Table S1). On the sea surface ($N = 9$ transects, Fig. 1B), a total of 236 microplastics were sampled, but some relatively larger items, not a target of this sampling method, were also found. Six plastic fragments (5–10 cm), four expanded polystyrene foam (PS) fragments, as well as entire positively buoyant objects ($N = 15$ items, e.g., three plastic bottles, one plastic ball, one PS container) were sampled. The density of marine litter varied between 0.009 and 0.244 particles/m^3 in transects L2 and L6, respectively (Table S2).

Marine litter pollution has now disseminated across the surface of the planet. Henderson Island, in the South Pacific Ocean, for instance, has been reported to have an exceptional accumulation of marine litter in a relatively short time (Lavers and Bond, 2017). Therein, the densities of marine litter items on beaches vary from 20.5 to 671.6 items/m^2 and are at least one order of magnitude higher than at the Albuquerque atoll. The densities for Albuquerque are also low compared to a remote island of the Colombian Caribbean sea, Isla Arena (2.87 items/m^2), with strong continental influence and therefore high accumulation rates of marine litter (Rangel-Buitrago et al., 2019). In the North Cay, the accumulation of marine litter has been occurring since a long time, but as a cleaning campaign was conducted shortly before the sampling, it can be assumed that the items > 10 cm have recently (< 1 month) deposited on the beach face.

As expected, most of the litter items in the North Cay beaches were made of plastic (> 90%, $N = 5508$), followed by materials classified as others (6%), glass (2%), and fishing related items (0.8%) (Fig. 2A). The category "others" included building material (2%) and Tetra Pack (1%), as well as rubber, fabrics, and non-plastic shoes (1% in total). The prevalence of plastic (74%) in relation to other types of materials was also reported at the San Andres island (Portz et al., 2018), the most populated island (> 60,000 inhabitants) in the SBR. The prevalence of plastic in the environment is, however, a topic of global concern (Moore, 2008; Cole et al., 2011; Jambeck et al., 2015). There have recently been (< 10 y) many publications on the subject, but the peak of the scientific attention has yet to come in the next couple of years (Halden, 2015), at least in relation to microplastic pollution. The literature now includes data outside the natural environment, such as the presence of microplastics in table salt, honey, and bottled water (e.g., Lee et al., 2019).

Among items classified as plastics, > 96% were fragments from larger items. In some cases, not fragments, but entire items were sampled, such as bottle caps and candy wrappers, as well as relatively larger items such as bottles, forks and packaging (Fig. 2B). The fragments included pieces of ordinary plastic polymers (i.e., polypropylene, polyethylene) that together represent > 50% of all virgin plastic resins ever manufactured (Geyer et al., 2017). Since these polymers are used in large volumes for various purposes, it is expected that they will reach marine environments in large amounts compared to other types of polymers, e.g., polystyrene (Andrady, 2017). Therefore, the prevalence of these fragments makes insights on potential sources of plastics limited. PS fragments are exceptions, as they might be directly related to fishing activities at sea. PS is mainly used in fishing material because it is relatively less dense than seawater and thus used to support floating fishing gears on the sea surface.

Furthermore, plastic fragments are apparently dominant on remote beaches as compared to urban beaches. In the SBR, 73% of all items were plastic fragments at the relatively pristine beaches in the North Cay (present study), while in San Andrés it represented 59% (Portz et al., 2018). The same pattern, i.e., the predominance of plastic fragments in remote beaches has also been reported in the Lanzarote Biosphere Reserve at the Canary Archipelago (Herrera et al., 2018; Edo et al., 2019). The difference is apparently marked by a relatively higher proportion of cigarette butts on touristic/urban beaches, i.e., San Andres island in the Caribbean Sea (Portz et al., 2018) and Gran Canarias Island in the Atlantic Ocean (Herrera et al., 2018), where local sources of marine litter are relatively more important.

