Spatial trends and drivers of marine debris accumulation on shorelines in South Eleuthera, The Bahamas using citizen science

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ABSTRACT

This study measured spatial distribution of marine debris stranded on beaches in South Eleuthera, The Bahamas. Citizen science, fetch modeling, relative exposure index and predictive mapping were used to determine marine debris source and abundance. 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. Marine debris, (~2.5 cm or larger) on each beach was monitored twice between March–May and September–November 2013 at the same locations using GPS. Approximately, 93% of all debris items were plastic with plastic fragments (≤ 2.5 cm) being the most common. There were spatial differences ($p \leq 0.0001$) in plastic debris abundance between coastal exposures. Atlantic Ocean beaches had larger quantities of plastic debris by weight and by meter (m) of shoreline. Stranded plastic may be associated with Atlantic Ocean currents associated with leakage from the North Atlantic sub-tropical gyre.

1. Introduction

Marine debris, predominately plastic pollution, has become a global environmental problem gaining considerable public attention for its impacts on marine organisms, ecosystems and human health (Derraik, 2002; Kershaw, 2016; Walker, 2018). These are growing concerns for scientists, governments, non-governmental organizations and global populations regarding mitigation strategies for plastic pollution (Xanthos and Walker, 2017; Schnurr et al., 2018; Schnurr and Walker, 2019). Plastics are non-discriminatory accumulating in terrestrial, open ocean, deep sea and Arctic environments of remote and densely populated regions around the world (Barnes et al., 2009). More than 8.3 billion metric tons (MT) of plastic has been produced up to 2015 with global production exceeding 34 billion MT by 2050; of which 12 billion MT will end up in landfills and natural environments (Geyer et al., 2017). Jambeck et al. (2015) estimated 4.8–12.7 million MT of plastics entered the oceans in 2010, mainly from rapidly developing coastal countries. Plastic pollution, originating from marine and land-based

sources, migrate into sub-tropical gyres, where it accumulates into zones of macro and microplastic deposits (Lebreton et al., 2012; Eriksen et al., 2013). Eriksen et al. (2014) estimated 5.25 trillion plastic particles are afloat at sea, mainly consisting of fragmented plastic (< 5 mm) known as microplastics. Microplastics, both primary (e.g., microbeads and industrial pellets) and secondary (fragmented larger plastics) can sorb persistent organic pollutants dissolved in seawater, creating a pathway for toxins to enter marine food webs if ingested (Andrady, 2011). Understanding potential human health impacts of plastic pollution from ingestion of fish, shellfish and other filter feeding species is also a growing concern (Karbalaei et al., 2018).

Marine organisms are negatively impacted by plastic pollution via ingestion or entanglement (Derraik, 2002; Worm et al., 2017). In 2015, Gall and Thompson (2015) estimated 693 species of marine biota were negatively impacted by interactions with plastic debris but has increased dramatically with documented impacts for 2110 species consisting of 40% of mammal species, 100% of sea turtles, and 46% of bird species (Worm et al., 2017; Litterbase, 2018). Plastics in the marine

environment can also reduce economic development and recreational opportunities (Mcilgorm et al., 2011). Estimated costs are US$13 billion/year, including negative impacts on recreational activities, vessel damage, impacts to public health, cleanup costs and reduced tourism revenues, especially for island nations heavily reliant on ocean-based tourism (Jang et al., 2014; Raynaud, 2014; Hardesty et al., 2015).

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 (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, disproportionally to their population consumption levels (UNEP and NOAA, 2011). 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). 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 (UNEP-CAR/RCU, 2008; Lachmann et al., 2017). The archipelagic SIDS of The Bahamas (S1) in the Western Atlantic Ocean comprises > 3000 low-lying islands. With a population of > 350,000 and coastline spanning > 3500 km, The Bahama Islands are ocean dependent to maintain a gross domestic product of US$2.7 billion from tourism and harvesting marine resources (Bahamas Ministry of Tourism, 2016a, 2016b). The Bahamas' orientation to ocean currents such as the Gulf Stream and those associated with the North Atlantic sub-tropical gyre create a sink for marine plastic debris (Lachmann et al., 2017). In 2010, plastic marine debris accumulation for The Bahamas were estimated between 200 and 533 million MT, projected to increase to 687 million MT by 2025 (Jambeck et al., 2015; Patil et al., 2016).

