A baseline analysis of marine debris on southern islands of Belize

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ABSTRACT

Marine debris is a global issue with acute impacts. This study investigates the relationship between human foot traffic and debris prevalence on 7 islands in the South Water Caye and Sapodilla Cayes Marine Reserves in the Caribbean country of Belize. Utilizing beach transect surveys, 1,754 items were cataloged based on object size, object form, material, physical condition, and economic use ("source"). The majority of litter were plastics (68.1%, 1,195 items) and associated with an urban source (74.8%; 1,312 items). The inclusion of a source-based analysis of debris provided insight into debris generation patterns, permitting more targeted future mitigation efforts. An inverse relationship between foot traffic and debris was found, indicating that debris persists at varied sizes and conditions irrespective of human presence or tourist incentives. This study provides a baseline for future studies in the region, especially as Belize's economy continues to shift away from single-use plastics.

KEYWORDS: Marine Debris, Plastic Pollution, Beach Litter, Belize, Islands, Caribbean

INTRODUCTION

As single-use plastics continue to accumulate in coastal environments, solid waste pollution is of growing concern. Marine debris ("debris"," litter") is found in virtually all environments on Earth (Barnes et al., 2009) and causes harm to organisms (e.g., entanglement or ingestion of debris) (Barnes et al., 2009) and local economies alike. Related economic effects include the loss of tourism revenue as a result of decreased beach aesthetics (Ballance et al., 2000).

Islands offer unique settings for debris accumulation. Due to their distance from the mainland, small permanent populations, and passive nature, islands often acquire and retain foreign materials. Debris can arrive on islands through global wind patterns and oceanic currents (Uneputty & Evans, 1997), potentially washing ashore anywhere in the world. A number of studies have found increased amounts of debris on island's beaches over time (e.g., Duhec et al., 2015; Lavers & Bond, 2017; McDermid & McMullen, 2004), emphasizing the degree to which debris accumulates absent intervention. Islands are often inaccessible to debris clean-up campaigns (Schmuck et al., 2017), have scant waste disposal infrastructure, if any, and are absent from mainland trash disposal efforts. The density of debris on islands can also be attributed to geographic isolation, where more remote islands have been found to have higher densities of debris compared to more accessible locations (e.g., Duhec et al., 2015; Lavers & Bond, 2017).

Lavers and Bond (2017) found that Henderson Island, an uninhabited remote island in the South Pacific Ocean, had one of the highest debris densities recorded in the world, estimated at 671.6 items/m^2, with approximately 37.7 million items present. Given the lack of human activity within 5,000 kilometers, the majority of debris accumulation must have resulted from the global

disposal and dispersal patterns of waste (Lavers & Bond, 2017). A similar study on the Cocos Keelings Islands, Australia, reported an estimate of 414 million pieces of anthropogenic debris on beaches, including both buried and surface-level debris (Lavers et al., 2019). Isolated islands such as these act as marine pollution proxies and reflect the more natural state of debris, providing insights into debris mobility and accumulation trends (Lavers et al., 2019; Santos et al., 2009; Galgani et al., 2015). With low human interference and limited populations, the pollution present on distant islands is the result of long-term solid waste mismanagement and among the most prominent negative visual of human effects on the environment (Claereboudt, 2004). Widespread accumulation of debris reflects the acute symptoms of the rapidly growing issue that is single-use plastic consumption (Geyer et al., 2017; Ivar do Sul & Costa, 2007), evident on beaches worldwide (Barnes et al., 2009; Lavers et al., 2019; Santos et al., 2009).

This article provides a baseline survey of marine debris on various southern Belizean islands. The waste management system of Belize has been historically ineffective (Grau et al., 2014; Villegas, 2018), contributing to the marine debris epidemic that currently exists in the Caribbean. With the recent government focus on the development of Belize's tourism sector, waste generation and waste mismanagement will increase, absent changes to the current waste management system, adding to marine debris accumulation on local beaches and elsewhere. Waste generated on Belize's mainland has the potential to travel to adjacent cayes (islands) lining the eastern coast of the country, supporting the need for marine debris investigation on Belize islands.