3.2. The size distribution of marine litter: insights on litter sources

The distribution of plastic litter at sea is very irregular for different reasons, such as winds and superficial marine currents, the geography of the coastline, and proximity to continental sources of litter, e.g., estuaries or to shipping routes (Barnes et al., 2009). While estuaries are recognized as significant sources of marine litter on continental coasts, marine currents might be more significant as potential sources of litter in remote islands (Duhec et al., 2015; Andrades et al., 2018; Edo et al., 2019). In this study, significantly higher amounts of marine litter were identified on beaches in the SE sector of the atoll bank, considering both the total number of items (48%) and only plastics (51%, Fig. 3). This sector of the bank faces the external part of the Albuquerque atoll and is then directly influenced by winds and, consequently, by superficial marine currents (Fig. 4A), which may play a role in the transport of items to beaches. The geography of the atoll arc might also play a role in the retention of items (mainly fragments) on the beach; for example, wave heights reach about 0.4 m in the SE-E sector of the North Cay (Fig. 4B) that potentially avoid larger items to be eventually removed from the beach face.

Earlier studies have reported the importance of circulation patterns in the transport of marine pollutants, including in the Caribbean Sea (Rangel-Buitrago et al., 2019). Monteiro et al. (2018), when analyzing the literature, identified that windward beaches, which are directly affected by winds, ocean currents, and waves, are frequently more polluted by relatively larger plastics from sea-based sources as compared to leeward beaches in islands. However, on touristic beaches

