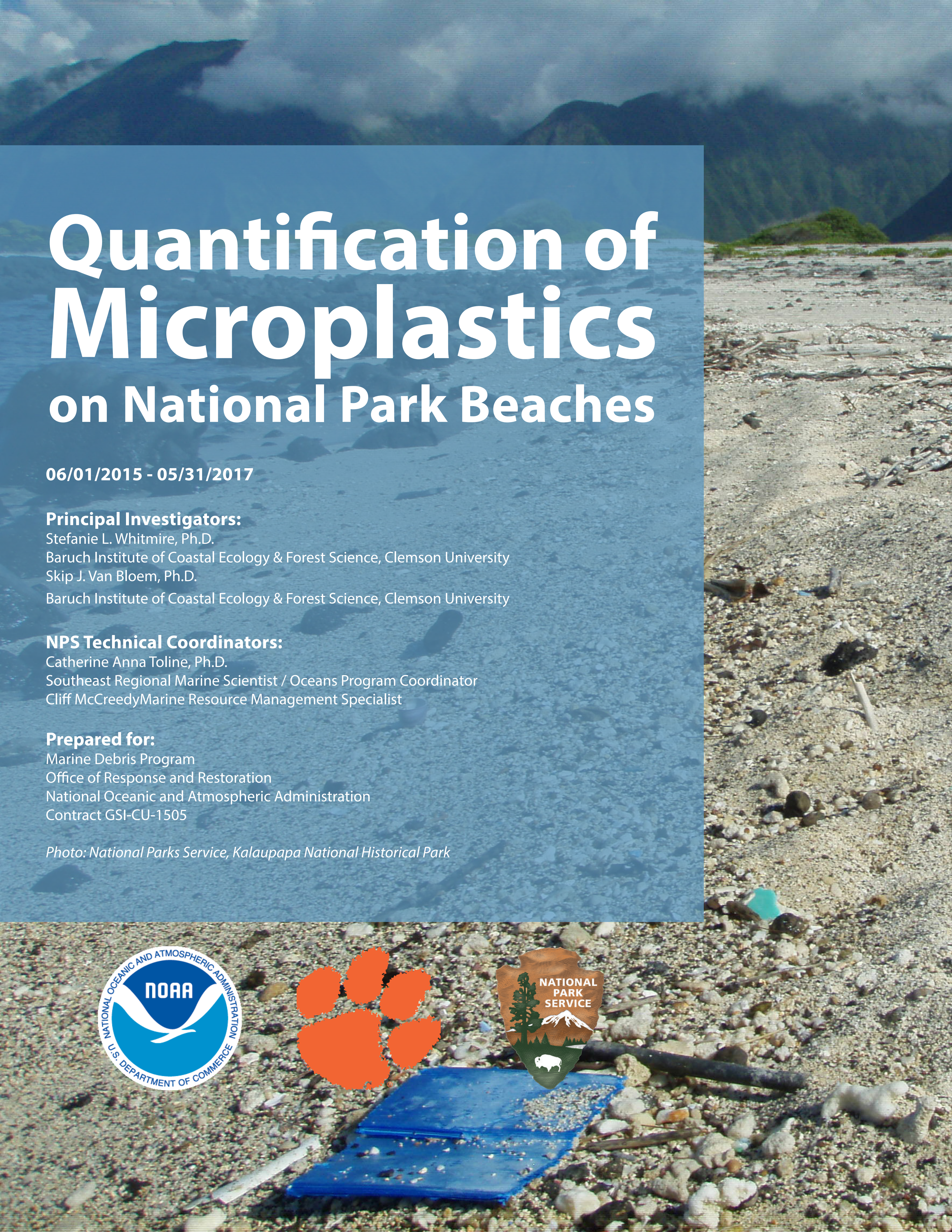

Quantification of Microplastics on National Park Beaches

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Photo: National Parks Service, Kalaupapa National Historical Park

1. INTRODUCTION

Plastic pollution is a global environmental concern. Most plastics are durable and degrade slowly, so discarded plastic remains in the environment for a long time, thus becoming an environmental hazard. Risks from large plastic debris, such as entanglement of marine life and ingestion by shorebirds, reptiles and fish, often cause injury or death and has been well-documented in marine systems (Derraik 2002; Gall and Thompson 2015). Plastic debris washing onto shore or into developed areas has economic impacts on tourism and industry on top of ecological effects (Avio et al. 2016, Critchell and Lambrechts 2016). There is no lack of plastics in society. In 2010, there was 275 MT of plastic waste generated globally (nearly 100 pounds per person) and another 270 MT of new plastic resins were produced (Jambeck et al. 2015). If even a small percentage of this annual plastic production is released into oceans, lakes, and rivers, it can accumulate into large amounts of plastic debris, as has been shown by many marine debris studies.

Scientists are not only finding large plastic debris in the ocean and around the globe, but also microplastics. Microplastics are defined as manmade plastic particles less than 5 mm in size that are mostly the result of either the breakdown of larger plastic items, such as water bottles and fishing line, or from manufacturing of small particles including cosmetic beads added to facial scrubs and toothpastes. Fibers from clothing such as fleece are also a substantial portion of microplastics.

Microplastics enter the ocean either indirectly from land-based run-off or through river transport, or as larger pieces already drifting in the ocean that degrade into smaller pieces (Browne et al. 2010, Yonkos et al. 2014). These very small pieces have been found in zooplankton, coral, copepods, marine worms, filter feeders, fish, and other organisms that serve as prey for larger species (Cole et al. 2013, Rochman et al. 2014, Wright et al. 2013, Setala et al. 2014). This is not surprising since microplastics are often the same size as food particles for these organisms. While studies continue to be published on the fate and effect of microplastics on an organism's physiology and the potential biomagnification in food webs, research has already demonstrated ingestion and potential toxicological risks (e.g. Browne et al. 2013, Wright et al. 2013, Farrell and Nelson 2013, Setala et al. 2014, Rochman et al. 2014, Avio et al. 2015). When plastic is manufactured, additives are commonly used such as phthalates (plasticizers to enhance flexibility), a possible carcinogenic compound, and bisphenol A (BPA- added to polycarbonate and plastic resins), an endocrine disrupter. Microplastics can also adsorb persistent organic pollutants, like polychlorinated biphenyl (PCB - e.g. coolants), which are present in many coastal environments. The fate and impacts of ingesting these small particles with these chemicals on whole ecosystems is an emerging topic for research and management (Besseling et al. 2013, Chua et al. 2014, Rochman et al. 2014, Koelmans et al. 2013, Koelmans et al. 2016). The introduction of these chemicals could have large implications for coastal food webs and potentially humans.

The purpose of this project is to quantify microplastic loads at single sites on selected beaches at a continental scale to better understand microplastic distribution. A collaborative effort with the National Park Service and NOAA Marine Debris Program provided the opportunity to sample a wide geographic distribution of coastal beaches to quantify microplastic loads in a snapshot of time. Beaches can capture microplastics from both open water bodies (oceans or lakes) and riverine systems. Additionally, beaches are dynamic systems, with constant movement of sand and other particles like shells, glass, and plastic.

While the type of manmade material found was not determined, the techniques employed maximize the separation of microplastics from sand, so we assumed that mostly plastic was captured during this process as heavier materials, even if small, would have been separated from plastics. Given the ubiquitous nature of the microplastics concern, sampling beaches using a standard protocol provides an opportunity to compare relative amounts of microplastics across a wide geographic region. The overall approach of a one-time sampling at multiple sites across a broad geographic area allows us to determine how widespread and variable microplastic pollution is and to begin to make inferences about sources and sinks. Data produced from this study should be used to gain a better understanding of where microplastics are located in the environment and an idea of the range of loads found along US coasts. However, NPS units should not use this single study to make strong inferences about the immediate risk of microplastics to wildlife and human health at their sites.

2. MATERIALS AND METHODS

2.1. Field Sampling Collections

Thirty-seven coastal sites from 35 National Parks Service (NPS) units were selected for this study. The sites include the Northeast Region, Great Lakes, West Coast and Pacific Islands, and the Alaska Region (Table 1, Figure 1). Sites in the southeast US were part of a previous study (Chow et al. 2016). and not resampled for this project. Sampling locations within a park were selected by park staff based on where they consistently observed large marine debris. All sand samples were collected by NPS staff or NPS volunteers using sampling kits provided by the Baruch Institute of Coastal Ecology and Forest Science. The sampling kits included a written procedure with a visual illustration (Supplement A), a metal sampling ring, a metal spoon, premade aluminum foil bags, a blank data sheet (Supplement A), and a box with return postage (Chow et al. 2016). Samples were collected at low tide along a 50-meter transect parallel with the shore between the high and low tide lines. To keep sample sizes consistent, the metal ring with a 25-cm diameter and 1.5-cm height (equivalent volume = 736 cm^3) was pressed into the top sand layer until the upper rim of the ring was flush with the sand; material within the ring was carefully collected to the bottom of the rim using the metal spoon and subsequently transferred into an aluminum foil bag (depth of sample is 1.5 cm). A total of 10 samples along the 50-m transect were collected from each site, with at least 1 m between each sampling point. The bags were carefully folded and packed, and shipped back to the laboratory at the Baruch Institute of Coastal Ecology & Forest Sciences in Georgetown SC for processing. Sand samples were collected from June to December 2015. Due to weather and remote access in the Alaska region, three locations there were sampled from June to August 2016 (Supplement Table B3).

2.2. Microplastic Isolation and Quantification

Beach sediments were dried at 70°C for 48 hours and then sifted through a 4.75-mm brass mesh sieve and then a 2-mm brass mesh sieve to remove larger pieces of debris and organic matter. The amount of microplastics from 2 – 4.75 mm was visually counted and recorded in the lab, and

Table 1. The region of the thirty-seven National Park Units sampled representing 35 National Parks. NPS unit abbreviation and geographical coordinates of sampling locations are listed.