Marine debris studies in the larger Caribbean commonly focus on island nations, such as the Bahamas, Jamaica, Aruba, the British Virgin Islands, Panama, and the Cayman Islands (e.g., Garrity & Levings, 1993; Schmuck et al., 2017; de Scisciolo et al., 2016; Singh & Xavier, 1997). Marine debris studies are scarce in Guatemala (Tedsen et al., 2014) and Honduras (Diez et al., 2019), both having a single known reference to solid waste accumulation, which neighbor Belize in the Gulf of Honduras. Few quantitative marine debris studies have been performed in Belize (e.g., Bennett-Martin et al., 2016); however, scientific marine debris studies focused on this research's sample sites are unknown. This study is the first to quantify debris on cayes in both the Sapodilla Cayes and South Water Caye Marine Reserves (see Figure 1).

In addition to creating a baseline survey of debris on islands of Belize, this study bridges the gap in source-based classification methodology of debris, which is lacking in the current literature (Santos et al., 2009). Source-based classification provides insights into anthropogenic uses and generation patterns of debris, permitting more targeted mitigation efforts by policy makers. Without a tested and unifying methodology for classification, confidence in results will continue to be varied.

STUDY AREA

Data was collected on cayes of southern Belize, including islands in the Sapodilla Cayes Marine Reserve (Lime Caye, Hunting Caye, Nicholas Caye, Franks Caye) and the South Water Caye Marine Reserve (South Water Caye, Tobacco Caye, and Twin Caye) (Figure 1). This focus on the southern coast of Belize allows for variation in data collection, as the study sites vary in population, size, and economic use (Table S.1). South Water Caye differs from the other sites in having both the largest permanent population and the highest frequency of visitor foot traffic. Lime Caye, Nicholas Caye, South Water Caye, and Tobacco Caye all have confirmed caretakers, indicating that washed up or littered debris is deliberately removed. While South Water and Lime Caye beaches are cleaned daily, the frequency of beach cleaning is unknown on Nicholas and Tobacco Cayes.