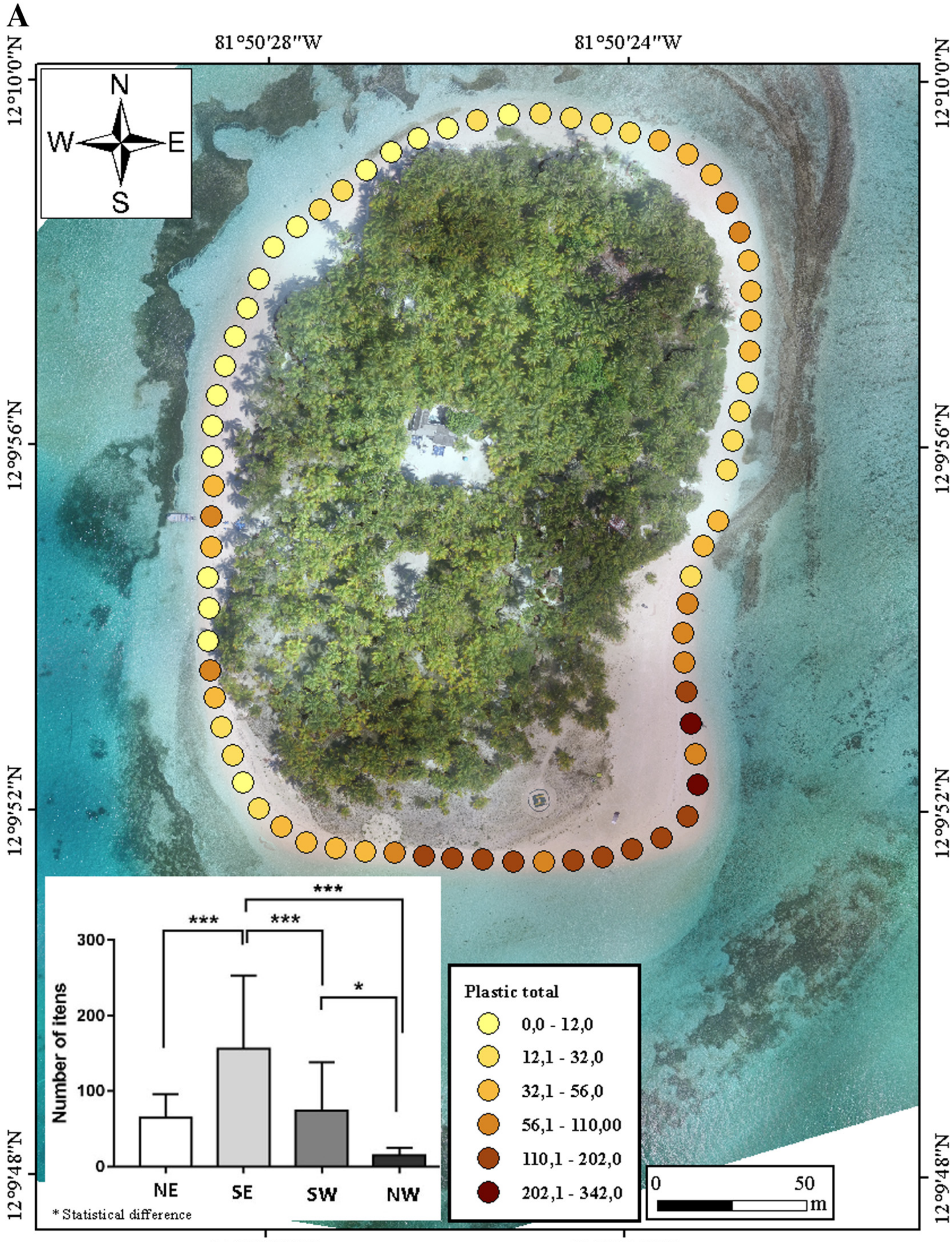

Fig. 3. Distribution of marine litter of > 5 cm in size in the 71 beach transects. A) Total items. B) Plastic items only. Statistical significance: *0.05, **0.01, ***0.001.

sheltered at the leeward side of islands, clean-up campaigns effectively remove macroplastics. Therefore, the contribution of sea-based and island-based (local) sources may be more prominent for smaller plastics and microplastics that are not effectively removed during beach cleaning (Schmuck et al., 2017).

In the North Cay (present study), the occurrence of large microplastics (1–5 mm) from sea-based sources was confirmed. Therefore, plastic resin pellets, the raw material from which plastic items are made (Ivar do Sul et al., 2009), were recognized among microplastic particles (Table S1). This indicated that at least some part of the particles is transported via sea currents, as there are no petrochemical facility in the atoll. The absence of plastic pellets in the inner lagoon can be explained by the partial isolation of the lagoon compared to its surroundings. Plastics are preferentially deposited on the SE sector of the atoll bank, when transported via sea currents rather than reaching the inner lagoon (Fig. 4).

Overall, the predominance of plastic fragments in the atoll makes it difficult to infer a particular origin. However, few local sources of plastics in the atoll, regardless of size and type, indicate that adjacent waters, i.e., sea surface currents might be the major contributor of marine litter and plastics to the atoll (Ivar do Sul et al., 2014).

After reaching the beach face, plastic fragments are exposed to UV rays from the sunlight and mechanic abrasions caused by waves, which make the fragmentation further smaller (Barnes et al., 2009).