High concentrations of stranded marine debris on Bahamian beaches can reduce local tourism income by 40%, equivalent to US$8.5 million/year (Krelling et al., 2017). Marine debris negatively impacts coral reefs, mangrove forests and seagrass beds which are all crucial ecosystems support the multi-million-dollar fishing industry of The Bahamas. Waste management is extremely difficult due to lack of inter-island waste infrastructure (Lachmann et al., 2017). The Bahamas produces 3.25 kg of garbage/capita/day, ranking 13th globally. Solid waste is disposed using landfills, where waste is burned, releasing atmospheric pollution (Hoornweg et al., 2012). The Bahamas has ratified international treaties, such as MARPOL Annex V, Cartagena Convention and 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 and innovative approaches for managing excess waste loads.

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 investigated spatial distribution of marine debris on beaches in South Eleuthera, The Bahamas based on proximity to coastal exposures of the Atlantic Ocean (AO), Exuma Sound (ES) or Bahama Bank (BB). Marine debris is easily identifiable and quantifiable, requiring relatively little scientific training, and is well suited for engaging citizen scientists (Bergmann et al., 2017). Citizen science studies have mainly focused on distribution and composition of marine debris in the intertidal zone and has strengthened collaborations between scientists and volunteers (Cohn, 2008; Hidalgo-Ruz and Thiel, 2015). Engagement goes beyond just beach clean-ups, and instead is used as a tool to bridge gaps between communities and scientists, while also raising awareness of the problem and inspiring solutions (Schnurr et al., 2018; Bahamas Plastic Movement, 2018). Public participation partnerships between scientists

and school students has produced real world data, influential for creating policy changes (Bravo et al., 2009). Providing participants with support to gain confidence in their data-collection skills is critical, which helps citizen scientists understand the spatiotemporal distribution of marine debris in remote and understudied areas (Bonney et al., 2009; Bergmann et al., 2017). Using data gathered by citizen scientists, this study provides a baseline understanding of marine debris composition, concentration and variation that can inform strategic and effective marine debris management plans for The Bahamas. This study assessed: abundance and composition of marine debris on beaches of South Eleuthera; relationships between debris abundance and coastal exposure; role of wind and relative exposure index (REI) as a factor in debris accumulation; and feasibility of predictive mapping as a marine debris management strategy.

2. Methods

2.1. Study area

The island of Eleuthera is located within the central Bahamas (S1). Three coastlines, AO, ES and BB were assessed. The AO (east of Eleuthera), is characterized by deep waters and circulating currents of the North Atlantic sub-tropical gyre (Law et al., 2010). The Bahamas archipelago consists of shallow-water carbonate banks like the BB and hosts deep channels and deep-water basins such as the ES, a largely enclosed basin > 1000 m deep, with steep canyons (Colin, 1995).

Sixteen beaches throughout South Eleuthera were monitored and grouped according to their exposure to three major coastlines (Fig. 1). Atlantic Ocean beaches were: 1. Winding Bay; 2. Half Sound; 3. Airport Beach; 4. Northside Beach; 5. Cotton Bay North; 6. Cotton Bay South; 7. Lighthouse Beach. Exuma Sound beaches were: 8. Bannerman Town Beach; 9. Wemyss Bight Beach; 10. Plum Creek; 11. Fourth Hole. Bahama Bank beaches were: 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 from industrial, commercial or densely populated areas (S2).

2.2. Citizen science

Each beach was monitored twice, once in Spring (March–May 2013) and again in Fall (September–November 2013), at the same location, verified using a handheld Garmin GPSMAP® 76 GPS, except for Lighthouse Beach which was only monitored once during the Fall, resulting in 4 less samples being obtained. There were no significant differences found between seasons ($p = 0.8$) so spatial and temporal data were combined. Citizen scientist teams (at least four individuals), were mobilized during each monitoring event, where surveys were performed to assess marine debris concentrations using a modified protocol developed by the 5 Gyres Institute based on NOAA Marine Debris Shoreline Survey Field Guide (NOAA, 2012). Extensive training was provided to all citizen science volunteers in South Eleuthera (S3). Approximately, 417 volunteers (S4) conducted 124 marine debris surveys on 16 beaches within coastal exposures AO ($n = 7$), ES ($n = 5$) and BB ($n = 4$). Date, time, weather conditions, wind direction and speed, tidal information, beach dynamics and site usage were documented during each monitoring episode (S5). Site usage was based on the authors local experience of visitation frequency.