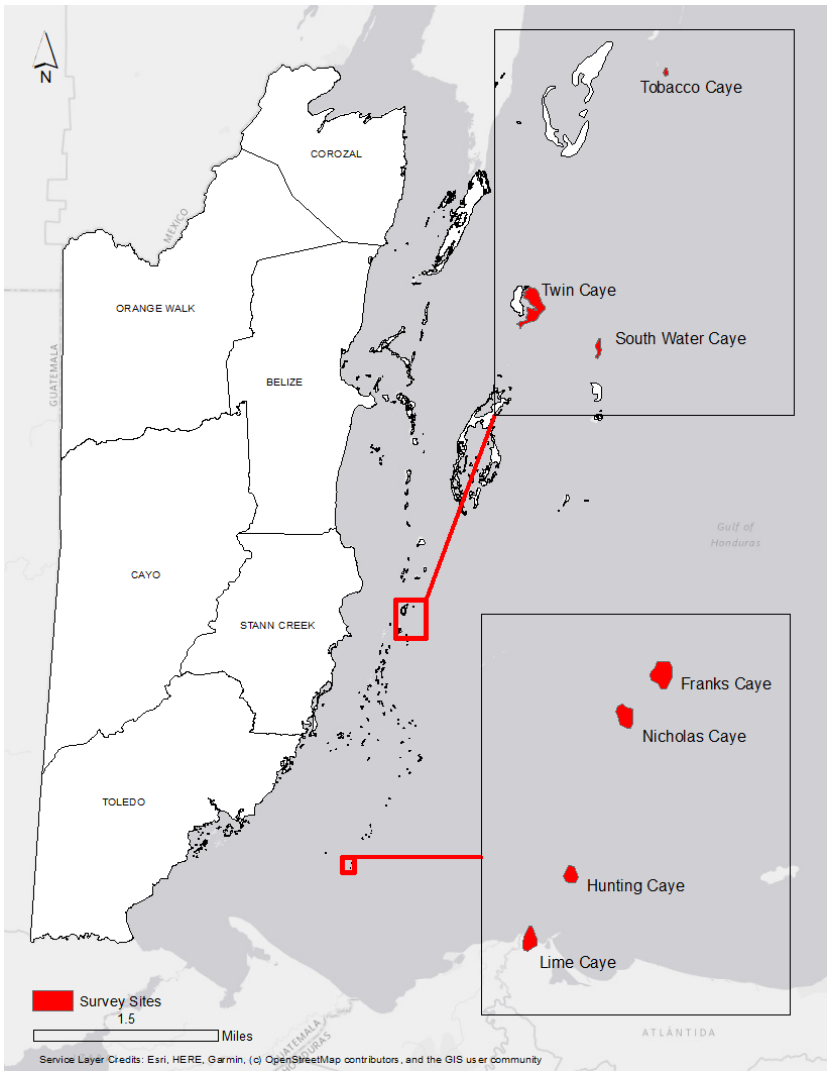

Figure 1: Map of Belize indicating survey sites. Sites include Tobacco Caye, South Water Caye, Franks Caye, Nicholas Caye, Hunting Caye, and Lime Caye (Belize boundaries: Meerman & Clabaugh, 2017).

METHODOLOGY

Field data was collected across 7 islands and 15 beaches during May of 2019 (Figure 1). Transects 20 meters long and 5 meters wide were used on each study site (optimal width based on de Araújo et al., 2006), both perpendicular and horizontal to the shoreline, allowing for the measurement of both fresh and accumulated debris (Velander & Mocogni, 1999). Similar to a shore litter survey in the Gulf of Oman (Claereboudt, 2004), each horizontal transect was placed in relation to the low tidemark. If the tidemark was variable or inconsistent, then the transect began from the location at which the sand was permanently wet or saturated (as defined in Velander & Mocogni, 1999); each perpendicular transect progressed from the tidemark to the vegetation line or end of sandy beach substrate (whichever came first). The use of perpendicular transects was contingent on accessible beach area, which was not available at all locations (Figures S.1 and S.2). The maximum area surveyed for one beach could be 100 m^2 (20 meters long and 5 meters wide) based on these ideal standards (Figure 2). Surface-layer debris was counted and categorized while walking along the given transects area.

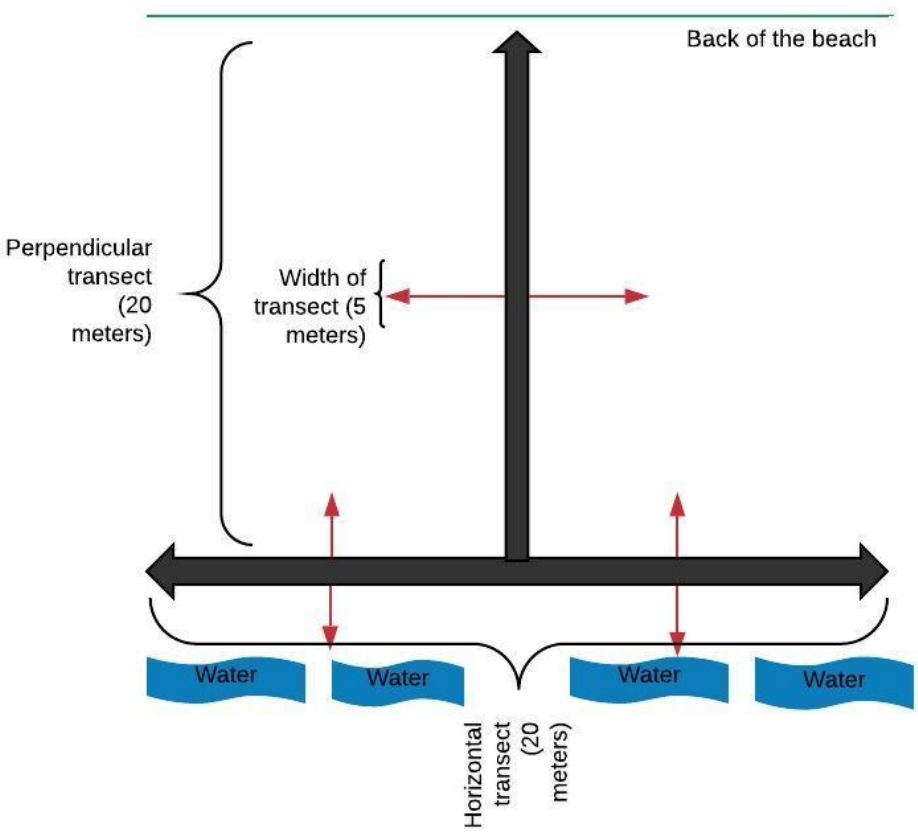

Figure 2: Diagram of transect orientations. The black lines represent horizontal and perpendicular transects and the red lines represent the transects width.

