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Incidence of marine debris and its relationships with benthic features in Gray's Reef National Marine Sanctuary, Southeast USA

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Abstract

Gray's Reef National Marine Sanctuary (GRNMS) is an increasingly popular site for recreational fishing and diving in the South Atlantic Bight (SAB). As a result, there has been heightened concern about potential accumulation of marine debris and its consequent effects on sanctuary resources. Field surveys were conducted at GRNMS in 2004 and 2005 to provide a spatially comprehensive characterization of benthic communities and to quantify the distribution and abundance of marine debris in relation to bottom features. The spatial distribution of debris was concentrated in the center of the sanctuary and was most frequently associated with ledges rather than other bottom types. On ledges, the presence and abundance of debris was significantly related to observed boating activity and physiographic features including ledge height, ledge area, and percent cover of benthic organisms. The results from this study will aid managers in optimizing cleanup efforts and long-term monitoring of debris accumulation patterns at GRNMS and other hard bottom areas in the SAB.
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Keywords: Derelict fishing gear; South Atlantic Bight; Georgia; Benthic marine debris

1. Introduction

The accumulation of anthropogenic debris in the marine environment is an increasing problem worldwide. Marine debris is aesthetically displeasing, can be a nuisance to boaters and the shipping industry, and can negatively impact marine biota (Derraik, 2002). The abundance and spatial distribution of marine debris is dependent upon several factors, including its origin/source (e.g., terrestrial versus maritime), ocean currents, wind patterns, and physiographic characteristics (Galgani et al., 2000; Donohue et al., 2001). Derelict fishing gear is a common debris type of aquatic origin often associated with areas of concentrated fishing activity (Hess et al., 1999; Galgani et al., 2000). Derelict fishing gear and other marine debris can impact organisms and environments in several ways. Floating debris may facilitate the spread of non-native species to new areas (Aliani and Molcard, 2003), and plastic items are often ingested by or entangle marine organisms, including fish, seabirds, sea turtles and marine mammals (Laist, 1997). Lost fishing gear, such as monofilament nets and traps, may affect marine organisms both by direct injury to benthic habitats and organisms (Donohue et al., 2001) and by continuing to catch fish and invertebrates (''ghost fishing'', Dayton et al., 1995).

Hook and line is a prevalent gear type, particularly among recreational fisheries, and can also be detrimental to marine organisms (Chiappone et al., 2005). Fishing effort is often concentrated at popular fishing sites, and consequently hook and line fishing may affect small areas but also inflict a high amount of damage within the affected areas (Asoh et al., 2004). Fishing line entangles readily in coral, which may lead to progressive fouling by algae and eventually, coral death (Schleyer and Tomalin, 2000; Yoshikawa and Asoh, 2004). Chiappone et al. (2005)

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documented numerous cases of tissue abrasion in branching gorgonians, milleporid hydrocorals, and sponges in the Florida Keys NMS. However, the association and impact of lost hook and line gear is not known for all bottom types, particularly in temperate regions.

Recently, there has been increased concern about the potential accumulation of marine debris in Gray's Reef National Marine Sanctuary (GRNMS), located in the middle of the South Atlantic Bight 32.4 km offshore of Sapelo Island, GA (NOAA, 2006; Fig. 1). Gray's Reef was selected as a sanctuary in part due to the complex mosaic of habitats (e.g., sand plains, caves, and rocky ledges) that support a diverse assemblage of benthic invertebrates and fish. Since the establishment of GRNMS in 1981, the population of neighboring coastal counties has increased substantially (40% from 1980 to 2000), and has been forecast to increase an additional 32% by 2015 (CGRDC, 2006). Coincident with this population increase, boat surveys indicate that recreational use of the sanctuary has also increased (NOAA, 2006). While most commercially employed gear has been prohibited in the sanctuary, Gray's Reef is a popular recreational fishing site both for king mackerel (*Scomberomorus cavella*) and bottom fish such as red snapper (*Lutjanus campechanus*), grouper (*Myctoperca microlepis* and *M. phenax*), amberjack (*Seriola* sp.), and especially black sea bass (*Centropristis striata*). Hook and line is the dominant gear type used to target these species, although spearfishing with non-power spearheads is also conducted. Several sport fishing tournaments take place off of the Georgia coast each year, with Gray's Reef being a premier location. The most recent GRNMS management plan addresses these concerns and calls for specific measures to assess, monitor, and remove debris from targeted areas within the sanctuary, and to prevent deposition

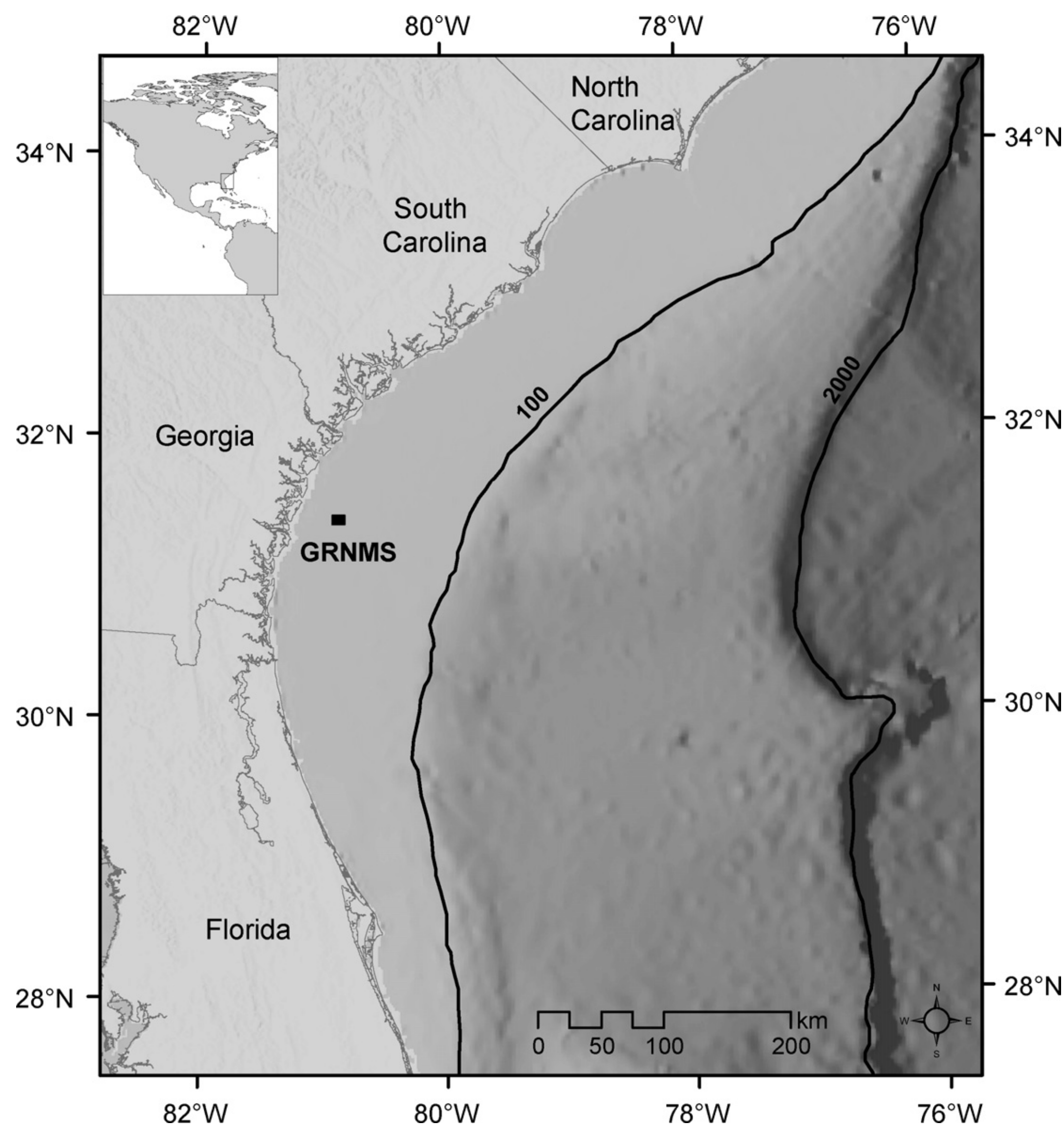

Fig. 1. Map of South Atlantic Bight region with location of Gray's Reef National Marine Sanctuary. The 100 and 2000 m contours are displayed. Seafloor bathymetry images are available from <http://www.ngdc.noaa.gov/>.

of new debris (NOAA, 2006). A key initial step to prioritizing removal efforts is effectively assessing the spatial distribution and density of debris. To date, these have not been quantified in GRNMS or even among the many similar hard bottom habitats distributed throughout the South Atlantic Bight.

Understanding the sources and processes that drive spatial patterns of marine debris distribution is crucial to remediation efforts. The characteristics of bottom features in Gray's Reef may influence the accumulation and spatial distribution of debris in the sanctuary. GRNMS encompasses approximately 58 km^2, about 75% of which is comprised of unconsolidated sediments, including flat sand plains and rippled sand (Kendall et al., 2005). The remaining substrate consists of outcroppings of carbonate hard bottom. The hard bottom ranges from areas with little or no vertical relief to areas of irregular, high-relief rocky ledges (up to 2 m in height) where invertebrate growth is abundant (Van Dolah et al., 1994; Kendall et al., 2005). The vast majority (97%) of the hard bottom at GRNMS is flat, covered by a thin veneer of sand overlying sandstone or limestone rock, and is sparsely colonized by sessile invertebrates. Densely colonized ledges account for <1% of the total bottom.

Despite their limited area, ledges are ecologically important and may be highly vulnerable to debris accumulation. Commonly referred to as "live bottom" areas, the rocky outcroppings within GRNMS support about 300 species of marine invertebrates (Gleason et al., 2007) and about 65 species of macroalgae (Searles, 1988). In turn, these benthic communities provide habitat for as many as 150 fish species including several of interest to recreational fishermen (Sedberry and Van Dolah, 1984). The abundance of sessile benthic organisms on ledges and structurally complex features such as overhangs and caves provide ample opportunities for debris items to become lodged or entangled. In addition, ledge features are the bottom type most targeted by fishermen due to the high abundance and diversity of target fishes that reside there.

At GRNMS, sessile invertebrates comprise the most diverse, abundant, and conspicuous component of hard bottom habitats, but previous assessments and monitoring attempts have not yielded appropriate data to quantify density and abundance, detect changes in benthic communities through time, and identify relationships between bottom communities and marine debris (NOAA, 2006). To fill this data gap, the current study provides a spatially comprehensive, *in situ* assessment of benthic communities, which can be used to design, implement, and maintain an invertebrate monitoring program at GRNMS. Moreover, this study provides data that will quantify detailed associations between bottom features and marine debris at GRNMS, elsewhere in the SAB, and beyond.

The objectives of this study were to (1) characterize the abiotic features and benthic communities within GRNMS, with particular attention paid to ledge bottom; (2) describe the abundance, types, and spatial distribution of marine debris in GRNMS; (3) to test the hypothesis that debris presence is associated with bottom type, and (4) to test the hypothesis that debris presence and abundance at ledges are related to physiographic features of ledges and observed boat activity.

2. Materials and methods

2.1. Field methods

Field surveys were conducted by SCUBA divers at GRNMS in August 2004, May 2005, and August 2005. Sites were selected randomly from within the four bottom categories (flat sand, rippled sand, sparsely colonized live bottom, and densely colonized live bottom or ledges) identified in recently completed benthic maps of GRNMS (Kendall et al., 2005). Most survey effort was devoted to the ledge bottom due to its high diversity and importance to the sanctuary. Less effort was devoted to the less diverse and lower complexity sparse live bottom and barren sand areas, as observations during benthic habitat mapping indicated that biotic cover and incidences of debris are less variable on these bottom types (Kendall et al., 2005). Benthic assessment and quantification of marine debris occurred within a 25 · 4 m belt transect for a total survey area of 100 m^2 at each site. A total of 179 sites were surveyed over the three survey periods (92 ledge, 51 sparse live bottom, 20 flat sand, 16 rippled sand). The number of ledges surveyed represents 21% of the total number of ledges mapped by Kendall et al. (2005) within the sanctuary. Mean site depth ranged from 16 to 20 m.