Region	Park	Park Abbreviation	GPS Coordinates	
Alaska	Aniakchak National Monument & Preserve	ANIA	56.683414	-157.550116
	Bering Land Bridge National Preserve	BELA	66.250086	-166.066845
	Cape Krusenstern National Monument	CAKR	67.066850	-163.343233
	Glacier Bay National Park & Preserve	GLBA	58.450867	-135.896033
	Katmai National Park & Preserve	KATM	58.441700	-154.069883
	Kenai Fjords National Park	KEFJ	59.727750	-149.927440
	Klondike Gold Rush National Historical Park	KLGO	59.488794	-135.357424
	Lake Clark National Park & Preserve	LACL	59.979251	-152.660911
	Sitka National Historical Park	SITK	57.045080	-135.311040
	Wrangell St. Elias National Park & Preserve	WRST	59.703650	-140.254400
Midwest	Apostle Islands National Lakeshore	APIS	46.976567	-90.859550
	Grand Portage National Monument	GRPO	47.962994	-89.682527
	Indiana Dunes National Lakeshore	INDU	41.709698	-86.931226
	Isle Royale National Park	ISRO	47.890898	-89.001956
	Pictured Rocks National Lakeshore	PIRO	46.659787	-86.177646
	Sleeping Bear Dunes National Lakeshore	SLBE	44.945422	-85.818134
Northeast	Acadia National Park	ACAD	44.329099	-68.182790
	Assateague Island National Seashore	ASIS	38.276093	-75.118890
	Boston Harbor Islands National Recreation Area	BOHA	42.316913	-71.010492
	Cape Cod National Seashore	CACO	42.002410	-70.022130
	Fire Island National Seashore	FIIS	40.686275	-72.998518
	Gateway National Recreation Area (Jamaica Bay)	GATE JB	40.561040	-73.883454
	Gateway National Recreation Area (Sandy Hook)	GATE SH	40.471999	-73.997320
	Gateway National Recreation Area (Staten Island)	GATE SI	40.530900	-74.134800
West coast	Cabrillo National Monument	CABR	32.668950	-117.244700
	Channel Islands National Park	CHIS	34.063375	-120.374063
	Golden Gate National Recreation Area	GOGA	37.736000	-122.507350
	Lewis and Clark NHP	LEWI	46.094638	-123.941734
	Olympic National Park	OLMY	48.031784	-124.682087
	Point Reyes National Seashore	PORE	38.026642	-122.960722
	Redwood National Park	REDW	41.300311	-124.090360
	San Juan Island National Historical Park	SAJH	48.459110	-123.023660
	Santa Monica National Recreation Area	SAMO	34.041899	-118.570992
Pacific Islands	Haleakala National Park	HALE	20.757000	-155.983000
	Hawai'i Volcanoes National Park	HAVO	19.270124	-155.253971
	Kalaupapa National Historical Park	KALA	21.211460	-156.966130
	National Park of American Samoa	NPAS	-14.251240	-170.672320

was only seen at 6 sites (Assateague Island National Seashore, Boston Harbor Islands National Recreation Area, Gateway National Recreation Area at Sandy Hook, Santa Monica National Recreation Area, Kalaupapa National Historical Park, and the National Park of American Samoa)

(Table B2). Since the amount of microplastics seen in the 2 - 4.75 mm size range was minimal (less than 1 piece per sample on average), these items were not considered in the analysis. The sieved samples were stored in glass jars with metal lids until further analysis. Four dried sieved sand samples from each site were randomly selected for microplastic isolation by density separation (Thompson et al. 2004, Hidalgo-Ruz et al. 2012). Dried sand (200 g) was mixed with 250 ml of a filtered concentrated saline solution (NaCl 1.27 g/ml) in 500 ml glass canning jars. Filtration of the saline solution was necessary to remove microplastic contaminants from the salt. The glass jars were sealed with metal lids and shaken for 3 minutes. After at least 2 hours of settling, the supernatant was removed with a metal baster and filtered through a glass filtration system and a sterile gridded 0.45 um nitrocellulose filter (Millipore). Extreme care was taken to not contaminate the samples by keeping the filtration system covered and washing the transfer apparatus with deionized water multiple times. All washing solutions were filtered through the same glass-fiber filter to minimize any sample loss due to adhesion of microplastics on the wall of any part of the filter apparatus. The microplastic isolation was repeated 3 times for each sample to ensure recovery. Since organic material was not a problem in the sand samples, no further processing was necessary to remove it during the density separation. The particles were

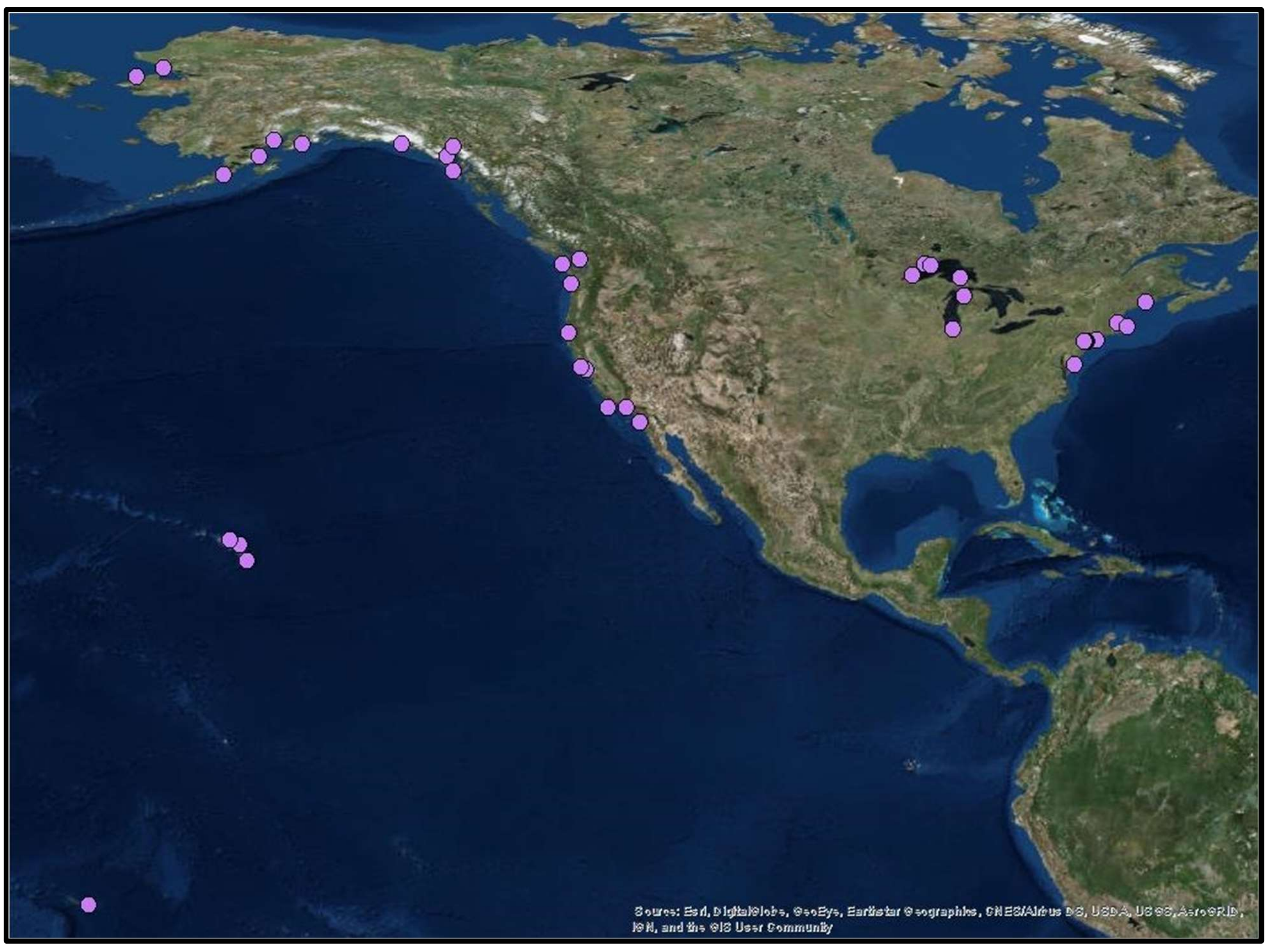

Figure 1. Geographic distribution of the thirty-seven NPS sites sampled for microplastics.

counted according to color and relative shape. For each NPS unit site, a blank consisting of the salt saline solution but with no sediment was run concurrently with the 4 samples to assess potential background contamination from the method or from the lab itself. These blanks had an average of 2 pieces (SD = 1.5) of microplastics.

To count and identify the shape of the microplastics, the filters were examined using an EMZ-5 Meiji Binocular Stereoscope (0.7X-4.5X binocular zoom stereo body, W.D. 93mm). The entire filter was scanned thoroughly. Large pieces of vegetative debris such as seaweed and dry leaves were picked out with tweezers. A total of 185 filters were analyzed (37 sites, four samples from each site, and a blank for each site) using pre-set criteria such as no visible organic structures and clear homogeneous colors (Hidalgo-Ruz et al. 2012). The abundance of microplastics in a sand sample was expressed as the number of pieces per kg dry sand.

2.3 Quantification of Urbanization Relative to Microplastic Distribution

To evaluate the potential relationship between urbanization and abundance of microplastics on coastal sites, total hectares of urban area within a 50-km diameter of each sampling site was quantified using Esri ArcMap 10.2 software (Esri Co. Ltd, USA). Land cover data were obtained from the National Oceanic and Atmospheric Administration’s Coastal Change Analysis Program (NOAA 2017). Hectares of urban area was determined by summing the hectares of high, medium and low intensity developed area as categorized by the land cover data.

2.4 Wastewater Treatment Plants

About 80% of debris is estimated to come from urban land-based sources (Andrady 2011). Since most of the microplastics humans generate through their daily routine (i.e., brushing teeth, washing face) or washing clothes (allowing fibers to enter the system) could pass through a wastewater treatment system (WWTS), the proximity of the sampling location to a WWTS might explain levels of microplastics found. Distance to wastewater treatment plants was measured using the ArcGIS distance tool in Esri ArcMap 10.2 software (Esri Co. Ltd, USA). The shortest distance via a water route between the sampling sites and the WWTS was recorded. Wastewater treatment plant locations were obtained from the Environmental Protection Agency’s Facility Registry Service (US EPA 2015).

2.5 Statistical Analysis

The summary statistics, graphs, and data analysis were generated using InfoStat statistical software, Version 2016 (Di Rienzo et al. 2016). Linear and non-linear regressions were preformed to determine if a there was a relationship between the mean abundance of microplastics at a site and hectares of urbanization, distance to the nearest river, and distance to WWTS. Only linear regressions are shown because non-linear regressions failed to improve statistical relationships. Statistical comparisons between regions or individual parks was not done because the sampling design did not include sufficient independent samples within parks or enough sites within regions for robust statistical analysis.

3. RESULTS

3.1 Sample Observations

Microplastics were found at all coastal sites but with variation between and within sites (Table 2; Figures 2, 3). Apostle Island National Lakeshore (WI), National Park of American Samoa (American Samoa) and Kalaupapa National Historical Park (HI) had the highest abundances of microplastics averaging between 170 and 225 pieces of microplastics per kg of sand. Sites with

Table 2: Mean microplastic loads (pieces/kg of sand), standard error, minimum, maximum, and median value for the NPS unit. Quartile rank is based on mean microplastic abundance relative to the other parks.

