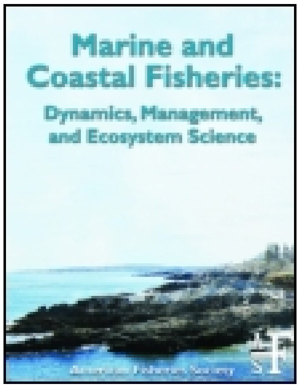

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Lobster Trap Debris in the Florida Keys National Marine Sanctuary: Distribution, Abundance, Density, and Patterns of Accumulation

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ARTICLE

Lobster Trap Debris in the Florida Keys National Marine Sanctuary: Distribution, Abundance, Density, and Patterns of Accumulation

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Abstract
The fishery for spiny lobster *Panulirus argus* in the Florida Keys National Marine Sanctuary is well chronicled, but little information is available on the prevalence of lost or abandoned lobster traps. In 2007, towed-diver surveys were used to identify and count pieces of trap debris and any other marine debris encountered. Trap debris density (debris incidences/ha) in historic trap-use zones and in representative benthic habitats was estimated. Trap debris was not proportionally distributed with fishing effort. Coral habitats had the greatest density of trap debris despite trap fishers' reported avoidance of coral reefs while fishing. The accumulation of trap debris on coral emphasizes the role of wind in redistributing traps and trap debris in the sanctuary. We estimated that 85,548 ± 23,387 (mean ± SD) ghost traps and 1,056,127 ± 124,919 nonfishing traps or remnants of traps were present in the study area. Given the large numbers of traps in the fishery and the lack of effective measures for managing and controlling the loss of gear, the generation of trap debris will likely continue in proportion to the number of traps deployed in the fishery. Focused removal of submerged trap debris from especially vulnerable habitats such as reefs and hardbottom, where trap debris density is high, would mitigate key habitat issues but would not address ghost fishing or the cost of lost gear.

According to the United Nations Environment Programme, as much as 70% of the global input of marine debris sinks to the seafloor in both shallow coastal areas and much deeper parts of the ocean (UNEP 2011). Many factors influence localized accumulation of debris, including size of debris items (e.g., length of a piece rope), bottom topography (e.g., ledges, crevices), oceanographic processes (e.g., tides, circulation patterns), meteorological events (e.g., hurricanes), distribution of fishing effort, and level of boating activity (June 1990; Galgani et al. 1995, 1996; Hess et al. 1999; Moore and Allen 2000; Acha et al. 2003; Boland and Donohue 2003; Katsanevakis and Katsarou 2004; Chiappone et al. 2005; Uhrin et al. 2005; Bauer et al. 2008; NOAA 2009). In a review of the literature on benthic marine debris, more than 60% of the

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studies cited marine activities (e.g., shipping, fishing) were the primary source of benthic debris worldwide (Spengler and Costa 2008). Although the contribution of abandoned, lost, or otherwise discarded fishing gear to marine debris has long been recognized worldwide, quantitative data on this debris are sparse for many regions (Macfadyen et al. 2009).

In 2007, 25,370 pleasure boats and 2,653 commercial vessels were registered in the Florida Keys (FLHMSV 2007), providing ample possibilities for intentional or unintentional littering and loss of gear and equipment, debris likely to settle on the seafloor. A large majority of registered commercial vessels target the spiny lobster *Panulirus argus* fishery (Milon et al. 1998; U.S. Office of the Federal Register 2011). Over the past 10 fishing seasons (2003–2012), the number of traps permitted annually in this fishery averaged 493,000. Lobster fishers reported that they lose 10–28% of their actively fished traps in nonhurricane years (Matthews and Uhrin 2009). The law requires that all lobster traps have an attached surface buoy; buoy lines are a navigational challenge in this region of high boat traffic and are often severed by boat propellers. The resulting absence of surface demarcation leads to impaired trap relocation and gear loss. Other causes of loss are vandalism, theft, entanglement of gear on the bottom, inability to relocate traps, and gear degradation. Although Florida lobster fishers are required by law to retrieve their traps before the close of the season, some abandonment of traps occurs. Strong winter storms, tropical storms, and hurricanes greatly exacerbate gear loss. Respondents of a mail survey reported a lobster trap loss of approximately 60% during the 2005–2006 fishing season when three hurricanes (Katrina, Rita, and Wilma) battered the Florida Keys during August–October 2005 (Lewis et al. 2009).