Using the same classification scheme from Kendall et al. (2005), an overall bottom type was assigned to each transect based on *in situ* observation. Surveys on sand and sparse live bottom were conducted along a random heading. Beyond the scarp and first 1–2 m of the top of the ledge, the bottom transitions into sparse live bottom. Transects at ledge sites were conducted solely along this edge and not the sparse live bottom behind it (Fig. 2). Data on the percent cover of biotia at each survey site were

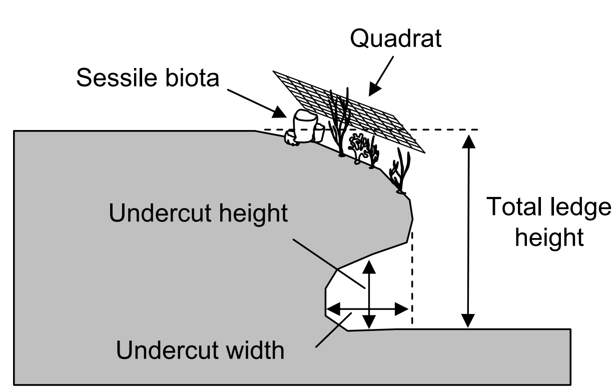

Fig. 2. Schematic representation of a ledge cross-section, depicting quadrat placement and the physical ledge dimensions measured during benthic surveys at GRNMS.

recorded within five 1 m^2 quadrats along the 25 · 4 m transect. Some sites in August 2005 had only four quadrats evaluated due to scuba diving time limits. The quadrat was placed at each randomly chosen meter mark and systematically alternated from side to side along the transect tape, except on ledges, where quadrats were placed along the ledge edge. The quadrat was divided into 100 smaller 10 · 10 cm squares with string (1 small square = 1% cover) to aid in estimation of percent cover. Percent cover (to the nearest 0.1%) of the sessile biota was determined for major taxonomic groups (corals, gorgonians, sponges, macroalgae, and other), which were further subdivided into categories based on morphology (see Table 1).

In addition, the dimensions of ledges were recorded at each quadrat position (Fig. 2). Total height was measured from the base of the ledge to the top of the substrate behind it but excluded the height of sessile organisms that were attached to the substrate. Undercut width – the distance from the leading face of the ledge to the farthest recess under the ledge – was visually estimated either by using the tape as a reference or by inserting the quadrat under the ledge. Undercut height – the height under the ledge – also was estimated visually with the length of the quadrat as a reference.

Marine debris was quantified within the entire 100 m^2 transect. Debris was defined as any man-made object and was separated into two main categories, fishing gear and non-gear. Subcategories of fishing gear were not always noted but included monofilament line, leaders, spear gun parts, and other/undescribed (e.g. jigs or lead weights). Subcategories of non-gear marine debris included cans, bottles, and other (e.g. clothing, twine, tennis ball, wood plank, and lift bag). Rope and mesh bags were found at a few sites and were scored as non-gear even though they may have been associated with fishing (e.g., rope could be used to mark ledge sites and mesh bags are often used for chumming). Fishing line that crossed the transect, but was not completely within it, was counted as a single item. Monofilament line with a leader attached was counted as a single piece of gear in the leader category.

2.2. Data analysis

Percent cover of all biotic cover groups was summarized and compared among bottom types. Sites were used as independent sample units and were considered replicates within each bottom type. Multiple quadrat measurements for biotic cover and physical dimensions within each site transect were averaged using the equation: $R(Q_{i \quad n})/n$, where Q_i = quadrat i, and n = total number of quadrats. Average site values were then used to calculate means and standard errors of measured variables for each bottom type. The percent cover of each biotic category was plotted by bottom type and the median and interquantile range (25th, 75th) were displayed in a box plot to aid in visualization of the distribution of the data. Since data was not normally distributed, non-parametric tests were used to determine how percent cover varied among bottom types

Table 1
Percent cover of biota measured at GRNMS by bottom types

Cover type	Morphology	Ledge		Sparse live bottom		Flat sand		Rippled sand	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE
Corals	Branching	1.2	0.2	<0.1	<0.1				
	Cup	<0.1	<0.1	<0.1	<0.1				
	Encrusting	<0.1	<0.1	<0.1	<0.1				
	Other	0.1	0.1	<0.1	<0.1				
Gorgonians	Sea rod/plume	1.3	0.2	1.5	0.2	<0.1	<0.1	<0.1	<0.1
	Sea fans	<0.1	<0.1	<0.1	<0.1				
	Sea whips	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		
Macroalgae	Filamentous/turf	18.1	2.5	0.3	0.1	<0.1	<0.1		
	Fleshy	<0.1	<0.1	0.1	0.1				
	Other	<0.1	<0.1						
Other	Tunicates (lobate)	6.3	1.1	0.7	0.1				
	Other	4.6	1.2	0.5	0.2	<0.1	<0.1	<0.1	<0.1
	Tunicates (encrusting)	2.9	1.0	0.3	0.2				
	Zoanthids (benthic)	0.4	<0.1	<0.1	<0.1				
	Anemones	<0.1	<0.1	<0.1	< 0.1	<0.1	<0.1	<0.1	<0.1
Sponge	Vase	3.5	0.4	0.4	0.1				
	Encrusting	2.4	0.4	0.4	0.2				
	Tube	0.7	0.1	0.2	<0.1				
	Ball	0.3	<0.1	0.1	<0.1				
	Finger	0.2	<0.1	0.3	<0.1				
	Rope	0.1	<0.1	0.1	<0.1				
Total		42.3	3.5	5.3	0.7	0.04	0.02	0.1	0.1

Blank cells indicate that zero organisms were observed.

for total cover and for major cover types. The hypotheses that the percent cover varied among bottom types was tested with Kruskal-Wallis Tests (JMP v5.1). When the main effect was significant, pairwise comparisons were performed with Dunn's multiple comparison tests.

Density of marine debris per site was recorded as number/100 m^2. Survey statistics for the quantity and types of debris were calculated for the entire survey domain and according to bottom types. Observed density of total debris was entered into a Geographic Information System (GIS) and mapped according to geographic position of each survey transect in ArcGIS v9.2. First, the hypothesis that presence of debris varies significantly by bottom type was tested using logistic regression (SAS v9.1, Proc Logistic). Bottom type was included as a class variable. For this analysis, flat sand and rippled sand were combined into a single "sand" category due to the low number of sampling locations in these bottom types compared to ledge and sparse live bottom. If the main effect was significant at the $a = 0.05$ level, contrast statements were then constructed in Proc Logistic to test for differences in debris density among each pair of bottom types.

Given that 90% of the observed debris was found on ledges, additional tests were performed to identify ledge characteristics that were associated with higher amounts of marine debris. Ledge characteristics that were suspected to be positively associated with debris accumulation were identified and included mean ledge height measured *in situ*, ledge area (m^2) based on previous GIS analysis (Kendall and Eschelbach, 2006), mean undercut width (m) measured *in situ*, and percent cover of benthic organisms measured *in situ*.

