Tools for marine debris management: A case study of beaches in South Eleuthera, The Bahamas

By

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The movement toward plastic pollution solutions in The Bahamas started with The Plastic Beach Project more than five years ago. It was sheer passion and curiosity that led me to implementing this citizen science initiative, but it was the support, guidance and faith of many individuals and communities that brought this project to fruition. I would like to acknowledge Dr. Marcus Eriksen, cofounder of the 5 Gyres Institute for granting me the opportunity to study plastic pollution and inspiring me to tackle this issue in my own country. Carolynn Box, science director of 5 Gyres, who guided me through the methodology for this project and gave me the tools I needed to succeed. To Annabelle Brooks, The Cape Eleuthera Institute and The Island School, who provided the in-kind support and scientific guidance to get this project of the ground, I'm forever grateful. Thank you to all student volunteers and teachers who assisted with data collection especially Tiffany Gray, Joanna Parker, Deep Creek Middle School, Preston Albury High School and The Island School Spring and Fall 2013 semesters. I would like to thank the Queen Elizabeth II Diamond Jubilee Scholarship Program, Dalhousie University and the Marine Affairs Program for enabling me to carry on this work and complete the Master of Marine Management degree. To my amazing supervisors Dr. Tony Walker, Dr. Joan Fabres and James Boxall, thank you for your guidance, expertise and unwavering support and belief in my ability to execute this project. I would also like to acknowledge Dr. Chris Greene who served as my second reader. Thank you to Georgios Fylakis, Levi Westerveld and GRID-Arendal for your GIS guidance and mentorship during my summer internship. I also wish to thank my family, friends, course mates and professors for their support during this program. Finally, to all my students, plastic warriors and people of Eleuthera, I thank you endlessly for supporting and inspiring this work.

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List of acronyms

AIMS: Atlantic, Indian Ocean and South China Sea

AO: Atlantic Ocean

BB: Bahama Bank

BPM: Bahamas Plastic Movement

DEM: Digital Elevation Model

ES: Exuma Sound

GDP: Gross Domestic Product

GIS: Geographic Information Systems

MAP: Marine Debris Action Planner

MT: Metric Tons

RAPMaLi: Regional Action Plan for Marine Litter

REI: Relative Exposure Index

SIDS: Small Island Developing States

USGS/EROS: United States Geological Survey /Earth Resources Observation and Science

WCR: Wider Caribbean Region

Abstract

There is a paucity of information on the abundance and distribution of marine debris on beaches throughout The Bahamas, making it challenging to inform policy aimed at identifying sources and mitigating local contributions. This study provided the first report of the spatial distribution of macro and micro plastic debris on beaches in South Eleuthera and examined tools such as citizen science, beach debris monitoring, fetch modeling, relative exposure index modeling and predictive mapping to aid in mitigation and management strategies for marine debris in The Bahamas. Here, trained citizen scientists quantified debris type and abundance on 16 beaches within three coastal exposures; The Atlantic Ocean, Great Bahama Bank and The Exuma Sound in South Eleuthera, The Bahamas. Marine debris, larger than 1mm, on each beach was monitored twice in one year between March-May 2013 and September-November 2013, at the same location, verified using GPS. Approximately, 93% of all debris types collected were plastic materials with plastic fragments ≤2.5 cm as the most dominant. There proved to be a spatial difference ($p=<0.0001$) in plastic debris abundance between coastal exposures with Atlantic Ocean beaches demonstrating larger amounts of plastic debris by weight and per length of shoreline. Such plastic deposits may be associated with Atlantic Ocean currents connected to waste leakages from the North Atlantic subtropical gyre.

Keywords: Marine debris, marine litter, plastic pollution, citizen science, Eleuthera, Bahamas, Atlantic Ocean, Exuma Sound, Bahama Bank, policy, marine debris management, marine debris surveys, relative exposure index (REI), predictive mapping, fetch modeling.

Chapter 1: Introduction

1.1 Marine debris and plastic pollution

Marine litter, commonly known as marine debris, is a multifaceted environmental problem with few universal solutions (UNEP and NOAA, 2011; Kershaw, 2016; Löhr et al., 2017). Marine debris, predominately plastic pollution, has become a global environmental problem that has gained considerable awareness and notoriety for its impacts on marine organisms, ecosystems and human health (Derraik, 2002). The commercial origins of plastic products date back to the 1950's (Barnes et al., 2009) and though an integral material in our economy (Walker and Xanthos, 2018), there has been growing concerns from scientists, governments, non-governmental organizations and global populations regarding mitigation strategies for plastic pollution (Ryan, 2015; Xanthos and Walker, 2017; Löhr et al., 2017). Global analyses of all plastic ever made suggests that more than 8.3 billion metric tons (MT) of plastic has been produced to date with global production exceeding 34 billion MT by 2050; of which 12 billion MT will end up in landfills and natural environments like the oceans (Geyer et al., 2017). Plastics are non-discriminatory and have accumulated in terrestrial, open ocean, deep sea and arctic environments of remote and densely populated regions around the world (Barnes et al., 2009; Taylor, 2018). Jambeck et al. (2015), estimated 4.8–12.7 million MT of plastics enter the oceans globally each year, mainly from rapidly developing countries with coastal borders. Plastic pollution, originating from sea and land-based sources, migrate into subtropical gyres, expansive vortexes of rotating currents, where it forms accumulation zones of macro and micro plastic deposits (Maximenko et al., 2012; Lebreton et al., 2012; Eriksen et al., 2013). Eriksen et al. (2014) estimates 5.25 trillion plastic particles weighing 269,000 tons are afloat at the sea surface, mainly reflective of fragmented plastic less than 5 mm in size known as microplastics. Microplastics, both primary (e.g., microbeads and industrial pellets) and secondary (deterioration of larger plastics) (GESAMP, 2015) are known to absorb persistent organic pollutants dissolved in sea water, presenting a credible route for toxins to enter the marine food web if ingested by marine species (Andrady, 2011). Emerging concerns have been generated as scientists aim to understand the human health impacts of plastic pollution as it enters the human food chain through ingestion of fish, shellfish and other filter feeding species (GESAMP, 2015; Xanthos and Walker, 2017; Karbalaei et al., 2018).

1.2 Ecological and economic impacts

Marine organisms of both spectrums of the food chain are negatively impacted by plastic pollution via the consequences of ingestion or entanglement of or in the material (Gall and Thompson, 2015; Worm et al., 2017). Gall and Thompson (2015) estimated that 693 species of marine animals were negatively impacted by interactions with plastic debris. This figure has since increased tremendously as literature from 1,147 publications suggest that 2,110 species of marine organisms are now negatively impacted by marine and plastic debris (Litterbase, 2018). Namely, 40% mammals, 100% sea turtles, and 46% bird species ingest or become entangled in plastic debris (CBD, 2016; Worm et al., 2017). Such interactions can result in impaired movement and disrupted feeding efforts, reduced reproductive output, lacerations, ulcers, and death (Laist, 1997; Derraik, 2002).

The presence of plastics in the marine environment can be a hinderance to economic development (Xanthos and Walker, 2017). Economic impacts of marine debris are measured by the reduction of opportunities to exploit the marine environment for play or profit (Faris and Hart, 1994; APEC, 2009; McIlgorm et al., 2011). The estimated costs of plastics impact on the marine environment is US$13 billion/year (Raynaud, 2014), stemming from reduced tourism revenues, negative impacts on recreational activities, vessel damages, damage to public health and the cost of cleanup (Raynaud, 2014; Hardesty et al., 2015; Xanthos and Walker, 2017). Marooned plastic along shorelines disrupt aesthetic appeal of beaches which can have a negative impact for tourism (Jang et al., 2014), especially for island nations heavily reliant on ocean-based tourism.

1.3 Small island developing states and marine debris

Small Island Developing States (SIDS), characterized as a distinct group of developing countries facing specific social, economic and environmental vulnerabilities, often rely on tourism as a dominant revenue source for the country (UN-OHRLLS, 2011). Usually located in the Caribbean Sea, Pacific Ocean or the AIMS region (Atlantic, Indian Ocean, and South China Sea), these islands are vulnerable to impacts of marine debris and are susceptible to receiving streams of ocean based plastic debris inconsistent with their consumption and population levels (Lachmann et al., 2017). Their proximity to sub-tropical gyres paired with a heavy reliance on imported goods and a lack of infrastructure for waste management creates a multifaceted pollution problem requiring challenging solutions (Starkey, 2017; Lachmann et al., 2017).

Marine debris and waste management have long been recognized as problems facing SIDS of the Wider Caribbean Region (WCR) due to increased waste generation resulting from economic growth, increased population, growing urbanization, and changes in consumption patterns, all lending to the urgency of addressing this issue on small islands (UNEP-CAR/RCU, 2008; UN-OHRLLS, 2011; Lachmann et al., 2017).

1.3.1 Marine debris and The Bahamas

The archipelagic SIDS of The Bahamas (Fig. 1. inset) sits in the Western Atlantic Ocean and is comprised of >3,000 low-lying carbonate islands (Buchan, 2000). With a population >350,000 and a coastline spanning >3,500km, The Bahama Islands are dependent on its seas to maintain a gross domestic product (GDP) of US$2.7 billion through tourism and harvest of marine resources (Buchan, 2000; Patil et al., 2016; Bahamas Ministry of Tourism, 2016). Warm waters and pristine white sand beaches draw 70% of the tourism market, which accounts for 60% of GDP (Buchan, 2000; Bahamas Ministry of Tourism, 2016). The Bahamas' orientation to ocean currents such as the Gulf Stream and those associated with the North Atlantic gyre make it a sink for marine plastic debris as it receives waste outputs from the subtropical gyre onto its shores (Buchan, 2000; Lachman et al., 2017). In 2010, estimated levels of existing plastic marine debris for The Bahamas were between 200-533 million MT, with a projected increase of up to 687 million MT by 2025, most of which is projected to have entered the Caribbean Sea (Jambeck et al., 2015; Patil et al., 2016). High concentrations of stranded marine litter on Bahamian beaches can potentially reduce local tourism income by 40% representing losses of up to US$8.5 million/year (Krelling et al., 2017). Marine debris can negatively impact coral reefs, mangrove forests and seagrass beds (Debrot et al., 2013) all crucial ecosystems that support the multi-million-dollar fishing industry of The Bahamas. Its geographic expanse makes waste management extremely difficult due to lack of organization and infrastructure catered to inter-island waste logistics (Lachmann et al., 2017). The country produces 3.25 kg of garbage per capita per day, ranking 13th for countries generating the most waste per capita (Hoornweg and Bhada-Tata, 2012; Illsley, 2016). Solid waste is disposed using landfills, where waste is openly burned, further releasing harmful toxins into the atmosphere (Hoornweg and Bhada-Tata, 2012). The Bahamas has ratified international treaties MARPOL Annex V, Cartagena Convention and the Regional Action Plan for Marine Litter (RAPMaLi) as a commitment to reducing land-based sources of marine debris (UNEP-CAR/RCU, 2008; UNEP-CEP, 2014). Despite such efforts, more consideration must be placed on mitigating marine debris impacts from sea to shore and innovating approaches for managing excess waste loads.

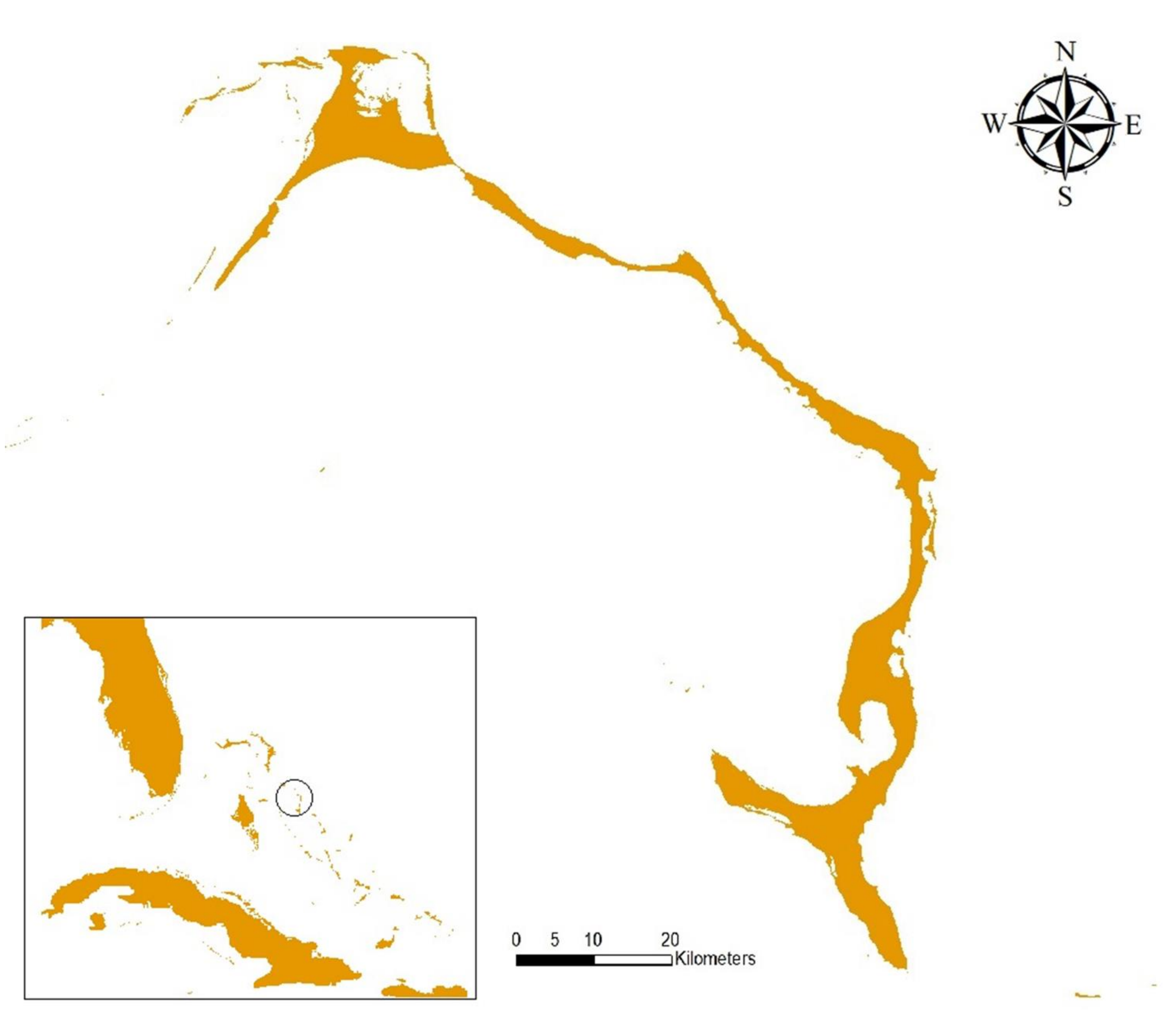

Fig. 1. Map of Eleuthera Island, Bahamas with The Bahamas archipelago (inset).

1.4 Management problem and research objectives

Information on abundance and distribution of marine debris on beaches throughout The Bahamas, is limited, making it challenging to inform policy to mitigate debris contributions. This study investigates the spatial and temporal distribution of marine plastic debris on beaches in South Eleuthera, The Bahamas based on its proximity to coastal exposures the Atlantic Ocean (AO), Exuma Sound (ES) or Bahama Bank (BB). Using data gathered by citizen scientists, the study offers a baseline understanding of litter composition, concentration and variation that can inform a strategic and effective marine debris management plan for The Bahamas. This study attempts to answer the question *Can understanding the abundance, spatial and temporal variability of marine plastic debris deposits onto beaches in South Eleuthera, The Bahamas lead to better debris removal efforts by using predictive mapping?:* and established the following objectives*: 1.* Determine the abundance and composition of marine debris on beaches of South Eleuthera, 2. assess macro and micro plastic debris concentrations on beaches of South Eleuthera3. assess the relationship between debris abundance and coastal exposure, 4. investigate the role of wind and relative exposure index (REI) as a factor in debris accumulation and 5. explore the feasibility of predictive mapping as a marine debris management strategy.

Chapter 2: Methods

2.1 Study area and methods

The island of Eleuthera (Fig. 1) is located within the central Bahamas and extends 177 km. Three coastlines, divided amongst North and South Eleuthera give us the basis for the study areas ; the AO, ES and the Great BB, noted as BB for this study. Due east of the island is the AO, characterized by its deep waters and circulating currents of the North Atlantic Gyre (Law et al., 2010). The Bahamas archipelago consists of shallow-water carbonate banks like the Great BB and hosts deep channels and deep-water basins such as the ES, a largely enclosed basin more than 1,000 m deep, with steep canyons (Colin, 1995). Sixteen beaches throughout South Eleuthera were monitored for this study and ranked geographically based on their exposure to the three major coastlines (Fig. 2). Beaches are ranked as: 1. Winding Bay; 2. Half Sound; 3. Airport Beach; 4. Northside Beach; 5. Cotton Bay North; 6. Cotton Bay South; 7. Lighthouse Beach; 8. Bannerman Town Beach; 9. Wemyss Bight Beach; 10. Plum Creek; 11. Fourth Hole; 12. Sunset Beach; 13. Sunrise Beach; 14. IS/CEI Boys Dorm Beach; 15. Paige Creek; and 16. Red Bays. Most beaches varied in beach dynamics, were remote and not located near industrial, commercial or densely populated areas (Table 1).

Each beach was monitored twice, once in Spring (March-May 2013) and replicated in Fall (September-November 2013), at the same location, verified using a handheld Garmin GPSMAP® 76 GPS. Citizen scientists teams consisting of a minimum of 4 individuals, were mobilized during each monitoring event, where two surveys were performed to assess macro and micro plastic debris concentrations using a modified protocol developed by the 5 Gyres Institute based on NOAA Marine Debris Shoreline Survey Field Guide (NOAA, 2012). Date, time, weather conditions, wind direction and speed, tidal information, beach dynamics and site usage were documented during each monitoring episode (Appendix 1). Site usage was based on the authors local experience of visitation frequency.

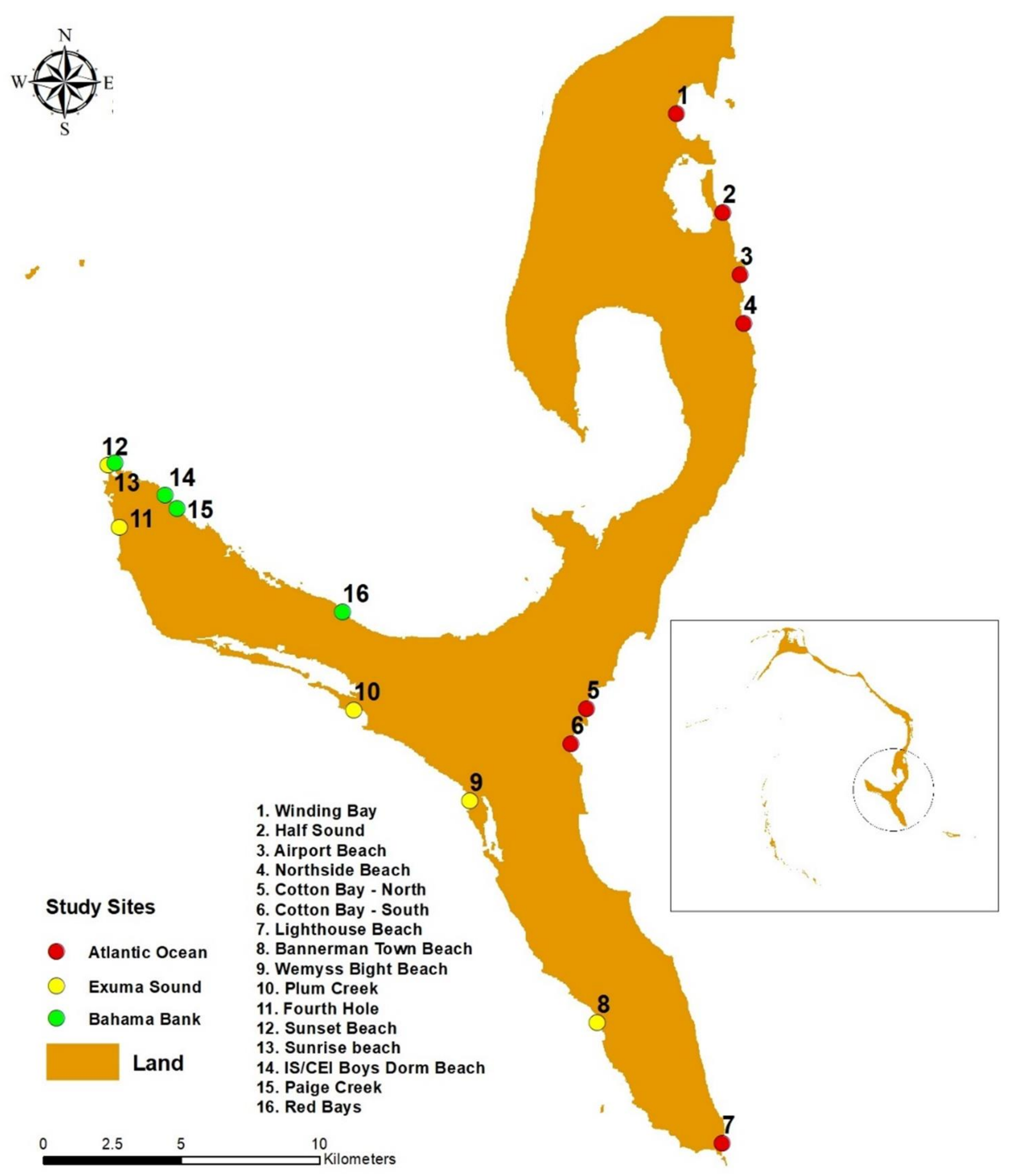

Fig. 2. Marine debris study sites for South Eleuthera, The Bahamas.

Table 1. Physical description of each study location and its proximity to the nearest township with a population >800 residents. Population data gathered from Bahamas Department of Statistics 2010 Population Census Report. *Rock Sound settlement is the largest township in South Eleuthera (population *n*=961).

Beach	Description (based on field notes)	Proximity to nearest community or *town (population *n*=>800) (km)
1	Coved area, sandy shore, lots of vegetation	8
2	High sand dune cliffs, vegetation on cliffs, rocky and sandy shoreline	5
3	Rocky and sandy shoreline, lots of vegetation	3
4	Sandy beach, lots of washed up seaweed, high sand cliff, high vegetation	3
5	Rocky coastline, high cliffs, sandy beach	13
6	Sandy beach with vegetation	13
7	Sandy with dunes and vegetation	29
8	Rocky shoreline, coarse sand, medium vegetation	25
9	Semi-protected large cove, low vegetation, coarse sand	18
10	Coved semi-rocky shoreline, semi coarse sand	16
11	Rocky shoreline, enclosed semi cove, brick sea wall and vegetation	20
12	Rocky shoreline, coarse sand, low vegetation	19
13	Rocky, semi-coarse sand, protected area, near houses	19
14	sandy shoreline, semi coarse sand, medium-high vegetation	18
15	Rocky, small beach width, high vegetation	18
16	Rocky shoreline, lots of deliberate waste left on and around beach	15

2.2 Macro and micro debris survey

Macro Survey: Four random 5 m wide transects within a 100 m section of shoreline were surveyed for all visible marine debris and plastics, inclusive of plastic fragments ≤2.5 cm. A measuring tape ran perpendicular to the shoreline from the back beach or first sign of vegetation to the high tide mark to identify the length of each transect. All debris was collected, sorted, weighed, and categorized.

Micro Survey: Four 1x1 m quadrats were randomly casted by volunteers, within the wrack line (high tide line where seaweed is deposited) of each transect selected for the macro debris survey. Using a small shovel, 3 cm of sand was scooped evenly across the grid and sieved through a set of nested sieve boxes with a mesh size 1 mm and 5 mm respectively. Only particles between 1 mm-2.5 cm were retained from each sieve tray and placed in separate waterproof bags labelled according to plastic size. ***Findings from microplastic data collected will be communicated in a parallel study.***

2.3 Sorting, weight, classification and quantification

Each sample was analyzed in an area of beach free of debris and sorted into major categories (plastic, metal, rubber, paper and processed lumber, glass, cloth and fabric) and separated by size and debris type before being quantified and recorded onto a standardized datasheet (Appendix 2). Total weight of all debris collected within each category per transect was recorded using a Super SS Waterproof Stainless-Steel Scale® to the nearest gram (g) ±0.5.

2.4 Data analysis

Data was analyzed using JMP® Statistical Analysis Software. Due to the non-normal distribution of the data, a Non-parametric Wilcoxon test was used to evaluate data.

2.5. Mean plastic items per square meter and per length of shoreline

The square area of each transect was attained by multiplying the standardized transect width of 5 m by the mean length of each of the four (4) transects for each beach. Mean number of plastic/m^2 were determined by dividing total number of plastic items collected at each beach by its average square area. Total length of beach surveyed at each study site was 20 m (4 x 5 m wide transects). Total amount of plastic debris collected within all transects were divided by 20 m to measure the quantity of plastic debris found per length (m) of shoreline.

2.6 Fetch modeling

Fetch, distance travelled by wind or waves over or across water, was calculated using the fetchR® software application which calculated fetch distances for each study site. The fetchR® application required two shape files, a polygon for the coastline of The Bahamas and surrounding region and one of geographic exposure points for each study site, in this case the geographic coordinates for each beach. The coastline shapefile was obtained from the Natural Earth Data website from the Cultural Vectors: Countries map (https://www.naturalearthdata.com/downloads/10m-cultural-vectors/). The uploaded shapefile had a map projection of 18R which correlates to The Bahamas. Following the upload of the polygon and exposure points shapefile, a maximum distance of 1,000 km was set. Fetch was measured for four (4) directions per quadrant, each set to calculate within 90°, giving a total of 16 wind directions. Once submitted, the software calculated the wind fetch by outputting fetch vectors (Fig. 3) in readable comma separated values (csv) files and keyhole markup language (kmz).

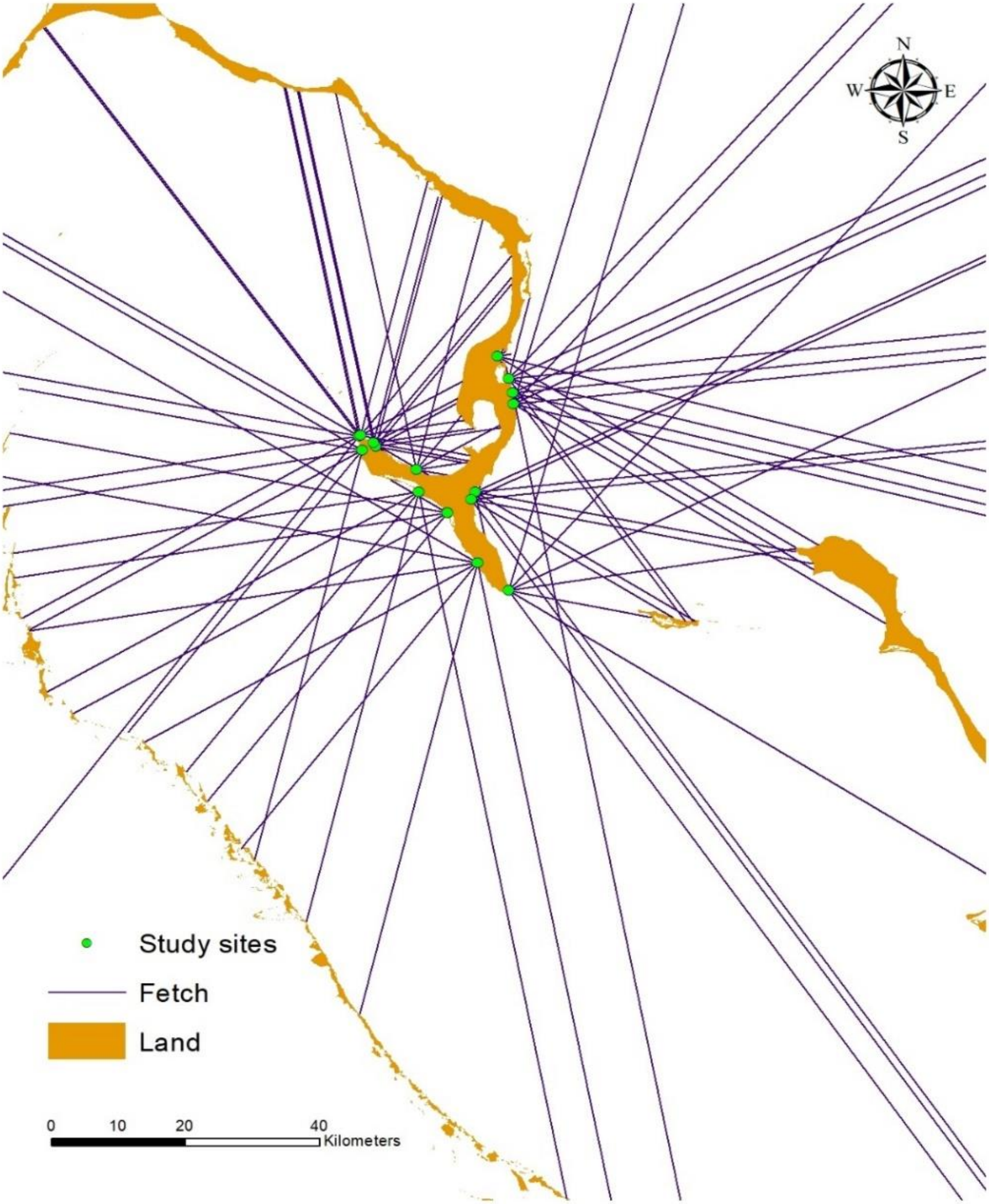

Fig. 3. Fetch projections for sixteen wind directions at each study site.

2.6.1 Wind calculation

Historic wind data for South Eleuthera was calculated using a nine-year wind frequency distribution dataset provided by The Bahamas Department of Meteorology. Wind data was collected from a wind tower in Rock Sound, Eleuthera for all 16 cardinal wind directions from January 2006-2014. All data points were recorded in units of days in which wind blew at a certain speed before being converted to wind speed (km h^{-1}).

2.7 Relative exposure index (REI)

Relative Exposure Index (REI) was used as an indicator of possible forcing of debris accumulation (Walker et al., 2006). Sixteen wind directions between 0-360˚ were analyzed based on the orientation of each beach study site. Using a method adapted from Walker et al. (2006) REI was calculated for each beach location:

$$REI = \sum_{i=1}^{16} \frac{\left(V_i \;\; P_i \, F_i \right)}{100}$$

Where V_i *is* the mean monthly wind speed (km h^{-1}) for wind directions 0-360° categorized as N (0°), NNE (22.5°), NE (45°), ENE (67.5°), E (90°), ESE (112.5°), SE (135°), SSE (157.5°), S (180°), SSW (202.5°), SW (225°), WSW (247.5°), W (270°), WNW (292.5°), NW (315°), NNW (337.5°). F_i is the fetch distance (km) and P_i is percent frequency from which the wind blew within each category.

2.8 Predictive mapping

The Marine Debris Action Planner (MAP), a novel GIS-based tool for predicting beach litter accumulation developed by GRID-Arendal and SALT was implemented to assess the feasibility of predictive mapping for this study (Haarr et al., 2018). A Digital Elevation Model (DEM) was obtained for the island of Eleuthera from USGS/EROS Data Center. The DEM is a raster dataset containing elevation and gradient (slope) data specific to each study location (Haarr et al., 2018). For this study, each raster represented a 30 m wide cell, reflective of the study area. Using the slope tool in QGIS®, slope values for each beach was extracted.

Field sampling methods specific to the MAP tool were not utilized within this study and limited the ability to gain crucial information on beach curvature, elevation and site selection using GIS.

Chapter 3: Results and discussion

3.1 Marine debris monitoring and citizen science

Approximately, 417 volunteers (Table. 2) conducted 124 macro and 124 micro marine debris surveys on sixteen (16) beaches found within coastal exposures AO (*n*=7), ES (*n*=5) and BB (*n*=4). There was no significant difference (p=0.8) in the amount of plastic debris found between seasons so all spatial and temporal data were combined. The relationship between plastic debris and tidal change found no significant difference (p=0.8). Marine debris monitoring provides a baseline understanding of litter composition, concentrations and source. It is a vital step towards reducing the ecological harms of plastic debris to marine ecosystems due to anthropogenic influences (Bennet-Martin et al., 2015). Monitoring is crucial for assessing the effectiveness of measures set forth to reduce both abundance and impact of plastic debris (Ryan et al., 2009). Most monitoring efforts for marine debris have focused on beach surveys of stranded plastic and other litter (Coe and Rogers 1997; Ryan et al., 2009).

Table 2. Total survey volunteers based on volunteer group and survey season.

Beach	No. Spring Volunteers	Group	No. Fall Volunteers	Group	Total Volunteers
1	4	CEI	32	P.H Albury High	36
2	4	CEI	8	CEI Gap Year Students	12
3	11	Island School	32	P.H Albury High	43
4	8	Island School	27	DCMS Eco Club	35
5	8	Island School	10	CEI Research	18
6	13	Island School	10	CEI Research	23
7	-	-	18	CEI Research	18
8	10	Island School	13	Palm Beach Day Academy	23
9	8	Island School	12	Round Square Del/DCMS	20
10	9	DCMS	8	IS Advisory	17
11	20	Lyford Cay	17	DCMS Eco Club	37
12	10	Link School	12	IS Art	22
13	16	St Andrews	12	IS Art	28
14	20	St Andrews	12	IS Art	32
15	14	IS/DCMS	12	IS Art	26
16	11	DCMS	16	P.H Albury High	27
Total	166		251		417

Shorelines of The Bahamas are constantly supplied with plastic from the ocean (Wilber, 1987), driving the need for increased research and management for marine debris. Beach sampling is more accessible, making it easy to facilitate research efforts that are cost effective (Dixon and Dixon 1981; Ribic et al., 1992; Rees and Pond,1995; Ryan et al., 2009). This study has provided substantial evidence on plastic abundance, diversity and distribution for beaches in South Eleuthera by monitoring large scale trends in marine litter using a citizen science approach.

Marine debris is easily identifiable and quantifiable, requiring relatively little scientific training, thus making the subject well suited for engaging citizen scientists (Hildago-Ruz and Thiel, 2015; Bergman et al., 2017). Citizen science studies have mainly focused on the distribution and composition of marine litter in the intertidal zone (Hildago-Ruz and Thiel, 2015) and has strengthened collaborations between scientists and volunteers (Cohn, 2008). Such engagement goes beyond the scope of simply cleaning a beach and instead is used as a tool to bridge gaps between community and science, while also raising awareness of the problem and inspiring solutions (Nelms et al., 2017; Bahamas Plastic Movement, 2018). Public participation partnerships between scientists and school students has produced real world data influential for creating changes at the policy level (Bravo et al., 2009). Providing participants with the support they require to digest project materials and gain confidence in their data-collection skills is critical (Bonney et al., 2009). Extensive training was provided to all volunteers (Fig. 4). As a result, data gathered has increased knowledge of the distribution of marine litter over space and time in remote and understudied areas of South Eleuthera (Bergman et al., 2017).

Fig. 4. Images taken during beach debris surveys (A) Volunteers from Preston H. Albury High School following a survey of Airport Beach; (B) plastic debris on Atlantic Ocean beach Cotton Bay-North; (C)

volunteers conducting macro debris survey of Airport Beach; (D) volunteers conducting microplastic survey at Sunrise Beach. Credit for A-D: Bahamas Plastic Movement.

3.2 Plastic debris composition

Approximately, 93% of all debris collected was plastic, representing a total of 5,489 plastic pieces weighing 62,200 g (±945.6 SE). Plastic was the most dominant debris type found across all beaches and showed a significant difference in concentrations across coastal exposures (p=<0.0001). Metal 1%, glass 2%, rubber 3%, paper and processed lumber 1% and cloth 0% accounted for 7% of debris collected (Appendix 3). More than 98% of plastic debris was collected by weight from all beaches with AO beaches 1-4, having the highest volumes of plastic debris (Fig. 5). ES beach, 9, had the lowest percentage of plastic by weight collected, 9%, with the remaining percentage composed of glass and metal material. (Fig. 5).

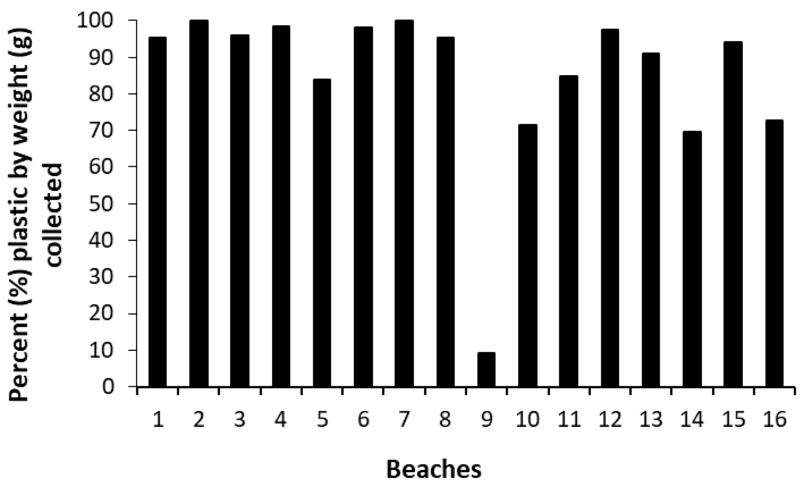

Fig. 5. Percentage of plastic debris by weight collected at each study site.

Plastic debris found across all beaches included plastic fragments, fishing gear (rope, buoys, floats, lures/lines, packaging straps), smoking (cigar tips, cigarettes, lighters), foodware (straws, food wrappers, utensils, cups, six-pack rings, balloons), plastic bottles and jugs, plastic bags and film, foam, plastic caps, personal care items and other. Plastic fragments (≤2.5 cm) were the dominant plastic debris type collected 69.4% (Fig. 6A), followed by plastic bags and film and fishing related plastic representing 7.5% and 7.4%

of plastic debris types collected (Fig. 6B). Beach 8, 84%, beach 14, 90% and beach 16, 83% yielded the highest concentrations of plastic fragments ≤2.5 cm compared to other debris categories collected within each beach (Fig 7A). Plastic bags and film were more common on beach 6, 40% (Fig. 7B), along with fishing related plastic debris commonly found on beach 6, 19%, beach 9, 17% and beach 15, 17% (Fig. 7B).

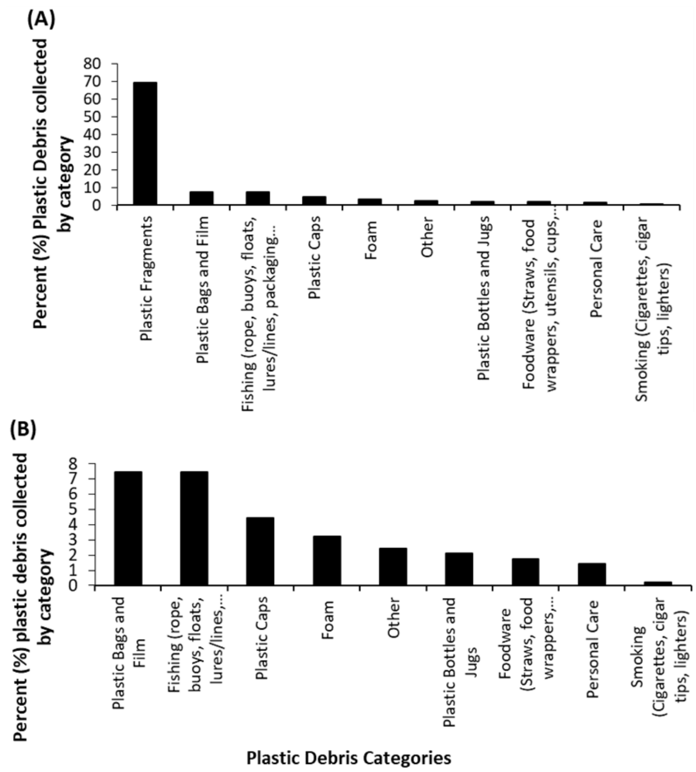

Fig. 6. (A) Total percentage (%) of plastic debris types collected inclusive of plastic fragments ≤2.5 cm; (B) total percentage (%) of plastic debris types collected exclusive of plastic fragments ≤2.5 cm.

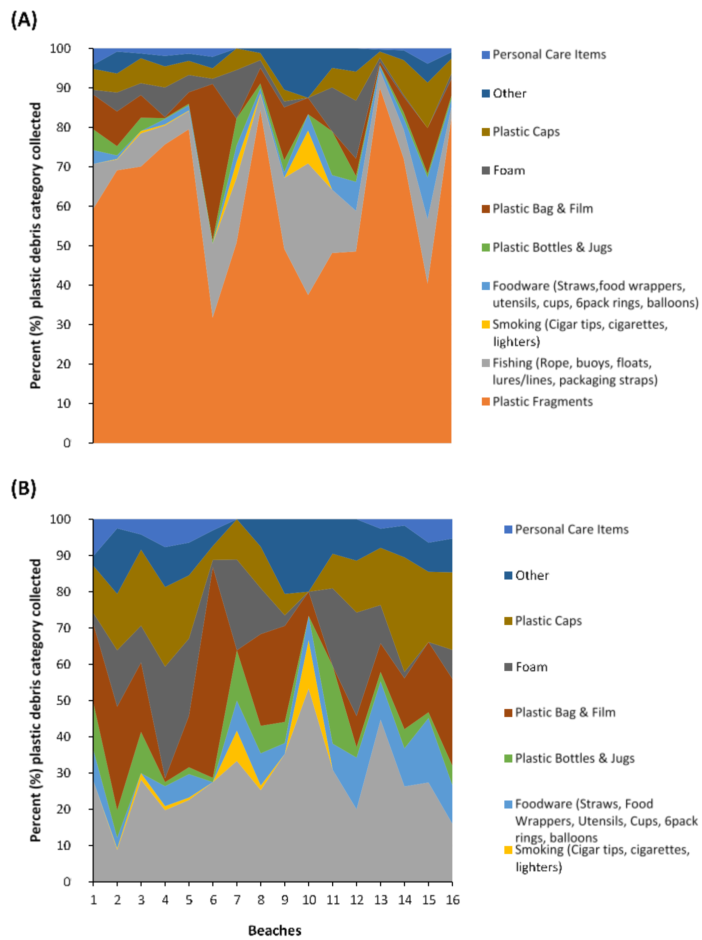

Fig. 7. (A) Percent (%) cover of plastic debris categories collected at each beach inclusive of plastic fragments ≤2.5 cm; (B) percent (%) cover of plastic debris categories collected at each beach exclusive of plastic fragments ≤2.5 cm.

The abundance and composition of plastic debris found within this study was congruent with beach debris surveys around the world and the WCR, with plastic accounting for 40-98% of all items recorded (Corbin and Singh, 1993; Debrot et al., 1999; Ivar do Sul and Costa, 2007; Scisciolo et al., 2016; Schmuck et al., 2017). Plastic fragments, despite the geophysical location of the study site, was the dominant plastic type collected. Each coastal exposure, AO, ES and BB had beaches with increased amounts of mean plastic fragments ≤2.5 cm/m^2 as seen in Fig. 8A. Mean plastic fragments ≤2.5 cm per length of shoreline differed significantly (p= <0.0001) and increased compared to mean plastic fragments ≤ 2.5 cm/m^2 (Fig 8B). Jude (1987) noted that beaches on remote isles of The Bahamas and areas of Bermuda were heavily littered with microplastic pellets and fragments of more than 2,000 pellets/m^2. This study's findings were consistent with high densities of fragmented plastic discovered on both leeward and windward coasts of WCR beaches (Debrot et al., 1999; Scisciolo et al., 2016). The appearance of this state of plastic is a direct result of weathering and photodegradation of the material, resulting in surface embrittlement and microcracking, yielding microparticles that are carried into water by wind or wave action before being transported to beaches (Andrady, 2011).

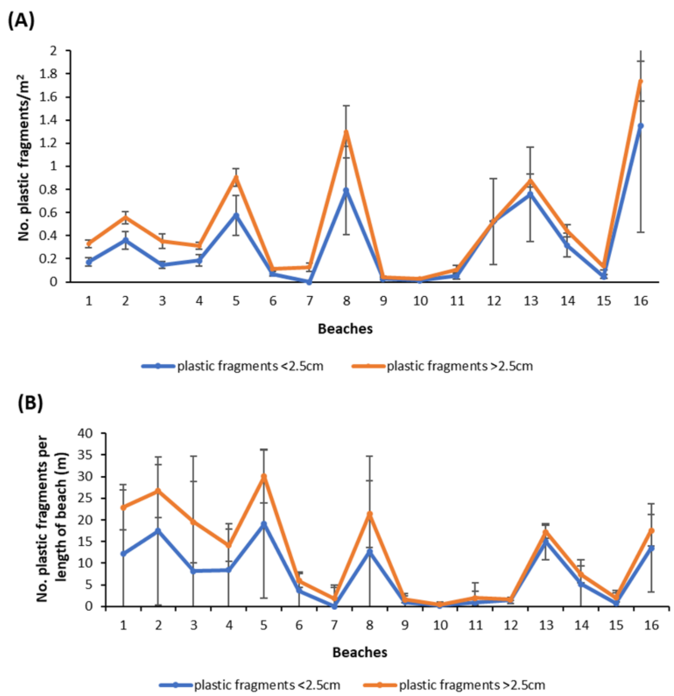

Fig. 8. (A) Mean number of plastic fragments/m^2 ≤2.5 cm; (B) mean number of plastic fragments per length of shoreline ≤2.5 cm. Error bars indicate ±SE of each sample (*n*=8) taken at each beach, except beach 7 where (*n*=4).

More than 70% of marine litter collected during the 2018 International Coastal Cleanup (ICC) were single use disposable plastics inclusive of plastic bags, plastic straws, food wrappers, styrofoam containers, plastic utensils and cups (Ocean Conservancy, 2018). Such items were present on all beaches sampled (Fig. 7) but were commonly found on beaches within the Exuma Sound and Bahama Bank exposures, most of which are moderate to heavily visited. Costs associated with removing all single-use plastics accumulating in the environment is estimated as higher than the costs of preventing littering today (UN Environment, 2018). Plastic bottle caps were ubiquitous in the study and were common on all beaches

(Fig. 6B). These high-density polyethylene caps, lightweight yet strong, possess a dynamic particle density that can increase overtime at sea (Morét-Ferguson et al., 2010). Particle-density data is critical for understanding what types of plastics are floating or sinking (Morét-Ferguson et al., 2010) and may be indicative of long-range marine debris transport.

3.3 Plastic distribution

Abundance and distribution of plastic varied by area and length of beach with lower mean abundances of plastic occurring per m^2 at AO sites compared to ES and BB beaches (Fig. 9A). There was a significant difference (p= <0.0001) in mean number of plastic items/m^2 at all beaches. Beach 16, 1.98 (±1.12 SE) and beach 8, 1.48 (±0.60 SE) had the highest levels of plastic items/m^2 (Fig. 9A). Comparatively, higher abundances of plastic debris occurred per length of shoreline at AO beaches compared to other coastal exposures (Fig. 10A). Mean plastic per length of shoreline had a significant difference (p= <0.0001) in debris abundance and increased compared to mean plastic/m^2 (Fig. 9A and 10A). Beaches 1, 37.15 (±17.01 SE) and 2, 38.45 (±15.93 SE), all exposed to the Atlantic Ocean, had increased levels of plastic per length of shoreline compared to locations at other coastal exposures (Fig. 10A).

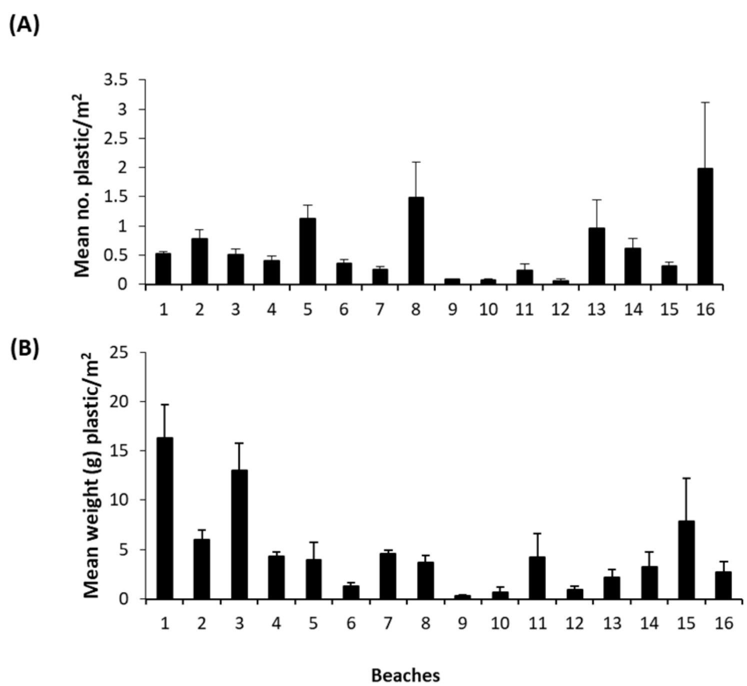

Fig. 9. (A) Mean number of plastic items/m^2; (B) mean weight (g) of plastic items/m^2.Error bars indicate ±SE of each sample (*n*=8) taken at each beach, except beach 7 where (*n*=4).

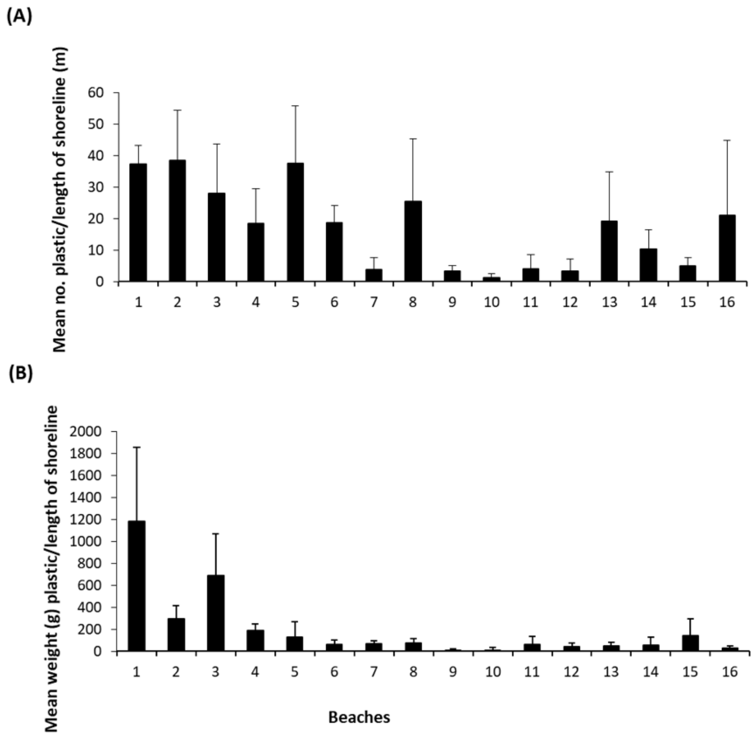

Fig. 10. (A) Mean number of plastic items per length of shoreline; (B) mean weight (g) of plastic per length of shoreline. Error bars indicate ±SE of each sample (*n*=8) taken at each beach, except beach 7 where (*n*=4).

Weight of plastic items/m^2 and per length of shoreline was higher at AO beaches (Fig. 9B). There was a significant difference (p= <0.0001) in mean weight of plastic items/m^2 at all beaches with beach 1, 16.3 g (±3.33 SE) and 3, 13.02 g (±2.74 SE) having the heaviest weight of plastic items/m^2 (Fig. 9B). Mean plastic weight per length of shoreline had a significant difference of (p= <0.0001) and showed beaches exposed to the AO having more weight per length of shoreline (Fig. 10B). Beaches 1, 1181 g (±675.76 SE), 2, 299.15 g (±116.97 SE) and 3, 689.55 g (±378.77 SE) had the heaviest weight of plastic per length of shoreline (Fig. 10B). Variations in mean weight of plastic/m^2 show that plastic debris was larger and heavier on AO beaches. Similarly, mean weight of plastic per length of shoreline maintained the presence of larger and heavier debris items on AO beaches while all ES and BB beaches had observed mean weights <200 g/length of shoreline (Figs. 9B and 10B). High accumulations of lightweight plastic fragments and single use plastic items, all common on ES and BB beaches, could explain the variation in plastic weight per length of shoreline. Mean amount of plastic debris/m^2 observed at AO beaches are consistent with studies conducted in the WCR (Debrot et al., 1999; Scisciolo et al., 2016; Schmuk et al., 2017). Schmuk et al. (2017) sampled 12 windward and leeward beaches in the northern, central and southern Bahamas and discovered high densities of plastic/m^2 at both locations with windward (AO) facing beaches having similar concentrations of mean plastic/m^2 as AO beaches within this study.

3.4 Fetch, wind and REI

Fetch values varied with study location and wind direction (Table 3). Sites exposed to the AO had fetch values of 1000 km for wind directions N (0°), NNE (22.5°), NE (45°), ENE (67.5°) and E (90°) (Table 3). Comparatively, ES and BB exposed beaches had lower fetch values from either wind direction due to their proximity to land masses (Table 3). Fetch, as a wind factor, and beach orientation have been shown to influence debris accumulation (Eriksson et al., 2013; Walker et al., 2006). Fetch projection models showed AO beaches with winds generated from N (0°), NNE (22.5°), NE (45°), ENE (67.5°) and E (90°) to have the largest fetch distances ≥1,000 km (Fig. 3). Wind speed and direction was documented for a total of 4,839 days from January-December 2006-2014. Mean wind speed was calculated for each cardinal direction with northern wind directions N (0°) 27.08 km h^{-1}., NW (315°) 23.38 km h^{-1}, NNW (337.5°) 22.83 km h^{-1}., having the highest mean wind speed (Table 4). Most days, wind blew from E (90°), ESE (112.5°), SE (135°), SSE (157.5°), and S (180°) with the strongest days with wind >40 km h^{-1} coming from N (0°) (Table 5).

Table 3. Fetch measurements calculated for 16 cardinal wind directions for each study site.

	Beach															
Wind Directions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
N	0.616397952	12.93145421	0.106415	1000	0.548105	0.102091	1000	0.147582	0.085474	0.088198	0.00024	0.021024	41.17534	39.81313	40.50654	40.42668
NNE	1.351093032	1000	0.150881	1000	0.993389	0.789893	1000	0.115901	0.072758	0.091606	0.000172	0.008296	34.62591	31.90434	31.17609	10.30438
NE	1.220437132	1000	1000	1000	1000	1000	1000	0.078875	0.060819	0.113218	0.000152	0.005709	15.81948	13.11005	12.50952	13.02626
ENE	1.717460674	1000	1000	1000	1000	1000	38.55137	0.067892	0.052234	0.17926	0.000158	0.004923	13.75501	13.36546	16.72008	6.765925
E	1000	1000	1000	1000	43.44686	46.32444	19.45427	0.068786	0.05282	0.34574	0.000196	0.004996	14.76239	12.92944	11.51932	4.091998
ESE	51.90364207	46.44347226	48.67173	60.14263	35.5449	32.50659	82.93688	0.082318	0.06314	0.536111	0.000321	0.005998	0.011838	8.889548	1.127132	0.016248
SE	1.095870032	45.42968188	42.72659	0.002819	197.8346	197.4663	188.1681	0.169065	0.096786	0.677352	0.001521	0.009267	0.006262	0.108522	0.001482	0.008364
SSE	0.701127824	0.030902054	147.0421	0.001061	6.643837	0.487264	0.679359	106.3182	0.182184	113.5415	0.063944	0.028578	0.003935	0.039309	0.000551	0.006275
S	0.000151498	0.021333502	0.035009	0.000721	0.043336	0.054704	0.017029	73.15715	0.339424	69.68885	66.32487	0.585339	0.002666	0.025038	0.000374	0.005643
SSW	5.87E-05	0.018432257	0.013453	0.000617	0.016338	0.014816	0.006655	55.02305	55.61339	53.95481	54.38452	322.6561	0.002278	0.017914	0.000319	0.005566
SW	4.02E-05	0.018736657	0.009192	0.000623	0.011108	0.009396	0.004567	52.50015	58.89991	58.59253	52.28732	53.10708	0.002294	0.015822	0.000322	0.006461
WSW	3.45E-05	0.022314754	0.007894	0.000742	0.009512	0.007742	0.003933	60.44252	58.22324	54.56358	141.5073	48.96822	0.002728	0.016403	0.000382	0.009407
W	3.50E-05	0.033927819	0.007982	0.00113	0.009594	0.007562	0.003986	65.21535	59.16038	0.286624	46.3333	94.06289	0.004141	0.085336	0.000581	0.024004
WNW	4.18E-05	0.090600349	0.00954	0.003486	0.011432	0.008682	0.004777	183.8294	9.021618	0.205235	75.14479	175.3965	0.012567	0.106106	0.001765	0.039524
NW	6.43E-05	0.447610229	0.014621	0.078897	0.017425	0.01241	0.007359	0.842494	0.814549	0.121037	0.05875	76.81291	76.88337	0.320973	0.031944	0.090965
NNW	0.000206346	1.765300382	0.046393	0.622889	0.039013	0.029659	0.023944	0.341965	0.195534	0.095777	0.000526	56.02733	55.95361	56.55065	57.07716	60.43893

Table 4. Mean wind speed km h^{-1} for Rock Sound, Eleuthera from January-December 2008-2014.

Wind Direction	Mean Wind Speed (km h^{-1})
N	27.08
NNE	18.48
NE	13.57
ENE	14.85
E	19.99
ESE	22.03
SE	20.41
SSE	21.70
S	18.64
SSW	17.77
SW	21.92
WSW	22.21
W	18.66
WNW	19.33
NW	23.38
NNW	22.83

Table 5. Days wind blew at a various wind speeds for 16 cardinal directions.

	Mean Wind Speed km h^{-1}						
	1 - 7	7- 12	12- 20	20-31	31-38	>40	Total
N	27	33	62	53	37	115	327
NNE	26	17	28	24	5	13	113
NE	69	37	45	22	9	5	187
ENE	60	37	57	26	13	5	198
E	59	53	87	99	36	28	362
ESE	70	61	138	164	64	64	561
SE	46	103	165	163	56	33	566
SSE	56	88	193	217	106	31	691
S	118	121	228	212	74	16	769
SSW	51	78	93	65	36	9	332
SW	10	40	47	62	27	15	201
WSW	18	16	41	58	23	12	168
W	23	34	62	38	13	11	181
WNW	3	16	29	14	7	3	72
NW	7	7	9	24	13	4	64
NNW	4	5	15	9	9	5	47
Sub-Total	647	746	1299	1250	528	369	4839

Geographic isolation of AO beaches from densely populated towns showed plastic debris at these locations to be more abundant, weathered, diverse and foreign in source as evidenced by product type or readable markings found on debris (Personal account), suggesting long range transport of plastic debris from a foreign source. Copious amounts of octopus pots (Fig. 12b, c and d), have been collected from AO beaches during the survey period and at several beach cleanup events occurring on the Atlantic coast of Eleuthera (Bahamas Plastic Movement, 2018). These fishing pots have been identified on beaches in

Fig. 11. Images displaying macro plastic debris deposits (A) Google Earth image displaying distance of documented plastic debris hot spot in the North Atlantic Ocean (Law et al., 2010) from Junk Beach-San Salvador, Bahamas. Credit: Google Earth; (B) large plastic debris, inclusive of octopus pots washed ashore on Junk Beach- San Salvador, Bahamas; (C) octopus pot and plastic water bottle washed ashore on Junk Beach- San Salvador, Bahamas; (D) octopus pot and other plastic debris washed ashore on Atlantic Ocean study site Cotton Bay-North, Eleuthera, Bahamas. Credit for B-D: Bahamas Plastic Movement.

Bermuda and San Salvador, Bahamas (personal account) and are used for artisanal octopus fishing off the Moroccan (Loulad et al., 2016) and Mauritanian (Tom Pitchford, personal account) coasts in the Northwestern Atlantic Ocean. Plastic octopus pots represented 95% of marine debris collected in waters off the Moroccan coast during a marine debris trawling study (Loulad et al., 2016). Damaged lines, bad weather, loss or release of gear, unregulated fishing, vandalism and theft have been linked to high densities of octopus pots in surface waters of the Northwestern Atlantic Ocean (Loulad et al., 2016).

Geographically, the African continent and its northwestern countries are due directly east of the island of Eleuthera, possibly suggesting a link between plastic debris transport. A study of the abundance, spatial and temporal distribution of plastic debris in the western North Atlantic Ocean documented 580,000 pieces of plastic km-^{2} at 24.6°N, 74.0°W (Law et al., 2010). The identified hot spot lies 73.41 km off the northeast coast of San Salvador, Bahamas, (Fig. 12a) where a high abundance of plastic debris has been documented on the Atlantic Ocean facing "Junk Beach" (Fig. 12b), termed by residents for its high debris concentrations (Personal account). Debris movements rely on the wind, often variable in time (Critchell and Lambrechts, 2016). Wind, wave, and storm track data analyzed by Hine (1977) showed that the strongest storm winds occurring in the northern Bahamas were predominately from the east (Hine et al., 1981). High wind speeds >40 km h^{-1} were documented predominately at N (0°) and E (90°) wind directions, coinciding with large fetch values for the same directions on AO beaches (Table. 3). REI values for each beach encompassed wind directions from 0-360° (Table 6). AO beaches had a higher REI value, 2906, compared to ES, 570, and BB, 142, sites (Table 6). No correlation was found between REI for wind directions between 0-360° and mean plastic per length of shoreline or plastic/m^2. Given the geographic orientation of Eleuthera, the probability of wind blowing from 0-360°at each beach is low. Thus, possible wind forcing directions were selected for each exposure: AO, NE (45°), E (90°), SE (135°); ES, S (180°), SW (225°), W (270°); BB NW (315°), N (0°). AO beaches maintained higher REI values, 1557, compared to ES, 212 and BB, 80, sites (Table 6). REI values summarized exposures to wind induced waves for each location and was used as an indicator of possible forcing of debris accumulation (Kelly et al., 2002; Walker et al., 2006; Mobilik et al., 2017). A correlation between REI and mean plastic per length of shoreline for selected wind directions (r=0.64), was identified and may link fetch and wind exposure to long-range transport of marine debris onto Atlantic beaches in The Bahamas, however, more studies are required.

Table 6. REI values for each beach encompassing wind directions between 0-360° and possible wind forced directions.

Beach	REI for Wind 0-360˚	REI for Selected Wind Directions
1	1636	1499
2	3311	2128
3	3310	2122
4	5043	2020
5	1782	1062
6	1758	1065
7	3502	1003
8	807	310
9	213	96
10	724	260
11	474	276
12	634	116
13	165	99
14	157	73
15	137	74
16	109	74

3.5 Spatial and temporal variation

The rapid increase in plastic debris on the ocean surface and beaches (Dixon and Dixon 1981; Derraik 2002; Barnes et al., 2009), has been documented globally in recent years. Though extensive monitoring of marine litter has been undertaken in various regions of the word, such efforts are complicated by the large spatial and temporal heterogeneity of debris abundance (Ryan et al., 2009) on both the sea surface and intertidal areas. Seasonal monitoring demonstrated no significant p=>0.5 temporal differences in debris abundance and distribution. This is likely attributed to the shortened time scale of the beach debris surveys, which can yield crude and biased data exclusive of human influences or natural patterns (Ryan et al., 2009; Browne et al., 2015). Smith and Markic (2013) discovered that the quantity of available debris is underestimated by 50% after only 3 days and by an order of magnitude after 1 month, indicating the importance of consistent temporal monitoring. Few studies suggest that the rate-of-loss for beach debris is surprisingly consistent regardless of geographic location (Smith and Markic, 2013).

Less frequented beaches, predominately on the AO coast, which were furthest from habitation were the most polluted. There proved to be a significant spatial difference ($p= <0.0001$) in plastic debris abundance between coastal exposures AO, ES and BB with AO beaches demonstrating larger amounts of plastic debris by weight and per length of shoreline (Fig. 5). Spatial abundance and distribution of plastic debris between beaches and coastal exposures was significant ($p= <0.0001$) with a clear variation in significance between beaches (Table 7) and exposures (Table 8). Variations in debris accumulation among beaches and exposures are linked to differences in both geographic location and local conditions between sites (Blickley et al., 2016). Local beach dynamics inclusive of currents and circulation patterns, wind and weather conditions, bathymetry, geophysical features, beach structure (slope or particle size), proximity to poorly managed landfills or densely populated areas, can all influence plastic debris accumulation (Storrier et al., 2007; Ryan et al., 2009; Browne et al., 2015; Schmuck et al., 2017).

Table. 7. Non-parametric Wilcoxon analysis of plastic debris concentrations between beaches. P-values indicated as *<0.05, **<0.01, ***<0.0001

	Beach															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	-	0.8747	0.2694	0.0086**	0.528	0.0009**	0.0084**	0.0827	0.0009**	0.0009**	0.0009**	0.0009**	0.0519	0.0009**	0.0009**	0.0135*
2	0.8747	-	0.4306	0.0273*	0.7929	0.0313*	0.0085**	0.1559	0.0009**	0.0009**	0.0009**	0.0009**	0.074	0.0039**	0.0009**	0.0273*
3	0.2694	0.4306	-	0.3717	0.3181	0.4606	0.0334*	0.8333	0.0019**	0.0011**	0.0026**	0.0019**	0.2268	0.0653	0.0053**	0.1033
4	0.0086**	0.0273*	0.3717	-	0.0458*	0.9581	0.1257	0.7927	0.0061**	0.0013**	0.0114*	0.0062**	0.9581	0.1272	0.0135*	0.8335
5	0.528	0.7929	0.3181	0.0458*	-	0.0181*	0.0085**	0.1275	0.0009**	0.0009**	0.0013**	0.0013**	0.1278	0.0019**	0.0009**	0.0406*
6	0.0009**	0.0313*	0.4606	0.9581	0.0181*	-	0.0138*	0.9581	0.0009**	0.0009**	0.0019**	0.0013**	0.5283	0.0458*	0.0009**	0.1563
7	0.0084**	0.0085**	0.0334*	0.1257	0.0085**	0.0138*	-	0.0504	0.0861	0.0131*	0.1988	0.1054	0.3949	0.7989	0.2688	0.1257
8	0.0827	0.1559	0.8333	0.7927	0.1275	0.9581	0.0504	-	0.0015**	0.0009**	0.0052**	0.0027**	0.3717	0.1033	0.0032**	0.3717
9	0.0009**	0.0009**	0.0019**	0.0061**	0.0009**	0.0009**	0.0861	0.0015**	-	0.0500*	0.7112	0.4257	0.0398*	0.0177*	0.341	0.0061**
10	0.0009**	0.0009**	0.0011**	0.0013**	0.0009**	0.0009**	0.0131*	0.0009**	0.0500*	-	0.4489	0.223	0.0022**	0.0013**	0.0084**	0.0013**
11	0.0009**	0.0009**	0.0026**	0.0114*	0.0013**	0.0019**	0.1988	0.0052**	0.7112	0.4489	-	0.8317	0.0307*	0.0576	0.267	0.0114*
12	0.0009**	0.0009**	0.0019**	0.0062**	0.0013**	0.0013**	0.1054	0.0027**	0.4257	0.223	0.8317	-	0.0133*	0.0235*	0.17	0.0038**
13	0.0519	0.074	0.2268	0.9581	0.1278	0.5283	0.3949	0.3717	0.0398*	0.0022**	0.0307*	0.0133*	-	0.4619	0.0924	0.7929
14	0.0009**	0.0039**	0.0653	0.1272	0.0019**	0.0458*	0.7989	0.1033	0.0177*	0.0013**	0.0576	0.0235*	0.4619	-	0.1028	0.2933
15	0.0009**	0.0009**	0.0053**	0.0135*	0.0009**	0.0009**	0.2688	0.0032**	0.341	0.0084**	0.267	0.17	0.0924	0.1028	-	0.0099**
16	0.0135*	0.0273*	0.1033	0.8335	0.0406*	0.1563	0.1257	0.3717	0.0061**	0.0013**	0.0114*	0.0038**	0.7929	0.2933	0.0099**	-

Table. 8. Non-parametric Wilcoxon analysis of plastic debris concentrations between exposures. P-values indicated as *<0.05, **<0.01, ***<0.0001.

Exposure			
	AO	ES	BB
AO	-	<0.0001***	<0.0001***
ES	<0.0001***	-	0.0008**
BB	<0.0001***	0.0008**	-

Densities of plastic debris discovered on AO beaches within this study and windward beaches of studies conducted in the WCR may be explained, in part, by exposure to major current systems of the AO and dominant trade winds (Schmuck et al., 2017). Geologic processes associated with the leeward, open carbonate bank margins allow an exchange of water on and off the BB and due to its away facing orientation from the dominant winds, a net flux of energy and sediment is directed off the bank (Hine et al., 1981). Research by Hine et al. (1981) documents vigorous offshore transport of carbonate sands along leeward margins of the Great Bahama Bank and suggests that during major storm events these shallow water sands are carried off into deep sea environments. Geophysical processes such as the resuspension of plastics from sediments and their sinking rates are poorly understood (Lusher, 2015). This study hypothesizes that the western boundary currents of the Gulf Stream, characterized as fast, deep, narrow and energetic (Steele et al., 2001) paired with sediment transport rates shown by Hine et al. (1981) and the potential for plastic debris to sink based on changes in density once in the marine environment (Lusher, 2015) as a potential explanation for lowered plastic debris abundance and deposition on Bahama Bank beaches. However, this is an unproven and unsupported hypothesis that requires extensive research.

The ES basin is suggested to have relatively self-contained circulation of surface waters with limited exchange with adjacent oceanic areas (Colin, 1995). An examination of surface currents within the ES showed that surface circulation was dominated by eddies and jets with a general northwestward movement (Colin, 1995). Satellite tracking drifters placed within the sound showed a clear movement from the ES into the AO only once and speculates that this occurrence was due to intensified weather (Colin, 1995). This may possibly suggest that debris can move into the sound but rarely gets out. A 2015 study conducted by the Cape Eleuthera Institute, investigated the presence of plastic at the sea surface of the ES. Microplastic trawl samples conducted in the ES showed a range of 22,500 to 125,000 pieces of floating plastic per km^{-2} in different sections of the ES, with a single trawl containing 1.95 million pieces per km^{-2} (Moore et al., 2015; Cape Eleuthera Institute). This study also assessed plastic ingestion rates of fish species found in the ES and found that the stomachs of 12 of the 64-fish dissected, contained plastic, with Mahi mahi (Coryphanea hippurus) a frequently consumed fish in The Bahamas, representing 19% of species sampled (Moore et al., 2015; Cape Eleuthera Institute). This study provided evidence on the occurrence of plastic debris ingestion in local fish species and provided foundational evidence on the spatial distribution of plastic within surface waters of the ES. Both studies infer reasoning for debris deposition on ES beaches but fail to address small scale dynamics specific to beaches therein, thus more research is required.

3.6 Predictive mapping

Beach litter removal is a crucial and effective mitigation strategy that reduces the redistribution and resuspension of already beached materials (Lee and Sanders, 2015; Simoneova et al., 2017; Haarr et al., 2018). Haarr et al. (2018) noted that global actions led by International Coastal Cleanup in 2017, engaged nearly 800,000 volunteers in removing more than 20 million pieces of trash from beaches and waterways around the world (Ocean Conservancy, 2018) and though effective and impactful in its approach, efforts associated with such cleanups tend to exclude high impact areas that are remote or more susceptible to long range transport of marine debris (Haarr et al., 2018).

Managing increasing threats associated with marine plastic pollution requires an understanding of where debris is accumulating and what factors drive the variation in debris abundance at different locations (Critchell and Lambrechts, 2016). Beach characteristics inclusive of gradient, curvature and substrate and location relative to litter sources and ocean transport can impact variability in beach litter accumulation, all characteristics that influence litter retention, resulting in sparseness of beach litter (Galgani et al., 2015; Critchell and Lambrechts, 2016; Hardesty et al., 2017; Haarr et al., 2018). Other processes known to influence the accumulation of plastics onto beaches include quantities of debris, the degradation of macroplastics into microplastics at sea and on beaches, the resuspension of beached plastics in relation to the wind shadow effect, the wind drift coefficient of floating plastics, and the rate at which plastics sink (Critchell and Lambrechts, 2016).

To maximize effectiveness of plastics debris removal for management and government agencies, geographic prioritization of removal efforts must be considered to enhance the effectiveness of targeted voluntary coastal cleanup actions (Critchell and Lambrechts, 2016; Haarr et al., 2018). Predictive mapping can provide a means to display approximations of distributions of debris along coastal shores and can unveil trends in debris deposition (Franklin, 1995; Kelly et. al, 2002) This is made possible by the ability of GIS to integrate digital spatial data and perform overlay analyses that extract information from collateral data layers (Kelly et al., 2002).

Oceanographic numerical models have predicted plastic debris accumulation at the sea surface from surface current patterns (Sebille et al., 2015), however emphasis must be placed on understanding arrival time and deposition location of ocean plastic debris. No correlation (r=0.35) was found between beach gradient and mean plastic/m^2 or mean plastic per length of shoreline for this study. The predictive model approach of our study proved inconclusive due to limited data on geographic and geological beach characteristics including gradient, elevation, curvature and substrate for each study site along with limitations of the DEM model provided. Effective monitoring and removal of marine debris from Bahamian shorelines may prove challenging given the geographic diversity of the archipelago and its remote coastal areas. Therefore, an understanding of where and how marine debris accumulates is paramount for optimizing clean-up efforts related to marine debris management that will mitigate threats to local ecosystems and economy. More data must be gathered using an updated methodology that would require reliable high-resolution oceanographic models, knowledge of the local wind fields and the influence of local topography on debris accumulation (Critchell and Lambrechts, 2016).

3.7 Future research

This study offers baseline data on the spatial trends of plastic debris around coastlines of South Eleuthera and can infer extensive marine debris abundance and distribution patterns for the wider Bahamas. As evidenced by our findings, high densities of plastic debris are marooned onto local shorelines, emerging concerns of potential threats to the ecological and economic wellbeing for the archipelago. Understanding the key drivers of debris deposition requires additional research on localized beach variability and small scale and large-scale oceanic processes such as currents, bathymetry, wind and wave patterns of The Bahamas and subsequently the WCR. Marine debris surveys must be scaled up to include surface sampling for plastic concentrations in and around Bahamian waters. Interconnected ecosystems seagrass beds, mangroves and coral reefs must also be assessed to determine if and how plastic debris may be infiltrating these environments and must explore its implications. Generally classified as either land-based or ocean-based, contingent on its water entry (Duhec et al., 2015), identifying litter source can influence mitigation strategies that reduce debris outputs and can offer more insight into where marine debris will end up. Beach debris monitoring must be continued and expanded to other Bahamian islands to paint a national picture of the extent of the problem. Temporal sampling associated with existing survey methodologies must consider daily or closely intermittent data collection that accounts for true rates of debris accumulation (Smith and Markic, 2013). In addition, such sampling must maintain citizen science engagement where applicable as it is an educational tool and can lead to direct lifestyle changes that can reduce single use plastic consumption. Studies focused on debris sources and pathways are crucial to understanding and creating better strategies and enhanced legislation for marine debris and solid waste management recycling and recovery. Once these new approaches are undertaken, studies of intertidal stranded marine debris can address this important global environmental problem and support feasible solutions.

Chapter 4- Conclusion and recommendations

Plastic pollution is entrenched in its negative implications for both human and environmental health, which often impedes existing positive solutions to combat this issue. This study provided a primary understanding of the impacts of plastic pollution to The Bahamas and examined tools such as citizen science, beach debris monitoring, fetch modeling, REI modeling and predictive mapping to aid in mitigation and management strategies for marine debris in The Bahamas. As plastic pollution transitions from a topic of concern within the scientific community to a global dinner table conversation, many interventions have been instituted that address plastic reduction at both legislative and non-legislative levels. Both approaches are instrumental as they influence each other by working in tandem, furthering reductions in marine plastic pollution. Within the Bahamas, non-legislative approaches have been instituted by The Bahamas Plastic Movement (BPM), an environmental non-profit organization that utilizes research, education, citizen science and policy change as a metric of change. Through citizen science-based research, public education and youth activism campaigns, this grass roots entity successfully engaged the Bahamian government in enacting legislation to reduce plastic pollution impacts through the implementation of a single use plastics ban for the nation, set to be implemented in 2020. The bottom-up approaches undertaken by BPM allowed for direct citizen engagement in science and education around plastic pollution, further translating into government action, whereas a top down approach would unlikely result in tangible change. Recently, many nations across the WCR including

Jamaica, Dominica, Antigua and Barbuda, Belize, Barbados and St. Lucia have announced plans to ban single use plastics including plastic bags, styrofoam and plastic straws within the coming years to address problems associated with marine plastic pollution. Though a progressive and crucial step, marine debris is a part of a broader problem of solid waste management that affects all coastal communities. SIDS must ensure that existing waste management strategies are effective and adequately address solid waste recovery, diversion and recycling, otherwise they will simply replace one waste product, in this case single use plastics, with another single use item with equal potential for environmental harm.

The struggle for marine plastic reduction has been a challenge for international governments for decades. The absence of adequate scientific research, assessment and monitoring creates barriers to addressing marine debris solutions. Information conducted within this study is critical to understanding marine debris source, abundance, distributions and impacts at both national, regional and global scales and can inform feasible and effective management schemes at all levels. Data derived from this study can be used as a metric to evaluate the effectiveness of single use plastic policies and can advise on adaptive management strategies to improve legislative efficacy. Continued research will be crucial as positive results due to interventions, can create a ripple effect for more single use plastic policies and potential marine debris management plans across different jurisdictions.

Microplastics, a derivative of photodegraded macroplastic deposits on beaches, were prevalent in this study and raises concerns due to its likelihood to deliver toxins across trophic levels. Mitigation of microplastics such as microbeads and microfibers have been addressed through policies that ban its sale and use in cosmetics. However, proactive management strategies that address the larger issue of macroplastics in the marine environment must be enacted to prevent the abundance of secondary microplastics. To address problems associated with plastic pollution and waste management in The Bahamas, the following is recommended: 1. standardized national monitoring and removal of marine debris that offers reliable and informative data on debris abundance and distribution to inform effective management approaches, 2. improved waste management practices that integrate marine debris and solid waste reduction, recovery and recycling, 3. expanded public education initiatives that support single use plastic reduction at the industry, business and individual level and 4. enforced legislation effective in its management of single use plastic reduction and illegal dumping in terrestrial and marine environments.

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Appendices

Appendix 1. Beach characterization data sheet

Bahamas Plastic Movement: PLASTIC BEACH PROJECT	
Beach Name	
Island, Country	
Number of volunteers/Origin	
Weather/wind direction and speed	
Date	
Start Time	
End Time	
Current Tide: High/Low/Slack	
Time of Last High Tide	
UTM Easting - start of transect (0m)	
UTM Northing - start of transect (0m)	
UTM Easting - end of transect (100m)	
UTM Northing- end of transect (100m)	
Average Width of beach (Avg T1:T4)(m)	
Direction of Transect when facing water	
Public or Private Beach	
# of beach users at time of transect	
Site Usage: High/Medium/Low	
Parking lot adjacent?	
Describe any pipes, channels, outfalls etc?	
Describe beach type and details	
Transect Points (numbers)	
Notes	

Appendix 2: Marine debris data sheets

MACRO DEBRIS DATA CARD				
Beach Name:	**Transect 1**	**Transect 2**	**Transect 3**	**Transect 4**
Transect length (m)				
PLASTIC				
Total plastic frag <2.5cm				
TOTAL plastic frag >2.5cm				
TOTAL foam plastic				
TOTAL plastic film				
TOTAL plastic utensils (straws, spoons etc)				
TOTAL food wrappers				
TOTAL plastic bottles				
TOTAL plastic jugs				
TOTAL plastic caps				
TOTAL cigar tips				
TOTAL cigarettes				
TOTAL cigarette lighters				
TOTAL plastic packaging straps				
TOTAL 6-pack rings				
TOTAL pieces of rope				
TOTAL buoys and floats				
TOTAL fishing lures/line				
TOTAL cups				
TOTAL balloons				
TOTAL personal care prods				
TOTAL plastic bags (or frags)				
TOTAL other				
TOTAL PLASTIC ITEMS				
TOTAL PLASTIC WEIGHT (g)				
METAL				
Aluminum /tin cans				
aerosol cans				
metal bottle caps				
other:				
TOTAL METAL WEIGHT (g)				
GLASS				
Beverage Bottles (whole)				
Jars				
Others: (include glass frags)				
TOTAL GLASS WEIGHT (g)				
RUBBER				
Flip-Flops				
gloves				
tires				
tar				
Others (include rubber frags)				
TOTAL RUBBER WEIGHT (g)				
PAPER and PROCESSED LUMBER				
Cardboard cartons (milk and juice)				
paper and cardboard				
paper bags				
lumber/ building material				
Other:				
TOTAL LUMBER AND PAPER WEIGHT (g)				
CLOTH/FABRIC				
Cloth (and clothing pieces)				
shoes				
towels/rags				
rope/net pieces (non-nylon)				
TOTAL CLOTH/FABRIC WEIGHT (g)				
OTHER/UNCLASSIFIABLE				
TOTAL OTHER WEIGHT (g)				
LARGE DEBRIS ITEMS (>1-foot or 0.3m)				
TOTAL LARGE DEBRIS WEIGHT (g)				
TOTAL WEIGHT of ALL Categories (g)				

MICRO DEBRIS DATA CARD				
Beach Name:	Quad 1	Quad 2	Quad 3	Quad 4
PLASTIC				
Plastic Fragments 1mm to 5mm				
Foam 1mm to 5mm				
Plastic Film 1mm to 5mm				
Plastic Utensils (straws, spoons etc) 1mm to 5mm				
Plastic Food Wrappers 1mm to 5mm				
Plastic Packaging Straps 1mm to 5mm				
Plastic Pellets 1mm to 5mm				
Plastic Fillament (fishing line, rope) 1mm to 5mm				
Plastic jugs or containers 1mm to 5mm				
Cigar tips 1mm to 5mm				
Cigarettes 1mm to 5mm				
Personal Care Products 1mm to 5mm				
Others:				
TOTAL PLASTIC WEIGHT (g)				
PAPER and METAL				
Paper and Cardboard				
Metal (aluminum foil)				
Others:				
TOTAL PAPER AND METAL (g)				
OTHER				
Balloons				
Glass				
Rubber Bands				
Tires				
Tar				
Other:				
TOTAL OTHER DEBRIS (g)				
TOTAL WEIGHT of all CATEGORIES (g)				

Appendix 3: Marine debris categories pie chart