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Trends in Marine Debris in the U.S. Caribbean and the Gulf of Mexico 1996-2003 *

Tendências do Lixo Marinho no Caribe Norte-Americano e no Golfo do México 1996-2003

Christine A. Ribic[@, 1], Seba B. Sheavly [2] & David J. Rugg [3]

ABSTRACT

Marine debris is a widespread and globally recognized problem. Sound information is necessary to understand the extent of the problem and to inform resource managers and policy makers about potential mitigation strategies. Although there are many short-term studies on marine debris, a longer-term perspective and the ability to compare among regions has heretofore been missing in the U.S. Caribbean and the Gulf of Mexico. We used data from a national beach monitoring program to evaluate and compare amounts, composition, and trends of indicator marine debris in the U.S. Caribbean (Puerto Rico and the U.S. Virgin Islands) and the Gulf of Mexico from 1996 to 2003. Indicator items provided a standardized set that all surveys collected; each was assigned a probable source: ocean-based, land-based, or general-source. Probable ocean-based debris was related to activities such as recreational boating/fishing, commercial fishing and activities on oil/gas platforms. Probable land-based debris was related to land-based recreation and sewer systems. General-source debris represented plastic items that can come from either ocean- or land-based sources; these items were plastic bags, strapping bands, and plastic bottles (excluding motor oil containers). Debris loads were similar between the U.S. Caribbean and the western Gulf of Mexico; however, debris composition on U.S. Caribbean beaches was dominated by land-based indicators while the western Gulf of Mexico was dominated by ocean-based indicators. Beaches along the eastern Gulf of Mexico had the lowest counts of debris; composition was dominated by land-based indicators, similar to that found for the U.S. Caribbean. Debris loads on beaches in the Gulf of Mexico are likely affected by Gulf circulation patterns, reducing loads in the eastern Gulf and increasing loads in the western Gulf. Over the seven years of monitoring, we found a large linear decrease in total indicator debris, as well as all source categories, for the U.S. Caribbean. Lower magnitude decreases were seen in indicator debris along the eastern Gulf of Mexico. In contrast, only land-based indicators declined in the western Gulf of Mexico; total, ocean-based and general-source indicators remained unchanged. Decreases in land-based indicators were not related to human population in the coastal regions; human population increased in all regions over the time of the study. Significant monthly patterns for indicator debris were found only in the Gulf of Mexico; counts were highest during May through September, with peaks occurring in July. Inclement weather conditions before the time of the survey also accounted for some of the variation in the western Gulf of Mexico; fewer items were found when there were heavy seas or cold fronts in the weeks prior to the survey, while tropical storms (including hurricanes) increased the amount of debris. With the development around the globe of long-term monitoring programs using standardized methodology, 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. Incorporating mechanisms producing debris into marine debris programs would be a fruitful area for future research.

Keywords: marine debris, beaches, U.S. Caribbean, Gulf of Mexico, trends, monitoring

@ - Corresponding author: caribic@wisc.edu
1 - U.S. Geological Survey, Wisconsin Cooperative Wildlife Research Unit, Department of Forest and Wildlife Ecology, University of Wisconsin, 218 Russell Labs, 1630 Linden Drive, Madison, WI 53706 USA
2 - Sheavly Consultants, 3500 Virginia Beach Blvd., Suite 212, Virginia Beach, VA 23452 USA; seba@sheavlyconsultants.com
3 - U.S. Forest Service, Northern Research Station, 1 Gifford Pinchot Drive, Madison, WI 53726 USA; drugg@fs.fed.us

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RESUMO

O lixo marinho é reconhecido como um problema global e generalizado. Informações confiáveis são necessárias para entender a extensão desse problema, para informar gestores costeiros e elaboradores de políticas públicas sobre as estratégias de mitigação e para avaliar a eficiência das estratégias de mitigação implementadas. Embora existam muitos estudos de curto prazo sobre lixo marinho, ainda carecemos de estudos sobre a região norte-americana do Caribe e do Golfo do México que apresentem uma perspectiva de longo prazo e, talvez mais importante, que sejam capazes de fazer comparações entre regiões. A realização de amostragens para estimar a quantidade de lixo marinho que se acumula nas praias é uma técnica consagrada para avaliar o status da contaminação, não apenas das praias amostradas, mas também como um índice das condições das águas adjacentes. Nós usamos dados obtidos do Programa Nacional Norte-Americano de Monitoramento de Lixo Marinho, um programa de monitoramento praial, para avaliar e comparar a composição e as tendências de itens de lixo marinho indicadores na região norte-americana do Mar do Caribe (Porto Rico e Ilhas Virgens Norte-Americanas) e no Golfo do México, de 1996 a 2003. O programa de monitoramento mediu a acumulação líquida de itens indicadores em um trecho de 500 m de praia a cada 28 dias; sítios foram escolhidos aleatoriamente. O comprimento de 500 m garantiu que um número adequado de itens indicadores fosse coletado para a análise. Itens indicadores forneceram um conjunto de dados padronizados para todas as amostragens; para cada item foi atribuído uma fonte provável: fontes marinhas, fontes terrestres, ou fontes gerais. Itens cuja provável fonte seja marinha são aqueles relacionados com atividades como a náutica/pesca recreativa, pesca comercial e plataformas de óleo e gás. Itens cuja fonte provável seja terrestre foram relacionados a recreação terrestre e sistemas de esgotamento sanitário. Fontes gerais representaram itens plásticos que podem vir tanto de fontes marinhas como terrestres, tais como sacolas plásticas, fitas para embalagens e garrafas plásticas (excetuando-se os vasilhames para óleos lubrificantes para motores). Nós analisamos 344 amostragens em 6 locais na região caribenha, 570 amostragens em 8 locais na região leste do Golfo do México e 182 amostragens em 4 locais na região oeste do Golfo do México. Nós utilizamos contagens médias de cada local (número/500m) e proporções para testar diferenças regionais em termos de quantidade e de categoria de fonte, usando um modelo linear; a significância estatística foi avaliada ao nível de $\alpha = 0.10$, conforme especificado no planejamento do programa de monitoramento. Nós usamos modelos aditivos generalizados para modelar eventuais padrões temporais, além de efeitos temporais intra-anuais e efeitos associados a eventos meteorológicos inclementes (eventos de alta energia). Nossa abordagem na modelagem dos dados permitiu acomodar possíveis relações não-lineares e foi ajustada para considerar padrões potenciais relacionados à variação temporal intra-anual e aos eventos meteorológicos inclementes, reduzindo a variabilidade e obtendo assim maior poder estatístico para testar padrões inter-anuais. Nós descobrimos que a carga de resíduos foi similar entre a região norte-americana do Caribe e a região ocidental do Golfo do México; contudo, a composição dos resíduos nas praias norte-americanas do Caribe foi dominada por itens indicadores de fontes terrestres, enquanto que a região ocidental do Golfo do México foi dominada por itens indicadores de fontes marinhas. Praias ao longo da costa leste do Golfo do México apresentaram as menores quantidades de lixo marinho; a composição foi dominada por indicadores de origem terrestre, similar ao que foi encontrado para o Caribe norte-americano. Cargas de resíduos nas praias do Golfo do México são provavelmente afetadas pelos padrões de circulação do Golfo, reduzindo as cargas na região leste do Golfo e aumentando as cargas na região oeste do Golfo. Para o Caribe norte-americano, nós identificamos uma grande redução na quantidade total de itens indicadores, assim como em cada categoria de origem, ao longo dos sete anos de monitoramento. Reduções de menor magnitude foram observadas para a quantidade total de itens indicadores ao longo da porção leste do Golfo do México. Em contraste, apenas os indicadores de origens terrestres diminuíram na costa oeste do Golfo do México; indicadores totais, de origens marinhas e de origens gerais permaneceram inalterados. Padrões mensais significativos dos itens indicadores foram encontrados apenas no Golfo do México; as contagens mais elevadas foram observadas durante maio a setembro, com picos em julho. Condições meteorológicas severas antes da data de amostragem também foram responsáveis por alguma variação na parte oeste do Golfo do México. Menos itens foram encontrados quando haviam ocorrido ressacas ou frentes frias na semana anterior a coleta, enquanto que tempestades tropicais (incluindo furacões) aumentaram a quantidade de lixo acumulado. As reduções dos itens indicadores de fontes terrestres não foram relacionadas à população humana nas regiões costeiras; a população humana aumentou em todas as regiões ao longo do período estudado. Mais investigação retrospectiva é necessária para determinar quais mecanismos podem ter causado essas reduções. Com o desenvolvimento ao redor do globo de programas de monitoramento de longo prazo baseados em metodologias consagradas, existe o potencial de se auxiliar o gerenciamento costeiro ao nível local, assim como a possibilidade de se gerar perspectivas de maior escala (regional e global) visando bem informar os tomadores de decisão. A incorporação de mecanismos que transformam resíduos em programas de lixo marinho seria uma área promissora para a pesquisa futura.