2.3. Marine debris 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. Debris items measuring over 2.5 cm, inclusive of plastic fragments ~2.5 cm, within the survey area were quantified (NOAA, 2012). A measuring tape ran perpendicular to the shoreline from the back beach or first sign of vegetation to the high tide

South Eleuthera, The Bahamas

Study Sites

Atlantic Ocean

Exuma Sound

Bahama Bank

Land

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
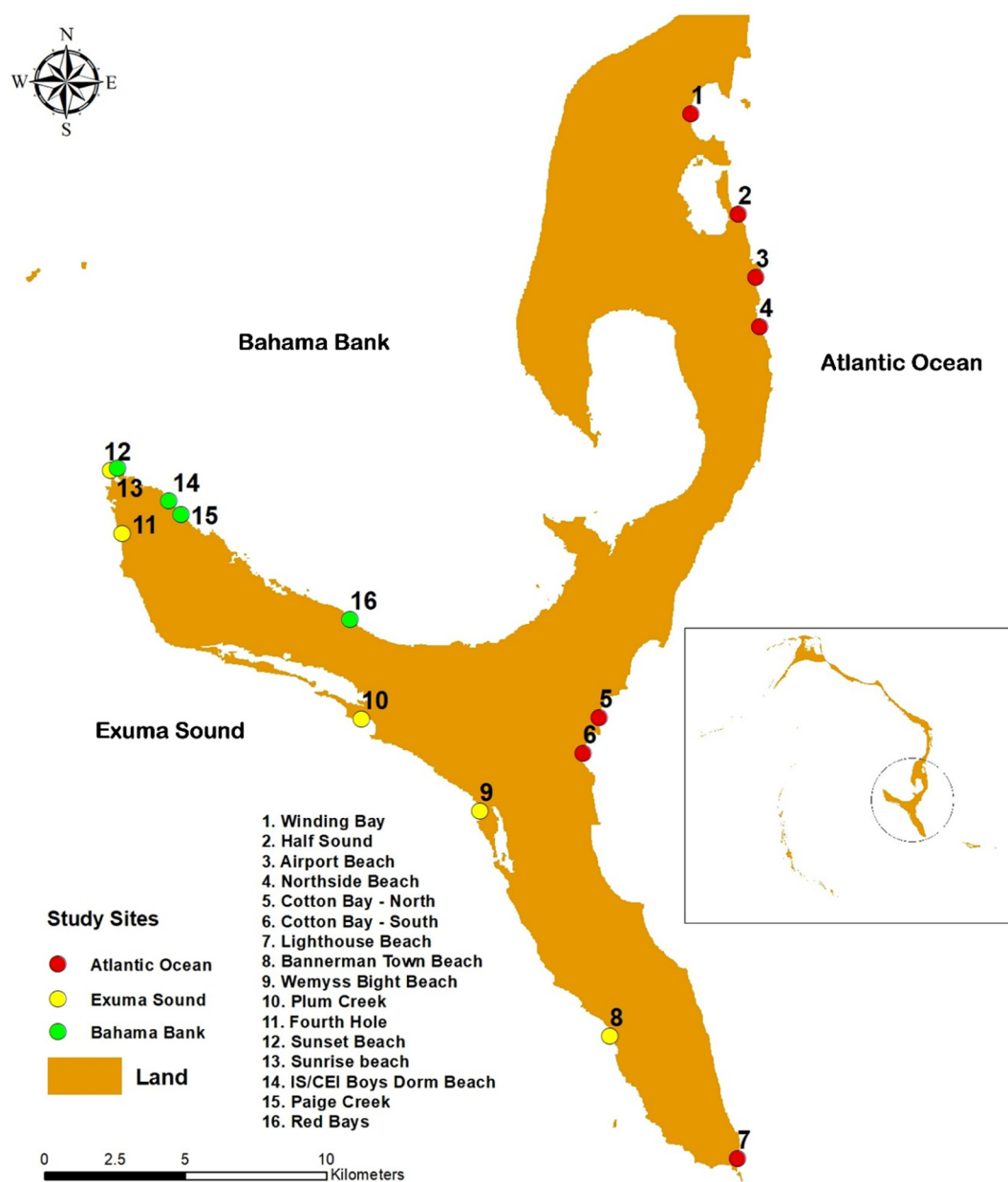16. Red Bays

0   2.5   5   10 Kilometers

Fig. 1. Marine debris study sites for South Eleuthera, The Bahamas.

mark to identify the length of each transect. All debris was collected, sorted, weighed, and categorized. 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 (S6). Total weight of all debris collected within each category per transect was recorded using a Super SS Waterproof Stainless-Steel Scale® to nearest (± 0.5) gram (g). Data was analyzed using JMP® Statistical Analysis Software. Due to non-normal distribution of the data, a Non-parametric Wilcoxon test was used. Transect area was calculated by multiplying standardized transect width of 5 m by mean length of each of the four transects for each beach. Total length of beach surveyed at each study site was 20 m (4 × 5 m wide transects). Total plastic debris items collected within all transects were divided by 20 m to measure quantity of plastic debris found per m of shoreline.

