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Accumulation and distribution of marine debris on barrier islands across the northern Gulf of Mexico

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ABSTRACT

Marine debris is an economic, environmental, human health, and aesthetic problem posing a complex challenge to communities around the globe. To better document this problem in the Gulf of Mexico we monitored the occurrence and accumulation rate of marine debris at twelve sites on nine barrier islands from North Padre Island, Texas to Santa Rosa, Florida. With this information we are investigating three specific questions: (1) what are the major types/sources of marine debris; (2) does debris deposition have seasonal oscillations; and (3) how does debris deposition change spatially? Several trends emerged; plastic composed 69–95% of debris; there was a significant increase in debris accumulation during the spring and summer seasons; accumulation rates were ten times greater in Texas than the other Gulf States throughout the year; and the amount of debris accumulating along the shoreline could be predicted with high confidence in areas with high freshwater influx.

1. Introduction

In recent decades, the topic of marine debris has gained recognition as a significant global ecological and economic problem. As the amount of debris in our oceans grows, the frequency of research and monitoring to understand its sources, concentrations, and impacts also increases. As the frequency of studies grow, the evidence and understanding of the negative effects of marine debris does as well (Rochman et al., 2016). Debris has been documented to have a range of effects from individual organisms with ingestion and entanglement (Gall and Thompson, 2015), up to entire habitats and ecosystems (Uhrin et al., 2005; Uhrin and Schellinger, 2011). Sound information and research is needed to inform possible management strategies and mitigation and removal techniques, as well as understand the impact and success rates of those strategies and techniques.

Global estimates of marine debris abundance range from four to 48,000 items per kilometer of shoreline (National Research Council, 2009), with the highest concentrations often observed on shorelines close to the main sources or population centers (Thiel et al., 2013; Jambeck et al., 2015). Since plastic was first discovered in the ocean (Carpenter et al., 1972), plastic-based products have begun to dominate the largest portion of debris in our oceans. Percent composition of marine debris for plastic ranges from 16% to 99% (Galgani et al., 2000; Bouwman et al., 2016). A 2015 study completed on plastic marine debris, estimated that 4.8 to 12.7 million metric tons of unmanaged plastic waste entered the ocean in 2010 (Jambeck et al., 2015). A study of marine debris sources along the coast of Central Italy found that urban areas are the main driver behind the occurrence of marine debris (Poeta et al., 2016). This estimate does not include plastic debris entering the coastal ocean through fishing gear loss, overboard disposal, or extreme events. The study found that the amount of uncaptured plastic waste available to become marine debris released by a specific country was mostly a function of that country's coastal population size and the quality of their waste management systems (Jambeck et al., 2015). Another study found that the top ten dirtiest rivers worldwide are estimated to dump 88–95% of the global plastic load into the oceans (Schmidt et al., 2017). Seasonal variations in the accumulation and fragmentation of plastic debris has also been noted in the Mediterranean and California, USA but not in a long-term study in the Hawaiian Islands (Barnes et al., 2009; Morishige et al., 2007; Rosevelt et al., 2013).

In the Gulf of Mexico, general trends of debris distribution have been shown throughout the region. A study focusing on National Seashores from 1989 to 1993, found that the Padre Island National Seashore in Texas (north-western Gulf of Mexico) contained 32 times more plastic debris on its shores than the Gulf Islands National Seashore off the coast of Mississippi in the north-central Gulf of Mexico (Ribic et al., 1997; Miller and Echols, 1996). In 1992, the average quarterly

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accumulation rates were 1771.4 and 54.4 pieces of plastic debris per 100 m for the Padre Island and Gulf Island National Seashores, respectively (Ribic et al., 1997). A 2001 study found that debris loads were similar in the U.S. Caribbean and north-western Gulf of Mexico, while both were significantly higher than those observed in the north-central Gulf of Mexico. That research monitored the same two National Seashores as the previously mentioned 2001 study, Padre Island and Gulf Islands, and noted that on average marine debris amounts recorded at Gulf Islands National Seashore were significantly lower (one-third) then those recorded at the Padre Island National Seashore (Ribic et al., 2011). A recent report analyzing International Coastal Clean-up data from across the USA identified Texas as one of the national hot spots, with high debris loads driven by coastal debris (Hardesty et al., 2017).

This research project represents two full years of monthly monitoring using standardized and established protocols that have been thoroughly researched and are in use at numerous other sites both in the Unites States and world-wide (Lippiatt et al., 2013). While other accumulation studies may have been limited in frequency (seasonal or yearly sampling), and duration (one season, or one year in length) reducing their capabilities to observe important trends, this study was able to accomplish and detect such trends. Previous work done in the northern Gulf of Mexico is limited, with the two previous studies (mentioned above) being completed 15 to 25 years ago. Changes in population, tourism, fishing, and shorelines have occurred over the last two decades, and this study provides a more recent understanding of the marine debris accumulation rates and composition found throughout the northern Gulf of Mexico. Another key component of this project, were its all-encompassing categories, recording data on all anthropogenic debris items, not just plastic or indicator items (Ribic et al., 1997; Miller and Echols, 1996). As far as we know this is the first study to look at seasonal and spatial variations in debris accumulation across all five Gulf coast states at multiple locations.

Using the National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program's adopted shoreline monitoring protocol (Opfer et al., 2012, Lippiatt et al., 2013), our objective was to use data collected from two monitoring programs, the Mission-Aransas National Estuarine Research Reserve and the Dauphin Island Sea Lab, located within the northern Gulf of Mexico to determine; 1) major types and possible sources of marine debris, 2) if there is a seasonal pattern to debris disposition within the Gulf of Mexico, and 3) how debris deposition changes between the eastern and western northern Gulf of Mexico.

2. Methods

2.1. Characterization and description of monitoring sites

This field study was conducted from February 2015 to August of 2017. Surveys took place over two years (22–26 sampling events) at twelve sites in the Gulf of Mexico (GoM), from the panhandle of Florida to central Texas, USA (see Table 1 for a summary description of all sites). These sites were all selected based on the guidance and requirements of NOAA Marine Debris Monitoring and Assessment Project (MDMAP) Shoreline Monitoring Protocols (Opfer et al., 2012, Lippiatt et al., 2013), features (e.g. slope, tidal inundation, beach width), and Gulf water-facing shoreline (Fig. 1). All sites were located on the oceanside of barrier islands, had a similar flat sandy shoreline and a diurnal tide with minimal tidal range (< 1 m), with the main difference among them being beach width (11–45 m). Sites also had year-round access, were not located near, or impacted by, breakwaters or jetties, and had no routine or regular cleanup activities associated with them.

The study contained two main areas: the north-central Gulf of Mexico (Louisiana, Mississippi, Alabama, Florida panhandle, sampled from February 2015–2017) and the north-western Gulf of Mexico (Texas, sampled from August 2015–2017). Six sites were located within the north-central GoM (ncGoM) and six were located in the north-western GoM (nwGoM). Land use of the sites was characterized as recreational or remote. Recreational is classified by sites that were more easily accessible (by car, boat, or pedestrian) and more likely to be used by fishermen, boaters, or beach users. The sites classified as remote were those sites more isolated, with some being completely inaccessible to the general public and requiring landowner permission.

Six sites located in the north-central GoM were spread out from eastern Louisiana to the panhandle of Florida covering over 250 km (km) of shoreline (Table 1). These sites were located on barrier islands that are between 3 and 40 km in length. Accessibility of these sites decreases as you move from east to west with Santa Rosa Island and Dauphin Island accessible by car/walking and the other islands are accessible only by boat. Petit Bois and Horn Islands, accessible only by private boat, are part of the Gulf Island National Seashore which are publicly accessible, but portions are closed during shorebird nesting season. Most of Cat Island is privately owned although many Mississippians fish along its shoreline since it is just 10 km south of Gulfport, Mississippi and accessible even with small, flat-bottomed boats. The Chandeleur Islands is a migratory bird sanctuary, with restricted access, but is a popular area for fishing year-round especially for red drum and speckled sea trout. There are several large watersheds located within the ncGoM study area. The largest watershed, Mobile Bay (4th largest watershed in the continental USA at over 116,500 square km), is located west of Santa Rosa Island and just east of Dauphin Island. Study sites were also downstream of the smaller Pensacola Bay, Pascagoula River, Biloxi Bay, and Bay St. Louis watersheds, with the Mississippi River located ~100 km south-west of the Chandeleur Islands (Fig. 1).

Sites in the north-western GoM were located an average of 185 km away from the border between the United States and Mexico, and span roughly 105 km of the Texas coast. The cities of Corpus Christi and Port Aransas, Texas are adjacent to the sites. Corpus Christi is a large city located on mainland, and Port Aransas is a coastal, tourism-based city located on the northern end of Mustang Island. Three of the six Texas sites were located on San Jose Island which is a privately-owned island currently used for cattle ranching. These three sites were considered remote. One site, Fish Pass, was located within the only non-maintained beach area on Mustang Island, a popular spring-summer tourists' destination. The other two sites were in the Padre Island National Seashore (PINS), one located in a pedestrian-only accessible area of the park, and the other located 16 miles further down the beach, often accessible only by 4-wheel drive vehicles. The sites on San Jose Island were located within the Aransas Bay watershed, while the site at Fish Pass was within the frontal Corpus Christi Bay watershed. PINS North and PINS South were located within the Upper Laguna Madre and Middle Laguna Madre watersheds respectively, which are moderate in size, with the Lower Laguna Madre being the largest at about 9000 sq. kilometers (Fig. 1).

Due to the lack of passes between the bays and Gulf of Mexico, the sites located within the nwGoM had minimal impact from their associated inshore-watersheds and were likely more influenced by offshore Gulf of Mexico waters. Sites on San Jose Island were anywhere from 9 to 24 km away from the closest pass, Aransas Pass. Fish Pass is 8 km from Packery Channel and 20 km from Aransas Pass. PINS North and PINS South were 18 and 53 km from Packery Channel, the closest bay inlet along the coast.

2.2. Marine debris shoreline monitoring procedure

This study design was based on the NOAA Marine Debris Monitoring and Assessment Project (MDMAP) Shoreline Monitoring Protocols (Opfer et al., 2012, Lippiatt et al., 2013). Prior to the start of the study, all marine debris was removed from each transect at the 12 sites. At each site, a 100 meter (m) transect was marked using signs or painted polyvinyl chloride (PVC) poles. Global positioning system (GPS) coordinates for the start and end of each transect were recorded in case the markers were lost during the study. Surveys were conducted every

Table 1
Characterization of Research Sites including; Site ID, Site Abbreviation, Land usage, access to site, the nearest up-current watershed to each shoreline site, how far away that watershed outlet is in km, and the average number of items or grams per meter of coastline per month.

Site name	Site ID	Land use	Access	Nearest watershed		Avg. monthly debris	
				Name	Distance (km)	(Pieces/m/month)	(grams/m month)
Santa Rosa, FL	SR	National Seashore	Vehicular- car	Choctawhatchee Bay	60	0.44	1.68
Dauphin Island, AL	DI	Recreational	Vehicular- car	Mobile Bay	7	1.21	14.32
Petit Bois, MS	PB	National Seashore	Isolated- boat	Mobile Bay	38	0.60	7.15
Horn Island, MS	HI	National Seashore	Isolated- boat	Pascagoula Bay	18	0.76	10.35
Cat Island, MS	Cat	Remote- Private	Isolated- restricted	Biloxi Bay	48	0.47	7.33
Chandeleur Island, LA	ChI	Remote- Migratory Bird Sanctuary	Isolated- restricted	Mississippi River	63	0.41	10.46
San Jose Island 16, TX	SJI 16	Remote- Cattle Ranch	Isolated- restricted	Matagorda Bay	65	9.11	167.38
San Jose Island 10, TX	SJI 10	Remote- Cattle Ranch	Isolated- restricted	Matagorda Bay	72	10.22	153.04
San Jose Island 6, TX	SJI 6	Remote- Cattle Ranch	Isolated- restricted	Matagorda Bay	80	7.36	147.80
Fish Pass, TX	FP	Recreational	Vehicular- car	Corpus Christi Bay	20	8.23	62.82
Padre Island N., TX	PINS North	Recreational	Pedestrian	Baffin Bay	48	5.44	93.03
Padre Island S., TX	PINS South	Recreational	Vehicular- car (4WD only)	Baffin Bay	80	5.67	68.87

28 days (± 3 days) at each site. All marine debris larger than 2.5 centimeters (cm) and cigarette butts (regardless of size) were collected from the water's edge to the vegetation or dune line. Once collected, the debris was separated by material type as specified in the procedure: plastic, glass, metal, rubber, processed lumber, or cloth/fabric and each category of debris was counted and weighed to the nearest hundredth of a gram (g). All counts and weights were recorded on the debris density data sheet (adapted from Opfer et al., 2012, Lippiatt et al., 2013). If items were too large to carry back to the boat or vehicle, they were marked, and area measurements were recorded in the field. Accumulation rates are reported as number of items or mass, per unit area, per month. To make the data more relevant and comparable to other coastlines all data in the results are reported as items per meter of coastline per month.

2.3. Data analysis

Differences in accumulation rates and debris types were analyzed with univariate analysis of variance (ANOVA) using IBM SPSS Statistics v22. The spatial differences were divided in two groups based on their location within the northern Gulf of Mexico and seasonal variation was separated in to spring (March–May), summer (June–August), autumn (September–November) and winter (December–February). ANOVA assumptions of normality and homogeneity of variance were assessed with the Kolmogorov-Smirnov and Cochran's C-tests, respectively. When assumptions were not met, the level of significance was set at 0.01 to reduce the possibility of committing Type I error (Underwood, 1997). When assumptions were met, a 0.05 significance level was used.

To determine influence of the nearest watershed to the amount of debris accumulating on a shoreline a curve estimation regression was run testing linear and logarithmic curves. The logarithmic regression, which is used to model situations where growth or decay accelerates rapidly at first then slows over time, was selected to understand the effect of the distance a beach is down-current from a watershed outlet on the amount of debris accumulating monthly on that beach. This regression was analyzed for all sites and then each region (nwGoM or ncGoM) separately.

3. Results & discussion

We sampled 12 barrier islands 26 times over a two-and-a-half-year period from 2015 to 2017 for a total of 270 data points. Monthly debris accumulation rates varied from a minimum of 0.01 items/m/month in May 2016 on Petit Bois Island, MS to 29.51 items/m/month in that same month at Fish Pass, Texas (Table 1).

3.1. Seasonal variations

The northern GoM, as a whole, varied seasonally and had more debris accumulating during the spring months (avg. accumulation rate 6.04 items/m/month) with concentrations increasing in March, peaking in May, and returning to site averages by July (Fig. 2). There was a slight delay in this seasonal trend from west to east, for the nwGoM and ncGoM sites (Figs. 2, 3). The nwGoM sites had a significantly different accumulation rate in the spring, summer/autumn, and winter months. The spring had the highest accumulation rate, 11.33 items/m/month, peaking in May with 12.71 items/m/month, summer and autumn rates averaging in the middle at 7.12 items/m/month, and the winter season experiencing the lowest rate with 4.05 items/m/month (Fig. 3, S1.1, one-way ANOVA, $F_{(3,121)} = 19.079$, $p < 0.001$). In the ncGoM there were also significant differences between seasons, but accumulation rates peak one month later, in June, during the summer, at 1.41 items/m/month, with the summer season averaging 0.95 items/m/month, and the winter season experiencing the lowest rate with 0.39 items/m/month (Fig. 3, S1.2, one-way ANOVA, $F_{(3, 140)} = 6.166$, $p = 0.001$).

Shoreline and maritime activities increase during the spring in the Gulf as the weather starts to improve, air and water temperatures are warmer, and the wind is calmer, increasing the numbers of people at the beach and on the water. Spring Break, Easter, and Memorial Day all occur during the spring, and bring an increase in population to the coastal areas. Many fishing seasons (both recreational and commercial) open or are more productive, during the spring (NOAA Fisheries, 2018). In addition, around March, both areas of the Gulf switch from predominantly offshore winds to onshore winds (lasting until August, NRCS, 2010) which could increase the amount of debris that washes ashore from the ocean. A recent study out of Australia found significantly higher debris loads in autumn then winter (the only seasons sampled), these high autumn debris loads also had higher debris arrival on the shoreline which could not be predicted by swells or wind (Brennan et al., 2018). Brennan et al. suggests that these trends are due to changes in the offshore debris load because of less urban runoff and decreased maritime use in winter.

3.2. Regional variations

Debris accumulation rates also varied significantly by region with the nwGoM accumulating ten times more debris per meter of coastline than the ncGoM (Fig. 4, S1.3, one-way ANOVA, $F_{(1,267)} = 276.239$,

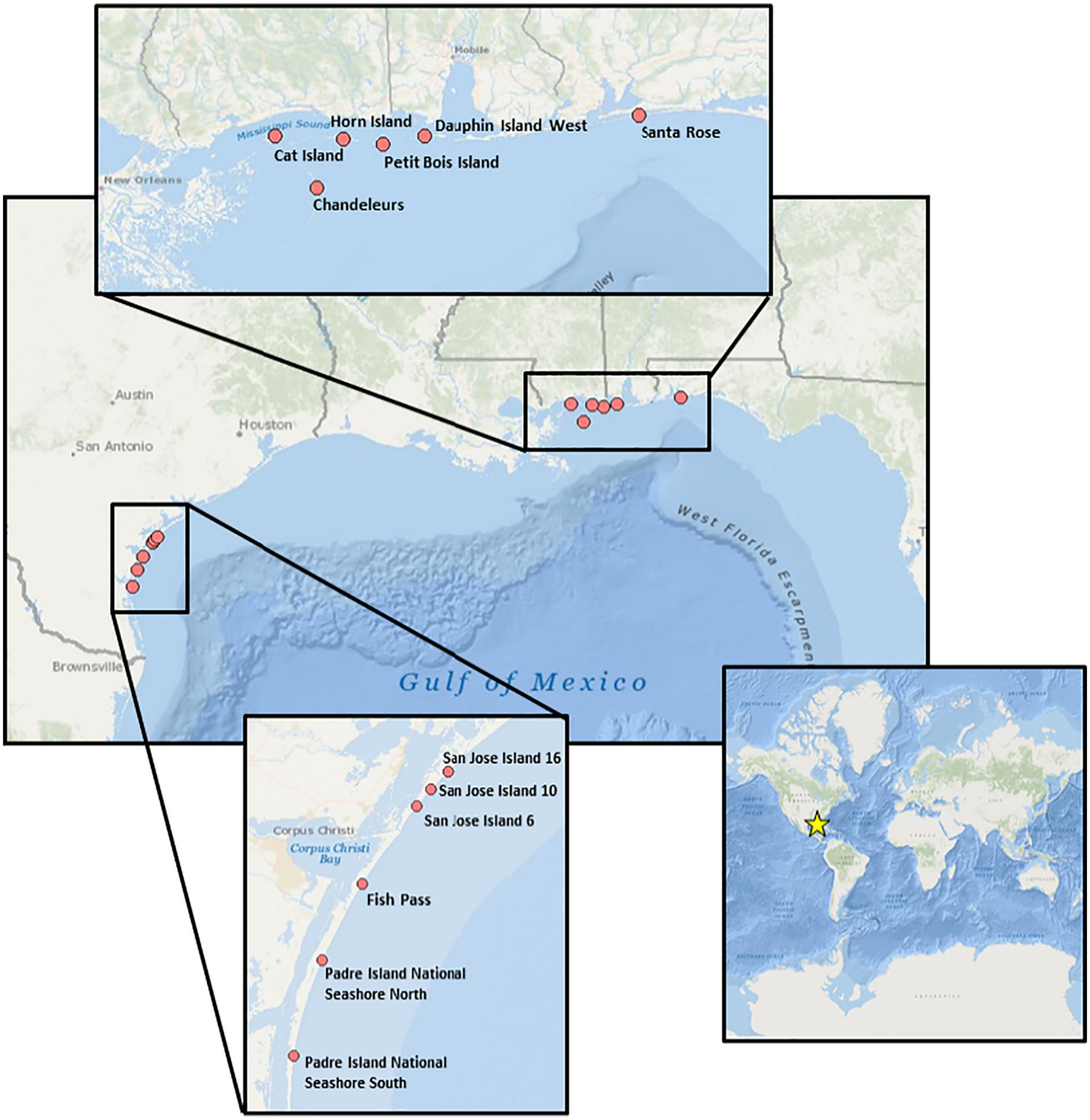

Fig. 1. Map showing the location of each site across the U.S. Gulf of Mexico. The top pop out shows sites in the ncGoM, and the bottom-left pop out shows sites in the nwGoM (Texas). The pop out to the right provides a global reference for the study sites.

$p < 0.005$). This is consistent with data from the Ocean Conservancy collected by citizen scientists during their international coastal cleanup from 2010 to 2015 that show Texas consistently has the most trash in pounds per mile of U.S. coastline (Hardesty et al., 2017). On average, over the course of the 2 years, accumulation rates in the nwGoM were 7.42 items/m/month and in the ncGoM were 0.64 items/m/month. In 2001 and 2002 Barnes and Milner (2005), determined single time point debris densities at a variety of locations worldwide. Based on their numbers the nwGoM monthly accumulation rate is similar to Menorca, Spain (8.8 items/m) and the ncGoM was almost the same as Scolt Head Island, UK (0.63–0.68 items/m). Menorca is the only island on their list of 16 that had more debris per meter than Texas barrier islands whereas the ncGoM fell right in the middle. Quarterly accumulation sampling from 1992 found 544 pieces of plastic per kilometer at Gulf Islands National Seashore. the same area as our Santa Rosa site in the ncGoM, and 17,714 pieces of plastics per kilometer at Padre Island National Seashore, where we also sampled two locations for the nwGoM (Ribic et al., 1997). If you adjust these quarterly rates to monthly and scale them down from a kilometer to a meter length Ribic et al. found 0.18 plastic pieces/m for the ncGoM and 5.9. If we look at just plastic accumulation we found 0.56 plastics pieces/m/month in the ncGoM and 6.9 plastic pieces/m/month in the nwGoM both accumulation rates are higher in our study. This could mean that either accumulation of plastics has increased in the last 13 years or that there is some error associated with converting a quarterly accumulation rate to monthly. There has been research showing that temporal scales are important to measuring accumulation rates and that measuring shorter time scales result in higher accumulation rates then seen over longer time scales (Wessel et al., In Prep).

In the Gulf of Mexico winds and currents have a major influence on nearshore conditions and potentially marine debris concentrations. Winds in the central Gulf of Mexico are generally offshore in direction, while in the western Gulf of Mexico, winds are typically stronger and mostly in the onshore direction (Morey et al., 2005). In the western Gulf

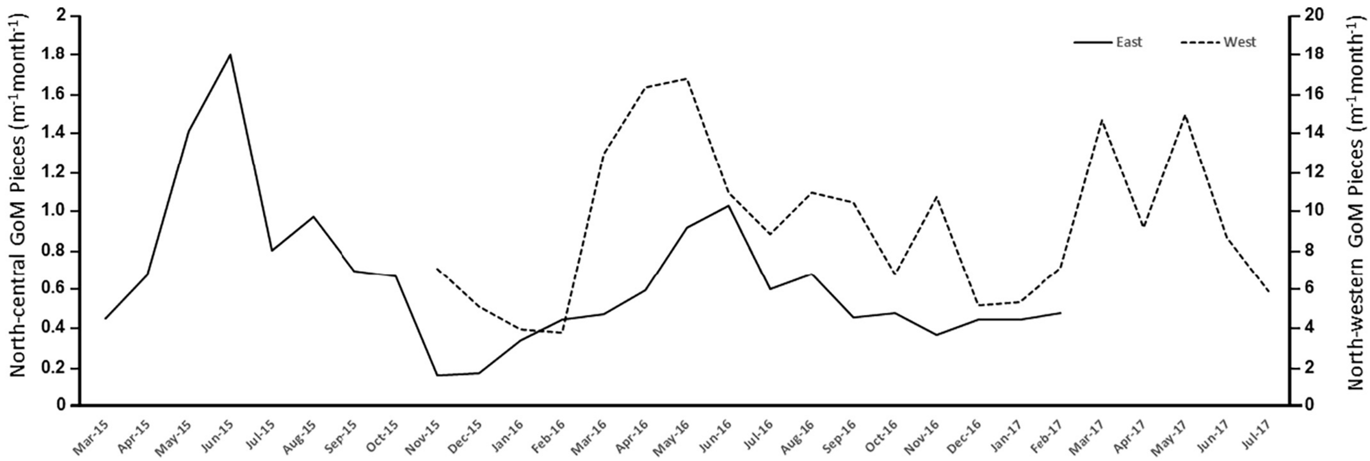

Fig. 2. The number of accumulating pieces of debris per meter of coastline per month (x-axis) in the North-central Gulf of Mexico (solid black line, left y-axis) and the North-western Gulf of Mexico (dotted black line, right y-axis, please note this axis is an order of magnitude larger).

of Mexico, two principal wind regimes dominate, with southeasterly winds from March through September and north-north easterly winds from October through March (Behrens and Watson, 1973; Brown Jr et al., 1976; Evans et al., 2012). It has been suggested in recent studies that onshore wind exposure can increase debris departure by pushing it from the shoreline into the backshore vegetation, which is not sampled as part of the NOAA protocols (Brennan et al., 2018). If this trend is also shown in the nwGoM the amount of debris that could be collecting in dunes and backshore vegetation would be staggering and cannot be ignored as a possible debris sink.

Shallow currents close to the coastal shelf in the western Gulf of Mexico are influenced by high river outflows and tend to flow in a counterclockwise direction. Whereas the deep shelf currents rotate in a clockwise direction due to the loop current (Wiseman and Sturges, 2003). The resulting combination of wind directions and current flows is that debris is pulled away from the coastlines in the eastern Gulf and directed to the west or Texas coast where strong, persistent offshore winds push the debris onshore (Ribic et al., 2011). While debris accumulation changes from east to west it appears to be largely dependent on what the dominant currents are (onshore, offshore, or longshore) and distance from the nearest up-current watershed (Table 1).

3.3. Potential sources

There was no correlation among the north-western GoM sites between distance down-current from the nearest watershed and debris accumulation. This suggests that sites located in Texas are less influenced by freshwater influx and more influenced by strong onshore currents. These currents bring debris, not only from the rest of the GoM, but also from Mexico, Central and South America, and the Atlantic on the loop current. Accordingly, it can be concluded that regardless of season, the ocean side of the long barrier island chains in Texas receive the bulk of the debris accumulating there as it washes ashore from the ocean (Fig. 4, Johnson, 2008). Sites in the north-central GoM on the other hand are dominated by high freshwater runoff and experience weak offshore and longshore currents which may carry debris away from the shoreline (Fig. 4, Bianchi et al., 1999). A logarithmic regression, which is used to model situations where growth or decay

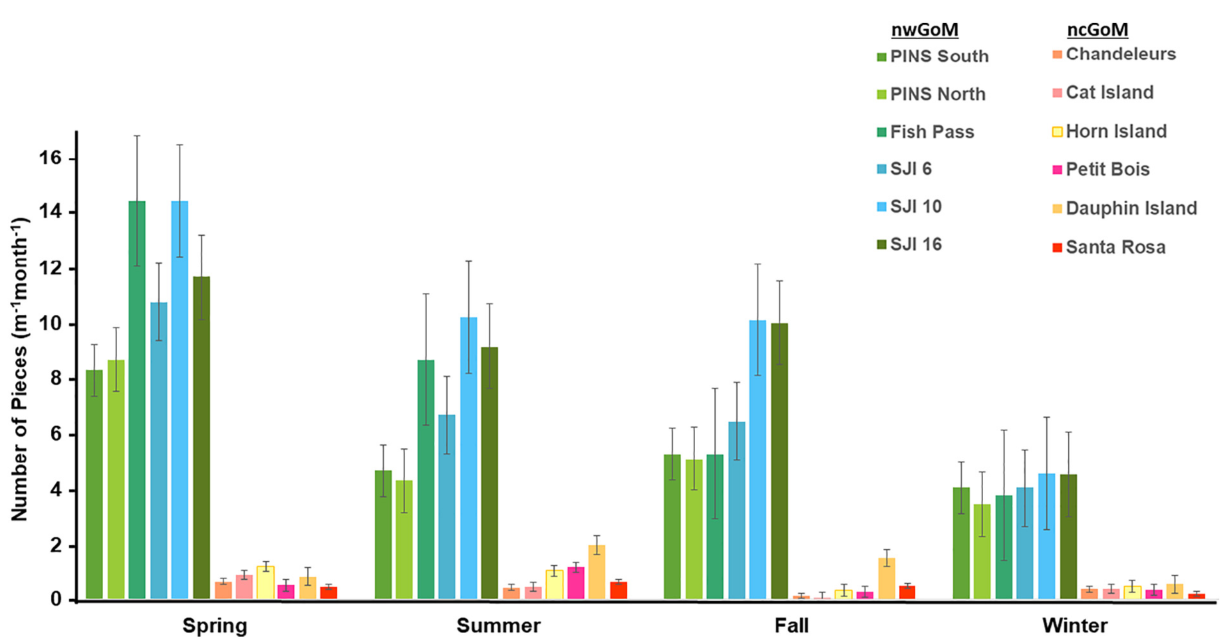

Fig. 3. The number of accumulating pieces of debris per meter of coastline per month (y-axis) on each island site (west to east) by season (x-axis). The sites in the north-western Gulf of Mexico are in cool shades of green and blue, and the sites in the north central Gulf of Mexico are in warm shades of yellow and red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

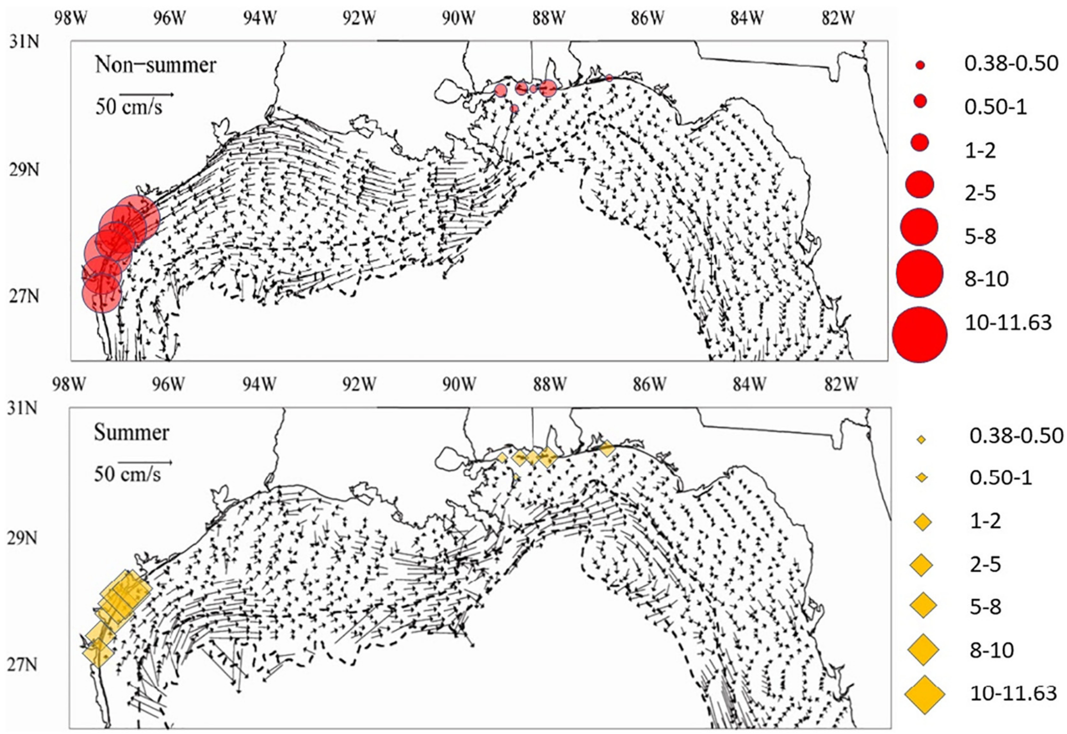

Fig. 4. The number of accumulating pieces of debris per meter of coastline per month for each site overlaid on a map showing the prevailing currents during 'non-summer' months (top, September–May) and during summer months (bottom, June–August). Current maps modified from Johnson, 2008.

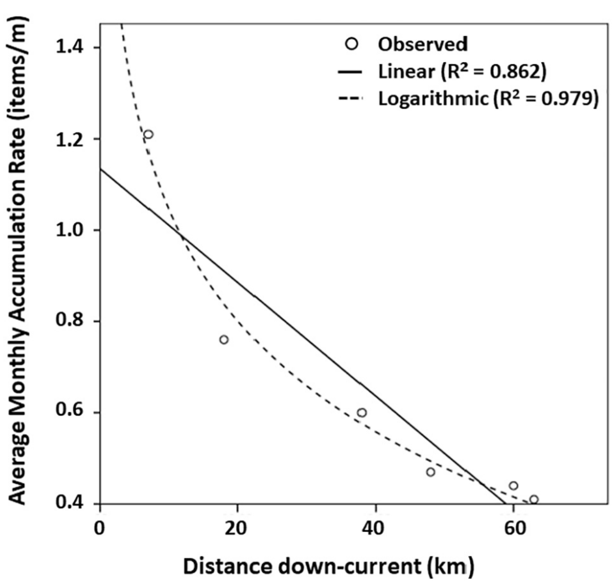

Fig. 5. The average monthly accumulation rate of debris per meter of coastline in the ncGoM (y-axis) by the distance (km) the site is down-current from the nearest fresh water inflow (x-axis). The circles show the field observed values, the solid line shows the linear regression, and the dashed line shows the logarithmic regression (best predictor). Regression tables are available in the Supplementary Materials.

accelerates rapidly at first then slows over time and had the best fit based on R squared values, was run to understand the effect of the distance a beach is down-current from a watershed outlet on the amount of debris accumulating monthly on that beach (Fig. 5, Supplemental 2). The amount of debris accumulating in the ncGoM could be predicted, with high accuracy, from the distance a beach is down-current from a watershed outlet using the following formula:

$$\text{debris} = 1.851 + -0.351 * \log(\text{distance}),\ R^2 = 0.979$$

The distance a beach is down-current from a watershed outlet statistically significantly predicted monthly debris accumulation, $F_{(1,5)} = 188.263$, $p < 0.001$, accounting for 98% of the variation in debris accumulation with adjusted $R^2 = 0.974$, a large size effect according to Cohen (1988). An extra kilometer down-stream of a watershed outlet leads to a reduction of 0.35 items/m/month of debris accumulating on the shoreline. This suggests in systems that are dominated by freshwater flow we can predict how much debris will end up on shorelines downstream and use this information to identify where the most debris will accumulate.

Predicted accumulation information can then be used for planning cleanup activities which benefit residents, visitors, and the economy (Tudor and Williams, 2008; Marine Conservation Society, 2012; Leggett et al., 2018). While there has not been a lot of research on the benefits of beach cleanups in reducing overall marine debris, other studies have examined the eudaimonia and hedonic well-being resulting from spending time on a clean beach or participating in a beach cleanup (Stickel et al., 2012, White et al., 2013, Wyles et al., 2014, Leggett et al., 2018). Exposure to natural environments can help restore emotional and cognitive resources leaving recreational users feeling relaxed and refreshed and improve their awareness of the marine environment (White et al., 2013; Wyles et al., 2014). One west-coast USA study showed that coastal communities spend approximately $13 USD per resident to combat and cleanup litter along the coast. Targeted cleanups that focus on areas with the most debris could help reduce these costs while still providing the economic benefits associated with reducing litter on beaches (Stickel et al., 2012; Leggett et al., 2018).

3.4. Types of debris

We were also interested in what types of debris were being found along the coastline and if there was a way to determine the sources of this debris. Debris was broken into six main categories according to NOAA protocols: plastic, metal, glass, rubber, processed lumber, and

Table 2
The average number of items per meter of coastline per month and percentage of debris from each category rounded to the nearest whole number.

Site ID	# of Items	% Plastic	% Metal	% Glass	% Rubber	% Processed lumber	% Cloth/fabric
PINS South	5.70	94	1	0	3	0	1
PINS North	5.44	90	2	1	5	1	1
FP	8.24	94	1	0	3	1	1
SJI 6	7.02	94	0	0	4	0	1
SJI 10	9.74	95	0	1	3	0	1
SJI 16	8.67	95	0	0	3	0	1
nwGoM avg	7.48	93.6	0.93	0.56	3.46	0.58	0.89
ChI	0.40	94	1	1	1	1	1
Cat	0.45	91	5	1	1	2	1
HI	0.76	93	2	1	2	1	1
PB	0.58	91	2	1	4	1	1
DI	1.21	70	5	20	0	3	1
SR	0.44	88	6	2	2	1	2
neGoM avg	0.64	87.9	3.51	4.32	1.67	1.58	0.98
nGoM avg	3.82	92.7	1.1	0.9	3.8	0.4	1.1

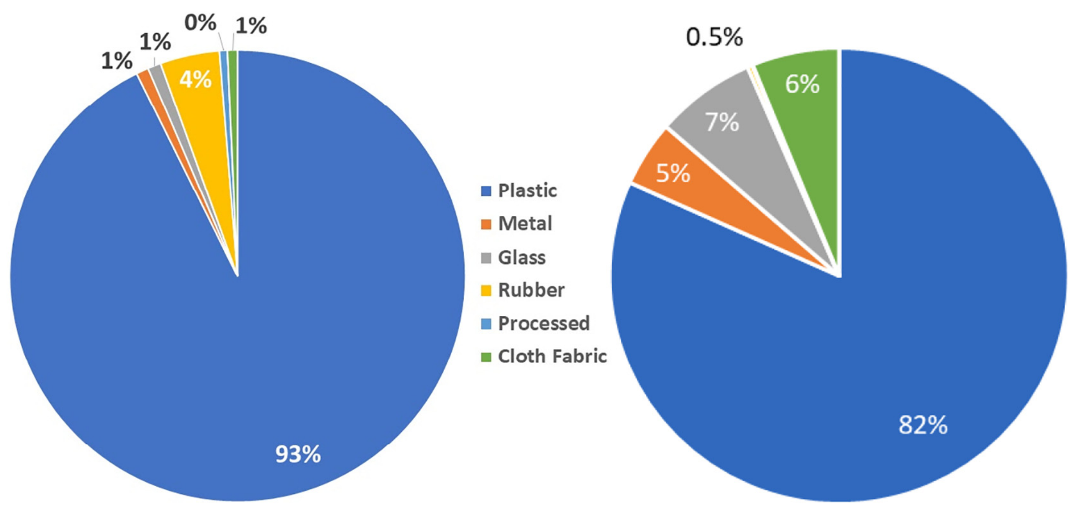

Fig. 6. The northern Gulf-wide breakdown of each type of debris collected during this study as a percent of the total number of pieces collected (left) and as a percent of the total mass collected (right, processed is not shown as it only accounted for 0.03%). Plastic is in dark blue, metal in red, glass in grey, rubber in yellow, processed lumber in light blue, and cloth/fabric in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cloth/fabric. Those six categories were then analyzed using the same methods as total debris accumulation. Plastics overwhelmingly dominated the debris types regardless of how you analyze the data (Table 2) and on average made up 93% (± 19%) of all pieces of debris collected or 82% (± 17%) of the total mass collected (Fig. 6). About 46% of all manufactured plastics are buoyant and are commonly found floating at the sea surface or washed up on the shoreline (EPA, 2006).

The types of debris, despite being mostly plastic (69–95%), were influenced by island and monthly variations. Dauphin Island (ncGoM) has significantly more glass, composed mostly of glass bottle fragments, than any of the other islands and only 69% of debris there was plastic (S1.4, One-way ANOVA, $F_{(11,258)} = 11.470$, $p < 0.005$). While we have no scientific explanation for this, observationally we can say that after Santa Rosa Island, Dauphin Island is the most accessible of the islands and does not enforce the prohibition of glass on the beach. We also found significantly more rubber accumulating during the month of March, 9%, than in other months, avg. 1.7% (S1.5, One-way ANOVA, $F_{(11, 258)} = 2.437$, $p = 0.007$).

We observed more plastic, especially among the sites in Texas, than other similar studies around the world. Given the strong influence of onshore winds and currents that impact this region of the GoM this is not surprising since many plastics are less dense than seawater, very durable, and easily transported by wind and currents (Barnes et al., 2009). A 2017 study of coastline debris is Tasmania, Australia found just 11% of debris was made of plastics with glass dominating their debris findings, whereas in Southeast Asia plastic made up 79%, and in Malaysia it is 90% of debris (Willis et al., 2017; Bouwman et al., 2016; Mobilik et al., 2014). Similar to the results from Ribic et al., 1997, fragment pieces made up of hard plastic or foam dominated the plastic category in our study. Following behind plastic fragments were single-use plastics (bottles, bottle caps, bags, etc.) with fishing-related plastics (lures, floats, line, etc.) at a distant third.

4. Conclusions

In summary, Texas has coastal debris accumulation rates ten times that of similar coastlines in the north central GoM. This trend is likely related to dominant wind and currents which affect these two areas differently with the Texas sites being dominated by onshore winds and currents and the ncGoM being dominated with freshwater flows from large watershed and weak longshore currents and varying winds depending on the season. Our results also suggest that in coastal systems that are dominated by freshwater inputs, like the north central GoM, mid-Atlantic states like Virginia, Maryland, Delaware, New Jersey, and international sites like the Mediterranean and Baltic Seas, we can predict how much debris will end up on shorelines downstream and use information as basic as how far away is the site from a freshwater input to identify how much debris will accumulate. Debris entering the marine environment from nearby freshwater rivers and bays suggest local origination of that debris which suggest local or regional solutions maybe be possible to reduce debris.

Seasonal accumulation rates varied across the Gulf with more debris occurring in the late spring and early summer months than in the autumn and winter. This predicted seasonal accumulation information combined with a prediction of how much debris accumulated on freshwater dominated beaches can then be used for planning purposes and to prioritize cleanup activities maximizing cost-benefits for the community. Coastal communities can analyze their beaches based on the distance they are from a freshwater input (river, bay, etc.) and focus clean-ups in the spring/summer to maximize the cost-benefits for residents and maximize economic return from visitors. For example, Ocean Conservancy's International Coastal Cleanup, which occurs globally every September, may do better to target the months of May or June in the northern Hemisphere.

Additionally, like many areas globally, plastics dominated the marine debris collected with a gulf-wide average of 93% ($\pm$ 19) plastic, and every single one of the 270 samples collected contained plastic. This information continues to highlight the prevalence of plastics in the environment and the need to reduce 'throw-away' plastic consumption.

Accumulation rates of marine debris vary widely around the globe and from site to site with many factors affecting them including, prevailing wind, currents, and population of the region. $<$ 75 years ago the mass production of plastics began and in this short time they have become the dominant type of marine debris, valued for the same traits that make them a persistent environmental issue. While concentrations of marine debris appear to be stabilizing in the open ocean, debris along coastlines is becoming an ever-increasing issue despite community clean-ups and an increased awareness. If the key to our 'plastic problem' is preventing waste from even entering the oceans we need to better understand its sources and pathways into the environment. Studies like this one are only a first step at understanding this complex issue and coastlines are only one collection point for marine debris in a very large network of global water bodies.

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Data associated with this manuscript can be found at https://mdmap.orr.noaa.gov

Appendix A. Supplementary data

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