Debris was categorized based on its material type (e.g., plastic, Styrofoam, paper, etc.), object form (e.g., beverage bottles, bags, shoes, etc.) economic activity ("source") (relating to recreational, fishing, or industrial activities) (Table 1), size, and condition. Each source was determined through inspection of the object (e.g., reading the label, identifying the object type); commonly known items such as tennis shoes and children toys were readily attributed to a recreational source - items used in people's households or in recreational activities. Items such as cement blocks and polyvinyl chloride (PVC) pipes were attributed to an industrial source, likely having been used in manufacturing rather than daily activities. Items involved in fishing activities, including fishing line, large ropes, buoys, and nets, were attributed to a fishing source. Any item that was ambiguous or unrecognizable (either in its material or object form) was classified as an unknown source.

*Table 1: Definitions of key terms used throughout this study. Categories are not exhaustive but represent the most common of those recorded. References Denote literature in which these categories were previously used. *Categories presented here in decreasing orders of abundance.*

Term	Definition	Categories*	Reference
Material	Material of each debris item	Plastic, Styrofoam, rubber/foam, glass, metal, aluminum, processed wood, textiles, paper, rope, other (cardboard, cement, ceramic, latex), and unknown	Haarr et al., 2019 Opfer et al., 2012
Object Form	Form that each debris items takes; the object of debris often indicates its intended use (e.g., plastic straws are used for drinking)	Beverage bottles, bottle caps/lids, containers (food and non-food), carrier bags, utensils, shoes, clothing, cigarettes, drinking straws, child's toys, beverage cans, personal care products, and unknown	Opfer et al., 2012
Economic Use ("Source")	The economic activities associated with waste (debris) generation. This is the perceived source use for debris	Recreational: Relating to common human uses and activities; commonly associated with consumer goods and are items used in daily lifestyles. Does not distinguish between Belizeans and tourists Unknown: Related to an unknown economic activity	Claereboudt, 2004 Barnett et al., 2016 Liu et al., 2015 Hengstmann et al., 2017 Sheavly & Register, 2007

	Industrial: Byproducts or materials used in the industrial or manufacturing processes; items not commonly used in everyday life
	Fishing: Related to fishing activities, both personal and commercial

Debris size classes ranged from small (< 2.5 cm), medium (≥2.5 cm;≤10 cm), large (> 10 cm; ≤1 m), and extra-large (> 1 m) (Ribic et al., 1992). Each item's condition ("degree of fragmentation") depended on its physical state, classified as either "whole", "partial", or "fragmented". "Whole" items were visibly intact and easily recognizable items, while "partial" items were those that seemed to be missing a substantial portion of itself. However, "fragmented" items were small debris pieces that were often indiscernible and related to unknown objects. While microplastics (debris < 5 mm in diameter) (Vince & Stoett, 2018) were present at these locations, they are outside the scope of this study and therefore excluded from surveys.

A one-way analysis of variance (ANOVA) (as in Santos et al., 2009 and Velander & Mocogni, 1999) was used to compare the effect of transect orientation (horizontal or perpendicular) on total counts of debris found in each size class and debris degree of fragmentation (condition). The categories of debris sizes and degrees of fragmentation were tested separately across the transect orientations.

RESULTS

A total of 15 beaches were surveyed using 24 transects, comprised of 18 horizontal and 6 perpendicular transects (Table 2). Given the large variation of area sampled on each island, some islands may not have sufficient data (e.g., Franks Caye) to accurately portray the baseline amount of debris present.