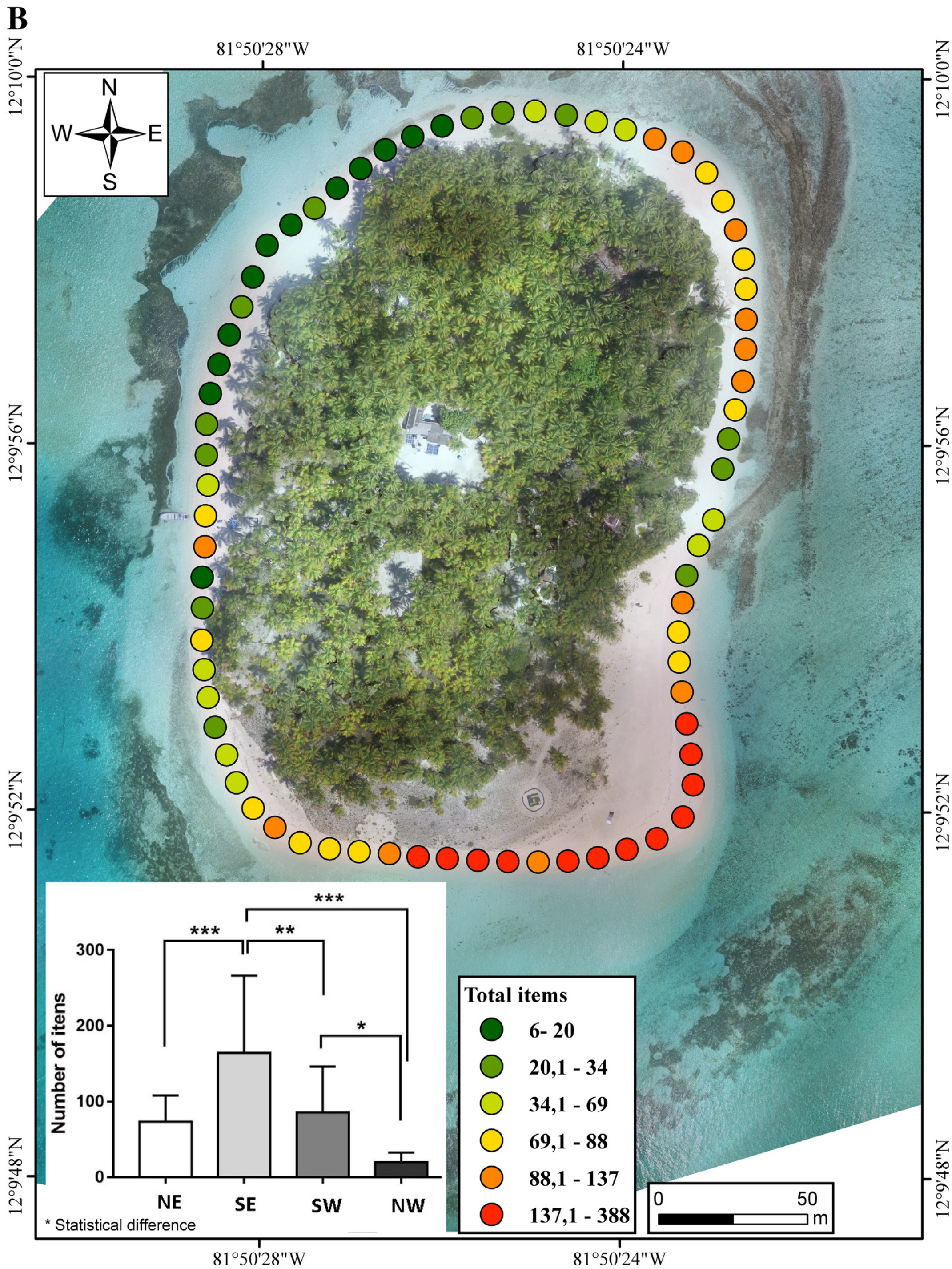

Fig. 3. (*continued*)

Microplastic particles are then of the same size as that of sediment sand grains and are likely to be sorted by the same hydrodynamic processes between the beach face and the insular shelf (Ivar do Sul et al., 2014). Therefore, beaches can also act as a temporary source of microplastics to the adjacent waters and beyond.

The marine litter items deposited on the bottom of the reef (12 items in total; Fig. S2) were mostly related to fishing activities, as they included fishing lines, anchors, and a harpoon. Other items of general use, such as a glass bottle and a plastic bag, were also sampled. Items were sampled mainly in the shallow canal that separates the North Cay, where beach sampling was conducted, and South Cay, where fishing activities are commonly reported. This indicates local fishery as a significant source of items, a pattern that has been previously reported in oceanic islands and also on undeveloped continental beaches (Ribic et al., 2012; Eriksson et al., 2013; Lavers and Bond, 2017). In the SBR, the fishery has been recognized as a traditional and intense activity (CCO, 2015; Gavio et al., 2015), and it might also be a significant source of plastics and microplastics to the atoll and beaches.