Palavras-chave: *lixo marinho, praias, região norte-americana do Caribe, Golfo do México, tendências, monitoramento*

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, yet potentially solvable pollution problems plaguing the world's oceans and waterways (Coe & Rogers, 1997; UNEP, 2009). Sound information is necessary to understand the extent of the problem and to inform management of potential mitigation strategies (Criddle *et al.*, 2009). However, a National Academy of Sciences review (Criddle *et al.*, 2009) concluded there was little quantitative information on amounts, sources, and trends of marine debris. This assessment was echoed specifically for the wider Caribbean and Latin America region by Ivar do Sul & Costa (2007). In addition, comparisons among regions are rare (*e.g.*, Ribic *et al.*, 2010) making it difficult to put regional information into perspective (Ivar do Sul & Costa, 2007).

Conducting surveys to monitor marine debris that collects along beaches is an established technique for evaluating the status of the debris, not just on those beaches, but also as an index of conditions in surrounding waters (Dixon & Dixon, 1981; Ribic *et al.*, 1992; Rees & Pond, 1995; Alkalay *et al.*, 2007; Cheshire *et al.*, 2009). Where long-term data have been collected (*e.g.*, Edyvane *et al.*, 2004) important insights into regional issues can be gained. However, there have been few large-scale and long-term programs available to fill information gaps (UNEP, 2009; Barnes *et al.*, 2009; Cheshire *et al.*, 2009).

One such large-scale program, the National Marine Debris Monitoring Program, was designed to determine quantitatively if the amount of debris on the U.S. coastline

was changing and what were its major sources (Escardó-Boomsma *et al.*, 1995). One geographic area of the study was the Gulf of Mexico, including Puerto Rico and the U.S. Virgin Islands (i.e., U.S. Caribbean). Following the design intent of the Program, our primary objective is to use Program data to determine whether there were trends in marine debris indicator items found in the U.S. Caribbean and Gulf of Mexico from 1996 through 2003. Our secondary objective is to compare the amounts and composition of the indicator items across regions. In all cases, we test the null hypothesis of no change or no difference among regions.

2. STUDY AREA

The U.S. Caribbean and the Gulf of Mexico are linked oceanographically by currents. The Caribbean Current transports water into the Gulf of Mexico as part of the clockwise Loop Current; the Loop Current joins the Florida Current to exit out of the Gulf northward (Fig. 1) (Gyory *et al.*, 2008a,b). As the Loop Current extends northward and westward into the Gulf, large clockwise-rotating rings are shed that slowly move westward or west-southwestward across the Gulf, transporting nutrients and water from the eastern Gulf to the western Gulf; in addition, meso-scale eddies of both clockwise and counter-clockwise rotation are found throughout the Gulf, affecting movement of water on-shore and off-shore in the Gulf (Wiseman & Sturges, 1999).

We classified sites west of the Mississippi River outflow as the western Gulf of Mexico region; those east of the outflow were the eastern Gulf of Mexico region (Fig. 1). Sites on Puerto Rico and the U.S. Virgin Islands made up the U.S. Caribbean region (Fig. 1).

