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Geophysical features influence the accumulation of beach debris on Caribbean islands

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ABSTRACT

Anthropogenic beach debris was recorded during beach surveys of 24 Caribbean islands during April 2014–April 2016. Beach debris was classified according to material type (e.g., polystyrene) and item use (e.g., fishing). Geophysical features (substrate type, beach direction, and human accessibility) of sample sites were recorded in order to investigate their relationship with debris density. Results suggest the density of macro debris (items > 5 mm) is highest on uninhabited, sandy beaches facing a leeward direction. Higher debris quantities on inaccessible beaches may be due to less frequent beach clean ups. Frequently accessed beaches exhibited lower macro, but higher micro debris (items 1–5 mm) densities, possibly due to removal of macro debris during frequent beach clean ups. This suggests that while geophysical features have some influence on anthropogenic debris densities, high debris densities are occurring on all islands within the Caribbean region regardless of substrate, beach direction, or human accessibility.

1. Introduction

Plastics are lightweight, versatile, inexpensive and durable, and therefore the material of choice for a wide range of consumer and industrial products since its invention in the early 20th century (Thompson et al., 2009). Current plastic use is unsustainable, because many products are designed as single-use, and then discarded after being used for only a few minutes, yet persist in the environment for decades (EPA, 2016). Effective coordination of waste management and recovery of plastic materials is lacking on a global scale, and as a result, up to 12.7 million metric tonnes per year of discarded plastic ends up in the oceans (Jambeck et al., 2015).

Preventing marine debris is challenging due to its non-point source nature with almost endless entry points and diversity of materials (Ryan et al., 2009). Sources of debris can be either land- or marine-based (Thompson et al., 2009) with the latter defined as items discarded at sea – either intentionally or accidentally from commercial shipping vessels, fishing fleets, or recreational boating (Whiting, 1998). Land-based sources are more diverse, ranging from leakages in plastic production and intentional dumping to unintentional littering (Singh and Xavier, 1997; Siung-Chang, 1997). Once in the ocean, the non-biodegradable nature of plastic combined with wind and wave action, and photodegradation contribute to fragmentation of larger items into increasingly smaller pieces. Depending on their size, fragments are typically classified as either macro- (> 5 mm) or micro-plastics (1–5 mm), although additional size categories are sometimes used (e.g., nanoplastics < 1 mm; GESAMP, 2015; Hanvey et al., 2017). While many items that remain afloat will accumulate along oceanic convergence zones and in gyres of the major ocean basins (Coulter, 2010), including the subtropical latitudes of the Atlantic Ocean (Law et al., 2010), plastic debris is distributed from pole to pole (Thompson et al., 2009).

A review of beach debris by Barnes (2005) highlighted a gradient of debris accumulation from the equator to the poles that mirrors the approximate distribution of the human population. However, few studies have quantified beach debris, and its associated impacts, in remote locations (Vegter et al., 2014). The limited information available suggests that beach-based marine debris has increased over the past two decades, and may be many orders of magnitudes higher compared with the 1980–1990s (Barnes, 2005; Lavers and Bond, in press). On remote, tropical islands, the density of beach debris can be exceptionally high and often increases in relation to isolation (Duhec et al., 2015; McDermid and McMullen, 2004), likely a result of the

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accumulation of debris over time, rather than proximity to waste sources (Barnes, 2005). This poses an aesthetic issue, but is also worrying as plastic items deposited on beaches may alter beach characteristics, inflicting biological and economic consequences, for example, negatively impacting the breeding behaviour of turtles (Fujisaki and Lamont, 2016), or contributing to reductions in beach tourism (Jang et al., 2014).

In the Caribbean, monitoring of land-based sources of marine pollution was initiated in 1999 by the Caribbean Environmental Programme (CEP; UNEP, 1999). Since that time, sewage treatment policies and adoption of legally binding agreements regarding levels of acceptable waste (Cartagena Convention, Annex 3; Siung-Chang, 1997; UNEP, 1999) have not resulted in significant improvements to waste management, largely due to a lack of disposal facilities in ports, difficulty in finding appropriate sites for landfills, and significant inputs of land-based debris through major rivers, urban centres, and industries (Siung-Chang, 1997). As a result, a number of pollution hotspots have been identified in the Caribbean region, located primarily adjacent to urban centres, agricultural areas, and tourism sites (e.g., Ivar do Sul and Costa, 2007; Williams et al., 2016). The main distribution pathway for marine debris was speculated to be prevailing ocean currents and winds, with seasonal fluctuations in debris abundance due to stronger onshore winds in the dry season (Garrity and Levings, 1993; Hastenrath, 1976). The two main currents in the wider Caribbean region (WCR; i.e., geographic area including the Caribbean islands, the Caribbean Sea, and the coastlines of North, Central, and South America bordering the Caribbean Sea) are the Caribbean Current, which enters the Caribbean Sea near Grenada and originates in the Panama Gyre, and the Antilles Current, which flows northward and is sourced from the dominant Atlantic current systems (Jury, 2011).

To date, few studies have investigated the issue of marine debris in the Caribbean. Most were conducted more than two decades ago (Corbin and Singh, 1993; Ivar do Sul and Costa, 2007; Singh and Xavier, 1997), focus on individual islands/countries (e.g., de Scisciolo et al., 2016) with an overall lack of standard methodology for sampling which complicates cross study comparisons of debris densities (Ryan et al., 2009). Here we investigated the density, dominant type, and source of marine debris on the beaches of 24 islands across the Caribbean Sea in relation to their geophysical features and level of accessibility to visitors. A primary objective of this research was to provide a snapshot on the density of anthropogenic marine debris, including micro items, found on 'pristine' beaches across a relatively large geographic region.

2. Methods

2.1. Sampling locations

In total, 42 beaches across 24 islands from 5 nations were sampled during April 2014, February–March 2015, and March–April 2016 including the Bahamas (n = 12), British Virgin Islands (n = 1), Dominican Republic (n = 5), Grenada (n = 3), St. Vincent and the Grenadines (n = 10), Turks & Caicos Islands (n = 2), Cayman Islands (n = 6), Martinique (n = 3), and St. Eustatius (n = 1; Fig. 1). In 2016, volunteer 'citizen scientists' were invited to contribute data to this project and were provided with a detailed sampling protocol, thereby ensuring consistent data collection. The protocol explained the transect method (e.g., dimensions; details provided below), the differences between macro- and micro-plastics, and included an identification and definition guide for different categories of debris, and datasheet for recording marine debris on beaches.