Table 2: Number of transects and sample sites per caye. Of the 7 cayes surveyed, 18 horizontal and 6 perpendicular transects were used.

	Lime	Hunting	Franks	Nicholas	South Water	Tobacco	Twin
Number of sites	3	1	2	2	6	3	2
Number of transects	3 H, 2 P	0 H, 1 P	2 H, 0 P	2 H, 0 P	6 H, 3 P	3 H, 0 P	2 H, 0 P
Area surveyed (m^2)	286	100	53	200	600.25	350	150

Collectively, 1,754 debris items were cataloged. Plastic was the most common material (1,195 items, 68.13%), followed by Styrofoam (166 items, 9.46%), and foam/rubber (141 items, 8.04%). Other frequently found material includes glass, metal, and aluminum (67, 45, and 34 items respectively). Among these, bottles were highly abundant (571 plastic and 53 glass bottles) and largely beverage containers (labels for soda, alcohol, and water brands).

55.1% of debris present were classified as large items (967 items; > 10 cm; ≤ 1 m), 30.5% as medium (535 items; ≥ 2.5 cm; ≤ 10 cm), 12.3% as small (215 items; < 2.5 cm), and the remaining 2.1% were extra-large (37 items; ≥ 1 m) (Figure 3). The highest incidence of large items was found on Hunting Caye, which also had the highest number of plastic bottles (307 items). While small debris was present at all locations, they were found most frequently on Tobacco and South Water Cayes. South Water Caye had the highest incidence of fragmented items (103 items) and Tobacco Caye had the second highest (48 items).

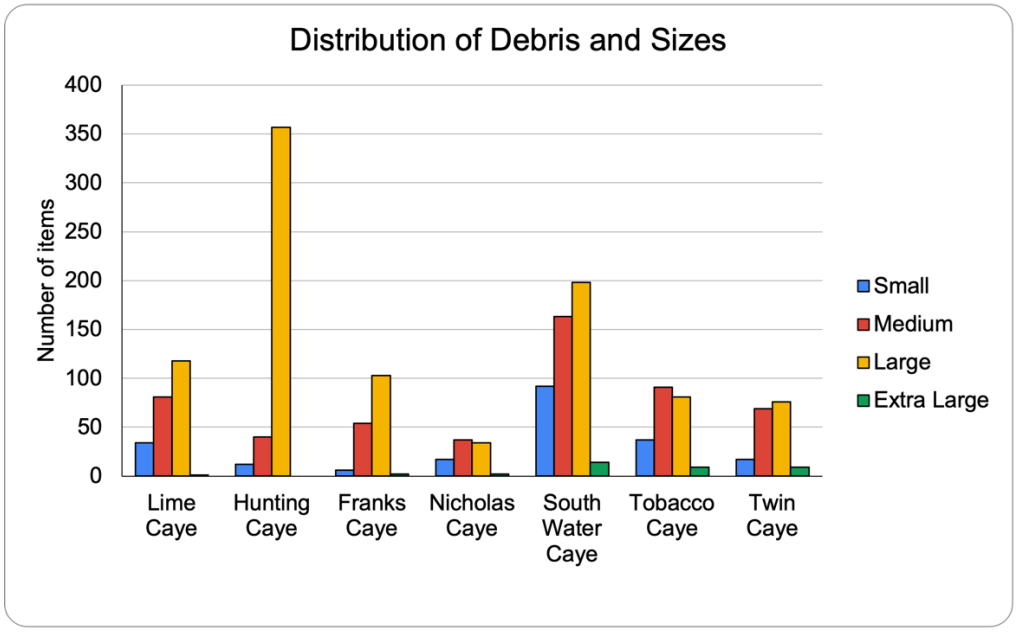

Figure 3: Size distribution of debris surveyed. With 1,754 items counted, 215 were small (< 2.5 cm), 535 were medium (≥ 2.5 cm; ≤ 10 cm), 967 were large (> 10 cm; ≤ 1 m), and 37 were extra-large (≥ 1 m). Hunting Caye had the highest occurrence of large items (357).

Horizontal transects contained 66.6% of total debris (1,168 items) and perpendicular transects contained the remaining 33.4% of debris (586 items). Both orientations primarily contained large items. Hunting Caye had the highest incidence of large litter per transect, contributing substantially to the total amount of debris found in all perpendicular transects. Horizontal and perpendicular transects were found to have a statistically similar distribution in debris size [F=1.48, p=0.22, α=0.05] and degree of fragmentation [F=0.33, p=0.57, α=0.05]. The similar distribution of debris sizes among horizontal and perpendicular transects contradicts previous literature (Barnes et al., 2009) where smaller fragmented debris items were most commonly found away from the beach's wrack line. Here, fragmented items were found throughout both horizontal and perpendicular transects (Table 3). However, when Hunting Caye was removed from the ANOVA analysis, both the sizes [F=2859.5, p=0, α=0.05] and conditions [F=546.7, p=3.206E-110, α=0.05] of debris were statistically different across horizontal and perpendicular transects.

Table 3: Debris degree of fragmentation ("condition"). Debris was categorized as either having a whole, partial, or fragmented condition. 1,168 items were recorded in horizontal transects and 586 items in perpendicular transects. N/A indicated no data.

	Lime	Hunting	Franks	Nicholas	South Water	Tobacco	Twin	*Total*
Horizontal (total)	102	N/A	165	90	422	218	171	1168
Whole	55		118	29	238	108	79	627
Partial	24		28	26	81	62	53	274
Fragmented	23		19	35	103	48	39	267

Perpendicular (total)	132	409	N/A	N/A	45	N/A	N/A	586
Whole	84	353			6			443
Partial	25	43			8			76
Fragmented	23	13			31			67

Cataloged debris are summarized in Table 4, which describes the average number of items found per square meter, consolidating debris quantities among study sites. Notably, Hunting Caye had the highest average items/m^2, likely a result of having one transect heavily compromised by litter. Conversely, South Water Caye had the largest area surveyed (600.25 m^2 across 6 sites and 9 transects) and 0.79 items/m^2(SD=22.39), the third lowest average. In addition, the three highest average items per square meter (4.09, 3.11, and 1.14) are also the only islands without confirmed caretakers (Hunting, Franks and Twin Cayes respectively).

Table 4: Summary of average amount of debris per square meter for each location.

	Total area surveyed: (m²)	Total items:	Average items/m²: (±SD)
Lime Caye	286	234	0.82 ± 2.15
Hunting Caye	100	409	4.09 ± 0
Franks Caye	53	165	3.11 ± 1.15
Nicholas Caye	200	90	0.45 ± 0.21
South Water Caye	600.25	467	0.79 ± 22.39
Tobacco Caye	350	218	0.62 ± 0.53
Twin Caye	150	171	1.14 ± 0.42

Of 1,754 debris items surveyed, 81.1% (1,422 items) were identified with plausible sources. The remaining 18.9% (332 items) had unknown sources, meaning that either the item itself was unrecognizable and therefore unknown, or its source was ambiguous. Debris related to recreational activities (e.g., home goods and personal items used in daily life) comprised 74.8% (1312 items) of the standing stock; commonly found recreational items include beverage bottles, shoes, clothing, bottle caps and lids, and food takeaway containers. 4.2% (74 items) of the debris was linked to industrial activities, including large pipes, metal, and wooden construction materials. Fishing related debris was 2.1% (36 items) of the standing stock, the items found most frequently being large nets and fishing line.

DISCUSSION

Cataloging debris characteristics permits insight into potential causes and sources of marine pollution in the region. Debris characteristics can be linked to anthropogenic sources of generation, such as urban populations, industrial and manufacturing activities, fishing, and tourism. Evidently, single-use plastics dominate the region and should be addressed.

Hunting Caye stands out in this study as an example of a heavily polluted area from recreational and urban sources, having the highest abundance of large plastic items (307 items) in one transect. This beach was heavily littered beyond the surface layer, leading to a conservative estimate of total debris. Hunting Caye is sparsely populated, suggesting that the majority of debris surveyed likely floated on shore over time through natural processes (Hengstmann et al., 2017; Lavers & Bond, 2017). While efforts to clean beaches on Hunting Caye were evident, there are no permanent caretakers or tourist resorts on the island. This lack of foot traffic could be attributed to the high number of debris left in the environment for longer periods of time, as the motive for clean beaches to attract tourist's revenue is lacking (Botero et al., 2017). The presence of heavy debris inundation here reflects the degree to which ocean-based debris is increasing, constantly washing ashore, and accumulating on remote islands (Lavers & Bond, 2017).

The persistent presence of small, fragmented items across cayes suggests that debris may have been degraded in the transit and disposal process. The discrepancy between debris sizes is largely a product of raked (cleaned) beaches; while raking beaches changes the composition of debris present (e.g., debris size and fragmentation), it does not necessarily change the overall quantity (Santos et al., 2009; Somerville et al., 2003). The process of raking beaches removes larger items but can leave behind smaller fragmented items; raking can also further break down debris, creating a higher quantity of small items left behind. This cleaning process often fails to remove these smaller items of debris (Somerville et al., 2003), therefore changing the composition of debris rather than the overall quantity. This is supported further in that heavily trafficked islands still had ample fragmented debris (e.g., South Water Caye) despite daily cleaning.

Differences in debris size and fragmentation were hypothesized between horizontal and perpendicular transects based on the assumed differences between fresh and accumulated litter. When all sites were included in analysis (ANOVA), these debris characteristics were not found significantly different, contrary to previous literature (Velander & Mocogni, 1999). Hunting Caye stood as an outlier in sheer abundance of debris and was excluded from further statistical analysis. Excluding this site, both debris sizes and conditions were found to be statistically different between transect orientations.

Debris was present across the region despite these differences in size and physical degradation. With the abundance of intact, large items on Hunting Caye, statistical analyses failed to support the hypothesis of characteristic differences between horizontal and perpendicular transects. Various degrees of fragmentation were evident among transects studied, suggesting varied rates of weathering and debris deterioration across the region.

The inclusion of the average amount of debris per square meter permits direct comparison of debris quantities between islands, as seen in Haarr et al. (2019), establishing a baseline for future surveys. Hunting Caye had the highest average items per square meter, (despite having one transect), while South Water Caye had the third lowest average and the largest area surveyed. These results further support the hypothesis that an island's foot traffic is inversely related to the quantity of debris present. Islands, specifically those with tourist resorts, have economic incentives to maintain beach's aesthetics in order to attract tourist revenue (Somerville et al., 2003). Thus, there will be more daily cleaning of beaches and improved waste management at heavily trafficked locations as opposed to the islands without these attractions (Botero et al., 2017). Recent literature has shown that the amount of litter on beaches is directly correlated with beach occupation (Santos et al., 2005; Tourinho & Fillmann, 2011), but the opposite was found with this study (e.g., Hunting Caye and South Water Caye).

Previous literature lacks a unifying methodology for the source-based classification of debris (Rochman et al., 2016), resulting in varying degrees of confidence in source identification. While this study attempts to fill this gap through three debris source categories (recreational, industrial and manufacturing, or fishing), these categories do not distinguish among different subtypes of influences. For instance, recreational sources could differentiate between foreign and local inhabitants, intentional littering or accidental littering, et cetera. This provides a larger scope of recreational sources than previous studies, and therefore a larger percentage of debris categorized.

While the majority of debris was associated with an economic activity (recreational, industrial, or fishing sources), the country or precise location of origin is much more difficult to pinpoint given debris' buoyant nature. It is difficult to quantify the extent of marine debris that washes onto Belizean beaches from other countries, warranting the inclusion of oceanic patterns and other natural phenomena with future source-based analysis.

Recognition of debris sources provides insights for Belize policymakers, permitting more targeted mitigation efforts to stop solid waste pollution at its generation point. The abundance of recreational goods identified in this study reflect the consumer nature of society, highlighting the intricate relationship between human activities and the environment. Steps toward source-oriented solutions (e.g., plastic bag taxes, container deposit legislation, and enhanced education campaigns) would have a greater chance of mitigating solid waste pollution on beaches.