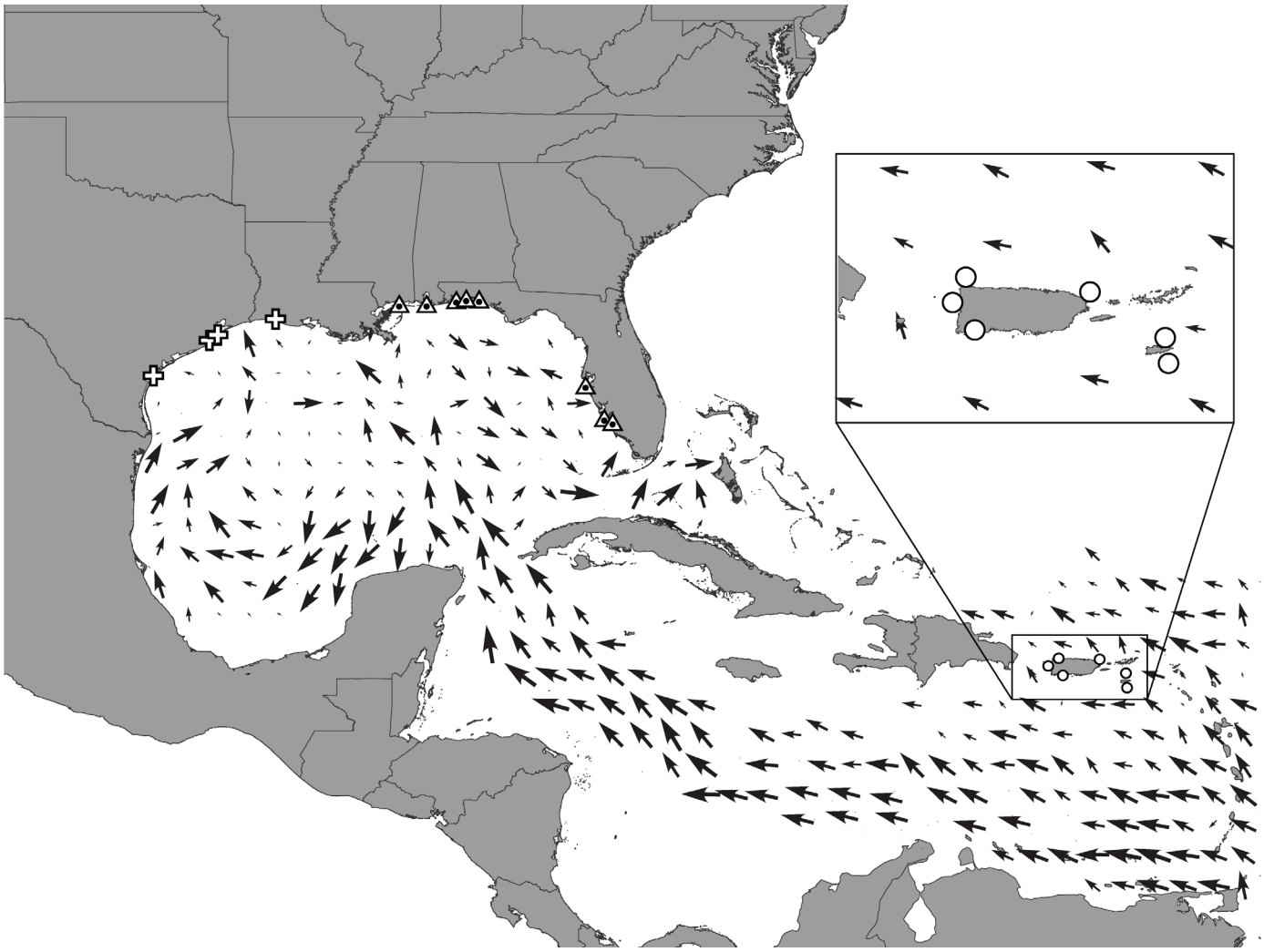

Figure 1. Study sites from the National Marine Debris Monitoring Program along the coasts of the Gulf of Mexico and the U.S. Caribbean. The western Gulf of Mexico sites are all sites west of the outflow of the Mississippi River (+), the eastern Gulf of Mexico sites are all sites east of the outflow of the Mississippi River to Florida (triangles), and the U.S. Caribbean sites (circles) are sites on Puerto Rico and the U.S. Virgin Islands. The current arrows are from the MGSVA ocean velocity data (April-June average) (Mariano *et al.*, 1995). Larger arrows indicate a greater velocity. The resolution of the data points is 1º x 1º.

Figura 1: locais de estudo do Programa Norte-Americano de Monitoramento de Lixo Marinho ao longo da costa do Golfo do México e da região norte-americana do Caribe. Os locais no Golfo do México ocidental são todos a oeste da foz do rio Mississippi (+), os locais no Golfo do México oriental são todos a leste da foz do rio Mississippi, até a Flórida (triângulos), e os locais na região norte-americana do Caribe (círculos) são locais em Porto Rico e nas Ilhas Virgens Norte-Americanas. As setas de corrente são dados de velocidade do oceano (média de Abril-Junho) (Mariano et al., 1995). Setas maiores indicam maiores velocidades. A resolução dos pontos de dados l é de 1o x 1o.

3. METHODS

3.1 Survey design

The monitoring program was designed to detect change in a region with power of 0.85 and Type I error rate (i.e., alpha) of 0.10 (Escardó-Boomsma *et al.*, 1995). The protocol was to measure the net accumulation of indicator items on a site's 500m stretch of beach every 28 days (Escardó-Boomsma *et al.*, 1995; Ribic & Ganio, 1996). A length of 500m was used to ensure that 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 that all surveys would collect; each item was assigned a probable source: ocean-based, land-based, or general-source (Appendix A). The items to include in the indicator set and their source categories were developed by marine debris experts in a series of workshops held during the development of the protocol (Escardó-Boomsma *et al.*, 1995). Probable ocean-based debris was related to activities such as recreational boating/fishing, commercial fishing and oil/gas platform activities. Probable land-based debris was related to land-based recreation and sewage systems. General-source indicators represented plastic debris items that can originate from either ocean- or land-based sources; these were plastic bags, strapping bands, and plastic bottles (excluding motor oil containers).

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 500m, low to moderate slope (15-45º), composed of sand to small gravel, direct access to the sea (not blocked by breakwaters or jetties), accessible to surveyors year round, not cleaned on a regular basis, 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 then randomly selected from this list.

3.2 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 500m survey segment; a global positioning system unit was used to record 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 of the survey sites was done to remove all debris that had accumulated previously (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 survey date; this temporal window was used to accommodate weather or other events that prevented the survey from being accomplished on the pre-selected date. Volunteers recorded weather information (air temperature, wind speed and direction, description of the weather conditions) at the time of the survey as well as during the weeks prior to the survey using local weather data from the U.S. National Weather Service.