2.4. Marine debris source modeling

Fetch, distance travelled by wind or waves over or across water, was calculated using fetchR® which calculated fetch distances for each beach. The fetchR® application required two shape files, a polygon for the coastline of The Bahamas and surrounding region and one of geographic exposure points (i.e., 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/). Uploaded shapefiles had a map projection of 18R, correlated to The Bahamas. Following upload of polygons and exposure points shapefile, a maximum distance of 1000 km was used. Fetch was measured for four directions per quadrant, each set to calculate within 90°, giving 16 wind directions. Once submitted, wind fetch was calculated by outputting fetch vectors (S7) in readable comma separated value (csv) files and
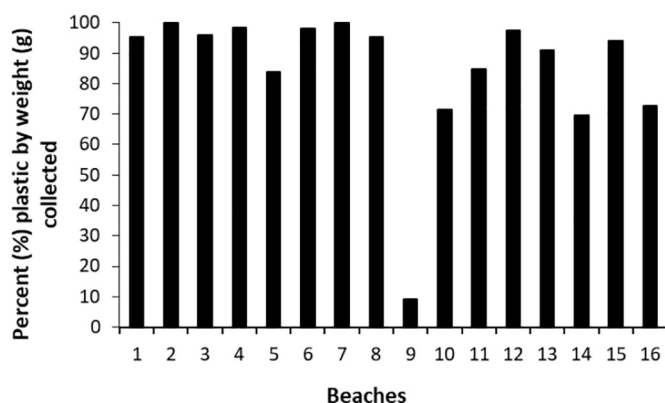
Fig. 2. Percent plastic debris by weight collected at each study site.

keyhole markup language (kmz).

Historic wind data for South Eleuthera were calculated using a nine-year wind frequency distribution dataset provided by The Bahamas Department of Meteorology. Wind data was collected from Rock Sound, Eleuthera for all 16 cardinal wind directions from January 2006–2014. All data points were recorded in days in which wind blew at a certain speed before converting to wind speed (km h^{-1}). Sixteen wind directions between 0 and 360° were analyzed based on orientation of each beach. REI was used as an indicator of possible forcing of debris accumulation for each beach location using a method adapted from Walker et al. (2006):

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

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°). P_i is percent frequency from which the wind blew within each category and F_i is the fetch distance (km).

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. 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., 2019). 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.

3. Results and discussion

3.1. Marine debris citizen science monitoring

Monitoring efforts for marine debris have mostly focused on beach surveys of stranded plastic and other litter (Walker et al., 1997, 2006; Ryan et al., 2009). Shorelines of The Bahamas are constantly supplied with plastic from the ocean, driving the need for more research and management of marine debris. Marine debris citizen science monitoring provides a baseline understanding of debris composition, concentrations and sources and helps inform policies to reduce ecological impacts of plastic debris on marine ecosystems (Bennett-Martin et al., 2015). The application of citizen science monitoring has established a large scale and long-term marine debris dataset for The Bahamas with greater spatial coverage, making it more accessible and easier to facilitate cost effective research efforts (Ribic et al., 1992; Ryan et al., 2009; Falk-

Andersson et al., 2019). Citizen science training applied consistent protocols that were scientifically reproducible and combined scientific and environmental values to support marine debris and plastic pollution education (Locritani et al., 2019). This baseline study provided evidence of marine plastic abundance, diversity and distribution for beaches in South Eleuthera using a citizen science approach. Exclusive of plastic fragments ≤2.5 cm, single use plastic bags and film were the most common plastic type found on beaches. Furthermore, monitoring is crucial for assessing effectiveness of policies to reduce abundance and impacts of plastic debris. In January 2018, this data was successfully presented to the Government of The Bahamas to influence legislation on disposable plastics use within the country.

3.2. Plastic debris composition

Approximately, 93% of all debris collected was plastic (by count), comprising a total of 5489 plastic pieces weighing 62,200 g (± 945.6 SE). AO beaches, 1–4 had the highest mean weight of plastic collected, with ES beach 9, having the lowest mean plastic weight, with most debris being composed of glass and metal (Fig. 2).

Plastic was the most dominant debris type found across all beaches and showed significant difference in concentrations across coastal exposures ($p \leq 0.0001$). Metal 1%, glass 2%, rubber 3%, paper and processed lumber 1% and cloth 0% accounted for 7% of debris collected. 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, followed by plastic bags and film and fishing related plastic (Fig. 3). Beaches 8, 14 and 16, yielded the highest concentrations of plastic fragments ≤2.5 cm, compared to other debris categories collected within each beach (Fig. 4A). Plastic bags and film were more common on beach 6, along with fishing related plastic debris commonly found on beach 6, beach 9, and beach 15 (Fig. 4B).

Abundance and composition of plastic debris found within this study was congruent with beach marine debris surveys around the world and the WCR, with plastic accounting for 40–98% of all items recorded (Schmuck et al., 2017). Plastic fragments, despite the geography of the study site, was the dominant plastic type collected. Mean plastic fragments ≤2.5 cm, found per m of shoreline differed significantly ($p \leq 0.0001$) across coastal exposures AO, ES and BB. Findings were consistent with high densities of fragmented plastic discovered on both leeward and windward coasts of WCR beaches (Scisciolo et al., 2016). Fragmented plastic is a direct result of weathering and photodegradation, 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).

More than 70% of marine debris 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. 4) but were commonly found on beaches within the ES and BB exposures, most of which are moderate to heavily visited and is broadly consistent with single-use plastic debris categories found in other studies (e.g., Pettipas et al., 2016). 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 common on all beaches (Fig. 4). These high-density polyethylene caps, lightweight yet strong, possess a dynamic particle density that can increase overtime at sea. 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
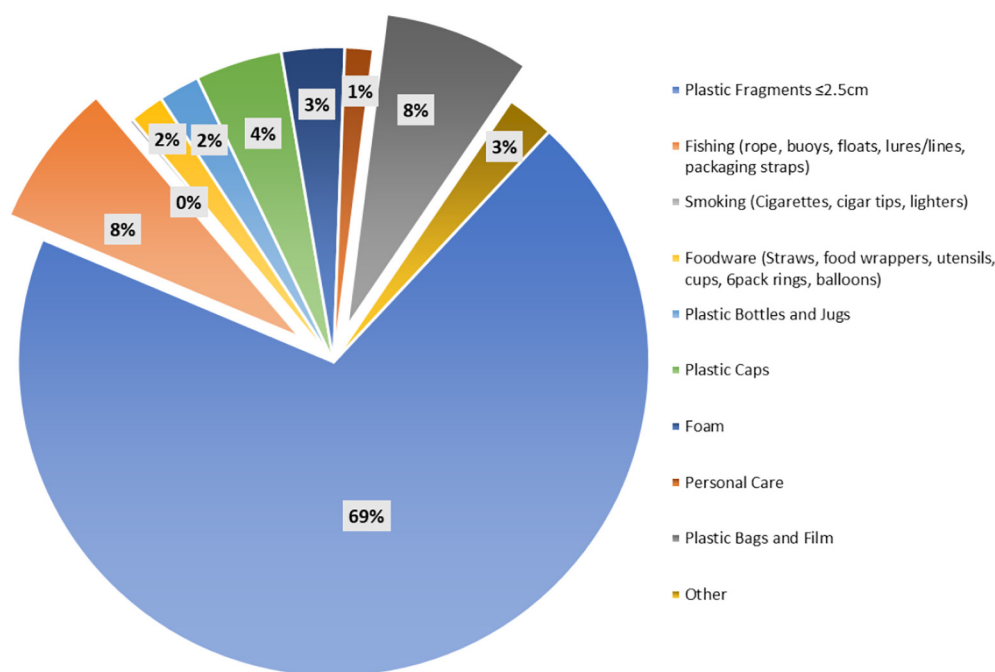
Fig. 3. Percent plastic debris types collected.

transport.

3.3. Plastic distribution

Mean plastic per m of shoreline had a significant difference ($p \leq 0.0001$) with higher abundances of plastic debris occurring per m of shoreline at AO beaches compared to other coastal exposures (Fig. 5A).