Derelict lobster traps and trap-generated debris are detrimental to seagrass and coral habitats (Chiappone et al. 2005; Uhrin et al. 2005; Miller et al. 2008; Lewis et al. 2009). Significant declines in seagrass density occurred during prolonged deployment of lobster traps (6 weeks) in beds of *Thalassia testudinum* and *Syringodium filiforme*; after 6 months, the area directly beneath the traps had been denuded (Uhrin et al. 2005). Trap debris causes tissue abrasion in scleractinian corals, octocorals, and sponges (Chiappone et al. 2005; Miller et al. 2008), which contributes to loss of living habitat; the area affected is greater than a trap's immediate footprint and can encompass several square meters when traps move during high winds (Uhrin et al. 2005; Lewis et al. 2009). During tropical storms and hurricanes a trap can move hundreds of meters from its site of deployment, possibly becoming repositioned in sensitive habitat not directly targeted by the fishery or an area in which fishing is prohibited (e.g., coral reefs, no-take areas). Areas of denuded substrate as large as 1.2 m^2 were observed in a *T. testudinum* bed as a result of trap movement during Tropical Storm Gabrielle in 2001. Less than 2 months later, all traps in the same area had been lost following the passage of Hurricane Michelle (Uhrin et al. 2005). During Tropical Storm Barry in 2007, individual intact traps experimentally deployed on hardbottom habitat in 4 m of water moved an average of 23.06 m, resulting in an average affected area of 21.27 m^2 per trap (Lewis et al. 2009). The affected area was largely denuded, and scleractinian corals, sponges, and gorgonians were sheared or detached (Lewis et al. 2009).

Efforts to address the accumulation of derelict fishing gear have included debris recovery and programs designed to reduce overall fishing effort. The annual Trap Retrieval Program (TRP), initiated in the Florida Keys in 1985, is still underway. Shoreline and on-the-water cleanups recover lost gear primarily comprising polypropylene rope, polystyrene foam buoys, trap parts, and plastic trap throats (NOAA 2011); most on-the-water efforts target only those traps that are easily identifiable from the water's surface (i.e., via surface buoys that are still attached). Each year 3,000–6,500 traps (spiny lobster and stone crab *Menippe mercenaria* combined) are retrieved from the waters of Monroe County in the Florida Keys (K. Miller, Florida Fish and Wildlife Conservation Commission, unpublished data). Excessive effort in the fishery (i.e., numbers of traps: Milon et al. 1999), which peaked at more than 900,000 traps in the early 1990s and was implicated in contributing to excessive mortality of sublegal-sized lobsters, declining trap yields, congestion and conflict on the water, and pollution, led to the implementation in 1993 of the Lobster Trap Certificate Program. Although annual trap reduction rates were established under this program, they have been amended over the years to include active reductions (10% of certificates held by each fisher are reverted back to the state) and passive reductions (up to 25% of certificates transferred in a sale from one fisher to another are reverted back to the state). The current 10% passive reduction rate has delayed progress toward meeting the existing trap reduction target of 400,000 established in 2005 (Florida Administrative Code R. 68B-24.009).