The disposal of waste into the ocean from ships is noted throughout the literature (Hengstmann et al., 2017; Leous & Parry, 2005; Monteiro et al., 2018; Sheavly & Register, 2007), adding to the ambiguity of debris sources and leaving adjacent beaches as casualties. While there is legislation in place to prevent this illegal disposal, such as the International Convention for the Prevention of Pollution from Ships (MARPOL), implementation and enforcement of these regulations continue to be an international issue (Leous & Parry, 2005). While MARPOL Annex V restricts at-sea disposal of solid waste, emphasizing a ban on the discharge of plastics at-sea (Leous & Parry, 2005), individual countries are responsible for implementing alternatives to at-sea disposal (e.g., proper disposal mechanisms at ports) and

enforcing the dumping ban. International legislation against marine pollution is a promising step, promoting collaboration and co-management among the environmental protection sector and government officials (Liu et al., 2015), but further initiative and compliance from participating countries to enhance positive change are needed.

Limited studies exist focusing on marine debris in Belize, and even fewer include a source-based analysis. The methodology of this project is readily usable for Belizeans for future investigation, permitting citizen science participation in debris mitigation efforts (Bennett-Martin et al., 2016). Further sampling is necessary to accurately portray the baseline of debris both on Belize's mainland and islands. Future analyses should investigate debris accumulation rates for insights into debris mobility trends. Long-term monitoring, waste audits, and an expanded sampling area would also provide insight into the effectiveness of Belize's waste management system, especially regarding the recent single-use plastic ban.

Manual beach clean-ups are cost-effective and commonly rely on volunteer labor and are therefore used prominently to tackle the ongoing marine debris crisis. Clean-up events on islands can be difficult to coordinate due to various logistics (e.g., cost, time, fuel, and the eventual dumping of collected debris in landfills) (Lavers et al., 2019). Therefore, a focus on debris prevention mitigates the amount of waste reaching the environment (Löhr et al., 2017) and evades costly clean-up events.

CONCLUSION

This study illuminates sources of generation, causes, and effects of marine debris in Belize. This investigation found an inverse relationship between a location's foot traffic and the amount of debris present, with less frequented beaches having more degraded debris. The presence of degraded debris on heavily trafficked islands can be attributed to the daily cleaning of beaches, which tends to alter debris composition (e.g., higher presence of smaller items after raking).

This study addresses the gap in the source-based analysis of marine debris, contributing unique analyses and quantitative methods to the marine debris literature. These results provide novel information regarding the magnitude of offshore debris present and provide insight for local government and policy makers. Further sampling is necessary to gain a longitudinal understanding of marine debris on Belize beaches. This survey establishes a baseline for future studies in comparing the effects of recent legislation against single-use plastics and Styrofoam.

While the results of this study are concerning with regard to existing environmental damage, policy shifts toward sustainability reflect the possibility of social mobilization for future waste reduction. Through persistent community participation, collaboration, and environmental stewardship, countries affected by marine debris have the opportunity to regain valuable environmental integrity and flourish through sustainable growth.

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SUPPLEMENTARY MATERIALS

*Table S.1: Descriptors of field sites. Area of islands obtained using shape file attributes in ArcMap 10.1. Remaining information obtained through personal observations and personal communications (*Wildtracks, 2010).*

Island	Area of Island (acres)	Presence of Tourist Resorts	Economic Industry of Island	Confirmed Caretaker
Lime Caye	0.86	Yes	Recreation, tourism	Yes
Hunting Caye	0.67	No	Government of Belize Research Facility	No
Nicholas Caye	1.08	No	Recreation, conservation (spawning aggregation site*)	Yes
Franks Caye	1.65	No	Unknown	No
South Water Caye	1.84	Yes	Recreation, tourism	Yes
Tobacco Caye	0.67	Yes	Tourism, fishing	Yes
Twin Caye	11.31	No	Government of Belize Marine Fisheries Station	No

Figure S.1: Example of a site on Tobacco Caye that did not permit the use of a perpendicular transect. The stark "edge" to the beach area permits horizontal transects to survey available beach area.

Figure S.2: Example of sample site on South Water Caye that relied on horizontal transects, as the transects width covered the available beach area (sandy area before vegetation).