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Keywords:
Marine debris
Beaches
Atlantic coast
United States
Trend
Monitoring

ABSTRACT
For the first time, we documented regional differences in amounts and long-term trends of marine debris along the US Atlantic coast. The Southeast Atlantic had low land-based and general-source debris loads as well as no increases despite a 19% increase in coastal population. The Northeast (8% population increase) also had low land-based and general-source debris loads and no increases. The Mid-Atlantic (10% population increase) fared the worst, with heavy land-based and general-source debris loads that increased over time. Ocean-based debris did not change in the Northeast where the fishery is relatively stable; it declined over the Mid-Atlantic and Southeast and was correlated with declining regional fisheries. Drivers, including human population, land use status, fishing activity, and oceanic current systems, had complex relationships with debris loads at local and regional scales. Management challenges remain undeniably large but solid information from long-term programs is one key to addressing this pressing pollution issue.

1. Introduction
Marine debris, defined as “any manufactured or processed solid waste material (typically inert) that enters the ocean environment from any source,” is one of the most pervasive and potentially solvable pollution problems plaguing the world’s oceans and waterways (Coe and Rogers, 1997; UNEP, 2009). Marine debris monitoring programs can clarify the problem — e.g., what are the types, what are the sources, how widespread is the problem — and provide a framework for the formulation of management strategies for abatement and prevention. Ongoing monitoring activities can then be used to assess the effectiveness of management strategies, and provide insight into when strategies need to be modified for changing conditions (Coe and Rogers, 1997; Cheshire et al., 2009). While this is a sound approach, a National Academy of Sciences review (Criddel et al., 1992; Rees and Pond, 1995; Alkalay et al., 2007; Cheshire et al., 2009). There have been relatively few large-scale and long-term programs (UNEP, 2009; Cheshire et al., 2009). One such program, the National Marine Debris Monitoring Program (hereafter the Program), was designed to determine quantitatively if the amount of debris on the US coastline was changing and what were the major sources of marine debris (Escardó-Boomsma et al., 1995). The Program concluded data collection in 2007, providing a decade of observations upon which to assess trends of marine debris on US coastal beaches. This paper uses Program data to (1) evaluate long-term trends in marine debris found on the Atlantic coast of the United States and (2) evaluate the importance of drivers that could explain debris deposition patterns.

2. Methods
2.1. Study area

The Program divided the Atlantic coast of the United States into three regions: Northeast Atlantic, Mid-Atlantic, and Southeast Atlantic (Fig. 1). The Northeast and Mid-Atlantic regions are influenced by the southward-flowing Labrador Current as part of the western North Atlantic gyre (Rowe et al., 2008). The Southeast Atlantic region is influenced by the northward flowing Gulf
Stream; the Gulf Stream and the western North Atlantic gyre merge off the coast at Cape Hatteras (Gyory et al., 2008) (Fig. 1).

2.2. Survey design

For each region, a comprehensive list of all potential survey sites was constructed. The potential study sites met the following criteria: length of at least 500 m, low to moderate slope (15–45°), composed of sand to small gravel, direct access to the sea (not blocked by breakwaters or jetties), accessible to surveyors year round, and no impact to endangered or protected species such as sea turtles, sea/shorebirds, marine mammals or sensitive beach vegetation. The survey sites used in the Program (Fig. 1) were randomly selected from this list.

The Program protocol was to measure the net accumulation of indicator items on a site’s 500 m stretch of beach every 28 days (Escardó-Boomsma et al., 1995; Ribic and Ganio, 1996). A length of 500 m was used to ensure an adequate number of indicator items would be collected for analysis. The survey interval reflected information that water quality measures are independent once 28 days have passed (Lettenmaier, 1978). Indicator items provided a standardized set of items that all surveys would collect; each indicator item was assigned a probable source: ocean-based, land-based, or general-source. Probable ocean-based debris was
2.3. Field logistics

Volunteer teams conducted all data collection for the monitoring program. Semi-permanent markers were placed at the beginning and ending points of each 500 m survey site; a global positioning system unit recorded latitude and longitude of the end points. Length of the site was measured with a surveyor’s measuring wheel. An initial beach cleanup at each survey site was done to remove all debris that had accumulated over an unknown period of time (Ribic et al., 1992). All surveys were then run on a pre-set 28 day schedule with a window of 3 days on either side of the target date; the window accommodated weather or other events that prevented the survey from being performed on the target date. Volunteers recorded weather information at the time of the survey as well as during the weeks prior to the survey.

Program staff went to each site to establish the monitoring area and provide training (e.g., debris identification, data recording) for volunteer groups to assure that volunteers understood the Program’s protocol. Survey directors were instructed to contact Program staff for questions regarding the Program protocol or completion of surveys. Each survey director was responsible for following quality assurance procedures during subsequent volunteer training and data collection activities. Quality assurance procedures covered (1) accuracy of debris identification, (2) accuracy of data cards, and (3) accuracy of debris collection. New monitoring groups re-inspected the trash bags’ contents, re-recorded the debris tallies and returned the card with the regular data card for analysis by Program staff. Once teams were proficient in debris handling and data recording, the survey director conducted random re-survey efforts to check for missed debris. Results indicated that volunteers occasionally missed small pieces of debris, but rarely larger, more visible debris items.

2.4. Data used in analysis

Because the volunteers were not always able to maintain the 28 day schedule across the entire sampling period, the data were initially screened for an inter-sample effect. To do this, inter-sample lengths (days) were calculated for each of the surveys at the sites with at least 5 years of data. The inter-sample lengths were binned for analysis. The starting bin was the protocol range of 25–31 days; this was extended backward and forward until 26 bins were created (roughly covering 6 months). Inter-sample lengths greater than 185 days were put into a single bin. The analysis examined debris counts separately for land-based, ocean-based, and general-source categories to allow for the processes driving those sources to respond differently to inter-sample length. We modeled the debris counts, log-transformed for normality, as a function of inter-sample length. Though not found in every region, there were significant \( P < 0.05 \) relationships between debris count and inter-sample length. The problem intervals were either very short (\( \leq 14 \) days) or very long (\( > 180 \) days). Therefore, we removed surveys separated by fewer than 20 days from the data set. For long gaps in the series, the first survey was removed from the data set; this was considered equivalent to treating the first survey as the clean-up survey in the protocol for initiating monitoring at a site.


2.5. Descriptive analysis

2.5.1. Regional comparisons

We summarized the surveys at each site by averaging the total number of indicator items collected by survey as well as the number of items in each of the three source categories. For each site, we also calculated the proportion of items that fell in the three source categories by survey and averaged these proportions to determine an average proportion by site for each debris source category. We used average site counts and proportions to test for regional differences using a linear model; significance was assessed at \( \alpha = 0.10 \) as per the Program’s design. We log-transformed counts and arcsine square root transformed proportions to stabilize variances. Analyses were done using R version 2.7.0 (R Development Core Team, 2004).

2.5.2. Assessment of trend

The Program’s primary objective was to determine if there was a trend in total indicator items as well as the land-based, ocean-based, and general-source categories. Our first modeling approach used the explanatory variables that were collected as part of the Program protocol. The variables were survey date, month, weather in the weeks prior to the survey, and weather at the time of the survey. Survey date modeled time trend with Day 1 = 1 January 1995; month modeled within-year variation. Weather in the weeks prior to the survey and weather at the time of the survey modeled impacts of inclement weather; weather was coded to reflect storms, rain, and high wind events. Though sites were chosen randomly, local physical processes that drive debris deposition can vary among sites; therefore, we also included a categorical site variable to descriptively model the collective effect of those local processes.

Because of potential non-linear relationships between debris counts and the other variables, we used generalized additive models (Wood, 2006) to model time trend and month effects. This approach allows more flexibility in modeling non-linear relationships and can identify linear and polynomial terms where appropriate; we used a gamma of 1.4 to avoid overfitting (Wood, 2006). After verifying the design expectation of inter-survey independence, we used a Gaussian error structure with no autocorrelation in all models; debris counts were log-transformed to stabilize variance.

We developed a set of models a priori and used Akaike’s Information Criterion (AIC) to rank the models (Burnham and Anderson, 2002); the best model was defined as the model with the smallest AIC value that had all significant variables. Significance was assessed \( \alpha = 0.10 \) as per Program design; adjusted \( R^2 \) described how well the model fit the data. We evaluated whether time trends varied among regions. If this interaction was significant, we analyzed the data by region. If the time trend was non-linear, we refit the model using a linear term to determine trend direction. The best models were tabulated by source category and region. Analyses were done using mgcv in R version 2.7.0 (R Development Core Team, 2004).

2.6. Drivers

2.6.1. Mechanism variables

Human activities and physical processes, other than weather, might affect debris deposition on beaches but were not explicitly considered in the Program; as the first of its kind in the United States, the scope of the Program was limited to trend detection.
and an evaluation of program feasibility. As explained above, Site was used in the first analysis as a proxy for all the processes that can affect debris deposition on a particular survey site. In this phase, we assessed whether information on some basic drivers could explain mechanistically the variability explained descriptively by Site. Being able to do this would be advantageous because “site effects” do not provide a foundation for creating or evaluating debris mitigation strategies, while knowing drivers, their relative importance, and the shape of their response curves can provide such a foundation. We explored land-based and ocean-based drivers. We did not consider drivers for general-source debris because of the difficulty in knowing what fraction of the debris was actually land-based and what fraction was actually ocean-based, and whether that composition changed seasonally or over time.

2.6.1.1. Land-based mechanisms. There are many mechanisms through which human population can function as a driver of deposition of land-based debris in an area. We considered local population size, tourism activity, waste management programs, and degree of site use.

Local population size was defined as the population within 40 km of the site. Population data were obtained from the 2000 Census (US Census Bureau, 2000). Site locations and Census 2000 TIGER/Line census block shapefiles within 40 km of the sites were plotted using ArcMap 9.2 (Environmental Systems Resource Institute, 2009). Total population from all census blocks intersecting a circle of a radius of 40 km around each site was calculated. The total population of a census block was included in the calculation, even if only a portion of the block fell within the 40 km radius circle.

Tourism activity was described in two ways. First, we assumed that large population centers close to the site meant an increased visitor presence. We defined a large population center as a city with at least 250,000 people; so one tourism variable was distance to nearest population center of 250,000. Second, we asked the local survey directors to determine the cities where people came from for a daytrip (i.e., daytrip cities). Based on this information, we measured the distance to the farthest daytrip city, assuming that there was more tourism if people were willing to travel farther to visit the site for a day. All distances were measured in kilometers in ArcMap 9.2.

For waste management, we considered aspects of solid waste management and sewage system impacts. For solid waste management, we determined whether the area had a recycling program. Most sites had established programs before the start of the Program; that variable was not used in the analysis. Impact of local sewage systems was defined as distance from the survey site to the nearest river outflow (both directions). We used nearest outflow in both directions from the site because we lacked information on near-shore circulation patterns which would affect transport of debris. The nearest outflow point in either direction was the location where a river or stream intersected the coast. When the survey site was located on a barrier island or jetty, the outflow point was the closest point along the coast to the entrance of the coastal lagoon.

Lastly, we defined degree of site use as whether a site was a beach or a refuge. A site was categorized as beach if the area around the site was open to recreation such as picnicking or water sports. A site was categorized as refuge if the area around the site was set up to protect coastal habitat and recreation was restricted.

2.6.1.2. Ocean-based mechanisms. Sources for ocean-based debris include recreational boating/fishing and commercial vessels (shipping, tourism, and fishing). Given the size and scope of commercial activities along the Atlantic coast, we focused on mechanisms related to commercial activity.

For commercial shipping, interest centered on vessel traffic; however, we are not aware of any database that reports monthly vessel traffic along the United States coast. Therefore, an indirect measure was defined using information on the location of commercial ports. We hypothesized that sites closer to commercial ports are exposed to more ocean-based debris. We used the list of commercial ports available from the US Army Corp of Engineers (US Army Corps of Engineers Navigation Data Center, 2008). We measured the distance (km) of the closest commercial port to the survey site in ArcMap 9.2.

To derive a measure of commercial fishing activity, we used the National Marine Fisheries Service’s (NMFS) monthly reports of commercial harvest by state, by port, and by type of fish (National Marine Fisheries Service, 2009). We used the fin fish statistics for our index of fishing activity, specifically metric kilotons of fin fish brought to port. Occasionally, the NMFS reported a value coded ‘NSP’ in addition to the state’s set of monthly values for the year. NSP reflected fish catch for which the month of catch was not specified. We treated these observations as missing at random, and allocated the reported catch proportionately across the months. Generally, the value for a site was set as the state’s total catch. However, when a state fell into two Program regions, we used the port data to partition the state values into state values by region.

Each beach survey was assigned two fishing values. If the date of the survey fell on or before the 15th of the month, then “current” fishing was described by the catch variable reported for the previous month and “lagged” fishing was described by the catch variable reported for the month previous to that. If the date of the survey fell after the 15th of the month, then “current” fishing was described by the catch report for the month and “lagged” fishing was described by the catch reported for the previous month.

Structure modeled the concept that debris generated at sea will take some time to travel to shore.

Two key circulation systems for the Atlantic coast are the Gulf Stream and the circulation pattern around Georges Bank (Census of Marine Life, 2008) (Fig. 1). The Gulf Stream can entrain debris and transport it away from its source both northward and eastward. Therefore, sites closer to the Gulf Stream may have more oceanic debris than those farther from the Gulf Stream. Similarly, debris may be concentrated around Georges Bank due to the same processes that make Georges Bank an important fishing area (Census of Marine Life, 2008). Thus sites closer to Georges Bank might have more ocean-based debris.

We defined the western edge of the Gulf Stream as that region of northward flowing warm water characterized by a sharp sea surface temperature (SST) gradient (Longhurst, 1998). We imported AVHRR Oceans Pathfinder SST satellite imagery (NASA, 2009) from each season in 2000 into ArcMap 9.2 to identify images that best highlighted this temperature gradient, and digitized the image that represented the average location of the Gulf Stream throughout the year. We imported Gulf of Maine bathymetry (Office of Geographic and Environmental Information (MassGIS), 2008) to identify and digitize Georges Bank, characterized by a large elevated area of the sea floor at the southern edge of the Gulf of Maine. We measured the shortest distance (km) from each site to the Gulf Stream and Georges Bank shapefiles in ArcMap. Our analysis variable was distance to nearest circulation system. For the Northeast Atlantic region, this was distance to Georges Bank; for the Southeast Atlantic region, distance to the Gulf Stream. For the Mid-Atlantic region, the nearest circulation system varied by region.

2.6.1.3. Evaluation of mechanism variables. We allowed for nonlinearity in our models. Assessing potential nonlinearity is a way to check for deviations from simple linear dynamics. For example, a
linear term for local population size and tourism activity reflects a "more people = more debris" paradigm. From a modeling perspective, this may not capture the true dynamics of the process.

In our analysis, nonlinearity was assessed by using a linear term in the raw scale and a second linear term in the log scale. This was not as flexible as higher dimension non-linear models, but it was more flexible than quadratic models in the range of functional forms that could be approximated. Thus, while potentially sacrificing some explanatory power from higher dimension models, this model form provided a reasonable compromise between ease of analysis and power for an exploratory modeling exercise.

To evaluate these variables, we defined four models:

- Model (A) = best trend model (from first analysis)
- Model (B) = Model A without Site
- Model (C) = Model B plus mechanism variables
- Model (D) = Model A plus mechanism variables

To assess reduction in Site effects due to the mechanism variables, we defined:

- \( \Delta D_A = \text{deviance explained for Model A} - \text{deviance explained for Model B} \)
- \( \Delta D_B = \text{deviance explained for Model D} - \text{deviance explained for Model C} \)
- \( \Delta D_D = \text{deviance explained for Model D} - \text{deviance explained due to Site in Model D} \)
- \( \Delta D = 100 \times (\Delta D_D - \Delta D_A)/\Delta D_A = \text{percent reduction in Site effect} \)

Analyses were done using R 2.7.0 (R Development Core Team, 2004).

2.7. Trend assessments at the regional scale

Because the influence of drivers can vary depending on the scale under consideration, we wanted to investigate if this was the case in our system. Specifically, we considered whether year-to-year changes in regional indicator debris were related to year-to-year changes in a regional driver. We had two drivers that we could measure at the regional scale: human population and commercial fishing activity. For human population, the regional mechanism variable we used was coastal population, which we defined as the sum of the estimated population sizes of coastal counties in the surveyed states by year (US Census Bureau, 2009a,b). Coastal counties were those counties exposed to the Atlantic Ocean as shown on National Atlas maps (Department of the Interior, 2009). For commercial fishing activity, the mechanism variable was regional fishing activity measured as metric kilotons of fin fish brought to port region-wide by year.

The debris variable was predicted number of land-based indicator items or ocean-based items by year for each region from the analyses described in Section 2.5.2. Predicted variables were used in order to remove site and month effects from the analyses. We used predicted variables for years that had complete survey coverage: 1999–2006 for the Northeast region and 1998–2006 for the Mid-Atlantic and Southeast regions. We used a one-sided test of significance \((z = 0.05)\) on Spearman’s \(p\) (Conover, 1999) to test for positive correlations. We plotted the variables by year to visually assess the correlations; the variables were standardized \([\text{value} – \text{mean}] / \text{standard deviation}\) to put them on the same scale. Analyses were done using R 2.7.0 (R Development Core Team, 2004).

3. Results

3.1. Regional comparisons

Overall, the Mid-Atlantic region had 5 times more total indicator debris than the Northeast and Southeast Atlantic regions (Table 1). By source category, the Mid-Atlantic region had 10 times more land-based debris and 4 times more general-source debris than the other two regions; ocean-based debris was similar across regions (Table 1). When looking at proportions, about half of the total indicator debris in the Mid-Atlantic region was land-based, which was higher than that found in the Northeast and Southeast Atlantic regions (Table 1). The proportion of general-source debris was highest in the Southeast Atlantic region (Table 1). Ocean-based debris made up about 40% of total indicator debris in the Northeast Atlantic region, which was twice that of the other regions (Table 1).

3.2. Assessment of trend

Time trends in total indicator debris varied among regions \((P < 0.001)\). Though the regions had significant non-linear patterns, there were no significant linear trends (Table 2). The Northeast and Mid-Atlantic regions also had significant effects due to weather in the weeks before the survey. Specifically, more debris was found on the beaches after periods of inclement weather (storms, rain, and heavy seas).

Time trends in land-based indicator debris varied among regions \((P < 0.001)\). There was a significant linear increase in the Mid-Atlantic region (Table 2). There was no significant trend for the Northeast Atlantic region; the Southeast Atlantic region had a significant non-linear pattern but no significant linear trend (Table 2).

Time trend in general-source indicator debris varied among regions \((P < 0.001)\). The Mid-Atlantic region had a significant increase in general-source debris over the study period (Table 2). Specifically, general-source debris in the Mid-Atlantic region increased after a drop early in the series (Fig. 2b). The Northeast and Southeast Atlantic regions had significant non-linear time patterns (Fig. 2a and c) but no significant linear trends (Table 2). The Mid-Atlantic region also had significant effects due to weather in the weeks before the survey. Specifically, more general-source debris was found on the beaches after periods of inclement weather (storms, heavy seas).

Time trend in ocean-based indicator debris varied among regions \((P < 0.001)\). There was no linear change in the Northeast Atlantic region (Table 2) though there were significant non-linear patterns (Fig. 3a). In contrast, ocean-based debris significantly decreased in the Mid-Atlantic and Southeast Atlantic regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of sites</th>
<th>Total indicator debris</th>
<th>Land-based debris</th>
<th>General-source debris</th>
<th>Ocean-based debris</th>
<th>Proportion (land-based debris)</th>
<th>Proportion (general-source debris)</th>
<th>Proportion (ocean-based debris)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast Atlantic</td>
<td>12</td>
<td>51.2(10.7)</td>
<td>14.2(3.8)</td>
<td>14.9(2.4)</td>
<td>18.7(5.2)</td>
<td>0.27(0.03)</td>
<td>0.32(0.02)</td>
<td>0.41(0.02)</td>
</tr>
<tr>
<td>Mid-Atlantic</td>
<td>14</td>
<td>214.3(100.6)</td>
<td>133.8(70.9)</td>
<td>61.1(26.4)</td>
<td>19.4(7.6)</td>
<td>0.52(0.04)</td>
<td>0.34(0.03)</td>
<td>0.14(0.03)</td>
</tr>
<tr>
<td>Southeast Atlantic</td>
<td>15</td>
<td>41.6(10.2)</td>
<td>16.3(3.9)</td>
<td>17.8(5.3)</td>
<td>7.5(1.5)</td>
<td>0.38(0.02)</td>
<td>0.42(0.02)</td>
<td>0.20(0.01)</td>
</tr>
</tbody>
</table>

Table 1
Means of marine debris counts (number/500 m) and proportions; data were collected as part of the National Marine Debris Monitoring Program for 3 regions on the Atlantic coast of the United States, 1997–2007. Standard errors are in parentheses. Within a column, values with the same superscript are not significantly different at \(z = 0.10\).
Table 2

<table>
<thead>
<tr>
<th>Debris category</th>
<th>Region</th>
<th>Best model</th>
<th>Adjusted $R^2$</th>
<th>Linear trend in survey date</th>
<th>$P$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>Northeast Atlantic</td>
<td>$s$(month) + $s$(survey date) + weather prior to survey + site</td>
<td>0.434</td>
<td>None</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Mid-Atlantic</td>
<td>$s$(month) + $s$(survey date) + weather prior to survey + site</td>
<td>0.723</td>
<td>None</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Southeast Atlantic</td>
<td>$s$(month) + $s$(survey date) + site</td>
<td>0.534</td>
<td>None</td>
<td>0.84</td>
</tr>
<tr>
<td>Land-based</td>
<td>Northeast Atlantic</td>
<td>$s$(month) + site</td>
<td>0.443</td>
<td>None</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Mid-Atlantic</td>
<td>$s$(month) + survey date + weather prior to survey + site</td>
<td>0.734</td>
<td>Positive</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Southeast Atlantic</td>
<td>$s$(month) + $s$(survey date) + site</td>
<td>0.531</td>
<td>None</td>
<td>0.23</td>
</tr>
<tr>
<td>General-source</td>
<td>Northeast Atlantic</td>
<td>$s$(month) + $s$(survey date) + weather prior to survey + site</td>
<td>0.291</td>
<td>None</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Mid-Atlantic</td>
<td>$s$(month) + $s$(survey date) + weather prior to survey + site</td>
<td>0.623</td>
<td>Positive</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Southeast Atlantic</td>
<td>$s$(month) + $s$(survey date) + site</td>
<td>0.456</td>
<td>None</td>
<td>0.57</td>
</tr>
<tr>
<td>Ocean-based</td>
<td>Northeast Atlantic</td>
<td>$s$(month) + $s$(survey date) + site</td>
<td>0.361</td>
<td>None</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>Mid-Atlantic</td>
<td>$s$(month) + $s$(survey date) + site</td>
<td>0.593</td>
<td>Negative</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Southeast Atlantic</td>
<td>$s$(month) + $s$(survey date) + site</td>
<td>0.392</td>
<td>Negative</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Fig. 2. Non-linear relationship of survey date and general-source debris for the National Marine Debris Monitoring Program sites from (a) the Northeast Atlantic region, (b) the Mid-Atlantic region, and (c) the Southeast Atlantic region. Survey date is coded so that 1000 = 26 September 1997 and 4550 = 27 April 2007.

(3.3. Drivers

3.3.1. Land-based debris and mechanism variables

Site improved the variance explained by the land-based indicator debris model in all regions; this improvement was particularly large in the Mid-Atlantic region where deviance explained increased by 70% when Site was in the model (Table 3, $\Delta D_A$). Adding mechanism variables to the models decreased the importance of Site by over 80% for the Mid-Atlantic region and by over 90% for the Northeast and Southeast Atlantic regions (Table 3, $\Delta D$).

All mechanism variables were significant ($P < 0.05$); the model terms (linear, log, or linear and log) varied among regions. For all regions, reserve sites had significantly fewer land-based indicator items than the beach sites. For the distance variables, land-based indicator items decreased as distance increased to the nearest population center of at least 250,000, increased with increasing population size within 40 km of the site, and increased as distance to the
closest daytrip city increased. Non-linear relationships indicated a potential threshold beyond which there was no effect of the variable on amount of land-based indicator debris (Fig. 4a). In other words, as population size increased the total amount of land-based debris also increased, but the per capita amount of increase decreased.

The effect of distance to outflows varied depending on where the site was in relation to an outflow. In all regions, there were more land-based indicator items if the site was closer to an outflow south of the site. In the Northeast and Southeast Atlantic regions there were more land-based items if the site was farther from an outflow to the north, while in the Mid-Atlantic region there was more land-based items if sites were closer to an outflow from the north.

3.3.2. Ocean-based debris and mechanism variables

Regardless of region, site effects improved the variance explained in the trend model for ocean-based indicator debris; this improvement was largest in the Mid-Atlantic regions where deviance explained increased by 58% when Site was in the model (Table 3, $D_A$). With the mechanism variables in the models, the importance of Site decreased by about 30% for the Northeast Atlantic, almost 50% for the Mid-Atlantic, and almost 75% for the Southeast Atlantic region (Table 3, $D_D$).

Distance to port and distance to the closest circulation system were always significant ($P < 0.0001$), although the exact terms (linear, log, or linear and log) varied among regions. In all regions, the number of ocean-based indicator items declined with increasing distance from a port and with increasing distance from the nearest

Table 3

Percentage deviance explained for trend models of land- and ocean-based indicator debris involving site and mechanism variables for data collected as part of the National Marine Debris Monitoring Program for 3 regions on the Atlantic coast of the United States, 1997–2007. All values are in percent.

<table>
<thead>
<tr>
<th>Region</th>
<th>Northeast Atlantic</th>
<th>Mid-Atlantic</th>
<th>Southeast Atlantic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Land-based</td>
<td>Ocean-based</td>
<td>Land-based</td>
</tr>
<tr>
<td>Trend model with site (A)</td>
<td>45.3</td>
<td>37.9</td>
<td>73.9</td>
</tr>
<tr>
<td>Trend model without site (B)</td>
<td>6.1</td>
<td>4.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Trend model with mechanism variables (C)</td>
<td>42.0</td>
<td>17.9</td>
<td>61.7</td>
</tr>
<tr>
<td>Trend model with mechanism variables and site (D)</td>
<td>45.3</td>
<td>40.3</td>
<td>73.9</td>
</tr>
<tr>
<td>Improvement in trend model without mechanism variables when site is added ($D_A$)</td>
<td>39.2</td>
<td>33.2</td>
<td>70.4</td>
</tr>
<tr>
<td>Improvement in trend model with mechanism variables when site is added ($D_D$)</td>
<td>3.3</td>
<td>22.4</td>
<td>12.2</td>
</tr>
<tr>
<td>Change in importance of site when mechanism variables are added ($D_D^C$)</td>
<td>$-91.6$</td>
<td>$-32.5$</td>
<td>$-82.7$</td>
</tr>
</tbody>
</table>
ocean circulation system. In the Northeast and Mid-Atlantic regions, the relationship with distance from port was the stronger of the two relationships. In the Southeast Atlantic region, however, the relationship with distance from the Gulf Stream (the nearest ocean circulation system) was the stronger effect.

In contrast, the fishing variables were not always significant. In the Northeast Atlantic region, ocean-based indicator items increased as fishing activity in the survey month and the previous month increased ($P < 0.001$); this relationship was non-linear with an upper asymptote (Fig. 4b). In contrast, in the Mid- and Southeast Atlantic regions, ocean-based debris did not show significant relationships with fishing activity.

### 3.4. Trend assessments at the regional scale

The Northeast Atlantic coastal population increased 8% over the study period; in the Mid- and Southeast Atlantic regions coastal populations increased 10% and 19%, respectively. However, there was a significant positive relationship between regional land-based indicator items and regional coastal population only for the Mid-Atlantic region ($\rho = 1.00$, df = 8, $P < 0.001$); predicted land-based debris loads increased linearly and estimated coastal population also increased every year (Fig. 5a). In contrast, there was no relationship for the Southeast Atlantic region though coastal population increased every year ($\rho = -0.083$, df = 8, $P = 0.85$). Because land-based indicator items had no time trend in the Northeast Atlantic region (Table 2), no correlation was calculated.

There were significant positive relationships between predicted ocean-based indicator debris loads and regional commercial fishing activity for the Mid-Atlantic and Southeast Atlantic regions (Mid-Atlantic: $\rho = 0.60$, df = 8, $P = 0.043$; Southeast Atlantic: $\rho = 0.65$, df = 8, $P = 0.033$). These relationships showed yearly oceanic indicator debris loads declining as yearly commercial fishing activity declined (Fig. 6b and c). For the Northeast region, in contrast, there was no relationship at this scale ($\rho = 0.32$, df = 7, $P = 0.22$; Fig. 6a).

### 4. Discussion

For the first time, we have been able to document regional differences in amounts, composition and long-term trends of marine debris indicators along the Atlantic coast of the United States. We were also able to evaluate these differences in light of drivers that either produce or affect deposition patterns of marine debris.

#### 4.1. Amounts and trends

Amounts of indicator debris varied by region along the Atlantic coast. Amount of total indicator debris was highest in the Mid-

![Fig. 4](image_url). Relationship between (a) land-based indicator debris and population within 40 km of the site and (b) ocean-based indicator debris and fin fish catch in the month of the survey for the Northeast Atlantic region of the National Marine Debris Monitoring Program.

![Fig. 5](image_url). Standardized regional predicted land-based indicator debris (dashed line) and regional coastal population (solid line) by year for the (a) Mid-Atlantic and (b) Southeast Atlantic regions of the National Marine Debris Monitoring Program.
Atlantic region, specifically due to the predominance of land-based debris items. The dominance of land-based debris in the Mid-Atlantic was similar to that found by Ribic (1998) and Thornton and Jackson (1998) for two different beaches in the Mid-Atlantic region. While dominance of land-based debris has been found for a variety of beaches in different areas of the world (e.g., Coe and Rogers, 1997; Cunningham and Wilson, 2003; Silva-Iniguez and Fischer, 2003; Storrier et al., 2007), this pattern was not followed in the Northeast or Southeast Atlantic regions. The Northeast region has the smallest coastal population of the three regions and has a relatively stable fishery, leading to a predominance of ocean-based debris. The Southeast Atlantic region has about half the population of the Mid-Atlantic region but also has a strong current moving along the coast, potentially affecting deposition patterns.

There were also regional differences in trends. In the Northeast Atlantic region, no change was detected in the amounts of land-based, general-source, or ocean-based indicator debris over the 10-year span of this study. The coastal population of this region increased only 8% during this period and year-to-year changes in fishing activity were relatively small. In the Mid-Atlantic region, land-based and general-source debris increased while ocean-based debris decreased. The increase in land-based debris paralleled the 10% increase in the coastal population; the decrease in the ocean-based debris paralleled the decrease in regional commercial fishing activity. In the Southeast Atlantic region, despite a 19% increase in coastal population there was no detectable change in land-based or general-source debris, while ocean-based debris decreased. As was the case for the Mid-Atlantic region, the decrease in ocean-based debris was correlated with the decrease in regional commercial fishing activity.

Within-year variability by season or by month, such as we found for the Atlantic coast, is well known and often linked to human activities and extreme weather events (e.g., Golik and Gertner, 1992; Frost and Cullen, 1997; Madzena and Lasiak, 1997; Thornton and Jackson, 1998; Abu-Hilal and Al-Najjar, 2004; Martinez-Ribes et al., 2007). In contrast, between-year variability has not been as well characterized. In our study, in all regions we found complex nonlinearities in debris deposition patterns across years, also observed by Ribic (1998) for a single site on the Atlantic coast. What processes drive between-year variability remain to be elucidated. Indeed, researchers are just beginning to understand how much spatial and temporal variability there is in these systems and how that variability can affect conclusions regarding debris patterns. For example, Sheavly (2007) considered a 5-year subset of

![Fig. 6. Standardized regional predicted ocean-based indicator debris (dashed line) and regional fishing activity (solid line) by year for the (a) Northeast Atlantic, (b) Mid-Atlantic, and (c) Southeast Atlantic regions of the National Marine Debris Monitoring Program.](image-url)
this data set and drew conclusions about debris trends that turned out to be limited to just that 5-year period; the trends were not sustained when considering a longer period of time (this study). Thus, whether looking for trends or assessing the impact of mitigation strategies, spatial and temporal variability are key considerations for constructing monitoring programs and analyses that will yield robust results.

4.2. Drivers

4.2.1. Land-based debris

Previous work on drivers, particularly human population (e.g., Garrity and Levings, 1993; Golik, 1997; Frost and Cullen, 1997; Madzena and Lasiak, 1997; Thornton and Jackson, 1998; Debrot et al., 1999; Cunningham and Wilson, 2003; Ivar do Sul and Costa, 2007; Martínez-Ribes et al., 2007; Storrier et al., 2007; Silva et al., 2008) have assumed a simple linear relationship between the driver and debris load. In many disciplines, shifting from simple linear to non-linear dynamics has yielded new insights into the processes under study. We found that the simple concept of more people producing proportionately more debris was not supported. At the local level, in areas of higher population the amount of land-based debris generated per capita was smaller than in areas of lower population. This may indicate that as population grows on the Atlantic coast more resources are used to manage waste. This can range from laws making reducing packaging mandatory to broader recycling programs to funding of better waste management facilities. All these activities can decouple population size from debris deposition. This decoupling may be behind the lack of relationships between regional population growth and land-based debris loads in the Northeast and Southeast regions.

Our exploratory results also suggest that the relationships between river outlets and debris deposition are not always straightforward (i.e., close by river outlets = more debris; Storrier et al., 2007; Cheshire et al., 2009). We found two effects: (1) there was a minimum distance from a river outlet that the beach had to be beyond to see an effect and (2) effects were detectable farther away than a simple linear model would predict. The dynamics of near-shore circulation patterns, which are poorly-understood, likely play a role in linking outlet debris sources to beach deposition.

Reserve sites had significantly fewer land-based debris items in all three regions. Because reserve sites had minimal human presence, this suggests that on the Atlantic coast of the United States, a substantial amount of debris is directly deposited by people visiting beach areas (not simply washed ashore). Therefore, debris management strategies targeted at changing people’s behaviour have some potential for reducing the debris load on beaches. In addition, loads on reserve sites may provide a benchmark against which to measure success.

Overall, for land-based debris the straightforward mechanism variables and non-linear dynamics for those variables replaced a very localized descriptive variable, Site. This is useful for efforts to mitigate land-based marine debris. A descriptive site average provides little insight into the potential utility of mitigation strategies. On the other hand, identifying controlling processes, how much variability they control, and the shape of their response curves can provide very useful insight into what mitigation strategies might be successful as well as how successful.

4.2.2. Ocean-based debris

We found significant relationships between levels of ocean-based indicator items and commercial fishing activity at both local and regional scales. There have been few studies that have tried to link fishing activity and beach debris loads. Walker et al. (1997) found a qualitative positive inter-year relationship between longline fishing and beach debris in a six-year study on Bird Island, South Georgia (Southern Ocean); Edyvane et al. (2004) discussed how a reduction of some ocean-based debris items over a 10 year period was likely related to a documented decline in specific inshore fisheries. Cunningham and Wilson (2003) detected a positive relationship between fishing debris on three beaches and a measure of the number of commercial fishing vessels during a single season. Overall, these qualitative and quantitative results support the expectation that oceanic fishing activity is related to the amount of oceanic debris deposited on coastal beaches.

We found that the scale at which relationships appeared was linked to the scale at which the driver was varying. When fishing activity was relatively stable over time at the regional scale, as in the Northeast, relationships were detected at the local scale. In contrast, when fishing activity was declining regionally over time, as in the Mid- and Southeast Atlantic, relationships were detected at a regional scale. The relationship between ocean-based debris and commercial fishing activity in our study might have been stronger if there was information about how much fishing occurs at various distances from shore. The National Marine Fisheries Service began to collect and share this information in 2008, after the conclusion of our study.

Distance to ports, an indirect measure of commercial shipping activity, was also influential for understanding ocean-based debris. We were unable to find any previous work showing quantitative relationships between ports and debris. Storrier et al. (2007) found no relationship between the amount of total beach debris and presence of a harbor or marina near the survey beaches; Abu-Hilal and Al-Najjar (2004) discussed how ports near their sites were the likely source of beach debris. For our study, the relationships linking distance to port and debris load might have been stronger if information on the amounts and types of commercial shipping activities occurring at the ports had been easily available. In addition, other measures of commercial shipping activities, such as information on shipping lanes and their usage, not currently available for the Atlantic coast, would provide a promising avenue for understanding ocean-based debris loads.

We found that large-scale circulation systems affected ocean-based indicator debris loads. Although we are not aware of any previous work linking Atlantic circulation systems and marine debris, understanding circulation patterns was an important component of Edyvane et al. (2004) in Australia, including experiments to understand near-shore circulation patterns. Gregory and Ryan (1997) qualitatively considered the effect of circulation patterns in interpreting beach debris in their review of Southern Hemisphere marine debris. The influence of near-shore circulation on beach litter deposition for islands is also known (e.g., windward versus leeward, Debrot et al., 1999). Morishige et al. (2007) investigated a variety of physical processes that might affect beach debris deposition patterns on French Frigate Shoals, a remote island in the Pacific Ocean; they only found one process (El Niño-Southern Oscillation) to be important. There are likely other aspects of the oceanic system that need to be considered when thinking about drivers affecting beach debris patterns.

Overall, for ocean-based debris our effort to delineate drivers that could replace site effects was successful, but not nearly as successful as for the land-based analysis. While we had some direct information on fishing activity, we lacked direct measures of other potentially important drivers, such as commercial shipping and recreational activities. More work remains to be done to understand the drivers influencing deposition of ocean-based debris on beaches. Incorporating the idea of drivers into studies from the beginning rather than after the fact is recommended.
5. Conclusions

There were long-term changes in indicator debris on the Atlantic coast of the United States over the ten-year period of this study. The changes varied by region and differed by source category. The Southeast Atlantic region had low land-based and general-source debris loads and no increases despite the largest percentage increase in coastal population over the study period. The Northeast region, with a smaller percentage population increase, also had low land-based and general-source debris loads and no increases. The Mid-Atlantic fared the worst, with an increasing coastal population and heavy land-based and general-source debris loads that increased over time. Ocean-based debris did not change in the Northeast region where the fishery is relatively stable while it declined significantly over the Mid-Atlantic and Southeast regions. This decrease came at the economic cost of a significantly reduced commercial fishing sector.

Our study demonstrates the fundamental effectiveness of using fairly simple measurements based on human activity and physical processes to understand debris deposition, and it suggests significant potential for using knowledge of local and regional drivers to inform management strategies for reducing beach debris loads. While our analyses were informative, collecting data on drivers at the time of the surveys is the ideal situation. Thinking carefully about drivers during the planning of monitoring programs and collecting information about the proposed mechanisms during the program is likely to be more effective than attempting to deduce processes and collect information after the fact.

Although there are many short-term studies on marine debris, a long-term perspective has heretofore been missing. With the development of long-term monitoring programs similar to the National Marine Debris Monitoring Program around the world (Cheshire et al., 2009), there is the potential to help management at individual sites as well as generate larger-scale perspectives (from regional to global) to inform decision makers. Monitoring programs that address clear questions and generate data capable of answering those questions are an effective way to gather information that can fruitfully be integrated with research and adaptive management (Lovett et al., 2007). Management challenges are substantial (Cho, 2005; Criddel et al., 2009) but solid information like that provided by the National Marine Debris Monitoring Program is one key to addressing this pressing pollution issue.

Acknowledgements

This paper would not have been possible without the many volunteers and organizations that collected the data; we sincerely thank all who participated in the surveys. In particular we thank Dr. Gayle Kraus (University of ME-Machias), Ted and Paula Merritt, Jen Kennedy (Blue Ocean Society for Marine Conservation), Joe Cravalho (MA Beach Buggy Association), Sharon Sneed (Pen Bay Stewards), Carl Rasmussen and Russell Moehlich (Friends of Cape Cod National Seashore), Mary Marges, Suzan Bellincampi and Sarah Trudel (The Trustees of Reservation), Scott Comings (The Nature Conservancy), Bob Glover and Jack Isaacs (Audubon Society), Barbara Boyd and students (Marine Academy of Science and Technology), Carol Elliot and Tom Sherman (Alliance for a Living Ocean), Earl and Faith Chamberlin (DE Mobile Surf Fishermen), Bill Lewis (Strathmere Fishing and Environmental Club), Fred Pulls and Gerllyn Mirales (Chincoteague NWR), Dr. Gail Cannon and Zoe Meletis (Duke Marine Laboratory), Fred Hay and Susan Johnston (Sapeo Island NERR), Cathy Marsh and Ann Arnold (Volusia Flagler Sierra Club), Liz Melvin and Jim Kriewaldt (Keep Breard Beautiful) and Lynn Emerson and Andrea Povinelli (The Nature Conservancy, Blowing Rocks Reserve) for their efforts in carrying out monthly data collections for over 10 years. The US Department of Commerce National Oceanic and Atmospheric Administration Marine Entanglement Research Program and the US Environmental Protection Agency (EPA) Office of Water funded the workshops through the Center for Marine Conservation (now the Ocean Conservancy) that led to the development of the National Marine Debris Monitoring Program. The US EPA Office of Water funded data collection through the Ocean Conservancy. The US Geological Survey Cooperative Research Units Program and the US Forest Service funded the analysis of the data used in this paper. Mention of trade names or commercial products does not constitute endorsement for use by the US Government. We thank the Department of Forest and Wildlife Ecology, University of Wisconsin, Madison, for assistance with publication expenses.

Appendix A

See Table A4.

References


Table A4

| Indicator items by source category used for the National Marine Debris Monitoring Program. |
|-----------------------------------|-----------------------------------|-----------------------------------|
| Ocean-based                       | Land-based                        | General-source                    |
| Gloves                            | Metal beverage cans               | Plastic bags                      |
| Plastic sheets                    | Motor oil containers (1-quart)    | Strapping bands                   |
| Light bulbs/tubes                 | Balloons                          | Plastic bottles                   |
| Oil/gas containers                | Six-pack rings                    | (no motor oil containers)         |
| Pipe-thread protectors            | Straws                            |                                  |
| Nets (> 5 meshes)                 | Syringes                          |                                  |
| Traps/pots                        | Condoms                           |                                  |
| Fishing line                      | Tampon applicators                |                                  |
| Light sticks                      | Cotton swabs                      |                                  |
| Rope (> 1 m)                      |                                  |                                  |
| Salt bags                         |                                  |                                  |
| Fish baskets                      |                                  |                                  |
| Cruise line logo items            |                                  |                                  |
| Floats/buoys                      |                                  |                                  |