Region	NPS Unit	Mean count per kg sand	S.E.	Min	Max	Median	Quartile rank
Alaska	ANIA	51.3	10.5	20	65	`	0-25
	BELA	95.0	22.5	35	140	102.5	26-50
	CAKR	123.8	24.6	80	180	117.5	51-75
	GLBA	42.5	23.9	0	110	30	0-25
	KATM	128.8	36.1	75	235	102.5	51-75
	KEFJ	43.8	5.2	35	55	42.5	0-25
	KLGO	38.8	8.3	15	50	45	0-25
	LACL	40.0	12.1	20	75	32.5	0-25
	SITK	21.3	4.3	10	30	22.5	0-25
	WRST	97.5	25.3	55	155	90	26-50
Great Lakes	APIS	221.3	28.8	155	285	222.5	76-100
	GRPO	117.5	13.6	95	150	112.5	51-75
	INDU	152.5	7.8	130	165	157.5	76-100
	ISRO	88.8	8.0	65	100	95	26-50
	PIRO	65.0	5.4	55	80	62.5	26-50
	SLBE	156.3	29.9	105	235	142.5	76-100
Northeast	ACAD	126.3	43.2	30	235	120	76-100
	ASIS	112.5	15.1	80	145	112.5	51-75
	BOHA	100.0	6.5	85	115	100	51-75
	CACO	106.3	19.7	50	140	117.5	51-75
	FIIS	106.3	30.9	50	185	95	51-75
	GATE-JB	95.0	14.7	65	125	95	26-50
	GATE-SH	63.8	19.1	10	100	72.5	0-25
	GATE-SI	88.8	17.4	40	120	97.5	26-50
West Coast	CABR	38.8	7.2	30	60	32.5	0-25
	CHIS	56.3	10.5	35	85	52.5	0-25
	GOGA	140.0	24.8	100	210	125	76-100
	LEWI	87.5	17.0	60	130	80	26-50
	OLMY	115.0	29.0	40	180	120	51-75
	PORE	140.0	22.7	100	200	130	76-100
	REDW	98.8	14.8	70	140	92.5	51-75
	SAJH	67.5	18.3	40	120	55	26-50
	SAMO	80.0	15.1	40	110	85	26-50
Pacific Islands	HALE	131.3	18.3	100	170	127.5	76-100
	HAVO	98.8	27.7	20	150	112.5	51-75
	KALA	171.3	37.8	105	265	157.5	76-100
	NPAS	187.5	22.4	145	245	180	76-100

the lowest abundances included Sitka National Historical Park (AK), Cabrillo National Monument (CA), Lake Clark National Park and Preserve (AK), Klondike Gold Rush National Historical Park (AK) and Glacier Bay National Park and Preserve (AK), all of which had an average of less than 50 pieces per kg of sand. Samples from the other sites generally ranged from 50 to 125 pieces per kg of sand.

Fibers made up 97% of the microplastics counted, which is consistent with what other studies have found (e.g. Baldwin et al. 2016, Chow et al. 2016, Mathalon and Hill 2014, Stolte et al. 2015). Most of the fibers were translucent (47%) and blue (25%). While the majority of microplastic pieces were fibers, beads and fragments were also seen. Beads were observed at 6 sites: Boston Harbor Islands National Recreation Area (MA), Acadia National Park (ME), Cabrillo National Monument (CA), Haleakala National Park (HI), Indiana Dunes National Lakeshore (IN) and Gateway National Recreation Area at Jamaica Bay (NY, NJ). Boston Harbor National Recreation Area had an average of 5 beads per kg of sand and Haleakala National Park had an average of 2 beads per kg of sand. The other 4 parks only had an average of 1 bead per kg of sand. Beads were not encountered in the Alaska region. This does not mean that they are not present, just that the sampling did not capture them. Small plastic fragments (not beads or fibers) were seen at 15 of the parks scattered across the geographic distribution of NPS sites (Figure 4c). Most of them averaged less than 1 piece per kg of sand. Two sites had an average of 2 pieces per kg of sand: Indiana Dunes National Lakeshore and Kalaupapa National Historical Park (HI).

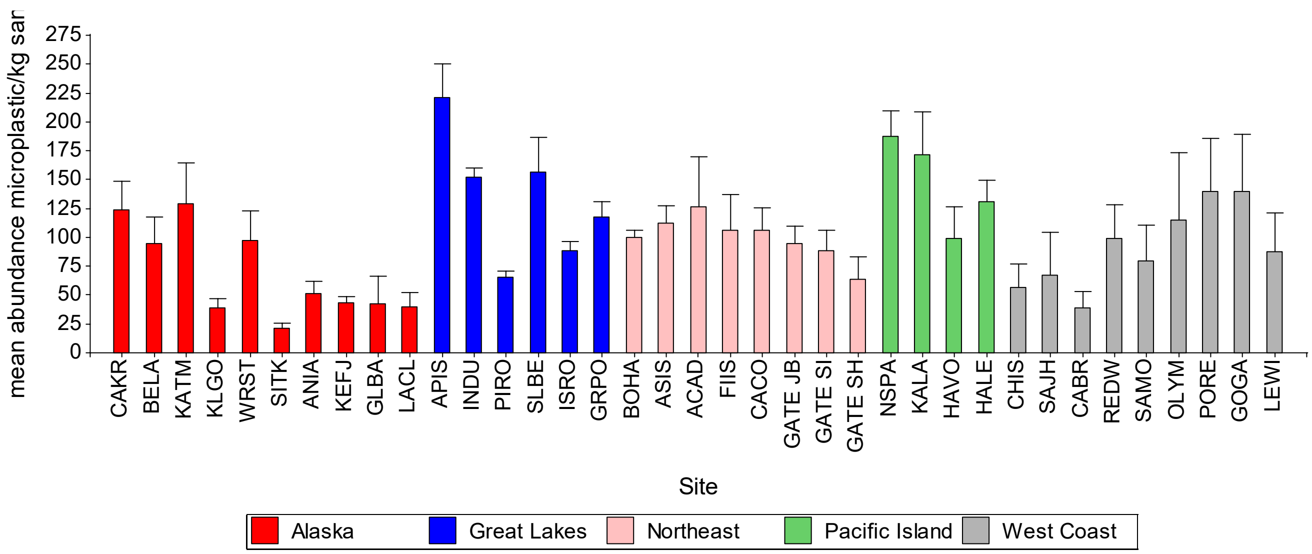

Figure 2: Mean abundance of microplastics per kg of sand for thirty-seven NPS units sampled during 2015 and 2016. Colors represent the region the park is located. Error bars represent standard error.

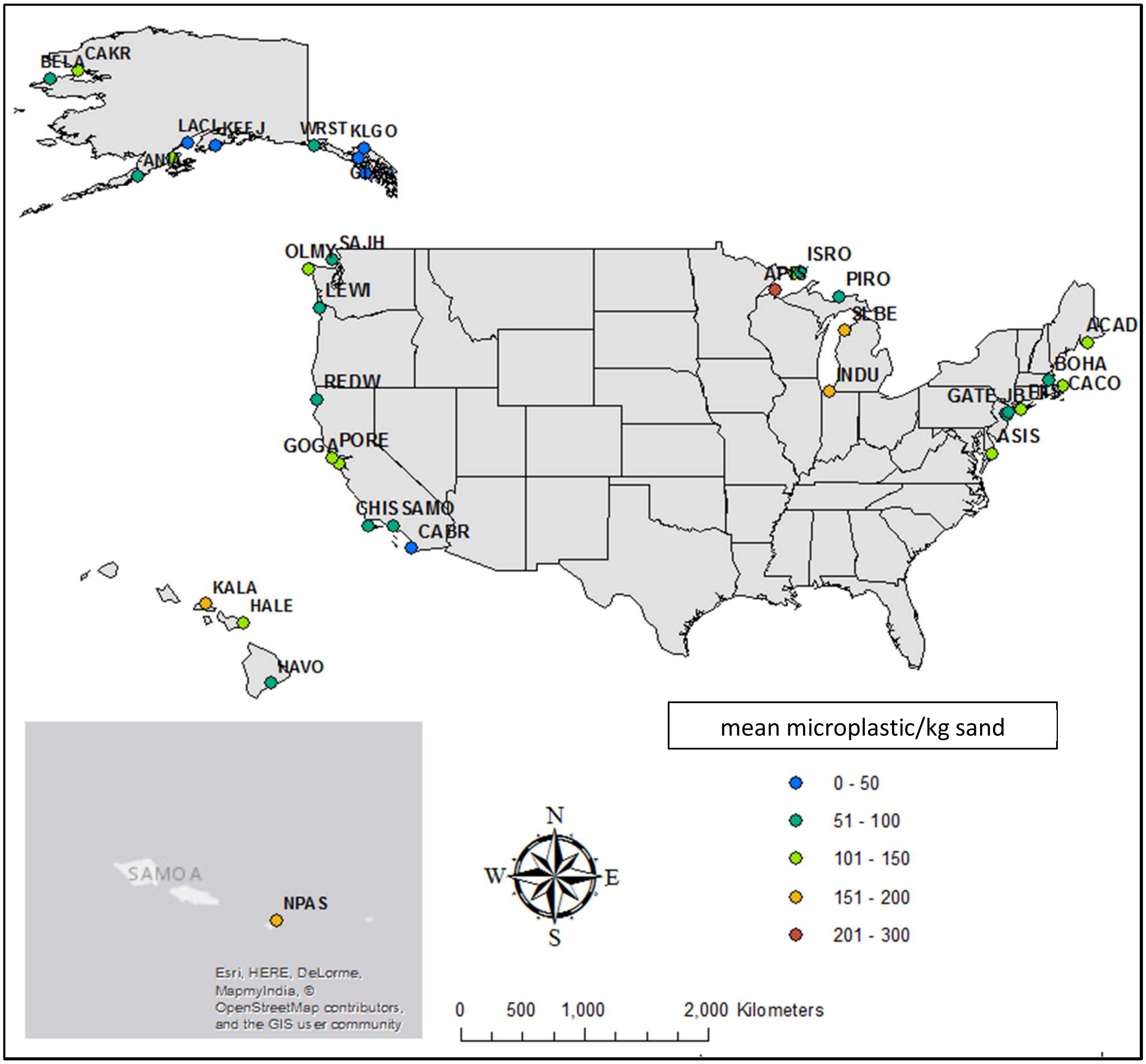

Figure 3: Geographic distribution of mean microplastic abundance for NPS units by bins of 50 pieces per kg of sand (by color).