3.3. Vulnerability of thereef biota to marine litter

The resident and migratory species in reef environments are negatively affected by marine litter and microplastics (see Chapron et al., 2018; Kroon et al., 2020; Lamb et al., 2018; Tan et al., 2020). There is

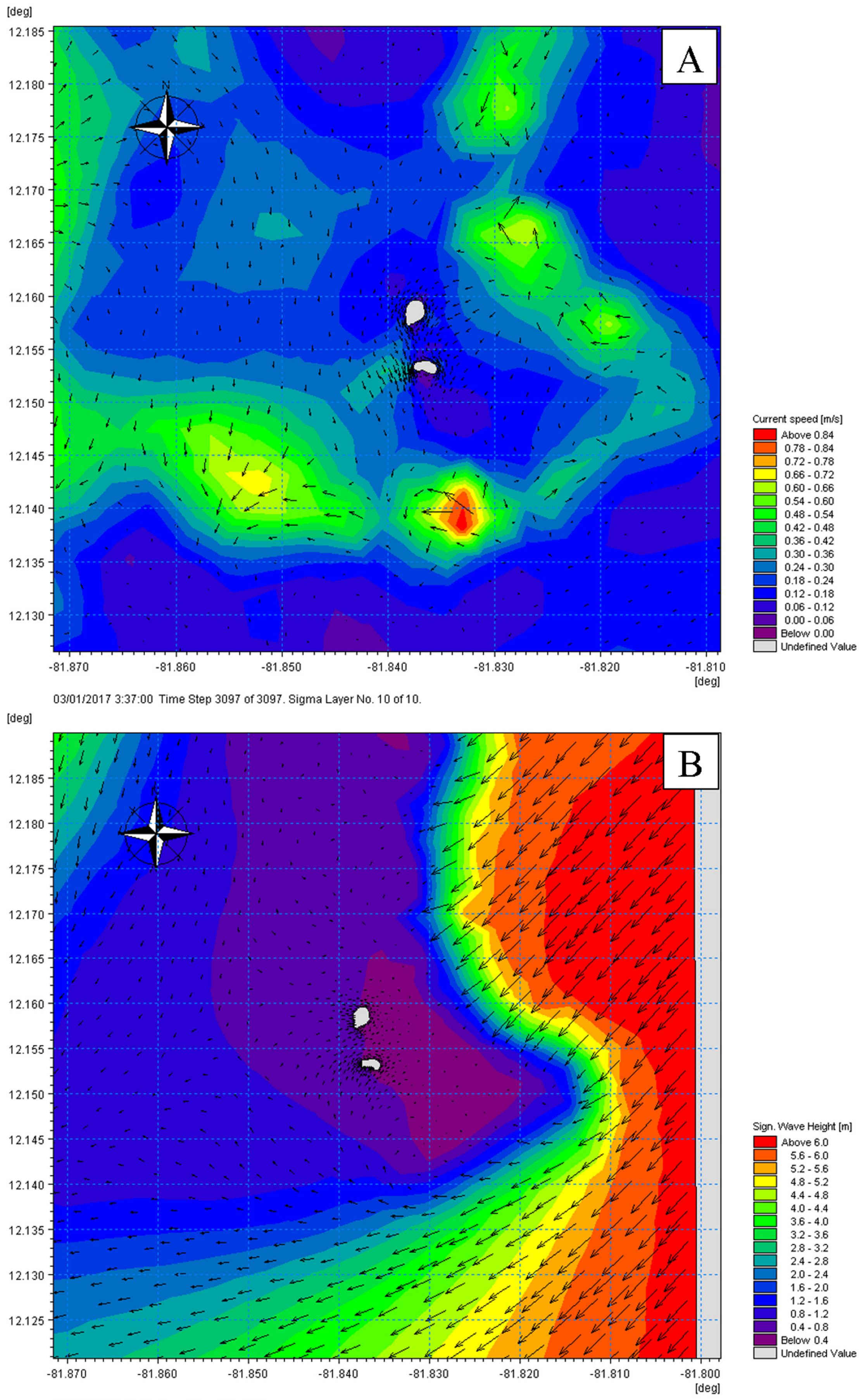

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Fig. 4. A) The surface currents speed and direction according to the model MIKE21. B) A significant wave height for the Albuquerque atoll area was seen (see Supplementary material for more information).

scientific evidence that species within all levels in marine food webs are affected, while the extent of impact may vary within groups. It has been hypothesized that microplastics are ingested because they are similar in size to many microorganisms belonging to the plankton and benthos communities. Some characteristics of microplastics, such as shape and color, could, therefore, be relevant, for example, to some seabird species that actively feed in the sea. This might be relevant at the SBR since 157 seabird species have been reported in the area, of which 55% are considered endangered (Prato and Newball, 2015).