An additional factor that may influence the distribution and abundance of debris is the level of fishing and boating activity. Positions of boats in GRNMS from 1998 to 2004 were integrated from multiple sources including national reconnaissance systems and entered into a GIS (Kendall and Eschelbach, 2006). Positional accuracy was within 26 m. To determine how the intensity of activity varied over space, the sanctuary was divided into 0.25 km^2 cells (500 m · 500 m) and the number of boats within each cell was calculated. We used the information on boat distribution patterns to divide the sanctuary into areas of relative "low" versus "high" boat density. The number of boats per 0.25 km^2 cell ranged from 0 to 99, with higher boat densities observed in the central part of the sanctuary. In nearly half of the sanctuary (107 out of 234 cells), no boats were recorded, while in much of the remaining cells, only a few boats were observed. A frequency histogram of boats per cell was used to determine a cutoff between low and

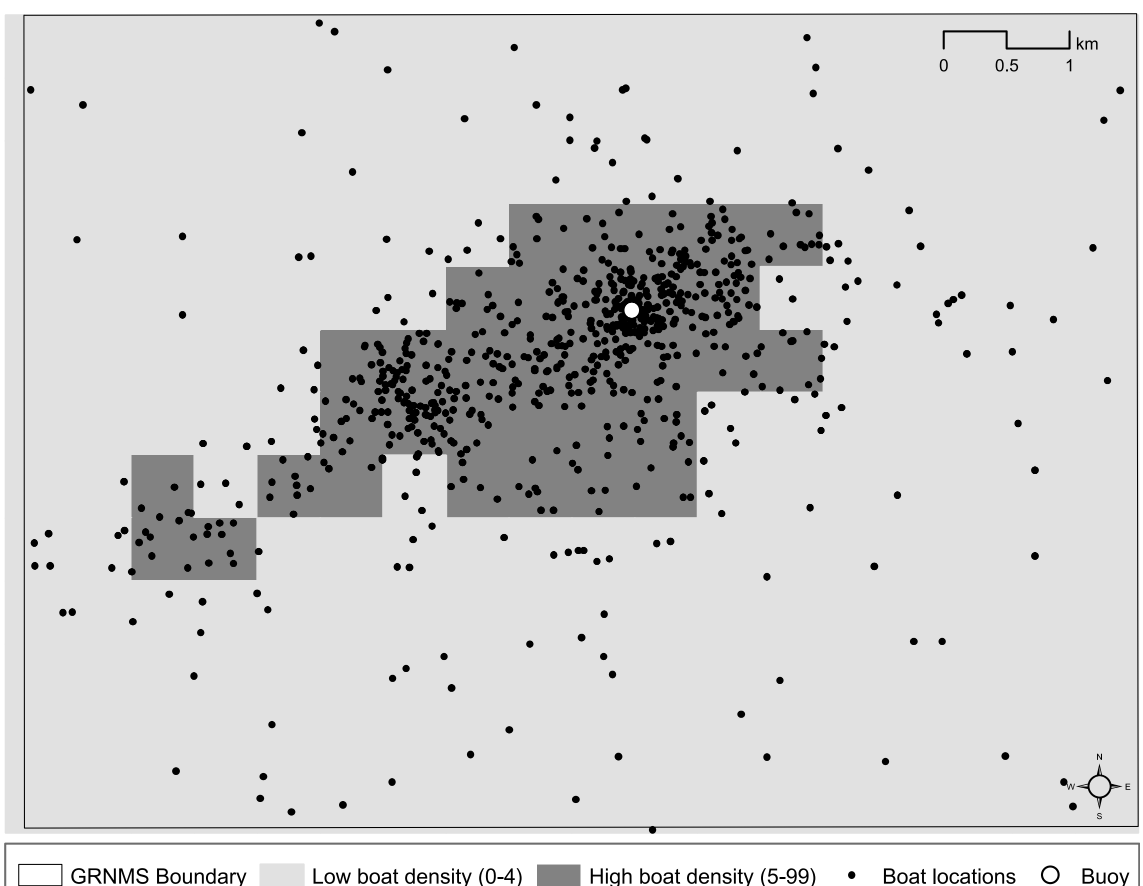

Fig. 3. Regions of low (0–4 boats/0.25 km^2 cell) and high (5–99 boats/0.25 km^2 cell) boat density. The black dots represent locations of the observed boats and the white star represents the location of the NOAA data buoy (Station 41008). Boat data were integrated from multiple data sets from 1998 to 2004.

high density areas. A natural break in frequency of cells occurred between density classes 4 and 5. Only 33 cells had an estimated density of P 5 boats, and further, these cells were clustered in the center of the sanctuary. Therefore, cells with 0–4 boats were defined as having low boat density, and cells with P 5 boats were defined as having high boat density (Fig. 3).

Next, we modeled debris data to determine if ledge characteristics and boat density were significant predictors of the presence and abundance of debris at ledge sites. Due to the presence of numerous sites with zero debris items, the data was analyzed using a two-step conditional model that is often used for zero-inflated data (Cunningham and Lindenmayer, 2005). This approach separates variables that determine whether or not debris is present from variables that determine the amount of debris, given presence. The variables included the boat density (low, high), mean ledge height (m), ledge area (m^2), mean undercut width (m), and total percent cover of epibenthic organisms. In the first step, the debris was treated as present or absent and the presence/absence data were modeled using logistic regression (SAS v9.1, Proc Logistic). In the second step, only sites in which debris was present were considered. At sites where debris was present, the number of debris items was modeled with a generalized linear model (SAS v9.1, Proc Genmod) with a negative binomial distribution and a log link. The negative binomial variance distribution was chosen because it requires fewer assumptions than the normal or Poisson distribution and is appropriate for modeling skewed count distributions (White and Bennetts, 1996). A Pearson's Chi-Square test was used to assess the goodness of fit of the negative binomial model to the data. At both stages, only main effects were considered, and conservative models were selected by using backward elimination of non-significant variables (a = 0.05).

3. Results

Cover of corals and gorgonians were generally low (Table 1). Branching coral was the most frequently encountered coral type, and sea rod/plumes were the most frequently encountered gorgonians. A high cover of filamentous macroalgae was typical at many of the densely colonized ledges, while several of the northernmost ledges were characterized by high cover of sponges, tunicates, and miscellaneous species (including bryozoans, molluscs, barnacles, and other unclassified taxa) within the "other" category. Numerous sponge types were observed throughout the sanctuary, including encrusting, tube, and vase morphotypes.

Multiple comparison tests indicated that cover of coral, macroalgae, sponges, and other benthic organisms was significantly greater on ledges than the other bottom types (Fig. 4). However, the percent cover of gorgonians did not vary significantly between ledges and sparse live bottom. Flat sand and rippled sand bottom types were characterized by low percent cover (0–2%) of benthic organisms at all sites (Fig. 4). Percent biotic cover at sparse live bottom ranged from 0.7% to 26.3%, but was only greater than 10% at 7 out of 51 sites. On ledge bottom type, percent cover ranged from 0.42% to 100% and was greater than 50% at 36 out of 92 sites.