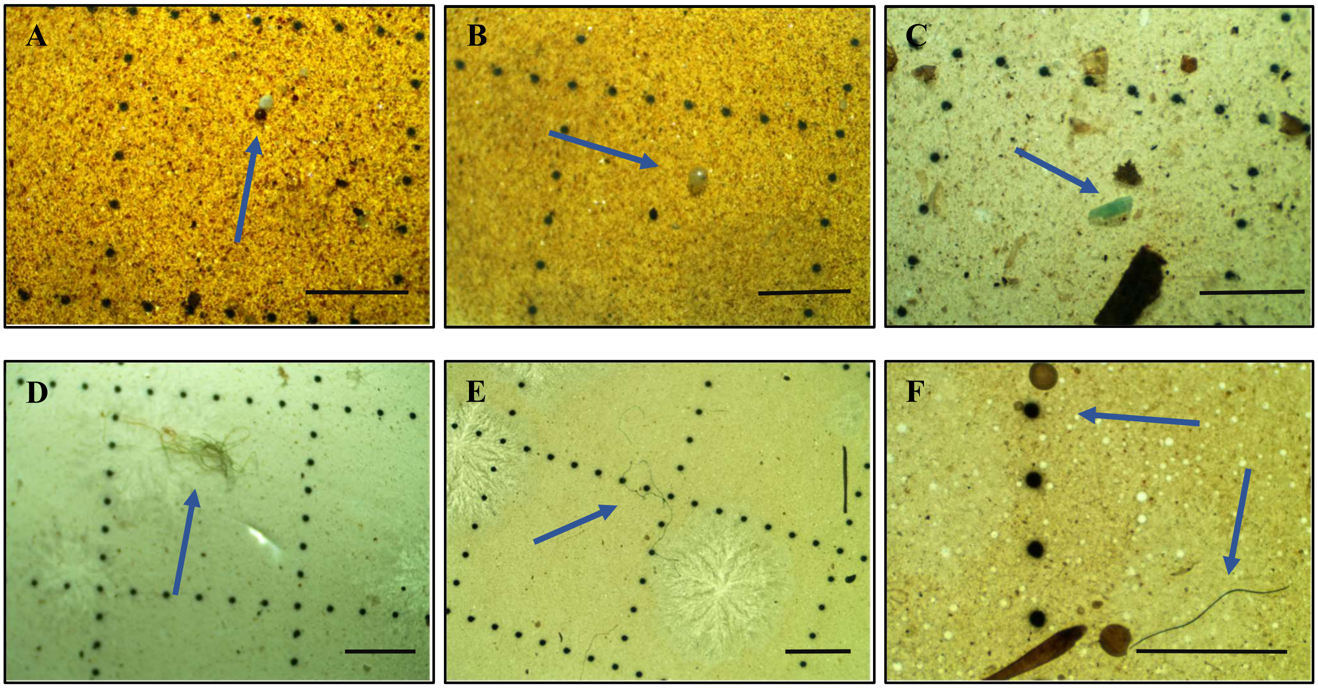

Figure 4: Examples of the types of microplastics seen during analysis of shoreline samples. A: Dark and light microbead; B: white microbead (HALE); C: blue plastic piece with organic material (KALE); D: tangle of fibers (NPAS); E: fibers; F: Fibers and beads (BOHA). The black dotted lines are the grid lines on the filter paper, the blue arrows point to the microplastics, and the black line at the bottom right of each frame equals 0.5 mm.

3.2 Environmental and Human Influences

Many studies state that plastic debris is highest closest to more urbanized areas (Barnes et al. 2005, Browne et al. 2015). It has also been stated that the majority of microplastics are the product of land-based human activity, with as much as 80% moving from land to ocean (Andrady 2011, Newman et al. 2015). This can come from mismanaged plastic waste (Jambeck et al. 2015) as well as wastewater treatment plants. We calculated the hectares of developed area around the sampling point to see if proximity to developed land correlated to the amount of microplastics on the beach. Unlike other studies (Chow et al. 2016), there was no relationship between developed area and number of microplastic particles seen (Figure 5). Indeed, many sites in the study are very remote and far from urban centers but still have over 100 pieces per kg of sand, especially in Alaska, along the northwest Pacific coastline, and the islands in the Pacific.

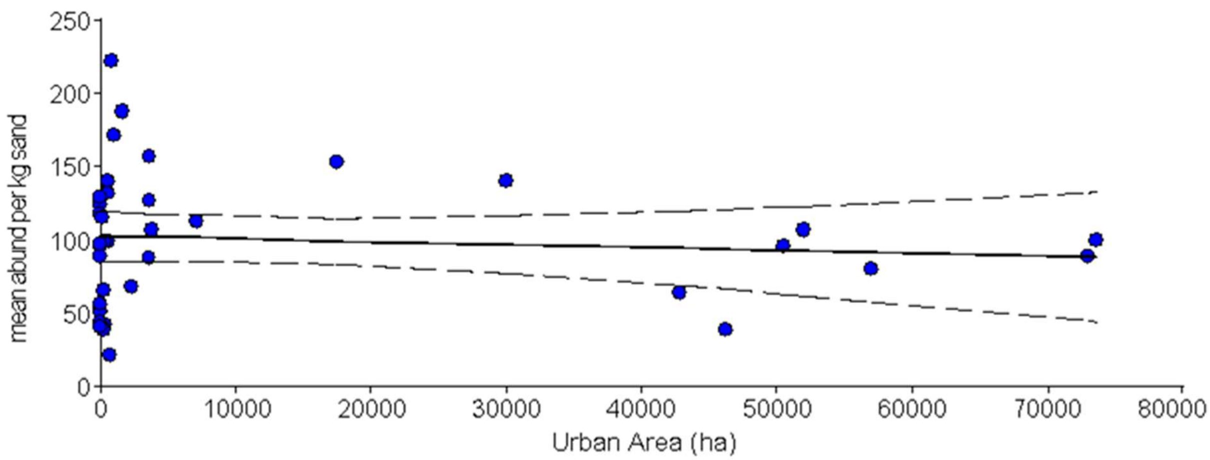

Figure 5: Linear regression of developed area (ha) in a 50km diameter buffer and mean abundance of microplastics per kg of sand (solid line) shows no relationship between urbanization and microplastic abundance (dashed line: 95% confidence interval).

Wastewater treatment plants (WWTP) process household and industrial waste in many areas of the US. While many systems also process storm runoff, they were designed to help remove solids and prevent them from entering downstream environments. They were not designed to remove small solids such as microplastics. There was no relationship between distance to the nearest WWTP and the sample study sites in this study (Figure 6).

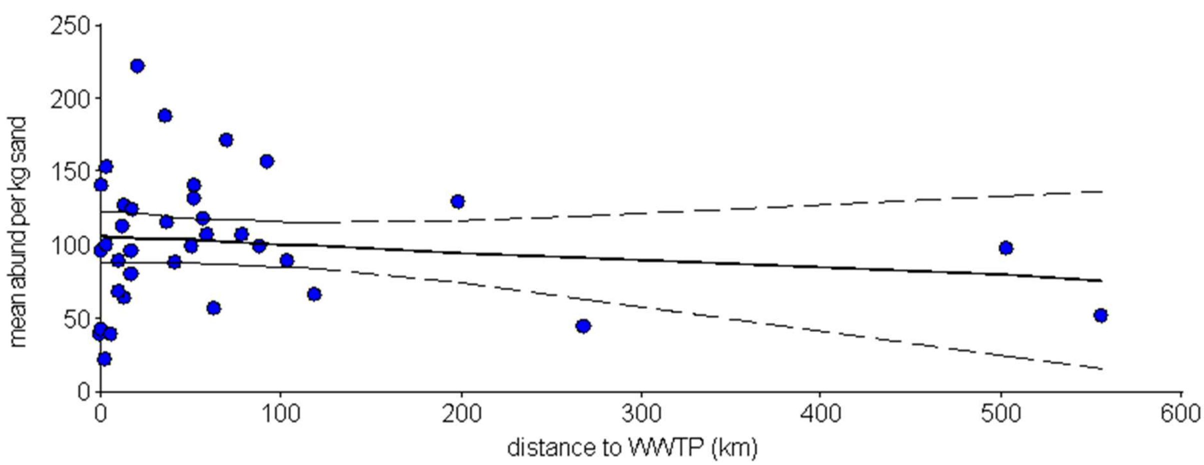

Figure 6: Linear regression of distance to the nearest waste water treatment plant (WWTP) in km and mean abundance of microplastics per kg of sand (solid line) shows no relationship between distance to WWTP and microplastic abundance (dashed line: 95% confidence interval)

Rivers also represent a potential source for microplastics. They drain both rural and urban areas, along with WWTP outflow. This material is taken downstream and released to estuaries and coastal systems, where the microplastics can be deposited on shorelines. Again, there was no relationship between the distance to the nearest upstream river and the amount of microplastics at a sampling location (Figure 7).

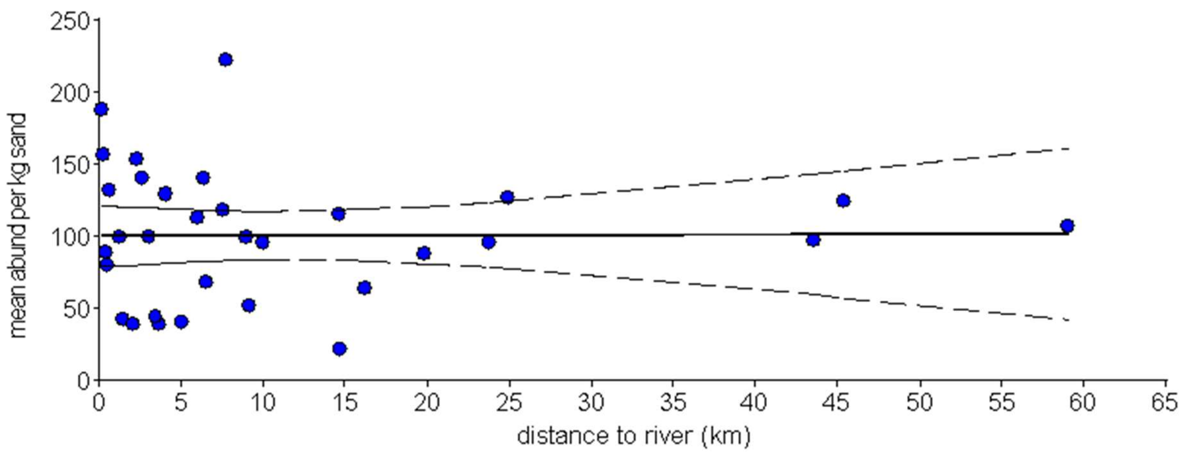

Figure 7: Linear regression of distance to the nearest river in km and mean abundance of microplastics per kg of sand (solid line) shows no relationship between (dashed line: 95% confidence interval).