Understanding the sources and processes that drive the spatial distribution of marine debris is crucial to remediation efforts (Martens and Huntington 2012). Previous efforts to characterize benthic marine debris in the Florida Keys National Marine Sanctuary were conducted in conjunction with studies of coral reef ecology and were confined to that habitat (Chiappone et al. 2002, 2004; Miller et al. 2008). Herein, we conducted marine debris surveys in the area primarily targeted by the commercial lobster fishery across all benthic habitats in the sanctuary (FWC and NOAA 2000; Matthews 2003; Sheridan et al. 2005). Basic information on the abundance and distribution of derelict lobster traps is required for evaluating the environmental impact of the spiny lobster fishery in the Florida Keys. Studies have measured either habitat degradation or lobster mortality due to confinement (Hunt et al. 1986; Uhrin et al. 2005; Lewis et al. 2009), but the magnitude of the problem could not be put into context fisherywide due to the lack of an estimate of the number of derelict traps. The objectives of this study were to (1) generate estimates of the abundance, composition, and spatial distribution of benthic marine debris in the sanctuary, with special regard to commercial trap debris, (2) describe habitat-mediated patterns of debris accumulation, and (3) relate spatial

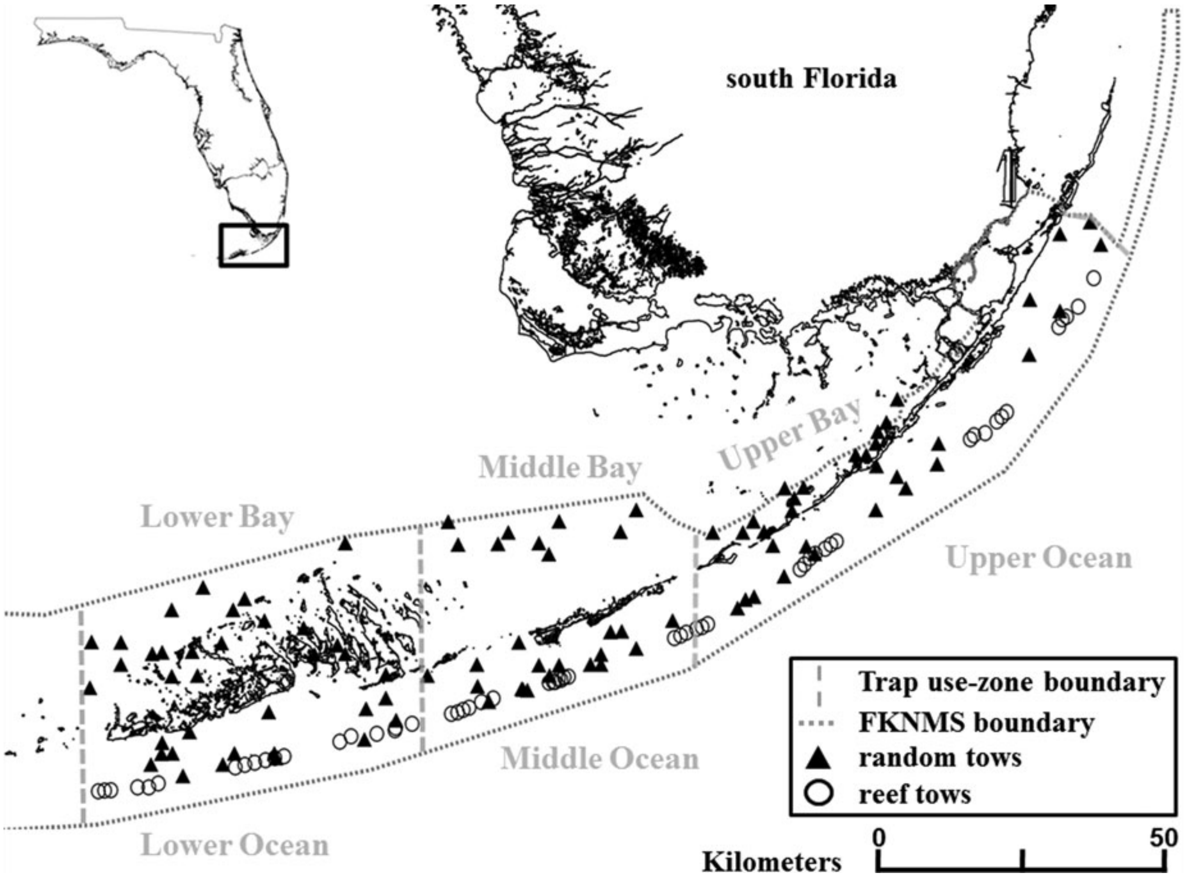

FIGURE 1. Locations of towed-diver marine debris surveys conducted in the Florida Keys National Marine Sanctuary. Filled triangles indicate random tows while open circles indicate reef-specific tows. The vertical dashed lines separate the six historic trap-use zones encompassing our sample domain. The dotted line is the boundary of the Florida Keys National Marine Sanctuary.

patterns of debris accumulation to known spatial patterns of commercial trap fishing effort.

METHODS

Study Area

The Florida Keys National Marine Sanctuary comprises approximately 9,500 km^2 of water and submerged lands surrounding the Florida Keys archipelago (Figure 1, dotted line). The region is a carbonate-sediment-based, subtropical marine environment consisting of inshore and offshore coral reefs, scattered mangrove islands, and extensive seagrass beds as well as patch reefs, mud shoals, and elevated coral rubble banks.

Study Design and Sampling

Study design.—A stratified random sampling design was used to obtain data on the abundance, composition, spatial distribution, and density of marine debris found in the sanctuary. The sample domain encompassed all benthic habitats in water ≤20 m deep within the boundaries of a subsection the sanctuary. The sample domain was partitioned into six sampling strata reflecting historic commercial spiny lobster trap-use zones in the sanctuary. These zones are the Upper Keys extending southwest from the easternmost trap-use