2.2. Sampling design

Beach substrate was recorded as sandy, rocky, or mixed. Beach direction was defined as leeward or windward facing. Beaches were classified as windward when facing the dominant oceanographic currents that typically flow from the Atlantic Ocean into the WCR (i.e., windward beaches were those beaches located on the north and north-eastern side of islands). Approximately 60% (n = 26) of the beaches surveyed during this study faced a windward direction (leeward: n = 17).

Transects were established parallel to the water and along the high tide mark and measured 2 m × 20 m. For a small subset of transects, the length and width was adjusted to overcome challenges related to beach characteristics (e.g., the beach was too narrow). In areas of especially high plastic density, transect area was reduced to 20 m^2 (10 m × 2 m) in order to enable data collection within a reasonable time frame. On a subset of beaches, the density of micro-debris items was estimated within existing transects, or by establishing one quadrat (typically 10 × 10 cm) along the high tide line, which enabled detailed counts of all visible items. While the micro-debris surveys were limited in number (n = 11) and located primarily on beaches with high accessibility (n = 9), they provided valuable insight into the proportion of small debris items that are typically missed during traditional beach surveys that focus on macro pieces.

2.3. Anthropogenic debris classification

Anthropogenic debris items recorded on beaches were categorised as follows: plastic, glass, metal, polystyrene (e.g., foam), and wood. Plastic items were further subdivided into the following categories: disposable user items (e.g., straws, bottles), fishing related (e.g., rope, floats), film (e.g., bags, wrappers), unidentifiable fragments (micro- and macro-debris reported separately), clothing (e.g., shoes) and miscellaneous (e.g., toys, cosmetic items).

2.4. Debris density estimation

The density of marine debris items in each transect or quadrat was estimated as the total number of debris items (excluding micro-debris) per m^2 (± S.D.). The recorded number of debris items per transect was summed and then divided by transect area to generate the density per m^2. For later analysis the resulting density estimate for each transect was then calculated for a 40 m^2 transect area. We calculated the mean debris density per site and per country/territory (in cases when multiple beaches were sampled within the same country/island). For the quadrats, the density of micro-debris items was estimated separately, then scaled up to the corresponding density for a 20 × 2 m (40 m^2) transect and reported as items/40 m^2.

2.5. Statistical analysis

Statistical analysis was carried out in R 3.3.1 (R Core Team, 2016). To test the hypothesis that geophysical island features influence the abundance of debris on Caribbean beaches, factors considered in the models were split into two groups: geophysical island features (substrate, beach direction) and accessibility. Beach accessibility was defined as human presence and categorised as: inhabited (high), visited only (medium), and neither visited nor inhabited (low). As sites were surveyed only once, and our hypotheses concerned geophysical beach features, the year of collection was not included in our analysis. The uneven distribution of data was dealt with by calculating the number of debris pieces per 40 m^2 transect to produce count data that could be used in a Poisson generalized linear model. Parameter estimates are given with 95% confidence intervals.

3. Results

3.1. Density and type of anthropogenic debris on beaches

The abundance of macro debris on Caribbean beaches ranged from

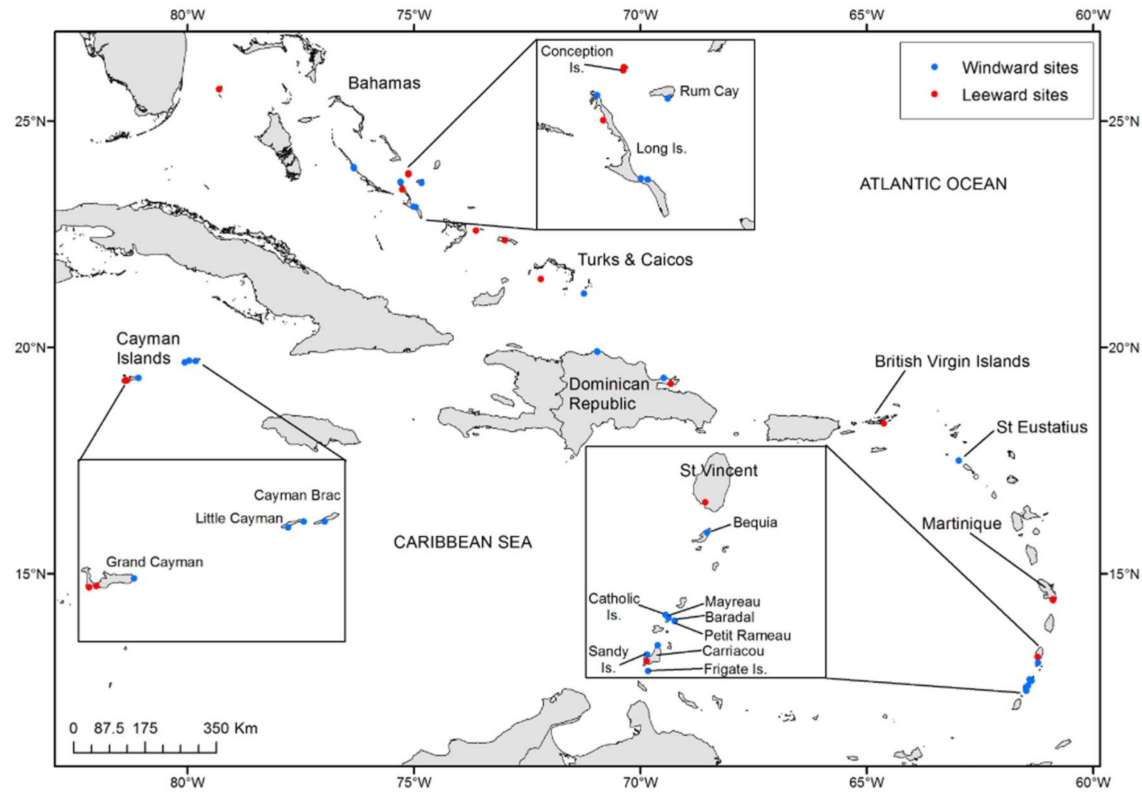

Fig. 1. Beach debris sampling sites on Caribbean islands during 2014–2016.