4. DISCUSSION

Microplastics were found at all 37 NPS sampling sites, with loads varying about 10-fold among sites (Figure 2). The high variation among sites is not surprising due to the variety of factors that influence source and movement of debris and the heterogeneous and dynamic environment of beaches. Additionally, material is likely continually being taken from and re-deposited onto the coastline at all sites to varying degrees. Among-site variation has been shown to be high in large marine litter found along the coastline, both temporally and spatially (Browne et al. 2011, Browne et al. 2015). There is no reason to think that microplastics would be any different; however, local spatial and temporal patterns have not been examined much in the literature. This study was not intended to quantify within site variation, but to give a broad snapshot of what might be found on a typical day along US NPS coasts. This sampling scheme was developed to allow for a broad geographic view of the distribution of microplastics along US coastlines which will lead to a better understanding of the overall distribution of this debris and what factors may influence distribution. It is important to remember that sampling was targeted to beaches within each National park that were known to accumulate large marine debris.

Even though differences in methodologies make comparisons with other studies challenging, the microplastic quantities observed in this study did fall within the global range reviewed in Van Cauwenberghe et al. (2015; see also Stolte et al. 2015, Lusher 2015). This study found lower levels of microplastic loads than a study in the Southeast US, where some sites at the base of large rivers and samples from the Virgin Islands averaged over 300 pieces per kg of sand (Chow et al. 2016). Consistent with many studies, fibers were the most common microplastics (Claessens et al. 2011, Stolte et al. 2015). Every color of fiber was seen, but most of our fibers were translucent or blue. This was consistent with a study from Taiwan (Kunz et al. 2016) and the German Baltic (Stolte et al. 2015) but not with the SE US study, which saw predominately blue fibers and not many translucent ones (Chow et al. 2016). As fibers are exposed to oxidative stress from the sun, they tend to bleach out and disintegrate (Stolte et al. 2015, Andrady 2016). It is possible more fibers in this study were in the environment longer than those in the SE study. The chemical composition of the fibers was not determined; however, the density separation method used maximizes separation of microplastics from sand. Even if the fibers were not plastic (i.e. cotton or rayon), they could potentially pose threats to the environment (Remy et al. 2015).

4.1 Human influences

It is challenging to determine the source of anthropogenic microplastics. Studies state that as much as 80% of microplastics come from urban, land-based sources (Andrady 2011, Newman et al. 2014, Browne 2015, Yonkos et al. 2014). For the sites in this study, there was no relationship between microplastic load and the amount of urbanized area. This seems generally surprising based on known sources of microplastics. Even though many of the NPS sites are remote, some still have midrange counts of microplastics relative to other sites in this study (like Bering Land Bridge National Preserve in Alaska and Pictured Rocks National Lakeshore in Michigan). Other studies have failed to observe a relationship with urban development and microplastic loads. For example, in a study of tributaries in the Great Lakes region there was no relationship between microplastic loads and proximity of the sites to urban area (Baldwin et al. 2016). The large geographic area sampled here contains sites with so many different geographic influences that local factors may over-ride generally expected patterns, such as increased microplastic loads with amount of urban area. Factors such as local currents or whether sites are on islands may have a greater influence on the presence of microplastics than urbanization.

Since most areas had WWTPs that process household waste (and some process stormwater as well), they were hypothesized to be a potential source of microplastic particles to rivers, estuaries and eventually ocean environments (Browne et al. 2015), however, the distance to wastewater treatment plants did not help explain the microplastic loads on the beaches. In the last few years, more studies have analyzed WWTP outflow directly, with mixed results. In the Great Lakes and California, WWTP's direct contributions were low (Baldwin et al. 2016, Carr et al. 2016, Mason et al. 2016) all averaging between 0.5 and 1.4 microplastic pieces per liter of outflow. Interestingly, these studies reached different conclusions on the microplastic contributions WWTP make. Carr et al. (2016) concluded that WWTPs were very effective at removing microplastic contaminants while Mason et al. (2016) suggested that they were responsible for an average of 13 billion microplastic particles being released into downstream systems every day. In New Jersey, WWTPs were a source for primary microplastics, but not the only source since background sites also had microplastics (Estahbanati and Fahrenfeld 2016). This suggests that other sources, like runoff, were important as well. While most parks studied were within 75 km of a WWTP (Figure 6), their locations were still fairly remote and the communities they serve were generally smaller as shown by the low amount of urban area nearby (Figure 5).

The issue of WWTP contribution to microplastic pollution is complicated and can vary from site to site depending on the age of facility, the stages of processing used, and the size of filters used at each location. While WWTPs seem to be effective at removing microplastic particles, some still pass through. Where sludge from WWTP settling tanks is applied to agricultural fields, it could subsequently contribute to microplastic pollution during overland flow and runoff (Mahon et al. 2017), creating another level of complexity to understanding microplastic sources. Like WWTP, septic tanks collect household waste. In rural areas, which are often far from WWTP, septic tanks are more common. Release of microplastics from septic systems could be significant in times of high runoff or flooding events and deserves more research.

Distance to the nearest upstream river was analyzed because rivers carry microplastics (Rech et al. 2014) from overland flow, discharge from WWTP, or from septic tanks during flooding. While high levels of microplastics have been seen in rivers and estuary systems (Mathalon and Hill 2014, Moore et al. 2011, Baldwin et al. 2016, Ballent et al. 2016), no relationship between the distance to the nearest river and microplastic load was found for the NPS sites (Figure 7). These findings were not surprising since there was a broad range of sites with many potential contributing factors, such as differences in location of sampling site (bay side versus directly on the ocean), river flow rates, shape of the sample-location estuary or shoreline that might influence accumulation or export of materials, ocean currents, WWTP processing, etc.

4.2 Local influences of Microplastics

Microplastic loads on shorelines come from either land-based sources such as rivers and wastewater treatment plants, or from the degradation of larger plastic pieces in the open ocean landing on the shore. Many studies have examined the amount of microplastics floating in the ocean, with amounts estimated from 93,000-236,000 metric tons, with most plastic being concentrated in the subtropical gyres (van Sebille et al. 2015). While models differed on the total amount of microplastics (Cozar et al. 2014), they all found the largest mass in the North Pacific Ocean while the North Atlantic had between 7-10% of what was found in the North Pacific (van Sebille et al. 2015, Kanhai et al. 2017). This difference was attributed to the amount of mismanaged waste estimated to enter coastal waters from Asia (Jambeck et al. 2015).

Storms often intensify the action of currents, waves, and tides and increase outflow from rivers (Yonkos et al. 2015). They bring increased winds and wave action that result in erosion and/or deposition of beach material – including microplastic particles. This study did not examine the impact of storms on the abundance of microplastics on beaches, but 14 of the 37 sites sampled reported a storm sometime during the two weeks prior to the sample being taken. The beaches with storms were distributed across the geographic range. Of the 14 sites with storms, 3 of sites had high levels of microplastics (Apostle Islands National Lakeshore (WI), Indiana Dunes National Lakeshore (IN), Haleakala National Park (HI)) while 3 sites had some of the lowest levels of microplastics (Cabrillo National Monument (CA), Kenai Fjords National Park (AK), and Gateway National Recreation Area at Sandy Hook (NY, NJ)). While storms might influence the amount of microplastics found, repeated sampling at various sites after a series of storms would be needed to understand this question.

Table 3: Sites with storms reported in the two weeks prior to sampling listed in order of increasing mean microplastic abundance within each region.

Region	NPS Unit	Mean count per kg sand	Quartile rank
Alaska	KEFJ	43.8	0-25
Great Lakes	PIRO	65.0	26-50
	ISRO	88.8	26-50
	GRPO	117.5	51-75
	INDU	152.5	76-100
	APIS	221.3	76-100
Northeast	GATE-SH	63.8	0-25
	GATE-JB	95.0	26-50
	FIIS	106.3	51-75
West Coast	CABR	38.8	0-25
	REDW	98.8	51-75
Pacific Islands	HAVO	98.8	51-75
	HALE	131.3	76-100

Pacific Islands
Hawaii is located at the convergence zone in the middle of the North Pacific Ocean (NOAA 2017) and close to the Pacific gyres where both wind and currents in the area will push floating microplastics to shore. Indeed, some of the highest microplastic loads were found in the Hawaiian Islands. Both Kalaupapa National Historical Park, located on the island of Molokai, and Haleakala National Park, located on the island of Maui, receive direct winds from the east (Xie et al. 2001), which could bring floating microplastics from these gyres onshore. In addition, there was a drain pipe that empties onto the beach within sight of the sampling location at Haleakala National Park (Personal Communication, 2015 J. Herbaugh, Park Ranger). This could carry more land-based material to the beach. The subtropical countercurrent that runs from the western Pacific toward Hawaii (Xie et al. 2001) could carry debris directly from the Asian coast. Hawai'i Volcanoes National Park had the lowest microplastic load of the three Hawaiian sites (but still in the top half of all sites in this study). Its location on the leeward (south) side of the island of Hawaii reduces onshore winds and places it near a current that pushes water away from shore (Xie et al. 2001), potentially reducing the microplastic load at that site.

National Park of American Samoa is the only US National park in the Southern hemisphere, located on the island of Tutuila. Tutuila has very steep slopes and very little flat coastal area (only 26 km^2) for 66,900 people and tourists. Winds are typically light, except during storms, but rain can be heavy. The steep slopes and increasing pressure from a growing population combined with heavy rains resulted in runoff into the bays and coral reefs surrounding the island (Fenner et al. 2008). They reported that the average sedimentation rate was 12.1 $g/cm^2/day$ into the bays. This input could be carrying microplastics from failed septic systems and other household or industrial discharge. Most marine debris on the island was from land based anthropogenic sources and not the ocean (Fenner et al. 2008). Thus, it is likely that most of the microplastic load we found at this site was from land and not the open ocean.

West Coast
Farther to the east in the Pacific, toward the US West Coast, there was less microplastic debris along the coastal areas (Law et al. 2014). The California Current moves south and offshore along the coast and is dominated by upwelling of deep ocean water (Personal Communication, A. MacFadyen, Physical Oceanographer, 6 March 2017). It was not surprising that the microplastic load found along the west coast was in the midlevel range in this study (Table 2, Figure 3) as ocean dynamics would counteract land-based sources. Sites that did have moderate to high levels of microplastics were probably receiving it from land-based sources. For example, Golden Gate National Recreation Area, which had one of the highest microplastic loads in the region, likely got most of it from the San Francisco Bay area, which is densely populated and drains much of the agricultural area of California. Olympic National Park, which had similar levels of microplastics as Golden Gate National Recreation Area, could get contributions from both the ocean and from the Strait of Juan de Fuca, which is downstream of Seattle, Washington. Olympic National Park is at the northern end of the California current, potentially allowing more contributions from the ocean to reach the shoreline before upwelling carries it away.

Alaska
In general, Alaska had very low microplastic loads, even though the sites were known to receive large marine debris. For most of Alaska, previous modeling work found very little plastic in

coastal waters (Law et al. 2014). Law et al. (2014) predicted there could be about 10,000 plastic pieces per km^2 in the Bering Strait and around Cook Inlet, which is near both Katmai National Park & Preserve and Aniakchak National Monument & Preserve. It is possible that some of this oceanic microplastic made it to Katmai National Park & Preserve beach. The predicted levels in the Bering Strait, which flows up to Bering Land Bridge National Preserve and Cape Krusenstern National Monument, could have also carried some to those shorelines as well. Both of these sites had moderate levels of microplastic counts (Table 2, Figure 3).

Atlantic Ocean

While the Atlantic Ocean reportedly had fewer floating microplastics (Law et al. 2010, van Sebille et al. 2015, Kanhai et al. 2017), it could still serve as a source for microplastics found on the East Coast. The Gulf Stream is the predominant current; however, it turns offshore around the Virginia–North Carolina state line (Rowe et al. 2017). The currents to the northwest of the Gulf Stream are less obvious but generally appear to head away from the coast (Gyory et al. 2017). This would tend to push microplastics away from the shoreline unless a prevailing wind carried it ashore. The coastal sites with high levels of microplastic loads were in estuary systems, such as Acadia National Park (ME) and Boston Harbor Islands National Recreation Area (MA). Surprisingly, the Gateway National Recreation Area parks (NY, NJ) were not as high given their proximity to New York City and locations within the Hudson River estuary.

Great Lakes

The Great Lakes had relatively high levels of microplastics in surface waters (Eriksen et al. 2013) as well as its tributaries (Baldwin et al. 2016, Ballent et al. 2016), but surface water microplastic abundance was variable. Lake Superior had as much as 12,645 pieces per km^2 (Eriksen et al. 2013). The lake has long turnover rates, which could allow microplastics to remain for long periods. The NPS sites in Lake Superior had some of the highest microplastic loads in the entire study (such as Apostle Islands National Lakeshore; Table 2). Most microplastics entered the Great Lakes via its tributaries (Baldwin et al. 2017, Ballent et al. 2016). This would explain the high counts at Apostle Islands National Lakeshore, which is located near the mouth of the St. Louis River. This river runs through Duluth, MN, and is the largest tributary of the lake with a 3,584-square-mile watershed. Strong currents that move from Duluth eastward toward the Apostle Islands, along with complicated wave action around the islands (Bai et al. 2013, Beletskey et al. 1999), would increase the probability of elevated microplastic loads. Pictured Rocks, a park at the other end of Lake Superior, had one of the lowest levels of microplastics in the Great Lakes. This park had very little developed land nearby and all the watersheds for this park flow south into Lake Michigan. Thus, most of the microplastic load here was probably transported from other areas of Lake Superior, but this transport was likely limited by being on the lee side of the Keweenaw Peninsula that sticks out into the lake between Apostle Islands National Lakeshore and Pictured Rocks National Lakeshore (Bai et al. 2013).

There are strong currents and long residence times for the waters of Lake Michigan as well. At the south end of the lake there is a strong counterclockwise coastal current that travels from Wisconsin to Muskegon, MI creating a rotating gyre in the southern basin of Lake Michigan that traps chlorophyll a (Kerfoot et al. 2008). This water movement could also trap microplastics in the southern basin of the lake, increasing the opportunities for the microplastics to be blown to the shores of parks on the east side of Lake Michigan such as Indiana Dunes (Bai et al. 2013).

The Great Lakes region was likely influenced by run-off as well. Neither our study nor Baldwin et al (2016) found relationships between the counts of microplastics and urban area or WWTP contribution. Baldwin et al. suggested that overland flow was a likely culprit of the levels of microplastic in tributaries. Sewage sludge that traps most of the microplastics from household waste is often applied to agricultural fields. Thus, during precipitation events, microplastics in applied sludge can run-off to downstream environments. The agriculturally-dominated landscape around the lakes increases the opportunity for this to be a microplastic source. Since much of the area is undeveloped, septic tank overflow during times of high flow events could also contribute.

Potential Threats

Plastic is known to absorb environmental contaminants, such as PCBs, and potentially transport them to other locations. It has been shown that both persistent organic pollutants and heavy metals adsorb to plastic (Brennecke et al. 2016). Microplastics have a large surface area relative to their overall size, allowing them to carry a greater amount of contaminant. Their small size allows smaller organisms to ingest them, increasing their risk of exposure as well as facilitating bioaccumulation in organisms higher in the food chain (Setala et al. 2014, Avio et al. 2015). Some of the threats to organisms exposed to microplastics with contaminants are blockages and abrasions of the digestive tract, satiation, and eventual starvation due to consumption of non-prey items, which can lead to reduced reproductive fitness and predator avoidance (Wright et al. 2013, Avio et al. 2015). Browne et al. (2013) found that plastic and contaminants harm the physiological functions of marine sedimentary organisms. They saw the desorption of contaminants directly from the plastic in the gut, as well as from sand. This could lead to not only organismal level effects but population level effects and changes in ecosystem dynamics.

More recently Koelmans et al. (2016) tested the hypothesis that microplastics would transfer hydrophobic organic chemicals to marine animals. They found that while there was some transfer to animals, the plastizers in the plastic were more harmful than the organic chemicals bound to the plastics. They also found that the fraction of contaminant in the plastic was small compared to the nearby water or sediment. While they demonstrated that contaminants desorbed from microplastic in the presence of gut fluid, they concluded that microplastic ingestion was not likely to increase exposure because the surrounding environment had a higher concentration of contaminants than the microplastics (Kolemans et al. 2016). Understanding how wildlife and humans will be impacted by microplastic ingestion is a priority but was not examined in this study.

4.3 Summary

The presence of microplastics in the marine environment poses risks to wildlife and human health. Not only is ingestion of plastic itself a concern, the potential contamination enhances that risk. These 35 units of the National Park System located on the Atlantic and Pacific oceans and Great Lakes include diverse coastal environments to evaluate factors affecting the distribution of microplastics. Microplastic contamination was widespread and found at even the remotest areas, which is not completely surprising given their global distribution (e.g., Thompson 2015). Microplastic loads among National parks were quite variable, with the highest loads recorded in individual parks in the Great Lakes and the Pacific Islands. Many sites in the study were far from urban centers but still had over 100 pieces per kg of sand, especially in Alaska, along the northwest Pacific coastline, and the islands in the Pacific. However, no clear relationship to geographical features was apparent. This was not completely unexpected given the broad geographic sampling scale and the numerous local factors that could influence microplastic abundance along these shorelines. Understanding the spatial and temporal movement and residence time of microplastics in beach environments will clarify the risk to wildlife in the future.

This study provides a broad geographic assessment of the distribution and abundance of microplastics on NPS beaches and provides an opportunity to make general inferences about sources. Because of this diverse geography and oceanography, the coastal parks have served an important role in advancing landscape and seascape-scale research on many issues affecting stewardship of public lands and waters. NPS scientists and managers will use this study in concert with other research to evaluate patterns of microplastic loadings in parks and regions where parks are located. This information will guide further investigations with partner agencies and academic institutions. In addition, NPS will communicate the results of this project to the public to expand understanding of microplastic's contribution to marine debris, and marine debris issues in the coastal environment in general.

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LITERATURE CITED

Andrady, A.L. 2011. Microplastics in the marine environment. Marine Pollution Bulletin 62 (8): 1596-1605.

Andrady, A.L. 2016. Persistence of plastic pollution in the oceans. In M. Bergmann, L. Gutow & M. Klages (Eds.), *Marine anthropogenic litter*. Springer, Berlin. pp 57-74.

ArcMap. 10.2. July 2013. Esri Co. Ltd., USA.

Avio, C.G., Gorbi, S., Milan, M., Benedetti, M., Fattorini, D., d'Errico, G., Pauletto, M., Bargelloni, L., and Regoli, F. Pollutants bioavailability and toxicological risk from microplastics to marine mussels. Environmental Pollution 198: 211-222.

Avio, C.G., Gorbi, S., and Regoli, F. 2016. Plastics and microplastics in the oceans: From emerging pollutants to emerged threat. Marine Environmental Research http://dx.doi.org/10.1016/j.marenvres.2016.05.012

Bai, X., Wang, J., Schwab, D.J., Yang, Y., Luo, L., Leshkevich, G.A., and Liu, S. 2013. Modeling 1993-2008 climatology of seasonal general circulation and thermal structure in the Great Lakes using FVCOM. Ocean Modelling 65: 40-63.

Baldwin, A.K., Corsi, S.R., and Mason, S.A. 2016. Plastic Debris in 29 Great Lakes tributaries: relations to watershed attributes and hydrology. Environmental Science and Technology 50(19): 10377-10385. DOI: 10.1021/acs.est.6b02917.

Ballent, A., Corcoran, P.L., Madden, O., Helm, P.A., and Longstaffe, F.J. 2016. Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. Marine Pollution Bulletin 110: 383-395.

Barnes, D.K.A. 2005. Remote islands reveal rapid rise of southern hemisphere marine debris. The Scientific World Journal 5: 915-921.

Beletsky, D., Saylor, J.H., and Schwab, D.J. 1999. Mean circulation in the Great Lakes. J. Great Lakes Research 25(1): 78-93.

Besseling, E., Wegner, A., Foekema, E.M., van den Heuvel-Greve, M.J., and Koelmans, A.A. 2013. Effects of Microplastic on Fitness and PCB Bioaccumulation by the Lugworm *Arenicola marina* (L.). Environmental Science and Technology 47(1): 593-600.

Brennecke, D., Duarte, B., Paiva, F., and Cacador, I. 2016. Microplastics as a vector for heavy metal contamination from marine environments. Estuarine, Coastal, and Shelf Science 178: 189-195.

Browne, M.A.; Chapman, M.G.; Thompson, R.C.; Zettler, L.A.A., Jambeck, J. and Mallos, N.J. 2015. Spatial and temporal patterns of stranded intertidal marine debris: Is there a picture of global change? Environmental Science and Technology 49: 7082-7094.

Browne, M.A. 2015. Sources and pathways of microplastics to habitats. In M. Bergmann, L. Gutow & M. Klages (Eds.), *Marine anthropogenic litter*. Springer, Berlin. pp. 245–312.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., and Thompson, R. 2011. Accumulation of Microplastic on Shorelines Worldwide: Sources and Sinks. Environmental Science and Technology 45(21): 9175-9179.

Browne, M.A., Galloway, T.S., and Thompson, R.C. 2010. Spatial Patterns of Plastic Debris along Estuarine Shorelines. Environmental Science and Technolology 44(9): 3404-3409.

Browne, M.A., Niven, S.J., Galloway, T.S., Rowland, S.J., and Thompson, R.C. 2013. Microplastic Moves Pollutants and Additives to Worms, Reducing Functions Linked to Health and Biodiversity. Current Biology 23(23): 2388-2392.

Carr, S.A., Liu, J., and Tesoro, A.G. 2016. Transport and fate of microplastic particles in wastewater treatment plants. Water Research91: 174-182.

Chow, A., Whitmire, S. Yu, X., Tolin, C.A., Ladewig, S., and Bao, S. 2016. Occurrence and distribution of microplastics from coastal national park units of the southeastern United States. Final Report (with two supplements).
Chua, E.M., Shimeta, J., Nugegoda, D., Morrison, P. D., and Clarke, B.O. 2014. Assimilation of Polybrominated Diphenyl Ethers from Microplastics by the Marine Amphipod, *Allorchestes Compressa*. Environmental Science and Technology 48(14): 8127-8134.
Claessens, M., De Meester, S., Van Landuyt, L., De Clerck, K., and Janssen, C.R. 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Marine Pollution Bulletin 62(10): 2199-2204.
Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., and Galloway, T.S. 2013. Microplastic Ingestion by Zooplankton. Environmental Science and Technology 47(12): 6646-6655.
Cozar, A., Echevarria, F., Gonzalez-Gordillo, J.I., Irigoien, X., Ubeda, B., Hernandez-Leon, S., Palma, A.T., Navarro, S., Garcia-de-Lomas, J., Ruiz, A., Fernandez-de-Puelles, M.L., and Duarte, C.M. 2014. Plastic debris in the open ocean. Proceedings of the National Academy of Science 111(28): 10239-10244.
Critchell, K. and Lambrechts, J. 2016. Modelling accumulation of marine plastics in the coastal zone; what are the dominant physical properties? Estuarine, Coastal and Shelf Science 171: 111-122.
Derraik, J.G.B. 2002. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 44(9): 842-852.
Di Rienzo J.A., Casanoves F., Balzarini M.G., Gonzalez L., Tablada M., and Robledo C.W. InfoStat versión 2016. InfoStat Group, Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba, Argentina. URL http://www.infostat.com.ar
Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., Farley, H. and Amato, S. 2013. Microplastic pollution in the surface waters of the Leurentian Great Lakes. Marine Pollution Bulletin. http://dx.doi.org/10.1016/j.marpolbul.2013.10.007.
Estahbanati, S. and Fahrenfeld, N.L. 2016. Influence of wastewater treatment plant discharge on microplastic concentrations in surface waters. Chemosphere 162: 277-284.
Farrell, P. and Nelson, K. 2013. Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus meanas* (L.). Environmental Pollution 177: 1-3.
Fenner, D., Speicher, M. and Gulick, S. 2008. The State of Coral Reef Ecosystems of American Samoa. pp. 307-351. In: The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. J.E. Waddell and A.M. Clarke (eds.) NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569 pp.
Gall SC, Thompson RC. 2015. The impact of debris on marine life. Marine Pollution Bulletin 92(1-2):170-179. http://dx.doi.org/10.1016/j.marpolbul.2014.12.041
Gyory, J., Mariano, A.J., and Ryan, E.H. 2017. "The Gulf Stream". Ocean Surface Currents. http://oceancurrents.rsmas.miami.edu/atlantic/gulf-stream.html.
Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., and Thiel, M. 2012. Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. Environmental Science and Technology. 46(6): 3060-3075.
Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., and Law, K.L. 2015. Plastic waste inputs from land into the ocean. Science 347(6223): 768-771.

Kanhai, L.D.K., Officer, R., Lyashevska, O., Thompson, R.C., and O'Connor, I. 2017. Microplastic abundance, distribution and composition along a latitudinal gradient in the Atlantic Ocean. Marine Pollution Bulletin 115: 307-314.

Kerfoot, W.C., Budd, J.W., Green, S.A., Cotner, J.B., Biddanda, B.A., Schwab, D.J., and Vanderploeg, H.A. 2008. Doughnut in the dessert: Late-winter production pulse in southern Lake Michigan. Limnology and Oceanography 53(2):589-604.

Koelmans, A.A., Bakir, A., Burton, G.A. and Janssen, C.R. 2016. Microplastic as a vector for chemicals in the aquatic environment: Critical review and model-supported reinterpretation of empirical studies. Environmental Science and Technology 50: 3315-3326.

Koelmans, A.A., Besseling, E., Wegner, A. and Foekema, E.M. 2013. Plastic as a carrier of POPs to aquatic organisms: A model analysis. Environmental Science & Technology 47(14): 7812-7820.

Kunz, A., Walther, B.A., Lowemark, L., and Lee, Y. 2016. Distribution and quantity of microplastic on sandy beaches along the northern coast of Taiwan. Marine Pollution Bulletin 111 (1-2): 126-135.

Law, K.L., Moret-Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., and Reddy, C.M. 2010. Plastic Accumulation in the North Atlantic Subtropical Gyre. Science 329(5996): 1185-1188.

Law, K.L., Moret-Ferguson, S., Goodwin, D.S., Zettler, E.R., DeForce, E., Kukulka, T. and Proskurowski, G. 2014. Distribution of surface plastic debris in the Eastern Pacific Ocean from an 11-year data set. Environmental Science and Technology 48: 4732-4738.

Lusher, A. (2015). Microplastics in the marine environment: Distribution, interactions and effects. In M. Bergmann, L. Gutow & M. Klages (Eds.), *Marine anthropogenic litter*. Springer, Berlin. pp. 245–312

Mahon, A.M., O'Connell, B., Healy, M.G., O'Conner, I., Officer, R., Nash, R., and Morrison, L. 2017. Microplastic in sewage sludge: Effects of Treatment. Environmental Science and Technology 51(2): 810-818.

Mason, S.A., Garneau, D., Sutton, R., Chu, Y., Ehmann, K., Barnes, J., Fink, P., Papazissimos, D. and Rogers, D.L. 2016. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Environmental Pollution 218: 1045-1054.

Mathalon, A. and Hill, P. 2014. Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. Marine Pollution Bulletin 81(1): 69-79.

Moore, C.J., Lattin, G.L., Zellers, A.F. 2011. Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. J. Integrated Coastal Zone Management. 11(1): 65-73.

Newman, S., Watkins, E., Farmer, A., Brink, P., and Schweitzer, JP. (2015). The economics of marine litter. In M. Bergmann, L. Gutow & M. Klages (Eds.), *Marine anthropogenic litter*. Springer, Berlin. pp. 367–394.

NOAA office of Coastal Management. 2017. 2010 and 2012 C-Cap data. Retrieved from NOAA's web site: https://coast.noaa.gov/dataregistry/search/collection/info/ccaphighres.

Rech, S., Macaya-Caquilpan, V., Pantoja, J.F., Rivadeneira, M.M., Madariaga, D.J., and Thiel, M. 2014. Rivers as a source of marine litter - A study from the SE Pacific. Marine Pollution Bulletin 82 (1-2): 66-75.

Remy, F. Collard, F., Gilbert, B., Compere, P., Eppe, G. and Lepoint, G. 2015. When microplastic is not plastic: The ingestion of artificial cellulose fibers by macrofauna living in seagrass macrophytodetritus. Environmental Science and Technology 49: 11158-11166.

Rochman, C.M., Kurobe, T., Flores, I., and Teh, S.J. 2014. Early warning signs of endocrine disruption in adult fish from the ingestion of polyethylene with and without sorbed chemical pollutants from the marine environment. Science of the Total Environment 493: 656-661.

Rowe, E., Mariano, A.J., and Ryan, E.H. "The North Atlantic Current." Ocean Surface Currents. (2017).

Setala, O., Fleming-Lehtinen, V. and Lehtiniemi, M. 2014. Ingestion and transfer of microplastics in the planktonic food web. Environmental Pollution 185; 77-83.

Stolte, A., Forster, S., Gerdts G., and Schubert, H. Microplastic concentrations in beach sediments along the German Baltic coast. 2015. Marine Pollution Bulletin. http://dx.doi.org/10.1016/j.marpolbul.2015.07.022.

Thompson, R. C. (2015). Microplastics in the marine environment: Sources, consequences and solutions. In M. Bergmann, L. Gutow & M. Klages (Eds.), *Marine anthropogenic litter*. Springer, Berlin. pp 185-200.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D.; and Russell, A.E. 2004. Lost at sea: Where is all the plastic? Science 304(5672): 838-838.

US Environmental Protection Agency. 2015. EPA Facility Registry Service (FRS): ER_WWTP_NPDES [metadata download]. Retrieved from https://catalog.data.gov/dataset/epa-facility-registry-service-frs-er-wwtp-npdes.

Van Cauwenberghe, L., Devriese, L., Galgani.F., Robbens, J. and Janssen, C.R. Microplastics in sediments: A review of techniques, occurrence, and effects. Marine Environmental Research, 111: 5-17.

van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B.D., van Franeker, J.A., Eriksen, M., Siegel, D., Galgani, F. and Law, K.L. 2015. A global inventory of small floating plastic debris. Environmental Research Letters 10. doi: 10.1088/1748-9326/10/12/124006

Wright, S.L., Rowe, D., Thompson, R.C., and Galloway, T.S. 2013. Microplastic ingestion decreases energy reserves in marine worms. Current Biology 23(23): R1031-R1033.

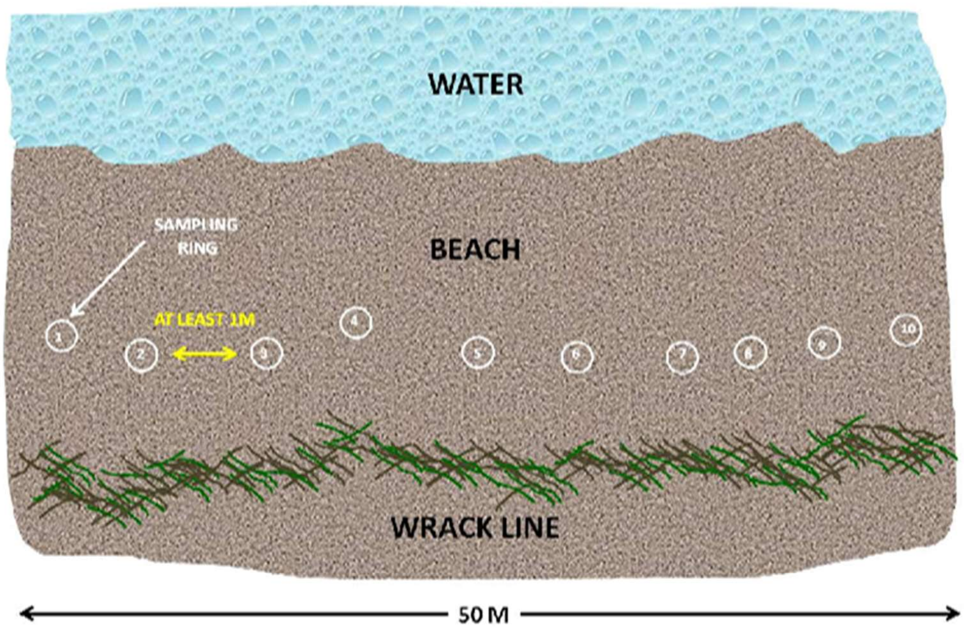
Wright, S.L., Thompson, R.C., and Galloway, T.S. 2013. The physical impacts of microplastics on marine organisms: A review. Environmental Pollution 178: 483-492.

Xie, S.P., Liu, W.T., Liu, Q. and Nonaka, M. 2001. Far-reaching effects of the Hawaiian Islands on the Pacific Ocean-Atmosphere System. *Science*. 292(5524):2057-2060.

Yonkos, L.T., Friedel, E.A., Perez-Reyes, A.C., Ghosal, S., and Arthur. C.D. 2014. Microplastics in Four Estuarine Rivers in the Chesapeake Bay, U.S.A. Environmental Science and Technology 48(24): 14195-14202.

Supplement A

Sand Collection Protocol



How to choose a sample location

- Choose a location where the most marine debris is found
  - 10 individual samples taken within a 50 m stretch of beach
  - Samples should be taken above the low tide line and below the high tide line.
  - Make sure it is a low enough tide so there is 1-2 m below the wrack line.
  - As a guideline there should be at least 1 m between placements of the sampling ring. (It is easiest to pick a point and then move a few steps and take another sample until you have 10)

- If you have a piece of debris that is this size of a quarter or less, include it in the samples.
  - You **do not** need to pick up larger samples.
  - Do not pick up anything that may cause you harm.

SAND SAMPLE COLLECTION DATA SHEET

LOCATION AND CONTACT INFORMATION

Park ______________________________ Beach/Site Name __________________________

Sample location (GPS Coordinates) ____

____

Geodetic Reference System (Circle) WGS 84 NAD83 DD

Or Other ____

Field Personnel ____

Contact email(s) ________________________ Contact Phone(s) _______________________

WEATHER

Date ____________________ Time of Day ____________________

Weather (circle) Sunny Cloudy Rainy Windy

Was there a storm with high waves within the last 2 weeks? Yes No Don't know

SITE CHARACTERIZATION

Number of Pictures of Site (circle) 1 2 3 4 5+

Do you see large debris within view? (ie.larger than a soccer ball?) Yes No

How many of these large pieces do you see? 1 2-5 6-10 11+

Do you do regular beach sweeps or cleanup at this site? Yes No

If so, how often? ____

When was the last cleanup? ______________________________

Is there a creek or river within view of the site? Yes No

Is there a pipe or drain input within view of the site? Yes No

How would you describe the site? (circle all that apply)

Smooth sand Some gravel Some mud Tide pools

Shells & fragments Other (describe in Notes below)

Notes

If you have any questions please contact Stefanie Whitmire, whitmi6@clemson.edu (843)-779-2393 1

Supplement B

Table B1: Microplastic loads (pieces/kg of sand), standard error, minimum and maximum value for the site, urban area (ha) in a 50km diameter buffer, distance to waste water treatment plant (WWTP) in km, distance to nearest river (km).

Region	NPS Unit	Mean count per kg sand	S.E.	Min	Max	Median	Urban Area (ha)	distance to WWTP (km)	distance to river (km)
Alaska	ANIA	51.3	10.5	20	65	60	0.0	555.7	9.2
	BELA	95.0	22.5	35	140	102.5	21.5	0.4	23.8
	CAKR	123.8	24.6	80	180	117.5	0.0	18.0	45.4
	GLBA	42.5	23.9	0	110	30	378.0	0.7	1.5
	KATM	128.8	36.1	75	235	102.5	0.0	198.9	4.1
	KEFJ	43.8	5.2	35	55	42.5	0.0	268.4	3.5
	KLGO	38.8	8.3	15	50	45	289.2	6.0	2.1
	LACL	40.0	12.1	20	75	32.5	0.0		5.1
	SITK	21.3	4.3	10	30	22.5	704.4	2.7	14.8
	WRST	97.5	25.3	55	155	90	0.0	502.7	43.6
Midwest	APIS	221.3	28.8	155	285	222.5	800.6	21.1	7.8
	GRPO	117.5	13.6	95	150	112.5	0.9	57.1	7.6
	INDU	152.5	7.8	130	165	157.5	17459.0	3.1	2.4
	ISRO	88.8	8.0	65	100	95	0.8	104.1	0.4
	PIRO	65.0	5.4	55	80	62.5	277.5	119.0	
	SLBE	156.3	29.9	105	235	142.5	3588.5	92.8	0.3
Northeast	ACAD	126.3	43.2	30	235	120	3592.5	13.4	24.9
	ASIS	112.5	15.1	80	145	112.5	7130.6	12.9	6.0
	BOHA	100.0	6.5	85	115	100	73669.4	3.3	3.1
	CACO	106.3	19.7	50	140	117.5	3790.0	59.1	59.1
	FIIS	106.3	30.9	50	185	95	52007.6	78.9	
	GATE-JB	95.0	14.7	65	125	95	50539.7	17.4	10.1
	GATE-SH	63.8	19.1	10	100	72.5	42901.0	13.1	16.2
	GATE-SI	88.8	17.4	40	120	97.5	72987.7	10.3	17.0
West Coast	CABR	38.8	7.2	30	60	32.5	46214.6	0.3	3.7
	CHIS	56.3	10.5	35	85	52.5	4.3	63.7	
	GOGA	140.0	24.8	100	210	125	30053.7	0.9	6.4
	LEWI	87.5	17.0	60	130	80	3639.2	42.0	19.9
	OLMY	115.0	29.0	40	180	120	231.1	37.2	14.6
	PORE	140.0	22.7	100	200	130	556.3	52.4	2.6
	REDW	98.8	14.8	70	140	92.5	345.2	51.1	1.3
	SAJH	67.5	18.3	40	120	55	2318.6	10.5	6.6
	SAMO	80.0	15.1	40	110	85	57043.0	17.7	0.5
Pacific Islands	HALE	131.3	18.3	100	170	127.5	524.4	52.5	0.7
	HAVO	98.8	27.7	20	150	112.5	616.0	88.3	9.0
	KALA	171.3	37.8	105	265	157.5	1017.1	70.5	
	NPAS	187.5	22.4	145	245	180	1641.9	36.4	0.2

Table B2: Mean abundance of plastic pieces per sample that were greater than 4.75 mm and mean abundance of microplastic pieces per sample that were 2.0-4.75 mm.

Region	NPS Unit	Mean count per kg sand (<2.0 mm)	Mean count 2.0-4.75 mm per sample	Mean count >4.75 mm per sample
Alaska	ANIA	51.3		
	BELA	95.0		
	CAKR	123.8		
	GLBA	42.5		
	KATM	128.8		
	KEFJ	43.8		
	KLGO	38.8		
	LACL	40.0		
	SITK	21.3		
	WRST	97.5		
Great Lakes	APIS	221.3		
	GRPO	117.5		
	INDU	152.5		
	ISRO	88.8		
	PIRO	65.0		
	SLBE	156.3		
Northeast	ACAD	126.3		
	ASIS	112.5	0.1	
	BOHA	100.0	0.1	
	CACO	106.3		
	FIIS	106.3		
	GATE-JB	95.0		
	GATE-SH	63.8	0.1	
	GATE-SI	88.8		
West Coast	CABR	38.8		
	CHIS	56.3		
	GOGA	140.0		
	LEWI	87.5		
	OLMY	115.0		
	PORE	140.0		
	REDW	98.8		
	SAJH	67.5		
	SAMO	80.0	0.2	
Pacific Islands	HALE	131.3		
	HAVO	98.8		
	KALA	171.3	3.3	0.7
	NPAS	187.5	0.7	

Table B3: Data entered on data sheet from each NPS unit. Large debris was defined as larger than a soccer ball and amount was categorized as 1, 2-5, 6-10, or 11+ (Supplement A). Not all parks recorded the type of large debris seen. If the park conducted regular cleanups, the date of last cleanup was also reported.

Region	NPS Unit	Date Sampled	Large debris in view of sample site	Number of large debris items	Type of large debris	Is there regular beach cleanup?	Date of last cleanup
Alaska	ANIA	5/9/2016	Yes	11+	Fishing line, bouys		
	BELA	5/27/2016	No			No	
	CAKR	7/9/2015	Yes	1		No	
	GLBA	7/16/2015	No			No	
	KATM	7/19/2015	Yes	1		1x/year	June 2015
	KEFJ	7/30/2015	Yes	2-5		Yearly	May2015
	KLGO	10/6/2015	No			No	
	LACL	7/5/2016	No			No	
	SITK	8/3/2015	No			No	
	WRST	6/19/2015	Yes	6-10		No	One time only early June 2015
Great Lakes	APIS	7/1/2015	No			Yes	N/A
	GRPO	6/29/2015	Yes	11+		Weekly	6/15/15
	INDU	6/24/2015	Yes	1		No	
	ISRO	7/21/2015	No			No	
	PIRO	8/7/2015	No			No	2005
	SLBE	7/10/2015	Yes	1	Large logs	1x/week	7/5/15
Northeast	ACAD	7/17/2015	No				
	ASIS	7/16/2015	No			No	April 2015
	BOHA	7/16/2015	Yes	2-5	Plastic and glass	A few times/year	7/16/2015
	CACO	8/3/2015	No			No	
	FIIS	7/13/2015	Yes		Balloons, bouys	No	
	GATE-JB	7/8/2015	Yes	6-10		No	
	GATE-SH	7/16/2015	Yes	2-5		No	
	GATE-SI	7/7/2015	Yes	2-5		2x/season	Unknown
West Coast	CABR	10/15/2015	No			1-2x/mo during Oct-April	10/11/2015
	CHIS	7/6/2015	No			No	
	GOGA	8/27/2015	No			Every 28 days	7/29/2015
	LEWI	7/31/2015	No			Quarterly	June 2015
	OLMY	7/17/2015	No			yearly	unknown

	PORE	7/15/2015	No			No	
	REDW	9/1/2015	No			No	
	SAJH	7/21/2015	No			No	7/20/2015
	SAMO	12/7/2015	Yes	2-5	Concrete blocks	unknown	unknown
Pacific Islands	HALE	7/17/2015	No			No	
	HAVO	10/30/2015	No			No	
	KALA	7/1/2015	Yes	2-5		quarterly	June 2015
	NPAS	7/15/2015	Yes	6-10	Glass, wood, tires, cans, plastic bottles	No	