Program staff traveled to each site to establish the monitoring area and provide basic training (*e.g.*, debris identification, data recording) for volunteer groups to assure that volunteers understood the monitoring program's protocol. It was the responsibility of each survey director to follow quality assurance procedures during subsequent volunteer training and data collection activities. The quality assurance procedures assured accuracy of debris identification, accuracy of recording information and counts on the data cards, and determination of missed/overlooked debris items.

3.3 Data used in analysis

Because the volunteers were not able to maintain the 28 day schedule across the entire sampling period due to severe weather events, breaks in volunteer scheduling, and other unforeseen interruptions, the data were initially screened for an inter-sample effect. To do this, inter-sample intervals (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 time. 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 (≤ 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 initial clean-up survey in the protocol for initiating monitoring at a site.

Data considered for analysis were collected between May 1996 and July 2003. After the screening, we analyzed 344 surveys from 6 sites in the Caribbean region, 570 surveys from 8 sites in the eastern Gulf of Mexico region, and 182 surveys from 4 sites in the western Gulf of Mexico region.

3.4 Descriptive analysis

3.4.1 Regional comparisons

We summarized the surveys at each site by averaging the total number of indicator items collected per survey as well as the number of items in each of the three debris source categories per survey (number/500m). 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 survey for each debris source category. Previous work in the Gulf of Mexico (Ribic *et al.*, 1997) and along the Atlantic Coast (Ribic *et al.*, 2010) indicated that regional patterns in debris source categories were highly likely to differ. We used the average site counts and proportions to test for regional differences using a linear model; significance was assessed at $\alpha = 0.10$ as per the monitoring program's design. We used the arcsin square root transformation on the proportions to stabilize the variances; mean counts are normally distributed by the Central Limit Theorem. Comparisons were done using Fisher's Least Significant Difference. We did not combine the debris source categories into one global analysis because the variances of the debris source categories were not homogeneous, violating an assumption of the linear model framework. Analyses were done using the statistical package R version 2.7.0 (R Development Core Team, 2009).

3.4.2 Trend assessment

The monitoring 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 modeling approach used the explanatory variables

that were collected as part of the monitoring protocol. The explanatory variables were survey date, month (and variables based on month), weather in the weeks prior to the survey and at the time of the survey, and site. Survey date was used to model time trend. Although sites were chosen randomly, the local physical processes that drive debris deposition can vary among sites, therefore Site was used to model those local effects. The temporal and weather variables were used to adjust for within-year patterns.

Debris deposition is known to have within-year patterns that have been hypothesized to be due to human activities and extreme weather events (*e.g.*, Golik & Gertner, 1992; Frost & Cullen, 1997; Thornton & Jackson, 1998; Martinez-Ribes *et al.*, 2007). These patterns add to the variation in the data making it difficult to detect trends. We incorporated the within-year patterns into the models to reduce variation and obtain a more powerful test of inter-year trend (i.e., the within-year variables are considered to be nuisance variables). We used three variables to assess within-year temporal patterns: month, terrestrial seasons, and hurricane season. Hurricanes and tropical storms are important weather events in the Caribbean and Gulf of Mexico (National Hurricane Center, 2010). During peak hurricane season (15 August – 31 October; National Hurricane Center, 2010), the expectation is that there will be more debris coming ashore overall (a large-scale effect) with less before and after the peak season. To account for this hypothesized pattern, we categorized the months as follows: pre-hurricane-peak (May-July), peak hurricane (August-October); post-hurricane-peak (November-January); no-hurricane season (February-April).

Weather in the weeks prior to the survey and weather at the time of the survey were used to assess potential transient temporal impacts of inclement weather on debris deposition. We focused on inclement weather events because of the potential role in adding to the variability of the debris counts. This could take the form of either reducing the amount of debris on the survey unit due to scouring or increasing the amount of debris on the survey unit due to deposition. Weather was structured as a categorical variable with the following categories: no inclement weather events, cold fronts, rain, storms, tropical storms (including hurricanes), heavy seas, and strong wind events.

Because of potential nonlinear relationships between debris counts and the other variables, we used generalized additive models (Wood, 2006) to model potential time trend and month effects. This approach allows more flexibility in modeling nonlinear relationships, but can also 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 first tested to see if there were differences in trends among the regions by source category. We did not combine the debris source categories into one global analysis due to nonhomogeneous variances among the source categories. If there were significant interactions, we then analyzed the data by region for each source category. Using a set of models developed *a priori* (i.e., the combinatoric set of explanatory variables listed above taken *n* at a time), we used Akaike's Information Criterion (AIC) to rank the models (Burnham & Anderson, 2002), and used the model with the smallest AIC value. Significance was assessed at $\alpha = 0.10$, as per the design of the monitoring program. We used adjusted R^2 to determine how well the model fit the data. If the time trend was non-linear, we used a model with a linear term to determine the direction of the trend line. The best models were tabulated by debris type and region. For all models with a significant linear trend, percent change was calculated as the difference between the yearly sum of predicted debris in 1997 and 2002 divided by the yearly sum of predicted debris in 1997 times 100; 1997 and 2002 were the first and last years of complete data. Analyses were done using *mgcv* in R version 2.7.0 (R Development Core Team, 2009).

4. RESULTS

4.1 Amounts and composition

Overall, total indicator debris, as well as land-based, general-source, and ocean-based indicators, varied among the regions; specifically, amounts in the eastern Gulf of Mexico region were different than the amounts seen in the U.S. Caribbean and western Gulf of Mexico regions ($P < 0.01$, all tests). The Caribbean and western Gulf of Mexico regions had almost 5 times more total indicator debris than the eastern Gulf of Mexico (Table 1). The Caribbean region had 5 times more land-based debris and 6 times more general-source debris than the eastern Gulf of Mexico (Table 1). The western Gulf of Mexico region had twice as much land-based debris and 5 times as much general-source debris as the eastern Gulf of Mexico (Table 1). The western Gulf of Mexico region had almost 6 times as much ocean-based indicators as the eastern Gulf of Mexico, with the Caribbean falling between the two Gulf regions with about 3 times as much ocean-based debris as the eastern Gulf of Mexico (Table 1).

However, when considering proportions, about 45% of the indicator debris was land-based in the Caribbean and eastern Gulf of Mexico regions; this was about 50% higher than the proportion found in the western Gulf of Mexico region (Table 1). All regions had similar proportions of general-source debris (about 40%; Table 1). The highest proportion of ocean-based debris was found in the western Gulf of Mexico region, which was slightly over twice the proportion found in the Caribbean region; the eastern Gulf of Mexico region value fell in between the Caribbean and western Gulf of Mexico proportions (Table 1).