0.10 items/m^2 (Cemetery Beach, Cayman Islands) to 48.25 items/m^2 (Flying Fish Marina Beach, Long Island, Bahamas; Table 1). Overall, the mean density of macro debris recorded across all Caribbean beaches sampled was 6.34 ± 10.11 items/m^2 and the mean density of micro-debris was 1.23 ± 1.69 items/m^2 (Tables 2 and 3). The most abundant debris type observed on all beaches was plastic (5718 items in total; including plastic, fishing gear, polystyrene, macro- and micro-plastic fragments) which accounted for ~90% of all items recorded. Plastic film (i.e., bags, wrapping) and polystyrene (much of which likely originated from food containers and fishing activities) were relatively common in transects, accounting for 17.0% and 13.0% of items recorded across all islands. Fragments of macro-plastic were the most abundant overall in transects (64.27 ± 2.35 items/m^2). Overall, the density of polystyrene, fishing gear, glass, metal, and wood was 32.95 ± 1.79, 15.98 ± 0.64, 12.90 ± 1.61, 1.80 ± 0.06, and 0.92 ± 0.02 items/m^2, respectively. In the micro plastic survey micro fragments were the most commonly recorded micro debris type in this study, accounting for ~94% of micro items recorded.

3.2. Factors influencing the density of macro debris

The density of macro debris was marginally, but significantly, greater on leeward (19.26 ± 53.51 items/40 m^2) compared to windward sites (18.00 ± 70.12 items/40 m^2; $z = -4.434$, $p < 0.001$), and was greatest on sandy substrate (median: 76.47 items/40 m^2, mean ± SD: 19.58 ± 76.47 items/40 m^2) compared to rocky (median: 56.25 items/40 m^2, mean ± SD: 19.98 ± 56.25 items/40 m^2; $z = 3.447$, $p < 0.001$) or mixed substrates (12.00 ± 21.23 items/40 m^2; $z = 15.541$, $p < 0.001$). Finally, beaches that received little human disturbance from visitors or residents had the highest density of macro debris (27.61 ± 67.40 items/40 m^2) compared to medium (11.45 ± 33.45 items/40 m^2; $z = -15.09$, $p < 0.001$) or high levels of disturbance (18.17 ± 72.51 items/40 m^2; $z = -18.90$, $p < 0.001$).

3.3. Factors affecting the density of micro debris

In total, micro-plastic debris estimates were available for 11 sites. All quadrats, except L'islet Beach, Carriacou and Anse Caritan, Martinique (Table 2) were located on islands northwest of the British Virgin Islands (Fig. 1) with the majority having sandy ($n = 7$) or mixed substrate ($n = 6$). There was significantly more micro debris on windward sites (39.77 ± 49.77 items/40 m^2) compared to leeward beaches (26 items/40 m^2; $z = 3.324$, $p < 0.001$), though only one site was on the leeward side of an island. There was no difference in the density of micro debris on beaches with mixed substrates (49.33 ± 69.17 items/40 m^2) and those that were only sand (34.29 ± 26.35 items/40 m^2; $z = -0.569$, $p = 0.57$); no rocky beaches were surveyed for micro debris. Human visitation had a significant effect on micro debris density, with more debris found on beaches with high human traffic (51.00 ± 56.73 items/40 m^2) compared to medium (19.25 ± 9.71 items/40 m^2; $z = -7.884$, $p < 0.001$) and low levels (7.00 items/40 m^2; $z = -5.398$, $p < 0.001$, though $n = 1$).

4. Discussion

We found that the density of anthropogenic debris items on Caribbean beaches varies in relation to a number of factors, including beach accessibility, direction, and substrate, though these relationships varied on the size class of debris considered. Beaches with local residents or visitors exhibited the highest densities of micro debris, but had lower densities of macro debris, possibly driven by proximity to point sources (e.g., run-off from urban centres) as well as local beach cleaning efforts which target larger items (authors' pers. obs.). Remote uninhabited beaches, such as Napoleon Island (Dominican Republic) and Big Sand Cay (Turks and Caicos; Table 1; Fig. 2), often had densities of macro debris > 10 × those found on inhabited beaches. An unnamed cove on Great Guana Cay (a largely uninhabited island in the central Bahamas) was extremely heavy polluted, particularly by large fragments (8.30 ± 0 items/m^2). Debris densities may be higher in

Table 1
Density of macro debris (> 5 mm; item/m^2) in relation to beach direction (leeward (LW) or windward (WW) facing) and accessibility for Caribbean islands sampled during 2014–2016. Sampling was undertaken using a transect. The total quantity of macro debris recorded is shown, along with the overall mean for each site, as well as the average for each country and overall mean density across all Caribbean islands. Substrate (Sub) is recorded as sandy (S), rocky (R), or mixed (M). Beach accessibility score (Access) was recorded as low (L; most remote), medium (M), and high (H; regularly visited).

Date	Location	Debris items recorded (n)	Sampled area (m^2)	Density (items/m^2)	Beach direction	Sub	Access
Bahamas		2238	240	9.32 ± 13.34			
Feb 2015	Site 20, Mayaguana Is., eastern beach, Abraham Bay	41	20	2.05	LW	S	M
Feb 2015	Site 21, West Plana Cay, east anchorage	7	20	0.35	LW	S	M
Mar 2015	Site 22, Long Is., northwest beach	4	20	0.20	LW	S	H
Mar 2015	Site 23, Long Is., northeast beach	46	20	2.30	WW	R	H
Mar 2015	Site 24, Long Is., Deans Blue Hole	379	20	18.95	WW	S	H
Mar 2015	Site 25, Long Is., Flying Fish Marina Beach	965	20	48.25	WW	S	H
Mar 2015	Site 26, Rum Cay, east of marina	23	20	1.15	WW	S	H
Mar 2015	Site 27, Conception Is., inlet	14	20	0.70	LW	R	M
Mar 2015	Site 28, Conception Is., anchorage	121	20	6.05	LW	S	M
Mar 2015	Site 29, Little Farmers Cay, Exumas Is.	55	20	2.75	WW	R	M
Mar 2015	Site 30 Unnamed Bay, Great Guana Cay	342	20	17.10	WW	S	M
Mar 2015	Site 31, South Bimini, Bimini Sands Resort	241	20	12.05	LW	S	H
British Virgin Islands							
Feb 2015	Site 17, Kelly's Cove, Norman Is.	28	40	0.70	LW	R	M
Cayman Islands		1097	240	5.73 ± 4.13			
Apr 2016	Site 33, Prospect Beach, Grand Cayman	365	40	9.13	LW	M	H
Apr 2016	Site 34, Cemetery Beach, South Sound	4	40	0.10	LW	S	H
Apr 2016	Site 35, Cayman Brac, south side	380	40	9.50	WW	M	H
Apr 2016	Site 36, Charles Bight, Little Cayman	85	40	2.13	WW	M	H
Apr 2016	Site 37, Owen Is., South Hole Sound	116	40	2.90	WW	M	H
Apr 2016	Site 38, Colliers Beach, Grand Cayman	425	40	10.63	WW	S	H
Dominican Republic		498	84	12.46 ± 19.27			
Feb 2015	Site 1, Napoleon Is., Samaná Bay	187	4	46.75	LW	R	L
Feb 2015	Site 13, Samaná Marina Beach	127	20	6.35	LW	M	H
Feb 2015	Site 14, Playa de Portillo Beach	77	20	3.85	WW	S	H
Feb 2015	Site 15, Luperon Beach, Resort	16	20	0.80	WW	S	H
Feb 2015	Site 16, Luperon Beach	91	20	4.55	WW	S	H
Grenada		412	120	3.43 ± 2.45			
Apr 2014	Site 2, Frigate Is., southeast beach	269	40	6.73	WW	R	L
Apr 2014	Site 3, Sandy Is.,	34	40	0.85	WW	R	M
Apr 2016	Site 39, Tyrell Bay	109	40	2.28	LW	S	H
Martinique		25	120	0.21 ± 0.70			
Apr 2016	Site 41, Anse Caritan	12	40	0.30	LW	S	H
Apr 2016	Site 42, Anse Meunier	7	40	0.18	LW	S	H
Apr 2016	Site 43, Pointe Dunkerque	6	40	0.15	LW	S	H
St Eustatius							
Mar 2016	Site, 32Lynch Beach, east side	48	40	1.20	WW	R	M
St. Vincent & the Grenadines		979	230	4.41 ± 3.10			
Apr 2014	Site 4, Catholic Is., T1[a]	80	20	4.00	WW	R	L
Apr 2014	Site 5, Catholic Is., T2[a]	35	20	1.75	WW	R	L
Apr 2014	Site 6, Catholic Is., north-east beach	212	40	5.30	WW	R	L
Apr 2014	Site 7, Mayreau Is., T1	96	20	4.80	WW	S	H
Apr 2014	Site 8, Mayreau Is., north-east beach	81	10	8.10	WW	S	H
Apr 2014	Site 9, Petit Rameau, Tobago Cay, north-east beach	42	20	2.10	WW	S	M
Apr 2014	Site 10, Baradal Is., Tobago Cay, east peninsular	42	20	2.10	WW	S	M
Apr 2014	Site 11, Sugar Reef, Becquia Is.	230	20	11.50	WW	S	H
Apr 2014	Site 12, St Vincent, Canash Beach	18	20	0.90	LW	S	H
Apr 2016	Site 40, L'islet Beach, Petit Carenage Bay Carriacou	143	40	3.58	WW	S	M
Turks and Caicos		270	60	2.25 ± 1.95			
Feb 2015	Site 18, Big Sand Cay	252	40	6.35	WW	S	L
Feb 2015	Site 19, French Cay, east side	18	20	0.90	LW	R	L
Total		5873	1174	6.34 ± 10.11			

[a] Two transects were completed at Catholic Island at opposite ends of a long beach on the same day.

remote areas, despite being distant from metropolitan centres and experiencing less direct input from recreational users, due in part to decreased chance of debris removal (e.g., fewer beach clean-ups) and therefore increased accumulation. A significant challenge when interpreting patterns in debris on beaches, and at sea, is accounting for the diverse range of factors that individually influence debris densities, but which often occur concurrently and may therefore act synergistically, such as the relationship between increased beach use and more frequent beach clean ups.

The mean density of macro debris recorded in this study (6.34 ± 10.11 items/m^2) appears to exceed debris densities reported by studies undertaken in the WCR prior to 2000 (Table 3). Unfortunately, a lack of standardised reporting protocol for estimating the density of debris in beach sediments limits our ability to compare our findings with historical data (Hanvey et al., 2017). The composition of beach debris reported in this study is relatively consistent with previous studies in the Caribbean, with plastic accounting for 40–98% of all items recorded throughout the region (e.g., Debrot et al., 1999; Debrot

Table 2
Density of micro debris (1–5 mm; item/m^2) in relation to beach direction (leeward (LW) or windward (WW) facing) and accessibility for Caribbean islands sampled during 2014–2016. Sampling was undertaken using either a transect (T) or quadrat (Q). To facilitate comparison across sites, micro debris densities in quadrats were scaled up to the standard transect area (20 × 2 m). The total quantity of micro debris recorded is shown, along with the overall mean for each site, as well as the average for each country and overall density across all Caribbean islands. Substrate (Sub) is recorded as sandy (S), rocky (R), or mixed (M). Beach accessibility score (Access) was recorded as low (L; most remote), medium (M), and high (H; regularly visited).

Date	Location	Sampling method	Debris items recorded (n)	Sampled area (m^2)	Density (items/m^2)	Beach direction	Sub	Access
Cayman Islands								
Apr 2016	Site 34, Cemetery Beach, South Sound	T	26	40	0.65	LW	S	H
Apr 2016	Site 35, Southside Cayman Brac	T	251	40	6.28	WW	M	H
Apr 2016	Site 36, Charles Bight, Little Cayman	T	36	40	0.90	WW	M	H
Apr 2016	Site 37, Owen Is.	T	8	40	0.20	WW	M	H
Apr 2016	Site 38, Colliers Beach, Grand Cayman	T	35	40	0.88	WW	S	H
Grenadines								
Apr 2014	Site 40, L'islet Beach, Carriacou	T	31	40	0.78	WW	S	H
St Vincent and the Grenadines								
Apr 2014	Site 6, Catholic Is.	T	7	40	0.18	WW	R	L
Apr 2014	Site 7, Mayreau Is., T1	T	9	20	0.45	WW	S	H
Apr 2014	Site 8, Mayreau Is., north-east beach	T	23	10	2.30	WW	S	H
Apr 2014	Site 10, Baradal Is.	T	11	20	0.40	WW	S	M
Turks and Caicos								
Feb 2015	Site 18, Big Sand Cay	Q	25	0.01	2500.00	WW	S	L
Total			493	390.01	1.23 ± 1.69			

Table 3
Summary of the density of debris reported on Caribbean beaches from 1993 to 2012, and overall debris densities (mean ± SD) for all sites in the Wider Caribbean Region (WCR) assessed during this study (2014–2016). Macro (> 5 mm) and micro (1–5 mm) debris densities are reported either as items per m^2 or items per linear meter (m^{-1}).

Location	Reporting metric	Density of debris	Source
St Lucia	Density range	4.5–11.2 items/m	Corbin and Singh (1993)
	Mean abundance	13 items/m (isolated beach)	Singh and Xavier (1997)
		12.5 items/m (recreational beach)	
Dominica	Density range	1.9–6.2 items/m	Corbin and Singh (1993)
Panama	Overall mean	3.6 items/m^2	Garrity and Levings (1993)
Curaçao	Geometric mean	60 (23–157) items/m	Debrot et al. (1999)
Puerto Rico	Mean abundance	3.9 items/m (isolated beach)	Singh and Xavier (1997)
Bonaire	Mean abundance, macro only, windward	295.5 ± 469.9 items/m	Debrot et al. (2013)
	Mean abundance, macro only, leeward	1.6 ± 1.5 items/m	
Aruba	Mean abundance, windward	0.91 ± 0.50 items/m^2 (29.7 ± 18.7 items/m)	de Scisciolo et al. (2016)
	Mean abundance, leeward	0.20 ± 0.07 items/m^2 (6.8 ± 2.5 items/m)	
WCR	Macro debris	6.34 ± 10.11 items/m^2	This study
	Micro debris	1.23 ± 1.69 items/m^2	
	Overall (combined)	6.66 ± 10.19 items/m^2	

et al., 2013; Ivar do Sul and Costa, 2007). Polystyrene, plastic food containers, and other disposable user items (i.e., plastics bottles, cans, lids) were consistently recorded on all beaches (Fig. 2; Tables S1 and S2). Overall, the most abundant item was unidentifiable plastic fragments, the majority of which likely resulted from user items breaking up (i.e., fragmenting) when exposed to the harsh marine environment (de Scisciolo et al., 2016).

The density of macro debris on windward beaches was only marginally lower than densities recorded on leeward beaches (Table 1). Densities on windward beaches may be explained, in part, by exposure to major current systems of the Atlantic Ocean and dominant trade winds. Oceanographic studies for the region (Hastenrath, 1976; Jury, 2011; Kinder et al., 1985) show the Atlantic North Equatorial Current flowing northward from the equator past the Caribbean islands. High densities of beach debris along the south-eastern coasts of islands are therefore likely to be influenced by inputs from this system, which transports ocean-based debris from offshore shipping and fishing activities and land-based sources elsewhere. Exposure to ocean currents has been highlighted as a primary factor influencing the density of beach debris on a number of islands in the Pacific (Agustin et al., 2015; Dameron et al., 2007; McDermid and McMullen, 2004) as well as previous studies in the Caribbean (Corbin and Singh, 1993; Debrot et al., 1999; Ivar do Sul and Costa, 2007). While leeward beaches may not experience the wind and wave energy from dominant currents, sandy beaches facing a leeward direction have been shown to be natural depositing environments (Ribic et al., 2012; Ryan et al., 2014). This is largely due to leeward beaches being more sheltered from the elements, trapping sandy sediments and likely accumulating marine debris.

There is an increasing trend in beach debris throughout the Caribbean, particularly on Aruba and Bonaire, two sites not sampled during the present study (de Scisciolo et al., 2016; Debrot et al., 2013). An increasing number of inputs, such as higher tourism numbers, and growing plastic production in combination with insufficient waste management on many Caribbean islands suggest the increasing trend in debris on beaches will continue for some time. Overall, the increasing trend in beach debris on Caribbean islands suggests that while the issue of marine debris was recognised by Caribbean governments approximately 20 years ago (UNEP, 2012), management of marine debris remains largely ineffective. For instance, while waste management has improved somewhat in recent years, it is still largely inadequate on many islands (Corbin et al., 2010). In addition to much-needed improvements in waste management to prevent items from entering the marine environment, organised or voluntary beach clean ups would also provide an alternative for controlling marine debris in coastal environments. While the cost of beach clean ups can be significant and have been shown to vary significantly depending on the amount of debris present, year or season, and whether the clean ups

Fig. 2. Examples of the density and composition of debris recorded during beach surveys in the Caribbean Sea in 2014–2016. A) Playa de Portillo, Dominican Republic (site 14). This sandy beach is situated in a tourist area (accessibility score: high). B) Big Sand Cay, Turks and Caicos. Remote, sandy beach (accessibility score: low). C) Napoleon Island, Dominican Republic. Remote, rocky beach (accessibility score: low). Most polluted beach recorded in this survey. D) Frigate Island, Carriacou. Remote, rocky beach (accessibility score: low) and most southerly island of this survey.

were undertaken by government employees or with the aid of volunteers (Ryan and Swanepoel, 1996), the benefits are also significant. For example, marine debris on beaches costs members of the Asian Pacific Economic Cooperation (APEC), an estimated US$1.27 billion per year (as of 2008; McIlgorm et al., 2008).

For many Caribbean islands, tourism is a primary source of income (Newman et al., 2015), generating about 16% of regional gross domestic product (JetBlue, 2014). Caribbean tourism actively promotes clean and pristine beaches, as well as aquatic activities like snorkelling and diving, which rely on healthy marine ecosystems. Without managing the present debris load, and preventing an increase in future debris, the tourism industry is susceptible to losses derived from marine environment degradation (Smith et al., 1997). Information on the impacts of beach debris on tourism can be drawn from a recent study in South Korea, which suggests tourism revenue losses following significant debris 'events' (e.g., large amounts of debris due to storms) is in the order of US$29–37 million (Jang et al., 2014). The tourism industry for most coastal countries is dependent on a healthy marine environment; therefore the degradation of these environments should be a significant concern even when data on the true financial cost/impact of debris are not available.

We did not collect data on the density of micro debris on most surveys due to the significant time required to collect and record small items, which was a particular challenge for the citizen science projects. All micro debris data reported here was also sourced from sandy beaches due to the difficulty of sampling on other substrates. Despite this, the micro debris data we did collect accounted for a significant proportion of the total number of items recorded (Tables 2 and 3). Existing beach surveys and clean up programs that do not account for items < 5 mm may therefore drastically underestimate the amount of micro debris on beaches (Lavers et al., 2016). While more labour intensive, data on the density of micro debris can also be generated by collecting the top layer of sediment from transects, and separating the sample into sediment and micro particles in the lab by floatation (i.e., plastic floats to the top while sediment and other particles may sink; Besley et al., 2017). Future surveys in the Caribbean should sample representative beaches to better understand the relationship between the densities of micro- and macro-debris. Such data are crucial to understanding on the impact of micro-plastics densities on in the local marine environment, including the potential for ingested micro-plastics to transport hazardous chemicals to wildlife (GESAMP, 2015).

Recent evidence suggests that one time sampling of beaches may severely misrepresent the actual debris loads of beaches (Ryan et al., 2014; Smith and Markic, 2013). Accurate estimation of accumulation rates can be achieved through daily consecutive sampling over a short period of time (Ryan et al., 2014), with an optional repeat sampling over several months (Smith and Markic, 2013). Beaches are dynamic environments and beach debris loads will reflect this dynamic nature, for instance, the potential high sediment turnover rates (Ryan et al., 2014). Although once-off debris inventories are useful, they are heavily influenced by external factors and may vary not only between years but even in monthly debris composition and loads (Ribic et al., 2012). Daily sampling of debris tends to yield increased estimates of debris abundance compared to less frequent sampling, which may be closer to the actual debris loads on beaches. Thus, daily sampling may allow determining the accumulation rate of debris, but also provide insight into debris turnover rate.

5. Conclusions

Our data provides only a brief snapshot of marine debris densities on Caribbean islands and therefore fails to capture the dynamic nature of beach debris. More intensive, repeat sampling is required to fully disentangle the effects of geophysical features and accessibility on trends in the accumulation and retention of beach debris. Future studies could also employ more complex modelling approaches such as drifter models (Duhec et al., 2015) to improve our understanding of how and where debris accumulates in the Caribbean region. However, we provide additional baseline information on debris densities across the wider Caribbean region, enabling limited comparison of debris densities across islands that have benefitted from repeat surveys over many years.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.marpolbul.2017.05.043.

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Table S1. Number (*n*) and frequency of occurrence (FO) of major categories (see text) of beach-washed anthropogenic debris recorded on islands in the Caribbean Sea during 2014 to 2016.

				Plastic fragment											
		Debris whole		Macro (> 5 mm)		Micro (1-5 mm)		Foam		Sheet		Thread		Other	
Location	**Lat/Long**	***n***	**FO**	***n***	**FO**	***n***	**FO**	***n***	**FO**	***n***	**FO**	***n***	**FO**	***n***	**FO**
Bahamas															
South Bimini, Bimini Sands Resort	25.7089°N -79.3012°W	25	0.10	23	0.10	1	0.01	181	0.75	0	0.00	0	0.00	12	0.05
Conception Is., anchorage	23.8452°N -75.1199°W	11	0.09	88	0.72	0	0.00	5	0.04	1	0.01	16	0.13	0	0.00
Conception Is., inlet	23.8245°N -75.1249°W	0	0.00	11	0.79	0	0.00	2	0.14	1	0.07	0	0.00	0	0.00
Little Farmers Cay, Exumas Is.	23.9616°N -76.3242°W	9	0.16	23	0.41	1	0.018	0	0.00	11	0.20	8	0.14	4	0.07
Long Is., north-west beach	23.4931°N -75.2560°W	3	0.75	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1	0.25
Long Is., north-east beach	23.6603°N -75.2983°W	12	0.26	2	0.04	0	0.00	0	0.00	20	0.44	6	0.13	6	0.13
Long Is., Deans Blue Hole	23.1063°N -75.0087°W	16	0.04	153	0.40	1	0.003	0	0.00	108	0.28	100	0.26	2	0.01
Long Is., Flying Fish Marina Beach	23.1004°N -74.9629°W	109	0.11	70	0.07	0	0.00	0	0.00	751	0.78	35	0.04	0	0
Mayaguana Is., eastern beach, Abraham Bay	22.3703°N -72.9902°W	6	0.14	21	0.51	0	0.00	0	0.00	3	0.07	9	0.22	2	0.05
Rum Cay, east of marina	23.6365°N -74.8284°W	7	0.30	6	0.26	0	0.00	1	0.04	0	0	8	0.35	1	0.04
Unnamed Bay, Great Guana Cay	23.9859°N -76.3284°W	61	0.18	166	0.49	0	0.00	1	0.01	38	0.11	75	0.22	1	0.01
West Plana Cay,	22.5808°N	2	0.29	1	0.14	0	0.00	3	0.43	0	0.00	0	0.00	1	0.14

east anchorage	-73.6273°W														
British Virgin Islands															
Kelly's Cove, Norman Is.	18.3228°N -64.6196°W	10	0.36	8	0.29	0	0.00	0	0.00	3	0.11	7	0.25	0	0.00
Cayman Islands															
Cemetery Beach, South Sound	19.2656°N -81.3809°W	0	0.00	4	0.13	26	0.87	0	0.00	0	0.00	0	0.00	0	0.00
Charles Bight, Little Cayman	19.7028°N -79.9606°W	20	0.17	24	0.20	36	0.30	1	0.01	14	0.12	9	0.07	17	0.14
Owen Is., South Hole Sound	19.6646°N -80.0620°W	23	0.19	23	0.19	8	0.07	32	0.26	21	0.17	1	0.01	16	0.13
Colliers Beach, Grand Cayman	19.3249°N -81.0843°W	78	0.17	158	0.34	35	0.08	126	0.27	10	0.02	6	0.01	47	0.10
Prospect Beach, Grand Cayman	19.5010°N -81.3330°W	21	0.01	52	0.14	0	0.00	6	0.02	2	0.01	1	0.01	283	0.78
Cayman Brac, south side	19.7020°N -79.8200°W	132	0.21	213	0.34	250	0.40	2	0.01	19	0.03	6	0.01	8	0.01
Dominican Republic															
Luperon Beach, resort	19.9101°N -70.9538°W	2	0.13	2	0.13	0	0.00	9	0.56	1	0.06	0	0.00	2	0.13
Luperon Beach	19.9028°N -70.9451°W	12	0.13	5	0.06	0	0.00	68	0.75	1	0.01	0	0.00	5	0.06
Napoleon Is., Samaná Bay	19.1952°N -69.3267°W	147	0.70	1	0.01	20	0.10	15	0.07	20	0.10	0	0.00	4	0.02
Playa de Portillo Beach	19.3228°N -69.4895°W	13	0.17	43	0.56	0	0.00	14	0.18	4	0.05	1	0.01	2	0.03
Samaná Marina Beach	19.2025°N -69.3361°W	16	0.13	23	0.18	0	0.00	28	0.22	58	0.46	0	0.00	2	0.02
Grenada															
Frigate Is., south-east beach	12.4112°N -61.4779°W	138	0.51	0	0.00	0	0.00	107	0.40	1	0.01	0	0	23	0.09
Grenadines															
Baradal Is.,	12.6348°N	5	0.09	15	0.28	11	0.21	0	0.00	0	0.00	0	0.00	22	0.42

Tobago Cays, east peninsula	-61.3600°W														
Petit Rameau, Tobago Cays, north-east beach	12.6332°N -61.3600°W	7	0.14	9	0.18	8	0.16	0	0.00	0	0.00	4	0.08	22	0.44
Sandy Is., Carriacou	12.4857°N -61.4823°W	12	0.35	0	0.00	0	0.00	9	0.27	2	0.06	2	0.06	9	0.27
Tyrrell Bay, Carriacou	12.4557°N -61.4834°W	43	0.39	0	0.00	0	0.00	2	0.02	7	0.06	1	0.01	56	0.51
Catholic Is., north-east beach	12.6601°N -61.3999°W	165	0.75	0	0.00	7	0.03	20	0.09	0	0.00	5	0.02	22	0.10
Catholic Is., south beach	12.6601°N -61.3999°W	89	0.77	0	0.00	0	0.00	7	0.06	3	0.03	1	0.01	15	0.13
Mayreau Is., north-east beach	12.6468°N -61.3878°W	28	0.13	79	0.38	32	0.15	35	0.17	1	0.01	12	0.06	12	0.06
St Vincent, Canash Beach	13.1293°N -61.1942°W	6	0.33	0	0.00	0	0.00	0	0.00	1	0.06	0	0.00	11	0.61
Martinique															
Anse Caritan	14.4288°N -60.8865°W	9	0.75	0	0.00	0	0.00	0	0.00	1	0.08	2	0.17	0	0.00
Anse Meunier	14.2400°N -60.5250°W	5	0.71	0	0.00	0	0.00	0	0.00	0	0.00	1	0.14	1	0.14
Pointe Dunkerque	14.4215°N -60.8915°W	4	0.67	0	0.00	0	0.00	0	0.00	2	0.33	0	0.00	0	0.00
St Eustatius															
Lynch Beach, east side	17.5010°N -62.9690°W	11	0.23	10	0.21	0	0	4	0.08	0	0.00	21	0.44	2	0.04
Turks and Caicos															
French Cay, east side	21.5073°N -72.1997°W	5	0.28	7	0.39	0	0.00	1	0.06	1	0.06	3	0.17	1	0.05
Big Sand Cay	21.1919°N -71.2477°W	48	0.17	167	0.60	25	0.09	20	0.07	0	0.00	17	0.06	0	0.00

Table S2. Number (n) and frequency of occurrence (FO) of the top 10 identifiable beach-washed litter items (non-standard sub-categories - see text) recorded on islands in the Caribbean Sea during 2014 to 2016.

	Plastic whole														Other					
	Bottles		Caps/lids		Straw		Cups		Rope/twine		Cutlery		Glass		Wood		Metal		Shoes	
Category	*n*	FO	*n*	FO	*n*	FO	*n*	FO	*n*	FO	*n*	FO	*n*	FO	*n*	FO	*n*	FO	*n*	FO
Bahamas																				
South Bimini, Bimini Sands Resort	6	0.03	8	0.03	2	0.01	0	0.00	0	0.00	3	0.01	4	0.02	2	0.01	9	0.04	1	0.01
Conception Is., anchorage & inlet	4	0.03	4	0.033	0	0.00	0	0.00	5	0.04	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Little Farmers Cay, Exumas Is.	3	0.05	6	0.11	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	2	0.04	0	0.00	1	0.02
Long Is., north-west beach	1	1.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Long Is., north-east beach	4	0.17	8	0.33	0	0.00	0	0.00	6	0.25	0	0.00	1	0.04	0	0.00	5	0.21	0	0.00
Long Is., Deans Blue Hole	1	0.01	11	0.96	3	0.03	0	0.00	100	0.33	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Long Is., Flying Fish Marina Beach	1	0.01	0	0.00	0	0.00	108	0.75	35	0.24	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Mayaguana Is., east beach, Abraham Bay	2	0.05	3	0.07	0	0.00	0	0.00	2	0.05	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Rum Cay, east of marina	1	0.04	2	0.09	0	0.00	0	0.00	8	0.35	1	0.04	0	0.00	0	0.00	0	0.00	0	0.00
Unnamed Bay, Great Guana Cay	8	0.02	37	0.11	0	0.00	0	0.00	74	0.22	3	0.01	0	0.00	0	0.00	0	0.00	1	0.00

West Plana Cay, east anchorage	2	0.29	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	1	0.14	0	0.00	0	0.00
British Virgin Islands																				
Kelly's Cove, Norman Is.	0	0.00	3	0.11	4	0.14	0	0.00	1	0.04	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Cayman Islands																				
Charles Bight, Little Cayman	0	0.00	5	0.04	3	0.02	3	0.02	9	0.07	2	0.02	16	0.13	0	0.00	1	0.01	0	0.00
Colliers Beach, Grand Cayman	9	0.02	34	0.07	3	0.01	1	0.01	5	0.01	9	0.02	33	0.07	4	0.01	2	0.01	0	0.00
Owen Is., South Hole Sound	7	0.06	6	0.05	6	0.05	0	0.00	1	0.01	0	0.00	6	0.04	3	0.02	1	0.01	0	0.00
Prospect Beach, Grand Cayman	0	0.00	0	0.00	0	0.00	1	0.01	0	0.00	2	0.01	282	0.77	1	0.01	0	0.00	0	0.00
Cayman Brac, south side	10	0.02	68	0.11	9	0.01	1	0.01	6	0.01	10	0.02	0	0.00	0	0.00	2	0.01	0	0.00
Dominican Republic																				
Luperon Beach, Resort	0	0.00	1	0.5	0	0.00	0	0.00	0	0.00	0	0.00	1	0.5	0	0.00	0	0.00	0	0.00
Luperon Beach	2	0.14	10	0.71	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	2	0.14	0	0.00
Napoleon Is., Samaná Bay	34	0.16	49	0.24	23	0.11	0	0.00	1	0.01	3	0.01	0	0.00	0	0.00	2	0.01	2	0.01
Playa de Portillo Beach	3	0.04	3	0.04	0	0.00	3	0.04	1	0.01	1	0.01	0	0.00	0	0.00	0	0.00	2	0.03
Samaná Marina Beach	5	0.04	9	0.07	0	0.00	0	0.00	0	0.00	2	0.02	0	0.00	1	0.01	0	0.00	0	0.00
Grenada																				
Frigate Is., south-east beach	128	0.45	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	4	0.02	19	0.07
Sandy Island,	8	0.24	1	0.03	0	0.00	0	0.00	2	0.06	0	0.00	3	0.09	2	0.06	3	0.12	0	0.00

Carriacou																				
Tyrrell Bay, Carriacou	0	0.00	7	0.06	5	0.05	1	0.01	0	0.00	1	0.01	32	0.29	4	0.04	8	0.07	0	0.00
Grenadines																				
Baradal Is., Tobago Cays, east peninsula	3	0.06	4	0.08	0	0.00	0	0.00	0	0.00	0	0.00	16	0.30	1	0.02	1	0.02	0	0.00
Petit Rameau, Tobago Cays, north-east beach	1	0.02	4	0.08	1	0.02	0	0.00	4	0.08	0	0.00	1	0.02	0	0.00	0	0.00	0	0.00
Sandy Island, Carriacou	8	0.24	1	0.03	0	0.00	0	0.00	2	0.06	0	0.00	3	0.09	2	0.06	3	0.12	0	0.00
Tyrrell Bay, Carriacou	0	0.00	7	0.06	5	0.05	1	0.01	0	0.00	1	0.01	32	0.29	4	0.04	8	0.07	0	0.00
L'islet Beach, Petit Carenage Bay, Carriacou	2	0.01	2	0.02	2	0.01	1	0.01	3	0.02	0	0.00	1	0.01	4	0.02	1	0.01	0	0.00
Sugar Reef, Becquia Is.	0	0.00	24	0.10	0	0.00	0	0.00	4	0.02	1	0.01	19	0.08	0	0.00	0	0.00	7	0.03
Catholic Is., north-east side	124	0.80	6	0.04	0	0.00	0	0.00	5	0.03	0	0.00	11	0.07	3	0.02	4	0.03	2	0.01
Catholic Is., south beach	76	0.85	0	0.00	0	0.00	0	0.00	1	0.01	0	0.00	6	0.07	0	0.00	4	0.05	2	0.02
Mayreau Is., north-east beach	11	0.05	15	0.09	1	0.01	0	0.00	12	0.07	2	0.01	5	0.02	0	0.00	2	0.01	2	0.01
St Vincent, Canash Beach	0	0.00	3	0.22	3	0.06	1	0.06	0	0.00	0	0.00	9	0.50	0	0.00	0	0.00	0	0.00
Martinique																				
Anse Caritan	3	0.33	0	0.00	0	0.00	3	0.33	2	0.22	1	0.11	0	0.00	0	0.00	0	0.00	0	0.00
Anse Meunier	1	0.20	0	0.00	0	0.00	1	0.20	1	0.20	2	0.40	0	0.00	0	0.00	0	0.00	0	0.00
Pointe Dunkerque	1	0.17	1	0.17	0	0.00	1	0.17	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
St Eustatius																				
Lynch Beach,	1	0.02	6	0.13	2	0.04	2	0.04	21	0.44	0	0.00	0	0.00	1	0.02	0	0.00	1	0.02

east side																				
Turks and Caicos																				
French Cay, east side	4	0.22	0	0.00	0	0.00	0	0.00	3	0.17	0	0.00	0	0.00	0	0.00	1	0.06	0	0.00
Big Sand Cay	14	0.01	18	0.07	4	0.02	0	0.00	7	0.03	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00