zone boundary (longitude, 80.25°W) to longitude 80.85°W, the Middle Keys extending from longitude 80.85°W to longitude 81.28°W, and the Lower Keys from longitude 81.28°W to longitude 81.83°W on both the Atlantic Ocean and Gulf of Mexico–Florida Bay sides of the archipelago (Sheridan et al. 2003; Figure 1). These zones are subsequently referred to as Upper, Middle, or Lower and as either Ocean or Bay. Waters west of the westernmost zone boundary were not included in the sample domain given the lower fishing effort in these areas (Sheridan et al. 2003) and logistical limitations on sampling due to distance.

We used a GIS and the benthic habitat component of the Florida Keys atlas (FWC and NOAA 2000) with its accompanying digital database of benthic habitats and bathymetry to facilitate spatial delineation of the sample domain, sampling strata, and sample units. The entire sample domain was overlain in a GIS with a grid in which each cell measured 1′ latitude × 1′ longitude. Within each trap-use zone (stratum), 20 cells to be surveyed were randomly selected a priori from the grid; the center point of each cell served as the starting point for a towed-diver survey transect (the primary sample unit).

Towed-diver technique and data collection.—The manta tow technique is an effective and versatile mechanism for broad-scale characterization of benthic habitat and assessments of census-specific benthic targets (e.g., algae, corals and other invertebrates, fish) and has recently been adapted for use in surveys of derelict fishing gear (Donahue et al. 2001; Boland and Donohue 2003; Dameron et al. 2007; Martens and Huntington 2012). Surveys were conducted in May–July 2007 when the season was closed for stone crab and spiny lobster, both of which are harvested using traps ($N = 96$; see Figure 1 for survey locations). The center point of each randomly selected grid cell was located using a Garmin GPSMAP 3206 chartplotter GPS. Paired scuba divers were deployed from a small boat, each with a tow board equipped with a reusable data sheet and a stopwatch. Tow boards were fastened to polypropylene line using a stainless steel swivel shackle and tow lines were individually secured to the stern cleats of the boat. The length of line deployed during each tow varied with water depth to allow divers to maintain a constant height above the seafloor. Configuration of the towlines allowed a separation of 4 m between the divers. Tows were begun following an arranged acoustic signal from the boat, at which time a coordinate (waypoint) was collected in the GPS to more accurately indicate the start of the tow. Using the GPS as a guide, the coxswain navigated for 1 km at a randomly selected bearing (0–360°), at approximately 1.6 knots to ensure the comfort level of divers. Tow direction was altered as necessary to avoid land, boats, and other navigation hazards.