4.2 Trend assessment

Trends varied among regions by source category (interaction; $P < 0.001$) therefore further analyses are presented by region. In the Caribbean region, total indicator debris linearly decreased over the course of the study; this was true as well for land-based and general-source debris (Table 2). There was a non-linear relationship with ocean-based debris with ocean-based indicator debris declining until July 2000 when the amount leveled off and stayed low (Fig. 2). The linear trend model for ocean-based indicator debris was significant and negative indicating an overall decline in ocean-based indicator debris (Table 2). The percentage changes between the predicted indicator debris for 1997 and 2002 were between 75-85% depending on the source category (Table 2). No significant within-year variables were found in the models for any debris source category.

In the eastern Gulf of Mexico, similar declining trends were found. Total indicator debris declined linearly over the course of the study; declines were found as well for land-based, general-source, and ocean-based indicator debris

Table 1. Means (number/500m) and proportions of marine debris indicator items by total and source category for the Gulf of Mexico and the U.S. Caribbean, 1996-2003. These data were collected as part of the National Marine Debris Monitoring Program. Standard errors are in parentheses. Within a column, values with the same superscript are not significantly different at α = 0.10.
Tabela 1. Médias (número/500m) e proporções de itens de lixo marinho indicadores em termos de total e de categoria de origem para o Golfo do México e região norte-americana do Caribe, 1996-2003. Esses dados foram coletados como parte do Programa Nacional Norte-Americano de Monitoramento do Lixo Marinho. Erros-padrão estão entre parêntesis. Dentro de uma coluna, valores com o mesmo sobrescrito não são significativamente diferentes ao nível de α = 0.10.

Region	Number of sites	Total indicator debris	Land-based debris	General-source debris	Ocean-based debris	Proportion (Land-based debris)	Proportion (General-source debris)	Proportion (Ocean-based debris)
U.S. Caribbean	6	193.4^{a} (51.0)	83.7^{a} (29.6)	84.4^{a} (24.8)	25.3^{a,b} (9.1)	0.45^{a} (0.06)	0.42^{a} (0.03)	0.13^{a} (0.03)
Eastern Gulf of Mexico	8	38.1^{b} (5.7)	15.0^{b} (2.1)	14.7^{b} (3.0)	8.4^{b} (1.5)	0.41^{a} (0.04)	0.36^{a} (0.03)	0.21^{a,b} (0.04)
Western Gulf of Mexico	4	158.2^{a} (35.5)	40.3^{a} (8.7)	72.0^{a} (26.0)	45.8^{a} (7.0)	0.27^{b} (0.06)	0.41^{a} (0.06)	0.31^{b} (0.04)

Table 2. Best models for the relationship of indicator debris to variables collected as part of the National Marine Debris Monitoring Program using data from the Gulf of Mexico and the U.S. Caribbean, 1996-2003; s(variable) indicates a significant nonlinear relationship. Percent change is the percent change in predicted debris counts between 1997 and 2002 when a significant linear trend in survey date was detected.
Tabela 2. Melhores modelos para a relação de itens indicadores com variáveis coletadas como parte do Programa Norte-Americano de Monitoramento de Lixo Marinho, usando dados do Golfo do México e da região norte-americana do Caribe, 1996-2003; s(variável) indica uma relação não-linear significativa. Porcentual de mudança é o porcentual de mudança nas contagens previstas de lixo entre 1997 e 2002 quando um padrão linear significativo na data da amostragem foi detectado.

Debris source category	Region	Best model	Adjusted R^2	Linear trend in survey date	P-value	Percent change
Total	U.S. Caribbean	Survey Date + Site	0.61	negative	< 0.001	-80.3
	Eastern Gulf of Mexico	s(Month) + Survey Date + Site	0.31	negative	< 0.001	-31.3
	Western Gulf of Mexico	s(Month) + s(Survey Date) + Weather in weeks before survey + Site	0.33	none	0.21	
Land-based	U.S. Caribbean	Survey Date + Site	0.53	negative	0.02	-74.8
General-source	Eastern Gulf of Mexico	s(Month) + Survey Date + Site	0.29	negative	< 0.001	-29.2
	Western Gulf of Mexico	s(Month) + Survey Date + Weather in weeks before survey + Site	0.34	negative	0.03	-43.0
	U.S. Caribbean	Survey Date + Site	0.51	negative	< 0.001	-85.4
Ocean-based	Eastern Gulf of Mexico	s(Month) + Survey Date + Site	0.35	negative	< 0.001	-20.7
	Western Gulf of Mexico	s(Survey Date)+ Weather in weeks before survey + Site	0.37	none	0.21	-85.9
	U.S. Caribbean	s(Survey Date) + Site	0.57	negative	0.002	-42.8
	Eastern Gulf of Mexico	s(Month) + Survey Date + Site	0.33	negative	< 0.001	
	Western Gulf of Mexico	s(Month) + s(Survey Date) + Weather in weeks before survey + Site	0.26	none	0.32	

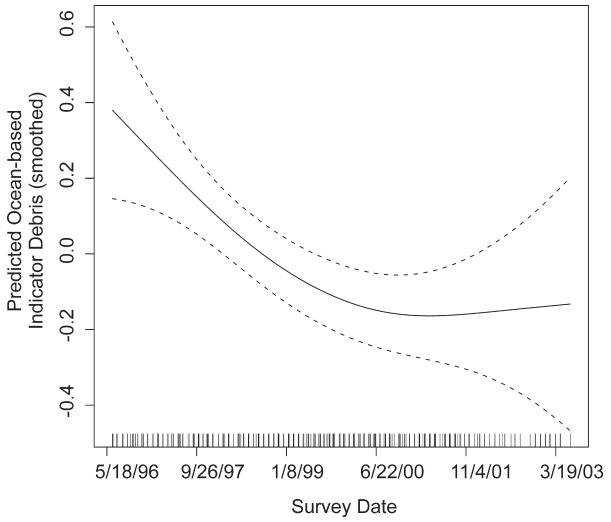

Figure 2. Non-linear relationship of survey date and ocean-based debris for National Marine Debris Monitoring Program sites from the U.S. Caribbean June 1996 – July 2003. Survey date is in mm/dd/yr format.

Figura 2. Relação não-linear entre as datas das amostragens e resíduos de origem marinha coletados pelo Programa Norte-Americano de Monitoramento de Lixo Marinho para a região norte-americana do Caribe, junho de 1996 – julho de 2003. Data da amostragem está no formato mm/dd/aa.

(Table 2). The percentage change between the predicted indicator debris for 1997 and 2002 varied between 20 and 40% depending on the source category; this is about one-quarter to one-half the change seen in the U.S. Caribbean (Table 2). Significant monthly variability in indicator debris existed on the sites for total items, land-based, and ocean-based debris. In all cases, debris was highest during May through September, with peaks occurring in July. Neither the seasonal nor hurricane season variables were significant ($P > 0.25$).

The pattern was different for the western Gulf of Mexico. In this region, there was no overall change in total, general-source, or ocean-based indicator debris; linear changes were not significant (Table 2). However, non-linear patterns were found, specifically a decrease in the late 1990s, an increase during 2000-2001, and then a decrease (Fig. 3). Land-based indicators decreased in the western Gulf; the percentage change of 43% between 1997 and 2002 was slightly higher than that seen in the eastern Gulf of Mexico (Table 2). Similar to the eastern Gulf, there was significant monthly variability in total indicator debris, land-based, and ocean-based indicators (Table 2). In all cases, more indicator debris was found on the sites during June and July. Neither the seasonal nor hurricane season variables were significant ($P > 0.25$) but weather conditions before the time of the survey accounted for some of the variation (Table 2). In the western Gulf, regardless of source category, fewer items were found when there were heavy seas or cold fronts the week prior to the survey, reducing the loads by 60-90% compared to the conditions without extreme weather events; tropical storms increased the amount of debris by about 200% (Table 3).

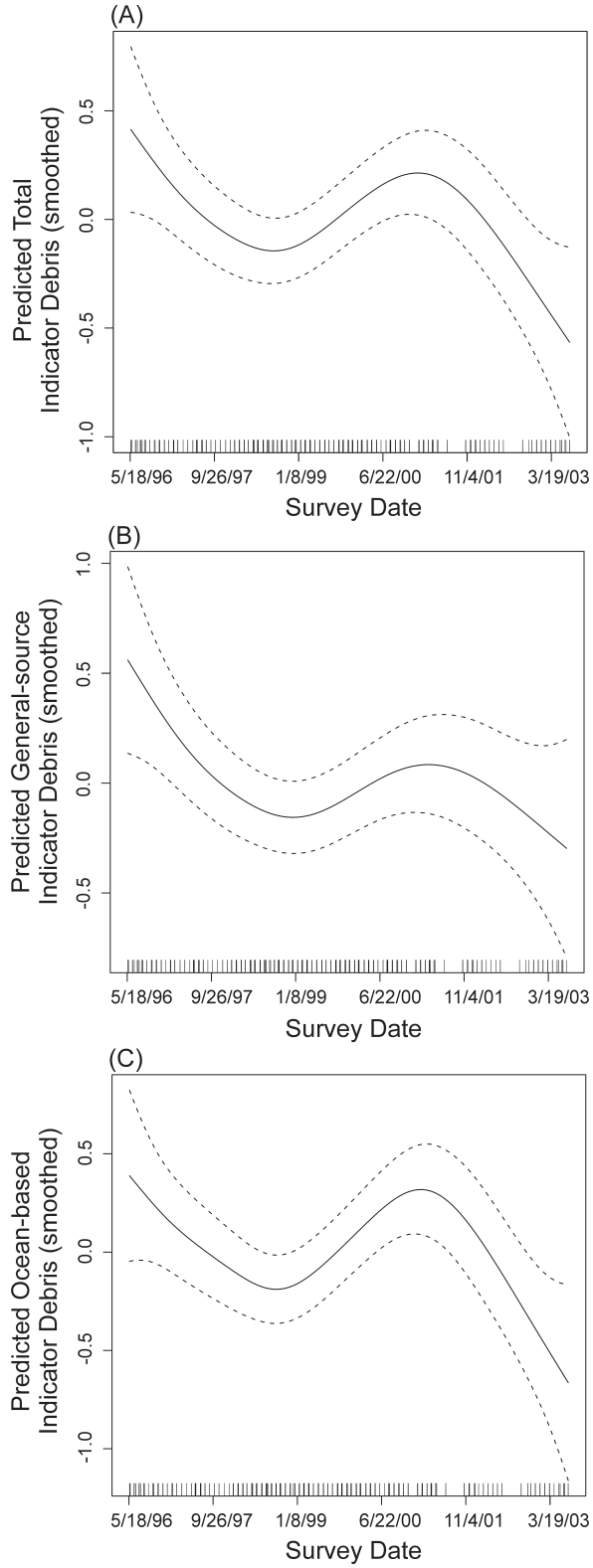

Figure 3. Non-linear relationship of survey date and (a) total indicator debris, (b) general-source, and (c) ocean-based indicator debris for the National Marine Debris Monitoring Program sites from the western Gulf of Mexico region June 1996-July 2003. Survey date is in mm/dd/yr format.

Figura 3: Relação não-linear entre as datas das amostragens e (a) número total de itens indicadores, (b) itens indicadores de fontes gerais, e (c) itens indicadores de fontes marinhas, para os locais do Programa Norte-Americano de Monitoramento de Lixo Marinho, da região ocidental do Golfo do México durante junho de 1996 - julho de 2003. Data da amostragem está no formato mm/dd/aa.

Table 3. Coefficients for the effects of weather in the weeks prior to the survey from the models of amounts of indicator debris in the western Gulf of Mexico, using data collected as part of the National Marine Debris Monitoring Program, 1996-2003. The coefficient values are relative to a value of 0 for normal weather. Coeff. = model coefficient; an additive coefficient significantly different from zero in the log scale results in a multiplicative change in the raw scale. %change = expected change in the normal debris load as a result of the weather event.

Tabela 3: Coeficientes para os efeitos do tempo meteorológico nas semanas anteriores às amostragens, dos modelos de quantidade de itens indicadores no Golfo do México ocidental, usando dados coletados pelo Programa Norte-Americano de Monitoramento de Lixo Marinho, 1996-2003. Os valores dos coeficientes são relativos a um valor de zero para um tempo meteorológico normal. Coeff = coeficiente do modelo; um coeficiente aditivo significativamente diferente de zero na escala logarítmica resulta em uma mudança multiplicativa na escala original. %change = mudança esperada na carga de resíduos como resultado do evento meteorológico.

	Debris source category											
	Total			Land-based			General-source			Ocean-based		
Weather variable	Coeff	P-value	% change	Coeff	P-value	% change	Coeff	P-value	% change	Coeff	P-value	% change
Cold front	-1.02	0.01	-64	-1.37	0.002	-75	-1.02	0.02	-64	-0.9	0.04	-59
Rain	-0.09	0.57		0.07	0.67		-0.14	0.35		-0.12	0.49	
Storm	0.16	0.41		0.16	0.44		0.33	0.15		-0.03	0.87	
Tropical storm	1.23	0.001	242	1.02	0.01	177	1.29	0.004	263	1.27	0.003	256
Heavy seas	-2.58	<0.001	-92	-3.8	<0.001	-98	-2.33	0.007	-90	-2.38	0.004	-91
Strong winds	0.33	0.27		0.43	0.18		0.19	0.59		0.44	0.19	

5. DISCUSSION

5.1 Trend assessment

The National Marine Debris Monitoring Program was set up to assess trends in marine debris loads over at least a five year time period. With respect to that primary objective, we found a very substantial decrease in marine debris in the U.S. Caribbean in all three source categories. There was also a substantial decrease in all three source categories in the eastern Gulf of Mexico. In the western Gulf of Mexico there was a substantial decrease only in land-based marine debris; there was no change in marine debris loads associated with general and ocean-based debris sources. Though these changes are large, there is some reason to be cautious in extrapolating beyond the time period of the study. Ribic *et al.* (2010) found smaller magnitude declines in debris deposition on the U.S. Atlantic coast occurring over the period covered by this study but these trends were largely reversed in later years, with only reductions in ocean-based debris in the Mid-Atlantic and Southeast Atlantic being significant over the longer (10-year) series.

The mechanisms behind the declines found in this study are unknown. It is unlikely that human population was the driver for the decrease in land-based debris; human population in the coastal counties of all three regions (US Department of the Interior, 2010) increased over the study period: 3% for the U.S. Caribbean, 27% for the eastern Gulf of Mexico, and 25% for the western Gulf of Mexico (US Census Bureau, 2009a, b). Fishing pressure is unlikely to be the driver in the declines in ocean-based debris in the eastern Gulf of Mexico. The fin fish and shrimp fisheries in both parts of the Gulf of Mexico were stable over the monitoring period, based on U.S. official commercial landings data (National Marine Fisheries Service, 2009); data for Puerto Rico for the same time period do not exist. Given the magnitude of the changes, particularly in the U.S. Caribbean, more retrospective work is needed to determine what drivers might have changed; for example, were there changes in tourism activity or waste handling?

5.2 Amounts and composition

We found a gradient of debris loads in the Gulf of Mexico with debris loads higher in the western Gulf and lower in the eastern Gulf, consistent with other research. On average, debris loads on quarterly surveys done at Gulf Islands National Seashore off Mississippi (in the eastern Gulf) were one-third of the debris loads found on Padre Island National Seashore in Texas (in the western Gulf of Mexico) (Ribic *et al.*, 1997). Aerial surveys for large floating debris in the Gulf of Mexico also found lower densities off Gulf Islands National Seashore compared to areas off Louisiana (in the western Gulf of Mexico) (Lecke-Mitchell & Mullin, 1992).

The high proportion of ocean-based debris in the western Gulf of Mexico that we found is similar to that found by other researchers; Miller *et al.* (1995) also found that ocean-based debris was the dominant type of debris deposited on Padre Island National Seashore and Matagorda Island National Wildlife Refuge beaches. Commercial fishing is an important part of the economy of the Gulf of Mexico region (National Marine Fisheries Service, 2009) and having ocean-based beach debris is likely a cost of having an active fishery, as has been found in other parts of the world (Cunningham & Wilson, 2003; Walker *et al.*, 1997; Ribic *et al.*, 2010).

The movement of debris within the Gulf of Mexico is likely influenced by the wind and current patterns of the Gulf (Wiseman & Sturges, 1999). Mean winds are offshore over the west Florida shelf in the eastern Gulf and onshore in the western Gulf (*e.g.*, Texas). Flow over the west Florida shelf is southward while flow along the Texas coast is influenced both from the north and from the south. For the western Gulf, most of the flow along the continental shelf (west of the Mississippi River) is counterclockwise, largely due to freshwater river outflows, while flow over the deep western Gulf is clockwise, due to Loop current eddies and some flow westward out of the Yucatan Strait along the Mexico coast (Wiseman & Sturges, 1999; J. Klinck, Center for Coastal Physical Oceanography, Old Dominion University, pers. comm.). The result is that, even though commercial fishing takes place in both the eastern and western Gulf, the flows would bring ocean debris to the Texas coast where persistent offshore winds could push debris onto the beaches; in contrast, the flow and wind patterns would keep debris from coming onshore along the Florida coast in the eastern Gulf. Current movements from east to west were implicated by Lindstedt & Holmes (1989) to explain the higher debris densities on western Louisiana beach transects compared to eastern Louisiana beach transects. This differential transport and deposition was seen in our study: although the fishery in the eastern Gulf is one-quarter the size of the fishery in the western Gulf (National Marine Fisheries Service, 2009), ocean-based debris loads in the eastern Gulf averaged less than one-fifth of the ocean-based debris loads in the western Gulf.

Circulation patterns were an important component of the study by Edyvane *et al.* (2004) in Australia, where they conducted experiments to understand near-shore circulation patterns. Coe *et al.* (1997) and Gregory & Ryan (1997) qualitatively considered the effect of circulation patterns in interpreting beach debris in their reviews of marine debris in the Caribbean region and Southern Hemisphere, respectively. Distance of the beach survey unit to large-scale oceanographic currents and other features was an important predictor of indicator debris loads on the Atlantic coast of the United States (Ribic *et al.*, 2010). Understanding near-shore and large-scale circulation patterns will be important for understanding the spatio-temporal variability in debris loads on beaches.

Our study found a large amount of debris on U.S. Caribbean beaches, similar to the loads found in the western Gulf of Mexico. However, there was a difference in composition with a preponderance of land-based items on U.S. Caribbean beaches; this result is consistent with other research done in Puerto Rico (Coe *et al.*, 1997). The preponderance of land-based items has been found in other research done in the wider Caribbean and Latin America (reviewed by Ivar do Sul & Costa, 2007) and is common on beaches near urbanized areas world-wide (Cunningham & Wilson, 2003; Martinez-Ribes *et al.*, 2007; Storrier *et al.*, 2007; Bravo *et al.*, 2009). Solid waste management is a global challenge (Liffmann *et al.*, 1997), however, the amount and dominance of land-based debris on the U.S. Caribbean beaches likely reflects the lack of adequate resources available to effectively manage solid waste. Researchers (*e.g.*, Liffmann & Boogaerts, 1997; Singh & Xavier, 1997) have described the myriad problems related to solid waste management in countries with limited resources, ranging from lack of roads to lack of waste handling facilities.

The most consistent aspect of debris composition among the three regions was the contribution of general-source debris, primarily composed of plastic bottles, making up almost 40% of all indicator items. Lindstedt & Holmes (1989) found a similar proportion of plastic bottles making up debris found on transects done along the coast of Louisiana. On the Atlantic coast of the United States, proportion of general-source items was 30-40% of indicator items (Ribic *et al.*, 2010). Our results are consistent with the assessment of the world-wide problem of plastic accumulation (Barnes *et al.*, 2009).

5.3 Temporal variability

Modeling within-year temporal patterns was useful in reducing the variance estimates in our models and thus improving our ability to detect trends over time; this was also found by Ribic *et al.* (2010). These temporal patterns are likely due to a combination of drivers. While there was no detectable effect of general hurricane season on debris loads, tropical storms (including hurricanes) did create transient effects on all source loads in the western Gulf of Mexico. In other work in the western Gulf, Miller *et al.* (1995) also reported that their one-year study found a relationship between weather and debris deposition on Padre Island beaches. Extreme weather events may be of interest in and of themselves; Thiel & Haye (2006) point out the importance of extreme weather events, such as intense hurricanes, for transporting organisms in the oceanic system.

Researchers are starting to consider long-term climate patterns to help understand long-term debris patterns. For example, the El Niño - Southern Oscillation cycle has been found to affect beach debris loads on remote islands northwest of the Hawaiian archipelago (Morishige *et al.*, 2007). However, we could not determine the potential importance of inter-year variability of tropical storm/hurricane frequency in our study; our study occurred during a time of above-average storm frequencies with 5 of the 7 years being above average (1997 and 2002 were below average) (National Weather Service, 2009).

5.4 Monitoring protocol

The monitoring program used to collect the data in this study was designed to compare a common set of items across large-scale regions and to that extent was successful. Although the protocol allowed for addition of regionally important indicator items, the effort needed to implement the national program precluded taking advantage of this option. Consequently, important regional processes were not effectively monitored with this program. In the Gulf of Mexico, for example, Miller *et al.* (1995) demonstrated a link between specific debris items on Padre Island National Seashore beaches and commercial shrimping activity, but the shrimping-specific debris items tracked by Miller *et al.* (1995) were not on our list of indicator items, and we could not evaluate whether the shrimping link continued to be important in later years. In the U.S. Caribbean, the regional commercial fishery is centered mainly on the reef ecosystem (Caribbean Fishery Management Council, 2010); some of the gear used to harvest the resources may be different from that used in fisheries in other parts of the United States (Matos-Caraballo, 2004) and adding additional region-specific items may have been useful.

In any marine debris study, it is important to document how the debris classification scheme was developed and how

the scheme addresses the objectives of the program. Different study objectives necessitate the use of different debris items and different classification systems when studying beach debris (*e.g.*, Silva-Iniguez & Fischer, 2003; Williams *et al.*, 2003; Tudor & Williams, 2004; Alkalay *et al.*, 2007; Silva *et al.*, 2008). Cheshire *et al.* (2009) discuss the factors that one should consider when determining what items to use in a monitoring program.

Two useful features of the National Marine Debris Monitoring Program were its temporal length (within and between years) and use of multiple sites. Whether looking at debris data from the Atlantic coast (Ribic *et al.*, 2010) or from the U.S. Caribbean and Gulf of Mexico (this study), the detailed temporal aspect of the data series permitted discovery of nonlinear time trends. As these nonlinearities showed broad decreases and increases in debris loads, they highlight the need for caution when interpreting results from relatively short periods of observation. Similarly, the high variability in debris loads due to site differences demonstrates the utility of incorporating multiple sites.

6. CONCLUSIONS

Although there are many short-term studies on marine debris, a longer-term perspective, and, perhaps more importantly, the ability to make comparisons among regions, has heretofore been missing in the U.S. Caribbean and the Gulf of Mexico. With the development around the globe of long-term monitoring programs using standardized methodology (Cheshire *et al.*, 2009), the potential exists to help management at individual sites as well as generate larger-scale perspectives (from regional to global) to inform regional policy makers and national governments. However, effective monitoring programs must address clear questions, use accepted methodologies, produce high-quality data, and be integrated with management and research (Lovett *et al.*, 2007). For example, the occurrence of severe hurricanes in the Gulf of Mexico in the mid-2000s (*e.g.*, Hurricane Katrina and Rita in 2005) has shifted the nature of the marine debris problem in the Gulf (NOAA, 2009); a regional monitoring program could be designed with such major events in mind, contributing to understanding the long-term consequences of debris to the Gulf.

Our study detected large declines in beach debris loads but we lacked contemporaneous measurements on drivers to understand why the declines might be occurring. Understanding mechanisms that might influence debris deposition (*e.g.*, by experiments, Silva *et al.*, 2008; by surveys, Tudor & Williams, 2008; incorporation into monitoring programs, Ribic *et al.*, 2010) would seem to be a particularly fruitful avenue for future research on and ultimately management of marine debris.

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Appendix A. Indicator items by source category used for the National Marine Debris Monitoring Program.
Apêndice A. Itens indicadores por categoria de origem usados no Programa Norte-Americano de Monitoramento do Lixo Marinho.

Ocean-based	**Land-based**	**General-source**
gloves	metal beverage cans	plastic bags
plastic sheets (≥1 m)	motor oil containers (1-quart)	strapping bands
light bulbs/tubes	balloons	plastic bottles (no motor oil containers)
oil/gas containers (> 0.95 L)	six-pack rings	
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		