The physical dimensions of the ledges surveyed exhibited wide variation and did not show distinct spatial patterns. Mean ledge height was 14.6 (±2.0 SE) cm and ranged from 0 to 170 cm. Mean undercut height was 4.0 (±0.7 SE) cm and ranged from 0 to 44 cm. Mean undercut width was 11.8 (±2.9) cm and ranged from 0 to 296 cm. Of the ledges surveyed, mean ledge area was 1886 (±164) m^2 and ranged from 211 to 7690 m^2.

A total of 93 debris items were found during field surveys at GRNMS. Debris was present at 32 out of the 179 survey sites. The number of debris items found within a 100 m^2 transect ranged from 0 to 10 items. Approximately two-thirds of all observed debris items were fishing gear, and about half of the fishing-related debris was fishing line (Table 2). Other fishing related debris included leaders and spear gun parts. Non-gear debris included cans, bottles, and rope. Other debris, classified as non-gear, included such items as wood, electrical wire, a knife, and items of clothing (e.g., pair of pants pockets).

Highest incidence of debris occurred at ledges in the center of the sanctuary (Fig. 5). Out of the 32 sites where debris was present, 29 were classified as ledge bottom type (Table 2). When debris was present on sand or sparse live bottom, it was always in low quantities. A total of two items were found on sand bottom types, and both were non-fishing gear items (e.g., can and plastic bottle). Results from the logistic regression indicated that the presence of debris varied significantly by bottom type ($v^2 = 15.5$, df = 2, $p = 0.0004$). The probability of debris presence was significantly greater on ledge compared to sparse live bottom ($v^2 = 9.2$, df = 1, $p = 0.002$) and sand bottom types ($v^2 = 7.3$, df = 1, $p = 0.007$). There was no significant difference in the presence of debris between sparse live bottom and sand ($v^2 = 0.8$, df = 1, $p = 0.386$).

Results from the two-part conditional model indicate that boat density and multiple characteristics of ledge features influence the observed distribution patterns of debris. Boat density was a significant predictor for presence of debris and abundance of debris, given presence (Table 3). The majority of debris items (80 out of 93) occurred in cells with high boat density (P 5 boats/0.25 km^2 cell), even though more than twice as many sites were sampled in the region of low boat density ($n = 122$ compared to $n = 57$, respectively). In addition, the composition of debris varied between the two regions. For example, 75% (60 out of 80 items) of the debris in the high boat density area were fishing gear, compared to 23% (3 out of 13 items) of the items found in the region of lower boat density. Of the three fishing gear items found in the low boat density region, two items were observed at a site in close proximity to cells with high boat density.

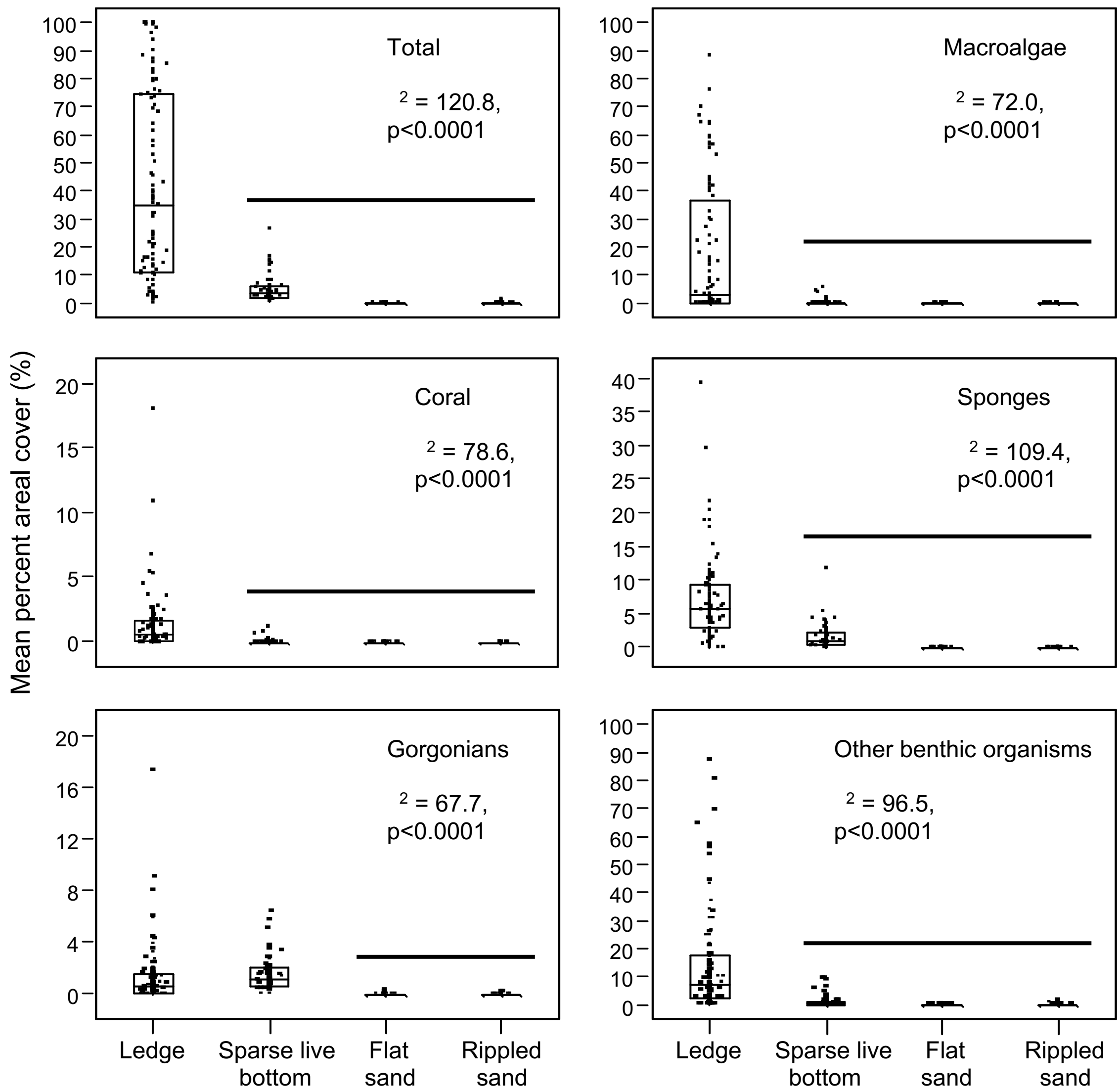

Fig. 4. Percent cover of main biotic cover groups on four bottom substrates at GRNMS. Box plots denote median and interquartile (25th, 75th) range. Results of non-parametric ANOVAs (Kruskal–Wallis tests) and Dunn's multiple comparison tests to determine significant differences among mean ranks are provided (df = 3, a = 0.05). Solid horizontal lines join groups that are not significantly different from each other.