Mean plastic weight per m of shoreline had a significant difference of ($p \leq 0.0001$) across coastal exposures and showed beaches exposed to the AO having increased weight of plastic per m of shoreline (Fig. 5B). Beaches 1, 1181 g ($\pm$ 675.76 SE), 2, 299.15 g ($\pm$ 116.97 SE) and 3, 689.55 g ($\pm$ 378.77 SE) had the heaviest weight of plastic per m of shoreline (Fig. 5B). Mean weight of plastic per m of shoreline maintained the presence of larger and heavier debris items on AO beaches while all ES and BB beaches had observed mean weights of $< 200\,\text{g/m}^2$ of shoreline (Fig. 5B). High accumulations of light-weight plastic fragments and single-use plastic items, all common on ES and BB beaches, could explain the variation in plastic weight per m of shoreline. Mean amount of plastic debris observed at AO beaches are consistent with studies conducted in the WCR (Scisciolo et al., 2016). Schmuck et al. (2017) sampled 12 windward and leeward beaches in the northern, central and southern Bahamas and discovered high densities of plastic at both locations with windward (AO) facing beaches having similar concentrations of mean plastic as AO beaches within this study.

3.4. Spatial variation

The rapid increase in plastic debris on the ocean surface and beaches (Derraik, 2002; Barnes et al., 2009), has been documented globally in recent years. Though extensive monitoring of marine debris has been undertaken in various regions of the world, such efforts are complicated by the large spatial and temporal heterogeneity of debris abundance (Ryan et al., 2009) at the sea surface and in intertidal areas. Seasonal monitoring demonstrated no significant ($p = 0.8$) temporal differences in debris abundance and distribution. This is likely attributed to the shortened time scale of the beach marine debris surveys, which can yield crude and biased data exclusive of human influences or natural

patterns (Browne et al., 2015). Less frequented beaches, predominately on the AO coast, which were furthest from habitation were the most polluted. Formal and informal beach cleanups seldomly occurred at more frequented beaches at ES and BB locations. There was a significant spatial difference ($p \leq 0.0001$) in plastic debris abundance between coastal exposures AO, ES and BB with AO beaches demonstrating larger amounts of plastic debris by weight and per m of shoreline (Fig. 5). Spatial abundance and distribution of plastic debris between beaches and coastal exposures was significant ($p \leq 0.0001$) with a clear variation in significance between beaches (S8) and exposures (S9). 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 (Browne et al., 2015; Schmuck et al., 2017).

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). Hine et al. (1981) documented vigorous offshore transport of carbonate sands along leeward margins of the BB 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 postulates that the western boundary currents of the Gulf Stream, characterized as fast, deep, narrow and energetic paired with sediment transport rates reported 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 BB beaches. However, this is an unproven hypothesis that requires further research.

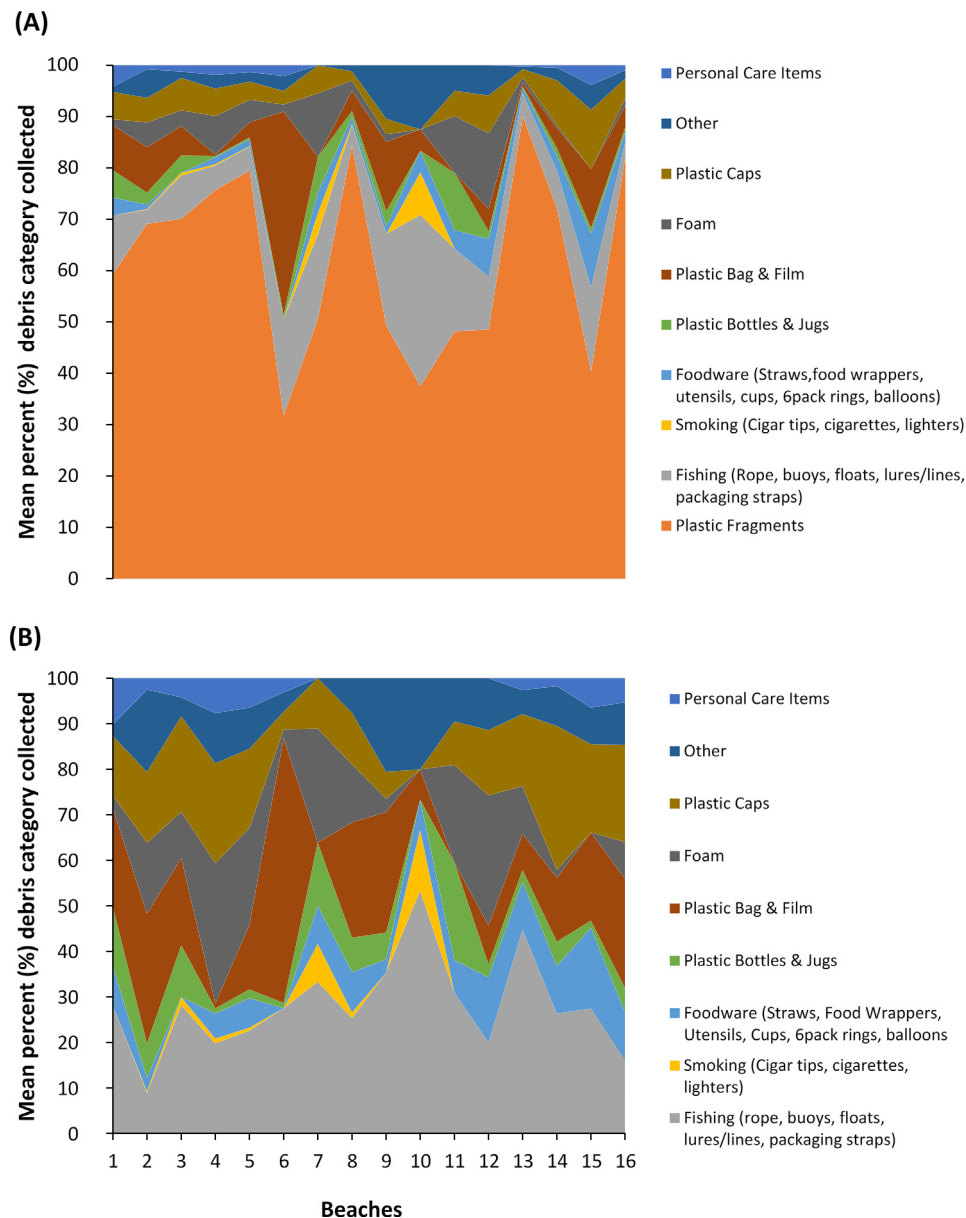The ES basin is suggested to have relatively self-contained

(A)

(B)

Fig. 4. (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.

circulation of surface waters with limited exchange with adjacent oceanic areas. An examination of surface currents within the ES showed that surface circulation was dominated by eddies and jets with a general northwestward movement. 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 suggest that debris can move into the sound but rarely gets out. A 2015 study conducted by the Cape Eleuthera Institute, investigated 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/km^{-2} in different sections of the ES, with a single trawl containing 1.95 million pieces/km^{-2}. 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). 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.

3.5. Marine debris source modeling

Fetch values varied with study location and wind direction (S10). 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°) (S10). Comparatively, ES and BB exposed beaches had lower fetch values from either wind direction due to their proximity to land masses (S10). Fetch, a function of wind and beach orientation, has been shown to influence debris accumulation (Walker et al., 2006; Eriksson et al., 2013). Fetch projection models showed AO beaches with winds generated from N (0°), NNE (22.5°), NE (45°), ENE (67.5°) and E (90°) had the largest fetch distances ≥ 1000 km (S10). Wind speed and direction was documented for a total of 4839 days from January–December
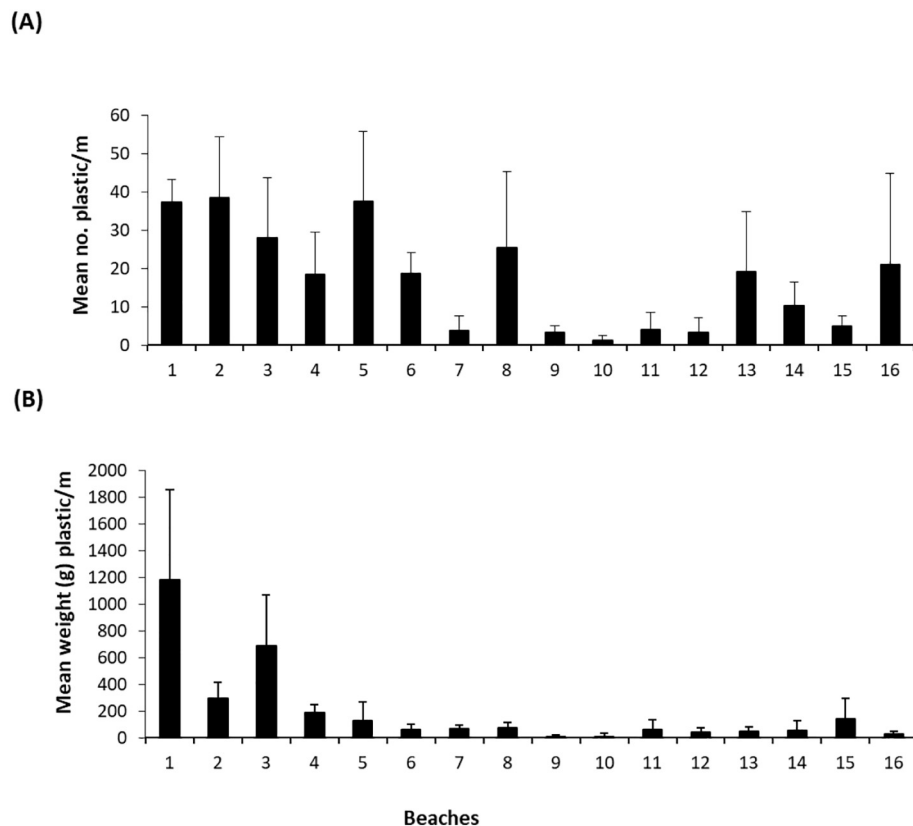
(A)

(B)

Beaches

Fig. 5. (A) Mean number of plastic items per m of shoreline; (B) mean weight (g) of plastic per m of shoreline. Error bars indicate ± SE of each sample ($n = 8$) taken at each beach, except beach 7 ($n = 4$).

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 (S11). 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°) (S12).

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, suggesting long range transport of plastic debris from a foreign source. Copious amounts of octopus pots (S13), 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 Bermuda and San Salvador, Bahamas and are used for artisanal octopus fishing off the Moroccan and Mauritanian coasts in the Northwestern Atlantic Ocean (Tom Pitchford, Personal communication). Plastic octopus pots represented 95% of marine debris collected in waters off the Moroccan coast during a marine debris trawling study. 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 (S13) where a high abundance of plastic debris has been documented on the AO facing "Junk Beach" (S13), 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 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 (S12).

REI values for each beach encompassed wind directions from 0 to 360° (S14). AO beaches had a higher REI value, 2906, compared to ES, 570, and BB, 142, sites (S14). No relationship was found between REI for wind directions between 0 and 360° and mean plastic per m of shoreline. Given the orientation of Eleuthera, the probability of wind blowing from 0 to 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 (S14). 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). A correlation between REI and mean plastic per m 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.

Beach debris removal is a crucial and effective mitigation strategy that reduces the redistribution and resuspension of already beached materials (Simeonova et al., 2017). Haarr et al. (2019) noted that global actions led by International Coastal Cleanup in 2017, engaged nearly 800,000 volunteers in removing > 20 million pieces of trash from beaches and waterways globally (Ocean Conservancy, 2018). 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., 2019). 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 debris sources and ocean transport can impact variability in beach debris accumulation, all characteristics that influence litter retention, resulting in sparseness of beach debris (Galgani et al., 2015; Hardesty et al., 2017; Haarr et al., 2019). 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 (Andrady, 2011; 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., 2019).

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). 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 per m 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).

3.6. 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 sources and 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 should 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 debris sources 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 (UNEP and NOAA, 2011).

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 solutions. Through citizen science-based research, public education and youth activism campaigns, this grass roots entity successfully engaged the Bahamian government in enacting legislation for 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 (UNEP-CEP, 2018). 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. Once these new approaches are undertaken, studies of intertidal stranded marine debris can address this important global environmental problem and support feasible solutions.

4. Conclusion

Marine plastic pollution reduction has been a challenge for international governments for decades. Absence of adequate marine debris monitoring data creates barriers to addressing marine debris solutions. This study provided baseline data of plastic pollution in The Bahamas using citizen science, beach debris monitoring, fetch modeling, REI modeling and predictive mapping to aid in management strategies to reduce marine debris. Citizen science monitoring helps educate and raise awareness among volunteers and community members. Data gathered during study is critical for understanding marine debris sources, abundance, distributions and impacts at national, regional and global scales. Future monitoring can be compared to data from this study to evaluate effectiveness of single-use plastic reduction policies and can help inform adaptive management strategies to improve legislative efficacy. Continued research on effectiveness of interventions, may trigger more single-use plastic policy interventions and potential marine debris management plans across the WCR. To address problems associated with plastic pollution and waste management in The Bahamas, standardized national monitoring and removal of marine debris that offers informative data on debris abundance and distribution to inform effective management approaches is recommended. Improved waste management practices that integrate solid waste reduction, recovery and recycling; expanded public education initiatives that support single-use plastic reduction at industry, business and individual levels and enforced legislation against illegal dumping of single-use plastics in terrestrial and marine environments is also recommended.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2019.03.036.

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