It has been hypothesized about seabirds that specific colors of microplastics, such as blue and dark colors, are potentially more ingested as they resemble the color of their prey in the sea (Kühn et al., 2015; Zhu et al., 2019). At the Albuquerque atoll, microplastics were found in many colors, mainly orange/brown (29%), green (21%), and white (22%) but also grey (10%), blue (9%), red (3%), yellow (6%) and black (1%) (Fig. S3). The occurrence and relative predominance of these colors are in accordance with other global studies on microplastics (Veerasingam et al., 2016; Baptista Neto et al., 2019; Chen and Chen, 2020; De-la-Torre et al., 2020). However, positive correlations between the amount of specific microplastic colors in the environment and their relative ingestion rates are difficult to analyze and are generally not reported in the literature. Rather, ingestion rates are more related to the availability of microplastics in the environment than to a potential color selectivity by organisms (Kühn et al., 2015).

Plastics and microplastics are not chemically inert. There is also a significant body of literature related to the potential of microplastics to concentrate persistent organic pollutants (POPs) at levels several orders of magnitude higher than those in the sea, and it also includes the microplastics sampled within insular habitats (Herrera et al., 2018). Therefore, microplastics do not only have physical impacts on the environment, as their accumulation might concentrate POPs to unprecedented levels, they may also have other associated impacts on the biota (Bouwman et al., 2016).

Finally, being the largest reef system in the Caribbean Sea, the occurrence of microplastics might also be significant to the survival of reef-building corals. Recent evidence suggests that large plastics promote coral diseases by causing damage to coral tissues through abrasion (Lamb et al., 2018). The unicellular individuals that compose coral reefs are also prone to ingest microplastics, although the extension of this impact is still to be confirmed (Hall et al., 2015).

4. Conclusions

This study represents a snapshot of the plastic contamination in the Albuquerque atoll, an unpopulated atoll in the Caribbean Sea. Once the occurrence of marine litter is confirmed, it is necessary to explore their potential sources to take steps for more effective management and regulations in the Seaflower Reserve.

As expected, plastic litter was reported in a wide range of sizes, from macro to large microplastics, and was present in all the beaches and also in the pelagic habitat around the island. The predominance of fragments highlights the atoll vulnerability to marine plastic litter since palliative measures (i.e., clean-up operations) are inefficient to remove them from beaches.

The predominance of fragments also makes it difficult to determine the sources. However, local sources are limited and indicate sea-based sources as significant to the atoll beaches. Once on the beach, plastic fragments continue to fragment and eventually incorporate in the natural sediment cycles, and then beaches are also sources of microplastics to the sea.

The biota in insular environments is particularly affected by plastic pollution. In the Albuquerque atoll, seabirds and the coral reef system were taken as representatives of a range of organisms that are at the menace of plastic pollution in the sea. Once the problem is reported, the biota is the next step to be investigated to understand the extension of the impact.

CRediT authorship contribution statement

Luana Portz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing - original draft, Writing - review & editing. **Rogério Portantiolo Manzolli**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Visualization, Writing - original draft, Writing - review & editing. **Guido Herrera Vasquez**: Data curation, Formal analysis. **Liliana Garcia Laiton**: Data curation, Formal analysis, Investigation. **Diego Andres Villate Daza**: Formal analysis, Funding acquisition. **Juliana A. Ivar do Sul**: Writing - review & editing.

Declaration of competing interest

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

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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.2020.111323.

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