Table 2
Frequency of debris types and average density of debris for individual bottom types and for the overall survey

Debris type	Number of debris				% of total debris
	Ledge ($n = 92$)	Sparse live bottom ($n = 50$)	Sand ($n = 37$)	Total ($n = 179$)	
Fish line	31	0	0	31	33.3
Leader	9	1	0	10	10.8
Spear gun parts	1	0	0	1	1.1
Non-descript/other gear	21	0	0	21	22.6
Total gear pieces	62	1	0	63	67.7
Cans	13	0	1	14	15.1
Bottles	1	0	1	2	2.2
Rope	4	0	0	4	4.3
Other	9	1	0	10	10.8
Total non-gear	27	1	2	30	32.3
Total debris	89	2	2	93	100
Number of sites with debris	29	1	2	32	–
Average # debris (±SE)/100 m^2 transect	0.97 (±0.21)	0.04 (±0.094)	0.06 (±0.04)	0.52 (±0.11)	–

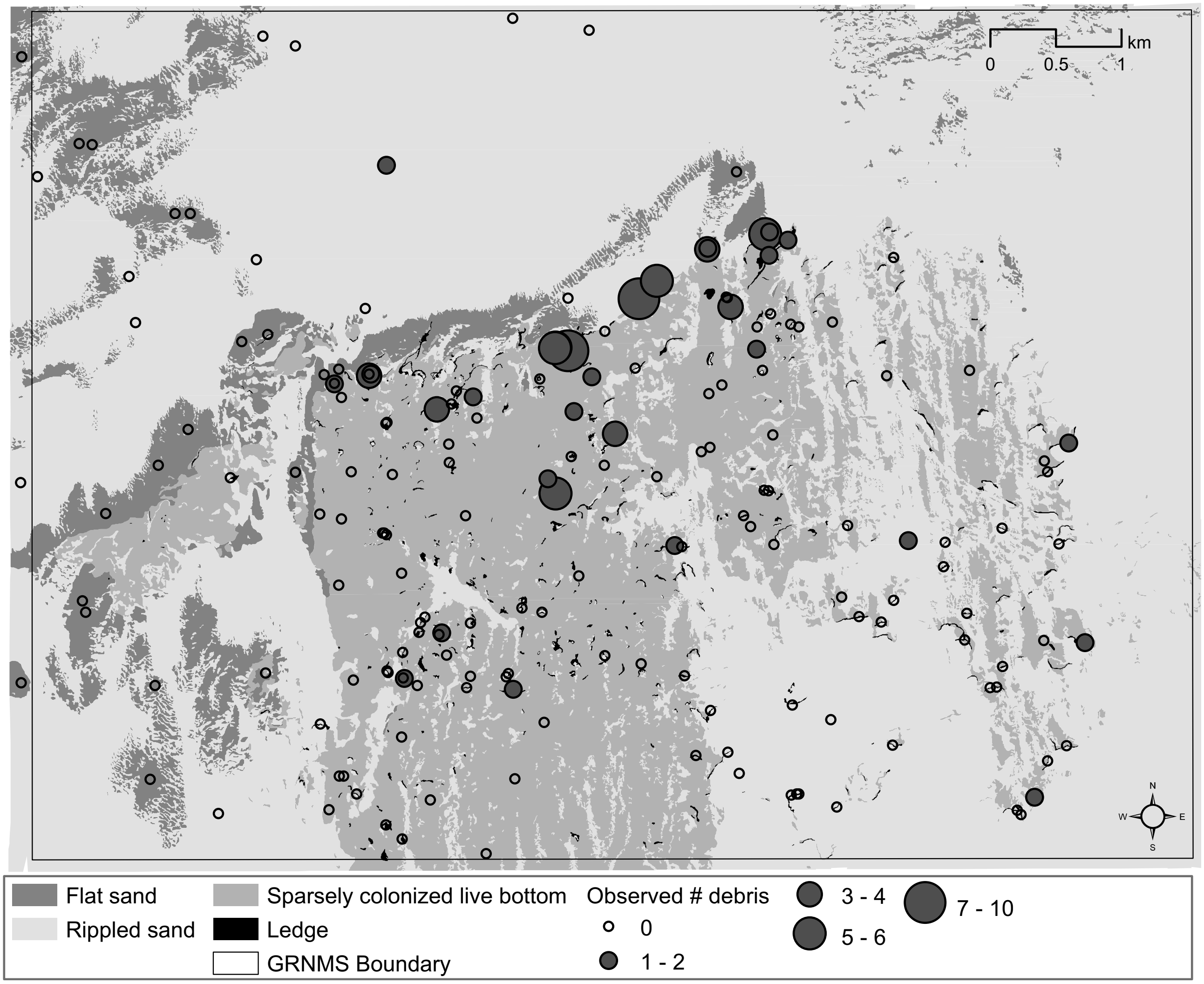

Fig. 5. Spatial distribution of observed debris (number per 100 m^2) in GRNMS.

Table 3
Two part conditional model for ledge bottom type to test for the effects of boat density (low, high) and ledge characteristics (ledge area, mean ledge height, mean undercut width, and percent cover of benthic organisms) on presence and abundance, given presence, of marine debris in GRNMS

	Variable	Parameter estimate	SE	Wald Chi-square	Pr > ChiSq
Stage 1	Boat density (high versus low)	0.65	0.29	5.1	0.024
	Ledge area	0.0004	0.00021	3.94	0.047
	Percent cover	0.024	0.0089	7.79	0.006
Stage 2	Boat density (high versus low)	0.82	0.35	5.41	0.020
	Ledge height	0.006	0.002	6.29	0.012

The first stage models presence–absence with logistic regression, while the second stage predicts density, given presence, with a generalized linear model and a negative binomial distribution.

Additionally, ledge area and percent cover were significant predictors of presence of debris, and mean ledge height was a significant predictor of abundance of debris, given presence. Debris was present at all of the five tallest ledges surveyed. However, at both stages of the model, the estimates for the significant ledge variables were small. The Pearson Chi-Square test statistic indicated that the negative binomial distribution was appropriate ($v^2 = 28.05$, df = 26, $p = 0.356$, the null hypothesis of this test was that the data fit the model).