Upon commencement of towing, divers started the stopwatches and maneuvered the tow boards to maintain a height of approximately 1 m above the seafloor. Divers documented the type of habitat encountered at 1-min intervals, recorded individual debris items observed within 2 m of either side of their towline, and noted the type of habitat associated with each debris item. Upon cessation of towing, divers recorded the total tow time and ended the dive. Data from the two nonoverlapping parallel transects were combined yielding an effective transect swath of $8 \times 1{,}000$ m (8,000 m^2, or 0.8 ha). Incidences of debris encountered by both divers (i.e., rope crossing both transects) were consolidated and reported as one item.

Benthic habitat was designated as one of five types. Four habitat types were defined using the four major classes in the benthic habitat component of the Florida Keys atlas (FWC and NOAA 2000) and accompanying digital habitat database: (1) bare substrate, (2) seagrass, (3) hardbottom (low-relief limestone substrate colonized with sponges, soft coral, and algae), and (4) coral reef (patch and platform margin reefs). The fifth category, macroalgae, incorporated upright algal forms found in patches of soft sediment scattered throughout seagrass beds as well as substrates dominated by mat-forming, rhizomatous algae.

Each incident of marine debris was recorded separately. All debris was described and categorized as commercial trap debris (spiny lobster or stone crab) or nontrap debris. Incidences of commercial trap debris were further described using various stages of trap degradation: (1) fishing (ghost) trap, (2) nonfishing trap, (3) wood slats only, (4) plastic throat (funnel entrance to a trap), and (5) rope. A ghost trap was defined as an intact trap that was still able to catch lobsters and incidental bycatch species (Figure 2A, B). Nonfishing traps were defined as traps at various stages of degradation but having their concrete ballast slabs intact, whether any other trap parts were present or not (Figure 2C–E). Construction material of each trap (wood, wire, plastic) was also noted. Traps from the two fisheries were distinguished by overall size; spiny lobster traps are rectangular ($81 \times 61 \times 43$ cm), while stone crab traps are smaller and usually square ($40 \times 40 \times 31$ cm). Two rectangular concrete ballast slabs are installed on each short side of the floor of lobster traps, while a single square slab, covering the entire floor is used in stone crab traps. Trap debris from each fishery was also distinguished by differences in throat shape and the size of the wood slats used (Figure 2A, B). The rope used in the fisheries in deploying lobster and stone crab traps (black polypropylene) was easily distinguished from nylon anchor or nautical lines, but it was usually impossible to assign trap rope debris to one of the two fisheries. Because an observation of trap debris could include more than one type of construction material, we reported for each piece of debris its component construction materials: wood, concrete, plastic, wire, rope, or polystyrene foam. For example, the debris item depicted in Figure 2C would be classified as a nonfishing trap composed of concrete, wood, and plastic. All nontrap debris items were characterized as follows: angling gear (including monofilament line, wire leaders, lures, and small weights), concrete, plastic, glass, metal, wire, rubber, fabric, lumber, paper, and unknown.

When the random surveys had been completed, it was apparent that a disproportionate amount of trap debris had been encountered on coral reefs, even though reefs covered less area than other habitats in the sample domain and in the sanctuary overall. To better estimate the amount of trap debris in coral reefs, we conducted additional stratified sampling ($N = 55$ transects) specifically targeting coral reefs in the three Atlantic Ocean trap-use zones (Figure 1, open circles). These surveys were conducted in September–December 2007. Because it was the open fishing season for spiny lobster, we did not record whole, intact traps having a buoyed rope to the surface, which were presumed to be in use and not derelict. