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Where does marine litter hide? The Providencia and Santa Catalina Island problem, SEAFLOWER Reserve (Colombia)

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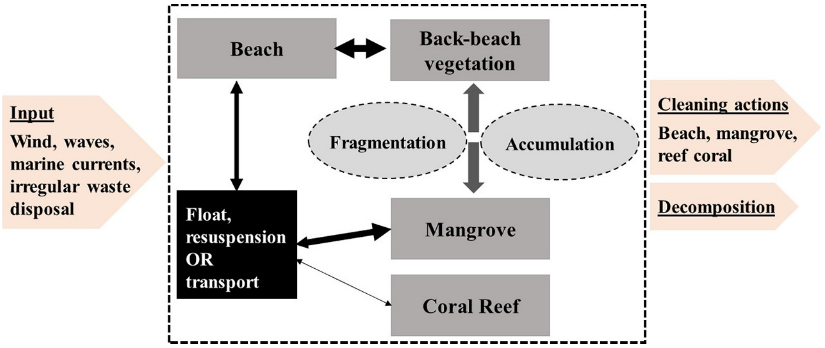
HIGHLIGHTS

- Island ecosystems are traps for marine litter which can act as final sinks.
- The marine litter, mainly plastics, was found in all ecosystems.
- Litter pollution was high in mangroves and back-beach vegetation.
- There are important marine litter flows between ecosystems.
- Litter accumulation rates varied between 0 and 16.17 items.m^{-2}

GRAPHICAL ABSTRACT



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ABSTRACT

The SEAFLOWER Biosphere Reserve (SBR) is the largest Marine Protected Area in the Caribbean Sea and the second largest in Latin America. Marine protected areas are under pressure from various stressors, one of the most important issues being pollution by marine litter, especially plastic. In this study our aim is to establish the distribution pattern and potential sources of solid waste in the different marine/coastal ecosystems of the islands of Providencia and Santa Catalina (SBR), as well as assess any interconnections between these ecosystems. At the same time, the distribution characteristics of marine litter in the different compartments facilitated a more dynamic understanding of the load of marine litter supplied by the islands, both locally and externally. We observed that certain ecosystems, principally back-beach vegetation and mangroves, act as crucial marine litter accumulation zones. Mangroves are important hotspots for plastic accumulation, with densities above eight items/m^2 (minimum 8.38 and maximum 10.38 items/m^2), while back-beach vegetation (minimum 1.43 and maximum 7.03 items/m^2) also removes and stores a portion of the marine litter that arrives on the beaches. Tourist beaches for recreational activities have a low density of marine litter (minimum 0.01 and maximum 0.72 items/m^2) due to regular clean-ups, whereas around non-tourist beaches, there is a greater variety of sources and accumulation (minimum 0.31 and maximum 5.41 items/m^2). The low density of marine litter found on corals around the island (0–0.02 items/m^2) indicates that there is still no significant marine litter stream to the coral reefs. Identifying contamination levels in terms of marine litter and possible flows between ecosystems is critical for adopting management and reduction strategies for such residues.

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1. Introduction

Inadequate solid waste management is one of the leading marine pollution-related issues of recent decades, and its consequences have been reported in coastal and marine areas around the world (Derraik, 2002; Woodall et al., 2014; Schuhmann and Mahon, 2015; Gall and Thompson, 2015; Anfuso et al., 2020; Gonçalves et al., 2020a; Portz et al., 2020). Marine debris is present in several ocean compartments: biota, coastal areas, on the surface, in the water column, and on the sea floor, as well as in the sediments and marine ice cover (Barnes et al., 2018; Bergmann et al., 2016; Borrelle et al., 2017; Brown and Takada, 2017; Mallory et al., 2021; Monteiro et al., 2018).

In the Caribbean sea, marine litter on the beaches of Colombia, Jamaica, Curacao, Bonaire, Southeastern Caribbean, Aruba (in the ABC Islands), and the Dutch Caribbean, has been widely reported (Gracia et al., 2018; Rangel-Buitrago et al., 2017, 2018; Wade et al., 1991; Debrot et al., 1999; Debrot et al., 2013; de Scisciolo et al., 2016; Debrot et al., 2014; Portz et al., 2018).

In a marine litter redistribution scenario, island ocean environments are considered particularly vulnerable to plastic accumulation (Monteiro et al., 2018) and behave as plastic pollution sentinels (Pham et al., 2020a, 2020b). The factors corroborating this statement include distance from the continent and direct exposure to marine currents (Barnes et al., 2018). Debris entering the marine environment, or even inhabited oceanic islands, from continents, can either circle around and be deposited on the coast near the source areas or be transported by currents, reaching remote areas far from the entry points.

Studies on the impact of marine debris in coastal areas have focused primarily on beaches (de Scisciolo et al., 2016; Garcés-Ordóñez et al., 2020; Giovacchini et al., 2018; Munari et al., 2016; Ribeiro et al., 2021), while little attention has been paid to ecosystems interconnected with beach environments. According to the study by Browne et al. (2015), up until 2015, more than 80% of studies had focused on sandy beaches, about 15% on gravel, pebble, or boulder beaches, and less than 5% included data from rock platforms, mangroves, mudflats, coral beaches, or salt marshes.

Although there is scant knowledge on the distribution and accumulation of debris in the different coastal ecosystems, some studies have included mangroves (Bijsterveldt et al., 2021; Garcés-ordóñez et al., 2019; Luo et al., 2021a, 2021b; Martin et al., 2019; Suyadi and Manullang, 2020), shallow water zones (Chiappone et al., 2002), coral reefs (Abu-hilal and Al-Najjar, 2009; Chapron et al., 2018; Kroon et al., 2020; Portz et al., 2020), dune systems (Andriolo et al., 2020b; Menicagli et al., 2019; Poeta et al., 2016; Portz et al., 2011) and even polar coastal environments (Anfuso et al., 2020).

Marine/coastal ecosystems are vital for maintaining and conserving the biodynamic balance of the food chain. For example, mangrove areas are deemed essential for the reproduction, nesting, and feeding of several species, and the likely consequences of solid waste accumulation on the physiology of the species have not yet been determined. Recent studies indicate that plant morphology is among the most important factors in the stranding of waste (Luo et al., 2021a, 2021b). Also, it is already known that dense mangrove edges serve as a mesh that prevents many residues from entering the inner areas (Vieira et al., 2011).

Moreover, coral reefs are biologically the most diverse ecosystems in the ocean (Allsopp et al., 2009). The Colombian Caribbean (SEAFLOWER Biosphere Reserve) possesses the third-largest coral reef area in the world, and this ecosystem provides a series of ecosystem services that include food, coastal protection, recreation, and so on (CCO, 2015; Prato and Newball, 2015). It is also deemed to be the Colombian ecosystem most isolated from anthropogenic threats, although it is severely threatened due to changes in biotic processes and anthropic interactions (Uribe et al., 2020).

Despite the tremendous environmental importance of the coastal system and oceanic island subsystems, certain factors may play a determining role in the reduced number of publications on these ecosystems (mangroves, dunes, and coral reefs) when compared to the beach system (e.g., Zorzo et al., 2021; Chen, 2021). These factors include the difficulty of access, cost of transport (vessels), need for diving equipment (e.g., in the case of coral reef areas), and so forth. Over the last few years, beaches, mangroves, and coral reefs have been treated as independent ecosystems and studies of the distribution and abundance of marine litter have been carried out in each compartment individually; all have begun to show unequivocal signs of contamination, some more than others. This contamination may become aggravated over the years and is a serious obstacle to the maintenance of biodiversity. Ideally, studies on the distribution of marine debris should be conducted in more than one marine/coastal ecosystem at a time to enable a more comprehensive understanding of a region's incoming litter load (Roman et al., 2020).

The various ecosystems of oceanic islands have both marine and terrestrial interconnectivity, facilitating the migration of species between different habitats. The same occurs with waste, both through dynamic agents (winds, currents, and waves) and active agents (people).

The problem of marine debris on the beaches of the islands that make up the SEAFLOWER Biosphere Reserve has been acknowledged within the last two decades, but only recently have some studies been undertaken to fill this knowledge gap. Contamination by solid waste on the beaches of San Andrés Island (SEAFLOWER tourist island) presented high rates due to human activities, mainly on account of beachgoers (tourists and local inhabitants) and inadequate waste disposal (Portz et al., 2018). On the islands where human activities are restricted (with minimal local sources), the predominance of plastic fragments, both on the sea surface and the beaches, highlights the importance of marine currents in these environments (Portz et al., 2020).

In terms of understanding marine litter accumulation on the islands in the SEAFLOWER reserve, in this study our aim is to establish the distribution pattern and potential sources of solid waste in the different marine/coastal ecosystems of the islands of Providencia and Santa Catalina, as well as assess interconnections between the ecosystems. In a broader sense, this study contributes to a better understanding of how the interconnections between ecosystems influence the redistribution and storage of marine waste.

2. Material and methods

2.1. Study area

The SEAFLOWER Biosphere Reserve (SBR) is situated in the southwestern Caribbean, and comprises a set of oceanic islands, atolls, and coral banks aligned NNE-SSW along the Nicaragua elevation, forming an archipelago of carbonate platforms, reef barriers resembling semi-atolls, and reef lagoons with varied geomorphologies (Dimar-CIOH, 2009; Geister and Díaz, 2007). It is one of the largest reef systems in the Atlantic Ocean and the most extensive reef area in Colombia (Diaz et al., 1996), and hosts a wide range of ecosystems that together account for a high level of biodiversity (CCO, 2015). Its biological and ecological importance has been highlighted in the literature, for instance, in terms of corals, echinoderms, fish, reptiles, and seabirds (Acero et al., 2019; Borrero-Pérez et al., 2019; Prato and Newball, 2015; Ramirez-Gallego and Barrientos-Muñoz, 2020).

The islands of Providencia and Santa Catalina (latitude: 13° 20′ 33.60” N; longitude: 81° 22′ 17.39” W) are remnants of an extinct andesitic volcano, predominantly comprising hills and mountains, including Quaternary deposits (Gómez, 2012). Providencia and Santa Catalina are separated by a shallow 150 m-wide channel and have a total area of approximately 18 km^2. The Old Providence McBean Lagoon National Natural Park (Fig. 1) protects part of the coral reef with a surface area of 9.95 km^2. The Park has been part of the Special Administrative Area of the San Andres, Providencia and Santa Catalina Archipelago since

1996, of the SEAFLOWER Biosphere Reserves since 2000, and of the archipelago's SEAFLOWER Marine Protected Area since 2004 (https://www.parquesnacionales.gov.co).

The atmospheric/oceanic conditions of the region are determined by several macroscale factors, including the warm Gulf current, cold fronts originating in North America, and the passage of tropical waves coming from the Gulf of Mexico. The prevailing surface current, the Caribbean Current, flows at a high-speed (>25 cm/s) from E to W (Idárraga-García and León, 2019). At the same time, the climate is hot and humid, with three seasons: a dry (December to April), transitional (May to July), and rainy season (August to November). The temperatures range from 26 to 28 °C (CIOH, 2010), and the interaction of weather patterns with the steep geomorphology also influences the local climate. The prevailing wind direction is between 50 and 55 degrees, with the most representative cardinal component being east-northeast (Fig. 1). The most intense winds blow in December, January, and February with velocities ranging from 5 to 8 m/s. The waves come from the E and ENE sectors in a period between 4 s and 6 s, and with an Hs of 0.5 m to 3 m, with the peak being at approximately 6 s and 2 m (Appendini et al., 2015).

The sandy beach areas are located in the northwest, west, and south of the archipelago (Fig. 1); the other areas have gravel beaches, rocky coasts, and mangroves. The most representative beaches for tourism are Southwest Bay, Manchineel Bay, and a portion of Fresh Water Bay, in addition to the small beach of Morgan's Head, which is accessed by a path over the elevated coastline in the southwest of Santa Catalina Island. Less touristic beaches are found in difficult-to-access and more isolated areas, including Old John Bay on Santa Catalina, or close to urban areas such as the Bottom House Cay, Smoothwater Bay, Old Town, and Black Sand beaches (the last two will be referred to as "Harbor" in this work) on the island of Providencia; the latter beaches present more pronounced anthropic effects (Coca-Domínguez et al., 2019). The sandy beaches are made of coral sand and fine terrigenous sediments and their average slope ranges between 4 and 12° (Posada and D., 2011).

The main mangrove areas are located in Mourning Tree Bay (the most well-conserved and extensive), Manchineel Bay (M4 – Fig. 1), and Southwest Bay, whereas the mangroves are more spread out along the coast in the strait between the islands of Providencia and Santa Catalina (Posada and D., 2011). In the northeastern sector of Providencia Island is the Old Providence McBean Lagoon National Park, a 995-ha marine area on the coast, controlled by the National Natural Parks Service (NNPS).

Coral terraces occur along almost the entire perimeter of the island, covering 255 km^2 (Geister and Díaz, 2007), a feature that provides the islands' nearly 5000 inhabitants with abundant marine resources and is the basis of a subsistence economy, mainly agriculture, fishing, and small-scale tourism (Garzón-Ferreira and Díaz, 2003; Matera, 2016).

2.2. Survey method

The samples were collected during the IV SEAFLOWER Scientific Expedition (September 9–19, 2019) to the islands of Providencia and Santa Catalina. This expedition was a joint effort between the Colombian Oceanic Commission (*Comisión Colombiana del Océano*; CCO), the National Navy, and the General Maritime Directorate (*Dirección General Marítima*; DIMAR).

Marine litter was examined following the protocols established by Galgani et al. (2013) and the UNEP (2009), and the different sectors for sampling were divided into mangroves, beach (tourist and non-tourist/sand and gravel), back-beach vegetation areas, and coral reefs (Fig. 1 and 1S supplementary material). The analysis method for each sector is outlined below:

2.2.1. Beach/back-beach vegetation areas

Marine litter on beaches was surveyed from twenty-two 10 m-wide transects covering most of the island's beaches (Fig. 1) from the strandline to the start of the vegetation or dunes (Fig. 1S, A, B and C supplementary material). Back-beach vegetation areas were considered to include up to 5 m from the beginning of the vegetation, and the area of each transect used was measured to estimate the waste present (m^2) (Table S1 and Fig. S2 - Supplementary material).

2.2.2. Mangrove

Four linear transects were conducted to collect debris in mangrove areas near the locals' access points (M1, M2, and M3) and on a tourist beach access (M4), as indicated in Fig. 1. The sampling area was determined as 10 m from the access edge to the mangrove, with a 5 m width towards the inner mangrove (Fig. 1S G and H supplementary material).

2.2.3. Reef coral

The marine litter deposited on the shallow insular shelf was sampled by free diving (Fig. 1S, J and I supplementary material), with three divers covering the entire diving area (≈500 m^2); all identified items (>5 cm) were collected for subsequent quantification and classification. The samples were gathered from thirteen collection points, with depths ranging from 10 to 30 m depending on the geomorphology in the area. All 13 dive sites were selected because they are sectors of the island commonly used for tourism by diving agencies.

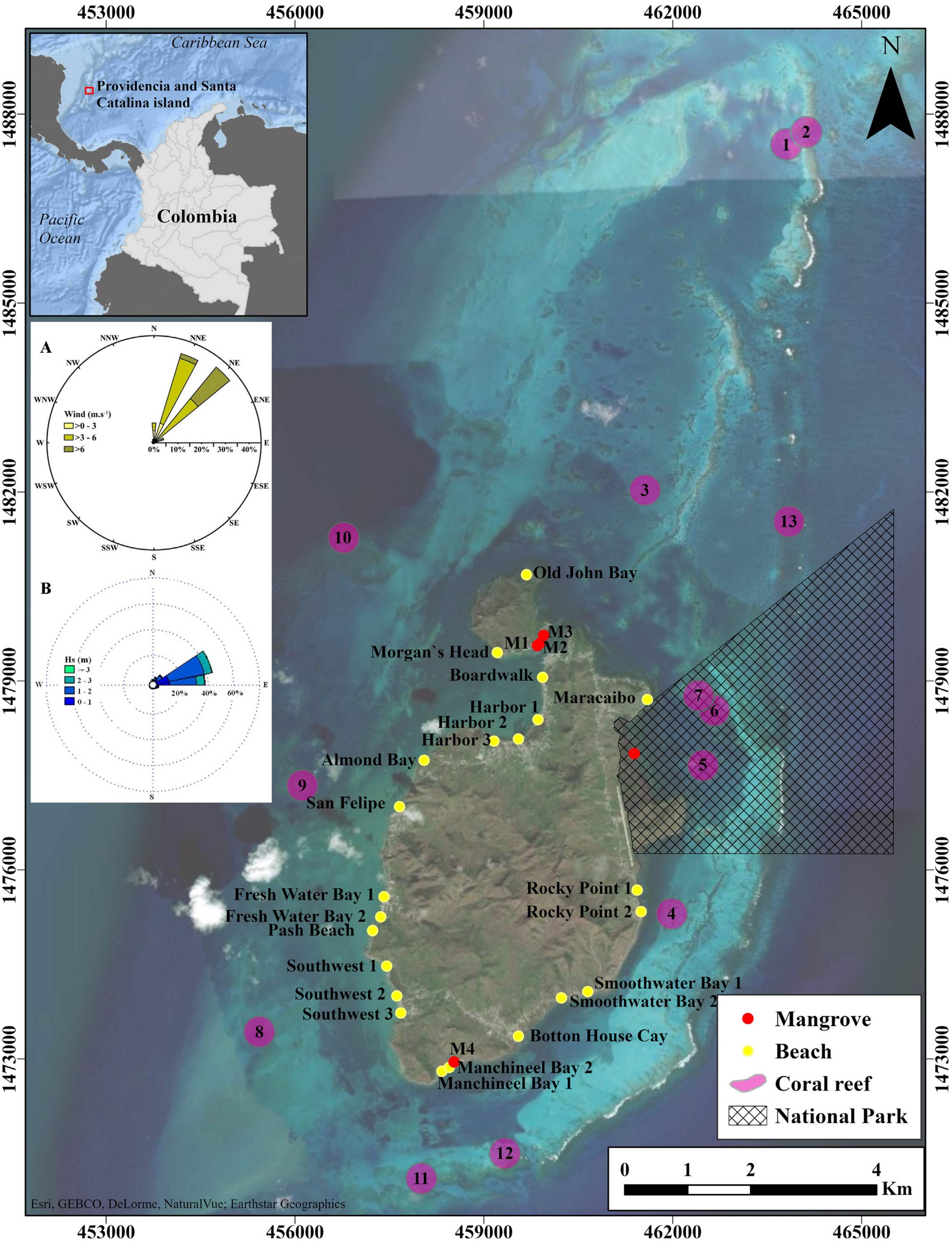
2.3. Classification and quantification

The debris sampled from the different sectors was processed by weighing and subsequent separation according to the OSPAR classification (OSPAR, 2010), and the marine debris concentration was calculated per transect using the number of items in each sampled area (m^2). Any items bigger than 2.5 cm were then classified per type of material (plastic, paper, cigarette butts, glass, metal, non-anthropogenic organic matter (O.M.), rubber, ceramic, and other, i.e., materials that did not fit into any of these categories) and/or source (e.g., fishing-related activities) (OSPAR, 2010). Cigarette butts comprise mainly cellulose-based polymers and were therefore quantified separately from the main litter categories (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 (pieces of plastic that are not recognisable as an item), clothing (e.g., shoes), and miscellaneous items (e.g., toys, cosmetics) (Portz et al., 2018, 2020).

For this study, five possible origin categories were identified and classified in line with the Ocean Conservancy (2010) into dumped material, shoreline & recreational activities, smoking-related activities, medical/personal hygiene, ocean/waterway activities (fishing), and undefined (other paper items, glass fragments and plastic/expanded polystyrene pieces). This classification links the items collected to the economic sector or human activity likely to have originated them.

2.4. Statistics

The statistical tests were performed using Past® 4.06b software (Hammer et al., 2001). Prior to performing inferential statistical analyses, we carried out the Shapiro-Wilk test to check for normal distribution in our dataset ($p < 0.05$). The null hypothesis that the data are normally distributed was rejected from half of the localities sampled (tourist beach, $p = 0.03$; gravel beach, $p = 0.02$; and coral reefs, $p < 0.01$). To determine possible differences in marine litter density (item/m^2 ± standard deviation) between the sectors (tourist and non-tourist beaches, back-beach vegetation, mangroves, and coral reefs) we employed non-parametric tests for equal means (Kruskal-Wallis, Dunn's post hoc). The differences between groups in terms of potential sources were tested employing the non-parametric contingency, Chi-square.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>6
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>= 3
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1
2
3
13
10
Old John Bay
M3
M1
M2
Morgan`s Head
Boardwalk
Maracaibo
7
6
Harbor 1
Harbor 2
Harbor 3
Almond Bay
5
9
San Felipe
Fresh Water Bay 1
Fresh Water Bay 2
Pash Beach
Rocky Point 1
Rocky Point 2
4
Southwest 1
Southwest 2
Southwest 3
Smoothwater Bay 1
Smoothwater Bay 2
8
Botton House Cay
M4
Manchineel Bay 2
Manchineel Bay 1
12
11
Mangrove
Beach
Coral reef
National Park
0
1
2
4
Km
Esri, GEBCO, DeLorme, NaturalVue; Earthstar Geographics

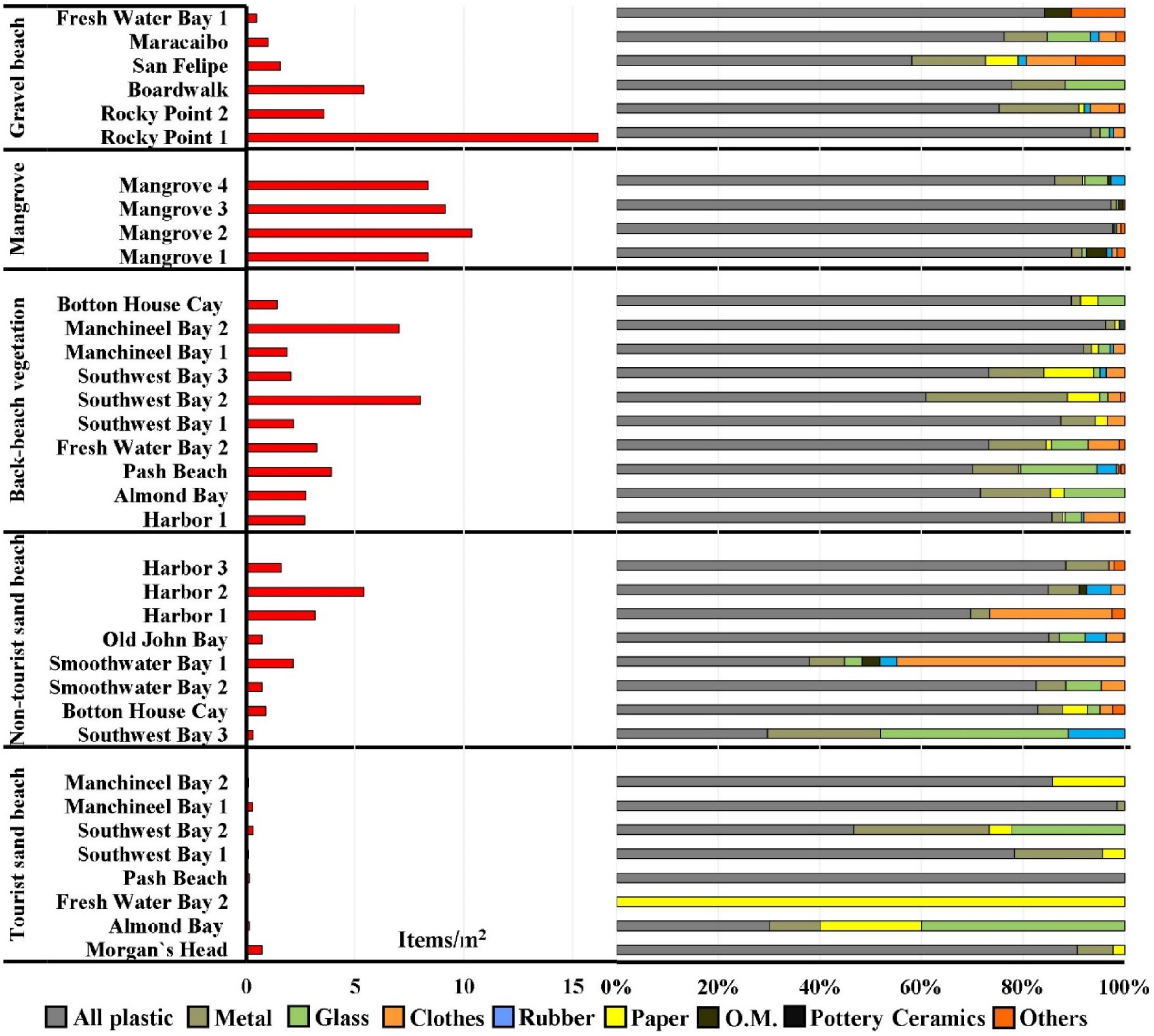

Fig. 2. Marine litter density (items/m^2) and frequency distribution per type in each sector. O.M. = organic matter.

3. Results

3.1. Litter density and spatial distribution

A total of 4899 items were sampled from 39 collection points. The number of items retrieved ranged from 0 items in some coral reef sectors to a maximum of 760 items at Rocky Point 1 (Gravel beach – non-tourist). The average litter density across the island was 3.40 items/m^2 (SD 3.90; Std. error 0.69), ranging from 0.01 at Fresh Water Bay 2 to 16.17 items/m^2 at Rocky Point 1 (Fig. 2).

The debris density was spatially heterogeneous in the Providencia and Santa Catalina islands, although in some sectors of ecosystem importance there was a high density of litter in the mangrove and back-beach vegetation areas (Fig. 3). The sectors with the lowest density were coral reefs (0.01 items/m^2), followed by sandy beaches in tourist areas (<0.30 items/m^2): Fresh Water Bay 2, Manchineel Bay 1 and 2, Southwest 1, Fresh Water Bay 3, and Almond Bay. The areas with the highest litter density (> 8 items/m^2) were the mangroves (M1, M2, M3, and M4), in addition to one non-tourist beach (Rocky Point 1).

The mangrove sectors had the highest density in terms of volume of debris, with an average of 9.07 items/m^2 (M1 minimum, 8.38 items/m^2; and M4 maximum, 10.38 items/m^2). Aside from these points, two mangrove areas on the island were not sampled due to access difficulties, but photographs were taken and a visual estimation of debris was made, resulting in these points being considered the most contaminated (Fig. 3S A and B supplementary material).

The sampling group with the second highest debris density was the gravel beach (Fig. 2). The sectors analysed in this category include two tourist spots located at the top of a slope (cliff) with a viewpoint for landscape observation (Town Boardwalk, 5.40 items/m^2; and Rocky Point 2, 3.56 items/m^2). These have a high concentration of characteristically tourist-derived litter, such as beverage cans and industrially produced food containers (snacks); since there is no direct access to the beach in these areas they are not cleaned frequently, resulting in high levels of litter accumulation.

Significant differences in litter densities were found among the different sectors sampled (Kruskal-Wallis test H(chi^2) 35.29; $p < 0.001$). The areas sampled from Coral reef showed no significant

Fig. 1. Location of the study area showing the geographic distribution of marine litter collection areas on beaches, in mangroves, and on coral reefs. A) The wind rose indicates the wind direction frequency and speed for Providencia and Santa Catalina (Source: NARR -monthly averages for 1979–2011). B) The wave rose for Providencia island is based on a 30-year (1979–2008) wave hindcast (Source: Appendini et al., 2015).

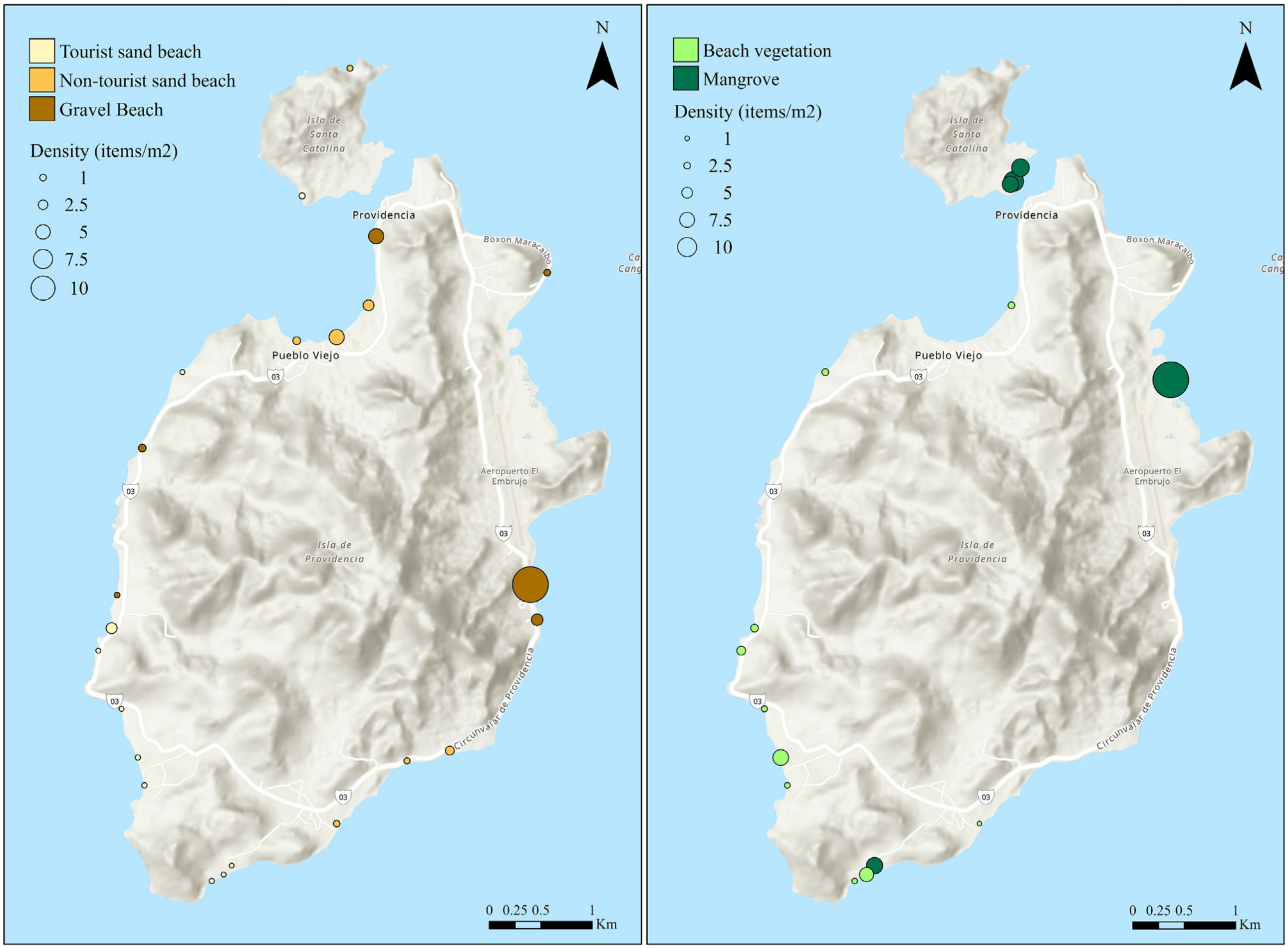

Fig. 3. Maps showing the litter density distribution (items/m^2) A) Mangrove and back-beach vegetation areas, and B) Beach areas (tourist sand beach, non-tourist sand beach, and gravel beach).

difference only in relation to the Tourist sand beach ($p = 0.19$). On the other hand, Gravel beach shows significant comparison only with the Tourist sand beach. As well as Non-tourist sand beach has significant comparisons with mangrove and coral reef. In addition, back-beach vegetation significant differences with respect to non-tourist sand beach ($p = 0.29$), mangrove ($p = 0.17$) and Gravel beach ($p = 0.81$) (Table S2 -Supplementary material). The density was significantly higher in the mangrove ecosystems, followed by the back-beach vegetation and gravel beach areas, than in the sand beach and coral reef areas. Compared to the average litter density on the beach (Tourist and Non-tourist) and back-beach vegetation, both sectors account for a significant difference (0.54 items/m^2 beach; and 3.51 items/m^2 back-beach vegetation).

3.2. Litter: composition and materials

Plastic/expanded polystyrene waste represents 83.77% of the total items collected; an amount significantly higher ($p < 0.005$) than the sum of all the other waste categories such as metal parts (6.21%), glass (4.02%), clothes (2.57%), and other materials (3.43%), including rubber, paper, wood (processed), O.M., ceramics, and others (Fig. 4Sa supplementary material).

Among the plastic items (Fig. 4Sb supplementary material), the most considerable fraction of items (42.5%) consisted of plastic fragments ranging from 2.5 to 50 cm in size, followed by expanded polystyrene (22%); larger plastic pieces (>50 cm) accounted for only 16.35% of the total collected. Other noteworthy items included bottle caps (7%), bottles (6.41%), candy and snack wrappers (4.09%).

The main items found in the island's mangroves were pieces of plastic/expanded polystyrene (49% of the waste found), followed by expanded polystyrene, plastic bottles, and lids. The number of items in each mangrove sector analysed were similar, with the sector close to the entrance to Manchineel bay (Mangrove 4) having the most significant number of items, mainly expanded polystyrene parts used for transporting food and beverage bottles.

Of the total amount of litter on tourist beaches, 73% was plastic fragments, followed by metal pieces, predominantly beer bottle tops. Concomitant with the abundance of bottle caps, there were many glass fragments, whereas, on non-tourist beaches, no single category particularly stood out, meaning there was a greater degree of diversity in the types of waste. Small plastic fragments (2.5–50 cm) represented 23.1% of the items collected in this ecosystem, with frequent larger plastic pieces (>50 cm). The back-beach vegetation areas analysed were mainly located on touristic sand beaches. Here, the predominant type of litter was plastic fragments (22%) and plastic pieces (15.2%), followed by expanded polystyrene, plastic bottles, candy and snack wrappers, as well as a lollipop stick.

On gravel beaches, the most abundant waste was expanded polystyrene (35.4%) followed by plastic fragments (10.9%) and plastic bottles (9.7%). In addition, the amount of fabric litter (shoes 1.4% and clothing 1.0%) was noteworthy. This ecosystem has different characteristics to other sectors sampled, and as they are not tourist beaches the litter tends to accumulate and linger.

The potential sources of the waste found in the different sectors of the islands were divided into dumping, shoreline & recreational activities, smoking-related activities, medical/personal hygiene, ocean/

Table 1
Correlation between presumable sources of waste according to the analysed sector.

	Undefined	Shoreline & Recreational Activities.	Dumping	Dumping/ Shoreline & Recreational Activities (expanded polystyrene)	Dumping (construction material)	Ocean/ Waterway Activities (Fishing)	Smoking-related Activities	Medical/ Personal Hygiene
Back-beach vegetation	626	518	150	145	37	27	12	2
Mangrove	518	205	95	206	9	7	1	0
Non-tourist sand beach	374	184	189	133	18	35	0	11
Gravel beach	252	288	110	407	24	25	1	44
Tourist sand beach	128	82	9	14	3	1	9	0

0 70 139 209 278 348 417 487 556 626 Items

waterway activities (fishing), and undefined - other paper items, glass fragments, and plastic/expanded polystyrene pieces (2.5 cm - 50 cm and > 50 cm) (OSPAR, 2010).

The differences between groups for potential sources were significantly different (Chi-square = 750.23, $p < 0.001$) (Table S3 -Supplementary material). The potential source of the identified waste varied according to the sector analysed, and most of the collected waste could not be associated with a specific source (38.7%). In the case of the mangroves, for example, ≈50% of the items were from an undetermined source; whereas ≈20% were from shoreline & recreational activities and another 20% were from dumping (expanded polystyrene) (Table 1).

Moreover, on tourist beaches, the majority of the waste cannot be linked to a specific source (52%), mainly due to the high concentration of fragments. However, 33.3% of the waste came from the recreational activities developed on the beaches or in nearby areas, such as hiking, picnics, sports, and festivals. Likewise, the waste in the back-beach vegetation areas had a similar potential origin (34.1%). Another point to highlight in these two sample sectors is the significant amount of litter sourced from smoking-related activities (3.7 and 0.8%) compared to the other sectors.

In contrast to all other sectors, most of the litter (35.4%) collected from the gravel beach areas was from dumping/shoreline & recreational activities (expanded polystyrene), and that sector had the lowest percentage of litter from an undetermined source (21.9%) (Table 1).

Litter from ocean/waterway activities (fishing) was more strongly represented on non-tourist beaches since local fishing activities occur in these areas.

4. Discussion

This is the first comprehensive study assessing the composition and distribution of marine litter in the different ecosystems in Providencia and Santa Catalina. These islands are economically dependent on marine resources and tourism. In this sense, the combined effects of the arrival of marine debris and local waste input can impact these activities. Other islands have systematically reported problems caused by solid waste, primarily due to its irregular disposal (see Andrades et al., 2018; Fastelli et al., 2016; Krishnakumar et al., 2020; Monteiro et al., 2018; Pham et al., 2020a, 2020b; Ríos et al., 2018; Verlis and Wilson, 2020). On the South Pacific islands of Moorea (0.75 items/m^2) and Tahiti (0.95 items/m^2), about 60% of the marine litter identified is derived from local watersheds, indicating that the majority has a local source (Verlis and Wilson, 2020). In this study, the average marine litter density at the points analysed on the islands was 3.22 items/m^2, similar to other islands occupied by humans, such as the Azores archipelago (3–4 items/m^2) (Ríos et al., 2018) and the Solomon Islands (2.5 items/m^2) (Binetti et al., 2020). In this study, the maximum value was an alarming 16.17 items/m^2 (Rocky Point 1), highlighting the need for urgent action. Oceanic islands far from the continent face a unique challenge in terms of the proper disposal of solid waste, mainly due to the limited space for adequate disposal or the building of recycling centres; indeed, disposal depends principally on this waste being exported by sea or air, or even incinerated. In this sense, new methods for litter disposal in this and other islands should be designed, incorporating circular economy action into the management of solid waste.

4.1. Ecosystems as waste reservoirs

The geomorphological characteristics of oceanic islands, coupled with their meteo-oceanographic conditions, mean that they can become deposition areas for the debris transported by currents, which can accumulate in large quantities (Alomar et al., 2020; Dunlop et al., 2020; Lebreton et al., 2018; Ríos et al., 2018). The possibility of high accumulation rates, the importance of natural island ecosystems, and the quantification of marine debris have focused increasing attention on these areas (Bouwman et al., 2016; Thiel et al., 2021). In this study, an integrated analysis was performed, where different ecosystems were evaluated within the same timeframe. The joint monitoring of the different environments resulted in a better understanding of the connections between the ecosystems and their role in retaining or exporting marine litter.

Beach/dune environments are critical marine litter accumulation points (Andriolo et al., 2020b; Portz et al., 2011; Poeta et al., 2017). The abundance of marine litter in beach areas compared with the results from back-beach vegetation areas (number of items/m^2) is quite different (Fig. 2). Tourist beaches are relatively low-density in terms of litter, while back-beach vegetation areas present significant accumulations. The relative abundance of marine debris on Providencia and Santa Catalina increased from the beach towards the backshore areas (back-beach vegetation). This distribution pattern results from the sum of two factors: firstly, and naturally, wind-transported debris arrives or is “left” on the beach and accumulates in the back-beach vegetation; secondly, anthropic action, such as daily beach cleaning, causes irregular waste disposal.

The vegetation present in the beach system is one of the most critical landscape components, providing a precious habitat for bird nesting, food, and faunal protection (Nordstrom, 2000). In the back-beach area, the vegetation is able to trap marine litter, fragmenting it and increasing it (in quantity) over time. A study by Hengstmann et al. (2017) also indicates that marine litter accumulates in the back-beach area, where the substrate becomes coarser and the vegetation is shrubby. The main factors involved in this accumulation process are onshore wind and swash processes, which determine marine litter transport and relocation within the beach system, as well as litter abundance and residence time related to beach slope and hydrodynamics-environmental forcing (Andriolo et al., 2020b; Gonçalves et al., 2020a).

This study shows that on the islands of Providencia and Santa Catalina, the greatest accumulation of marine litter in the beach system occurs on non-tourist beaches; its origin is considered to be mixed as it comes both from terrestrial and marine sources (currents). This finding emphasises the importance of improving waste management in the archipelago since the most popular beaches are cleaned on a daily basis, while the trend on non-tourist beaches is towards a gradual increase in marine litter accumulation over time. Portz et al. (2018) observed the same pattern on San Andres Island, also located within the SEAFLOWER Reserve.

The mangrove areas analysed in this study are close to either urban areas or tourism and fishing spots (Fig. 1S G and H in the supplementary material), perhaps being responsible for the high concentrations of litter in this ecosystem. The study by Barnes et al. (2009) indicates that debris stranding correlates directly with proximity to urban and tourist spots. However, in this study, the mangrove areas within the national park (accessible only by boats) present the most considerable amounts of marine litter in terms of visual accumulation, most likely brought into the area by marine currents since there is no access via land (Figs. 1 and 2). Results from other islands show that there is debris even within mangrove forests located in remote areas subjected to nearly no anthropic activities (Seeruttun et al., 2021). This observation is corroborated by the position of the national park in relation to the predominant wave and wind direction (NE/NEE) (Fig. 1A and B). Other studies, as well as the litter density data collected in this study, confirm that mangroves act as marine litter traps (Ivar do Sul et al., 2014; Li et al., 2018; Martin et al., 2019). Compared to the other ecosystems analysed (beach, back-beach vegetation, and coral reefs), the debris density in mangrove environments is three times higher than in back-beach vegetation areas and forty times greater than on tourist beaches; other authors also recorded around four times more litter accumulation in mangrove environments (21.23 items/m^2) than other habitats (beaches, open shore) (Smith, 2012). Despite the higher density of items observed in the mangrove areas, we found no differences in the diversity of items between the different sectors analysed. Comparing the number of items found at the M1, M2, M3, and M4 sampling points against other studies carried out in island mangrove ecosystems, we can estimate that these sectors have a relatively low concentration of waste since the amounts found by Suyadi and Manullang (2020) on a small island Maluku Indonesia show a mean density of 92 ± 28 items/m^2.

Contrary to what transpires in beach areas where marine litter can be redistributed over time and space (Andriolo et al., 2020b, 2021b) or may migrate to the adjacent dune system (Portz et al., 2011), in mangrove ecosystems, the large quantities found may be associated with gradual accumulation over time (Yin et al., 2020). Although waste retention can vary according to hydrodynamic characteristics and the density and type of vegetation at each location, mangroves generally tend to retain plastic for extended periods (months-years), regardless of the season (Ivar et al., 2014). Mangroves trap floating marine debris due to their inherent properties, as they reduce wave height and slow down the flow of water, causing the deposition of current-transported sediment and waste. Pneumatophore roots act as a filter, preventing large objects, advected to mangrove areas by tidal currents and waves, from being redispersed into the marine environment (Martin et al., 2019).

In contrast to the beach-dune and mangrove ecosystems, coral areas in the Providencia and Santa Catalina archipelago present reduced marine litter densities. The quantities in this study are similar to those described by Bouwman et al. (2016) on the shores of St Brandon's rock, an isolated tropical atoll in the Indian Ocean, where all of the debris found was on emerged grounds, instead of at dive sites. In another study estimating marine litter densities on reefs, plastic was predominant and represented 94.6% of all the objects sampled (Mulochau et al., 2020), most of which was fishing gear.

These coral areas are an excellent attraction for underwater tourism and several local agencies arrange regular trips to see them. However, the results for the sites selected for marine litter sampling that coincided with the main tourist diving spots suggest that this activity does not contribute to marine litter contamination in this ecosystem.

Globally, on-land mismanaged plastic debris increases the susceptibility of reef-building corals to disease (Lamb et al., 2018). This should be taken as a warning to adopt measures to prevent any such residue being transferred to coral reef areas due to their sensitive nature.

4.2. Sources of marine litter

Determining the sources of marine litter is complex and often impossible, as specific items (like expanded polystyrene) can originate from multiple sources (such as fishing or food delivery services), in addition to being transported by watersheds, winds, and marine currents to locations far from the actual source, causing classification schemes to differ widely among different studies.

On oceanic islands, surface currents play a crucial role in bringing marine litter to beaches and near-shore habitats (Andrades et al., 2018; Monteiro et al., 2018; Rangel-Buitrago et al., 2019). The effect of these currents on the transport of marine litter in the Caribbean Sea was demonstrated by Portz et al. (2020). In general, on the islands of Providencia and Santa Catalina, the marine litter gathered from the various ecosystems is mostly derived from external sources and was transported into the area by ocean currents. The presence of plastic pellets indicates that at least part of the marine litter found was transported by ocean currents, as there are no petrochemical facilities on the atoll. Furthermore, the archipelago is on the path of tourist ships and fishing boats, which can be a source of marine litter. In that regard, the archipelago of Providencia and Santa Catalina is located on the course of the Caribbean current, which is capable of carrying waste from distant areas. Several foreign labels were identified on the litter collected, indicating this was transported by ocean currents and vessels close to the archipelago; something similar was recorded in Rocas Atoll (South Equatorial Atlantic) (Soares et al., 2011).

Nevertheless, local activities such as tourism and fishing also involve a significant impact, depending on the ecosystem. The litter found on tourist beaches appears to be related to recreational activities and is low density due to daily cleaning. Cleaning primarily removes large items, resulting in a greater proportion of plastic fragments, something also observed in San Andres island, Colombia (Portz et al., 2018). On the other hand, non-tourist beach areas present a greater variety of potential waste sources and accumulation. It is worth mentioning that on beaches facing E/NE, there is a more substantial presence of disposal residues (dumping), often characterised by abrasion or unlabelled (characteristic of a long period at sea and having been transported by currents). The beaches facing W (tourism, port locations), protected from the ocean dynamics, principally accumulate marine litter from local disposal and fishing activities. The analysis point with the highest litter density is in the area primarily exposed to the prevailing wind (NE) and waves (N/NE) (Fig. 1a and b; Fig. 3). The same pattern of marine litter accumulation on leeward beaches was also observed at Albuquerque Cay Atoll, where 72% of the waste came leewardly and 28% windwardly (Portz et al., 2020).

The back-beach vegetation areas analysed in this study are mainly linked to tourist beaches, with recreational activities being the primary source of marine litter (shoreline & recreational activities). The marine litter disposal pattern on the back-beach is likely to be underquantified since a portion of the waste is buried (Fig. 5S - Supplementary material). The mangrove areas present a greater variety of potential waste sources and accumulation. One significant element is expanded polystyrene, the characteristics of which (density and buoyancy) mean it is easily transported and subsequently accumulated in the mangrove areas. The urbanised areas are predominantly coastal, and the island has a road around the perimeter, with several waste collection points (dumpsters). Poor disposal of solid waste means that part of this is transported seawards during torrential precipitation events.

4.3. Interconnections between ecosystems

The factors controlling flows between ecosystems in natural environments include geomorphological aspects, local meteo-oceanographic conditions, anthropic activities, and the proximity between different ecosystems (see Graphic Abstract). The shape and orientation of the islands are crucial for establishing current-transported waste deposition and redistribution patterns. The high concentrations of marine litter found on remote and uninhabited islands confirm that these act as primary deposition and accumulation hubs for current-transported litter in the open ocean (Ryan and Moloney, 1993; Andrades et al., 2018; Portz et al., 2020). In Providencia and Santa Catalina, the role of currents in the arrival of external litter to the island is evident. This role is particularly clear in the mangrove sectors at the Old Providence McBean Lagoon National Natural Park facing the prevailing wind direction. This sector presents visually higher densities, including in mangrove areas close to urbanised zones.

Most of the litter collected (plastic) in mangrove areas near urbanised areas (M1, M2, M3) possesses similar characteristics to the items retrieved from tourist beach areas, where most of the items collected represent improperly disposed-of beachgoer products. This similarity can be explained by two factors: active agents (people passing through all the ecosystems in the archipelago); and the transfer of litter by dynamic agents.

Another litter transfer possibility is present between the beach and the back-beach vegetation areas since the onshore wind can transport litter discarded in beach areas, according to the wind velocity and approach direction. The sea-inland gradient was studied, for example, by Šilc et al. (2018), who showed how bags and expanded polystyrene pieces could be transported by the wind since they are lighter than other plastic pieces. This study, and other recent works (Andriolo et al., 2020a, 2020b, 2021b; Laporte-Fauret et al., 2021), also revealed that different ecosystems are polluted by litter from different sources via various pathways, corroborating the interconnectedness of the coastal system. However, especially on tourist beaches, the accumulation of litter in the back-beach vegetation area is more strongly linked to beach cleaning, whereby waste is “swept away” from the gaze of tourists.

The low impact from marine litter on corals around the island indicates that there is still no significant waste stream to the coral reefs. At the dive sites within the Old Providence McBean Lagoon National Natural Park (very close to the mangrove areas with high waste density), no litter was found, indicating no export of waste from the mangroves to the nearby coral reefs. In addition, as 83.8% of the litter quantified on the island is plastic, it is far less likely to reach the coral areas due to its buoyancy. Sedimentation of initially floating solid waste (such as plastics) occurs due to various transformation processes, and the spatial distribution of vertical transport processes is still a significant knowledge gap (Sebille et al., 2020).

One of the difficulties in a study of this type, involving interconnected ecosystems, is the laborious sampling necessary. New technologies are being incorporated into data collection, such as litter quantification through remote sensing and the use of Unmanned Aerial Vehicles (UAV) to collect data in open areas (Andriolo et al., 2021a, 2021b; Deidun et al., 2018; Martin et al., 2021). This technology has mainly been used to scan the marine litter accumulated on the sand surface along beaches and coastlines (Salgado-Hernanz et al., 2021) because vegetation tends to make it challenging to recognise items (Gonçalves et al., 2020a, 2020b). In addition, remotely operated vehicles (ROVs) are being used to study shallow marine areas (Rodríguez and Pham, 2017; Stagličić et al., 2021), as well as deep marine zones (Angiolillo et al., 2021; Botero et al., 2020; Consoli et al., 2020, 2021).

5. Conclusions

This study confirms the ubiquity of marine litter, in all the ecosystems analysed. The evidence suggests that mainly back-beach vegetation areas and mangroves, act as essential retainers for both local waste and litter from outside the archipelago. Meanwhile, the mangroves are the primary plastic accumulation hotspots, with densities greater than 8 items/m^2, while the back-beach vegetation areas remove and store a portion of the litter that arrives on the beaches via dynamic agents (wind and currents) as well as active agents (irregular waste disposal and beach cleaning). Part of this litter can return to the marine environment and eventually reach other ecosystems.

The low density of items found at coral reef dive sites indicates that the interconnection between the dynamic agents is low. However, the similarity between the types of plastic found in the different ecosystems suggests that the waste might be being exchanged, either due to dynamic or active processes. The significant difference in item density between tourist and non-tourist beach areas is a result of the cleaning carried out, and such management initiatives should be extended to the other ecosystems in the archipelago.

Our analysis provides relevant information for understanding the fate and pathways of marine litter in the environment, demonstrating that oceanic islands serve as sentinels against ocean contamination by solid waste. Detailed monitoring of litter in different ecosystems can provide an efficient tool for assessing changes in residue quantities and composition in the SEAFLOWER Biosphere Reserve over time.

Despite all our knowledge of coastal ecosystems, their importance is clearly not respected, given the high number of items quantified in this and other studies. Much of the macro-litter found in the archipelago can be associated with external sources; however, locally sourced waste is also linked to the leading local economic activities (tourism and fishing). Future work will investigate the plastic bulk to characterize the different polymer composition.

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. **Diego Andres Villate-Daza:** Formal analysis, Funding acquisition. **Ángela Fontán-Bouzas:** Writing – original draft, 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

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