4. Discussion

We quantified major differences in the physiography of the four main bottom types at GRNMS. Ledge bottom is structurally complex, is more densely colonized by sessile biota, and has a higher density of derelict fishing gear and other marine debris than other bottom types. Furthermore, ledges are not uniform across the sanctuary and vary in height, area, degree of undercut, and biotic cover. In turn, many of these characteristics were significantly related to the distribution and abundance of marine debris. This information is vital to effectively designing cleanup activities and outreach programs to reduce sources of debris input at GRNMS and on hard bottom elsewhere in the South Atlantic Bight. In addition, the data serves as a baseline by which to monitor future changes.

Numerous cover types were observed on ledges, including macroalgae, sponges, tunicates, coral, and gorgonians. Similar types of macrofauna were also observed by Wenner et al. (1983) and Hopkinson et al. (1991) in Gray's Reef and other stations in the inner and mid-shelf. Temperate reefs such as those in GRNMS differ from coral reefs in other National Marine Sanctuaries (Florida Keys, Flower Garden Banks, NWHI) in numerous ways, including geologic origin (Harding and Henry, 1990) and dominant biota (Miller and Hay, 1996). Unlike tropical reefs, temperate reefs consist of pre-existing, submerged rocky outcrops that are colonized by epibenthic organisms (Harding and Henry, 1990). Corals are less common on temperate reefs and tend to form smaller colonies than in tropical regions (Miller and Hay, 1996). *Oculina arbuscula*, the primary coral species in GRNMS, ranges from the Carolinas to Florida (Humann, 1993) and has a wide temperature tolerance, although highest growth occurs in warm water under high light conditions (Miller, 1995). In the present study, coral was commonly observed at 75% of all ledge sites, however, it generally contributed a small percentage to total percent cover.

In contrast, sponges represent an important component of the benthic community in GRNMS, accounting for as high as 39% cover. Usually multiple morphological types and species were present in a single quadrat. Although less studied, sponges often exceed corals and algae in terms of diversity on coral reefs (Diaz and Rutzler, 2001), and some species may compete with coral for space (Aerts, 1998). Compared to tropical reefs, temperate SAB reefs have lower sponge species diversity, but higher density of species and individuals, particularly for encrusting species (Ruzika, 2005). Other invertebrate groups that exhibited locally high abundance included tunicates (both encrusting and lobate) and bryozoans (included in the "other" category). Macroalgal cover, which was composed primarily of filamentous/turf algae, exhibited wide variation in abundance at individual ledges (Fig. 4), exceeding 25% at 16 sites. Although macroalgae accounted for the highest mean percent cover of all cover types, it was typically short (1 cm) or formed an encrusting mat on rocks. In contrast, many of the invertebrates observed at GRNMS provide vertical structure upwards of 10 cm (e.g., gorgonians. tube, and vase sponges) or have numerous branches (e.g., *Oculina*) and may be more susceptible to damage by human activities.

Concerns were raised about potential human impacts on sanctuary resources, including benthic communities, in the recently updated GRNMS management plan (NOAA, 2006). Compared to other hard bottom habitats, regulations afford the sanctuary protection from trawling and dredging, which have been shown to damage sponges, gorgonians and corals (Van Dolah et al., 1987). However, recreational activities such as fishing and diving are allowed at GRNMS and can also negatively impact benthic fauna (e.g., anchoring and entanglement of fishing gear with the benthos). As such, a major component of this study was to characterize debris patterns in GRNMS to support cleanup and monitoring of debris in the sanctuary. To our knowledge, this was the first study to quantify the types and amount of debris in offshore Georgia waters and on hard bottom reefs in the SA region. A variety of debris items, including plastics, polystyrene products, metal, glass, and fishing-related items, have been observed and removed during beach surveys in coastal Georgia (Gilligan et al., 1992). While fishing gear constituted a small portion of the total debris found on the beaches, Gilligan et al. (1992) noted that the impact of small items such as fishing line and string may have a disproportionately large effect due to the potential for entanglement of the benthic substrate, organisms, and other debris items. In contrast, in terms of number of debris items, fishing gear was more common than consumer related items (e.g., bottles, cans, and packaging) in GRNMS, which is not surprising given the popularity of recreational fishing in the sanctuary. The types of debris observed in GRNMS are similar to those found in coral reef habitats in the Florida Keys National Marine Sanctuary (FKNMS). Both sanctuaries have a large recreational fishing contingent. Lost hook and line gear is the dominant debris type in both sanctuaries, although lost lobster traps are also common in FKNMS (Chiappone et al., 2004).

The distribution and abundance of marine debris in GRNMS is related to the bottom type, the level of boating/fishing activity, and local characteristics of benthic features. There is a significantly greater probability of presence of debris at ledges compared to other bottom types. Several factors may contribute to this observation. First, the abiotic features of ledges (e.g., crevices, changes in relief, and overhangs) provide numerous places for fishing line and other debris to snag or become trapped. As discussed previously, ledges also tend to be densely colonized with corals, sponges, and other biota, creating further opportunities for debris entanglement. For example, although association with corals was not routinely recorded, divers noted several instances where fishing line was found tangled in branches of *Oculina*. Second, due to the association of recreationally important fish species with ledges, these bottom features are often targeted by fishermen. Even in areas with many boat observations, there were almost no occurrences of debris at sand and sparse live bottom sites. This is probably due to the concentration of fishing effort at ledges, and because the low complexity of sand bottom types is less conducive to debris entanglement and accumulation.

Of all tested variables, boat density had the strongest association with both presence and abundance of debris at ledges. Boat density is highest in the center of the sanctuary on a SW–NE axis, with the largest concentration occurring in the vicinity of the data buoy (NOAA station 41008). The high density of boats in this region is likely attributed to several factors. Recreational fishermen noted that the buoy is a popular location to catch bait and troll for king mackerel, and a nearby ledge attracts bottom fishers (Captain Judy Helmey and William H. "Bing" Phillips, personal communication). Slightly further away from the buoy, boat activity is less dense but still high. Fewer boats were observed in the southern portion of the sanctuary, despite the presence of numerous ledges, which indicates less fishing occurs here compared to areas of high boat density. This is further supported by the difference in debris types and presence between the two areas. Three-quarters of the debris items found in the region of high boat density were fishing gear, whereas debris items observed in the region of low boat density were primarily non-fishing related.

In addition to the strong link with boat density, patterns of debris occurrence were also related to physiographic features of ledges. The presence of debris was significantly greater with increasing area and percent cover of ledges; and given presence, the abundance of debris was positively related to ledge height. It is not surprising that ledge area is a significant predictor of presence of debris because extensive ledges are more likely to be found and targeted by recreational fishermen who closely monitor their depth sounder (John Duren, personal communication). Once good fishing spots have been located, fishermen often return to those locations, and ledges with large area are easier to find on subsequent trips. Thus, high boat density in the center of the sanctuary, where many large ledges, including the five with the largest area, are located, may be indicative of preferred fishing spots.

Ledge height was not a significant predictor of debris presence but was a significant predictor of abundance given presence. This result could be related to the distribution of boat use relative to the occurrence of tall ledges. Tall ledges occur throughout the center section of the sanctuary, including the south-central area where boat sighting data indicated that there is less fishing activity. Such ledges in this area may not be well known by fishermen, which may partially explain why little debris was found on them (Captain Judy Helmey and William H. "Bing" Phillips, personal communication) and why ledge height was not significant in the first stage of the two-part conditional model. The importance of ledge height was, however, demonstrated in the second stage of the model. Among ledges with debris, taller ledges have greater concentrations. This makes sense since taller ledges provide more vertical surface area on which gear can snag and also tend to have deeper undercuts. Tall ledges are also more attractive to fish and fishermen. Fish may retreat under such features once hooked, thereby increasing the likelihood of gear entanglement on the ledge structure or its encrusting biota.

It is likely that most fishing-related debris originates from boats inside the sanctuary. The prevalence of gear that is not used locally is often an indication that it has traveled from elsewhere, as has been observed in the NWHI (Donohue et al., 2001). This was not the case in this study, as all observed fishing gear at GRNMS consisted of permitted gear types that are known to be used in the sanctuary. However, preliminary analysis of ocean current data from the NOAA buoy within GRNMS indicate that there is potential for debris from outside the sanctuary to contribute to debris accumulation in GRNMS (NOAA Station 41008, http://www.ndbc.noaa.gov; last access June 26, 2007). Throughout the water column, the distribution of current direction observations at the buoy was bimodal, consistent with an ebb and flow tidal cycle, and these dominant currents were situated on a southeast-northwest axis. Tidal-influenced and other currents could affect distribution of debris within the sanctuary in several ways. For example, a debris item originating landward of the sanctuary or over flat sections within it could roll over the featureless sand areas during a tidal cycle until it encounters a ledge and gets stuck. The influence of ocean currents on debris accumulation in GRNMS warrants further study, particularly in relation to items that may be more easily transported.

Debris density at GRNMS was slightly lower than at Florida Keys National Marine Sanctuary (FKNMS) as reported by Chiappone et al. (2004). Total marine debris in the high relief spur and groove and low relief bottom types in FKNMS were estimated as 1.15 ($\pm$0.14 SE) and 1.22 ($\pm$0.20 SE) per 100 m^2, respectively (Chiappone et al., 2004), which is slightly higher than the mean density observed on ledge bottom type (0.97) and twice as high as overall mean density (0.52) in GRNMS. Furthermore, the distribution of debris in FKNMS appears to be more widespread; debris was recorded at 92% of sites sampled in FKNMS (Chiappone et al., 2004). The differences between the two sanctuaries may be a reflection of the disparities in accessibility; GRNMS is further from shore and likely receives fewer fishing trips than FKNMS. However, due to the differences in the bottom types that were sampled, it is difficult to directly compare our results to those in the Florida Keys. Chiappone et al. (2004) also compared hook and line density between regions of varying fishing pressure (no fishing, fished, and catch and release zones) but surprisingly found no significant differences between the three areas. The authors hypothesized that this may be due to noncompliance with regulations and/or the deposition of debris prior to enactment of regulations in protected zones in 1997. Similarly, it is unknown when debris that we observed in GRNMS was deposited. Periodic monitoring and removal of debris at designated sites would greatly improve our understanding of debris accumulation rates in GRNMS and on hard bottom elsewhere in the SAB.

Results from this study have direct conservation implications for GRNMS. Information gleaned from the present analysis was used to devise a strategy for prioritizing cleanup efforts. Most obviously, because the overwhelming majority of debris was located in densely colonized ledge habitat, ledges should be considered a higher priority for debris removal. Second, due to the significant difference in presence and abundance of debris between regions of high versus low boat density, ledges positioned within the area of more intense fishing pressure are more likely to have debris. The number of ledges receiving top priority for clean-up can be reduced further by accounting for ledge height and area, since the results of this study demonstrated that presence and abundance of debris are positively correlated with these variables. After debris is removed, sites should be monitored periodically to measure rates of new debris accumulation to further optimize the frequency of clean-up activities. In addition, we would recommend expanding long-term monitoring efforts to include several ledges that are located in the areas of lower observed boat densities to compare accumulation rates. Periodic updates of boat sighting data will allow managers to detect any changes in recreational boating patterns in GRNMS. In addition to debris removal, the results from this study will aid the sanctuary in focusing education and outreach efforts for reducing debris input on the appropriate user group (i.e., recreational fishermen).

Marine debris may inflict both direct and indirect damage to biota in GRNMS. Although impacts on biota were not quantified as part of our study, in several instances fishing line was observed to entangle benthic organisms, particularly the branching coral *Oculina*. Fishing line, wire, hooks, and leaders can cause tissue abrasion when they snag on reef organisms. Once entangled, fishing line may become incorporated into the reef matrix if it is overgrown by individual organisms (Chiappone et al., 2005). In our study, fishing line was often fouled by algae. In time, progressive algal fouling of fishing line entangled in coral may lead to coral death (Schleyer and Tomalin, 2000; Asoh et al., 2004; Yoshikawa and Asoh, 2004). In GRNMS, taller ledges in particular may be most susceptible to damage because they tend to be most densely colonized with benthic organisms. The impacts of hook-and-line fishing gear and other debris on benthic organisms in GRNMS and elsewhere need further study because negative effects are likely to become more severe as use of the sanctuary increases.

Although this study was conducted in a specific geographic area, our findings also have conservation implications for other marine managed areas. As a representative hard bottom area in the SAB, the methods and analytical tools employed at GRNMS can be applied to similar habitats in the region to assess patterns in marine debris. By combining marine debris survey data with benthic habitat maps, *in situ* measurements of concurrent physiographic features, and relative human use patterns, we were able to demonstrate how marine debris was largely localized to densely colonized ledge habitat and was further mediated by small scale ledge features and the relative level of boating activity. The approach can be adapted to other locations depending on available data sources and site-specific characteristics.

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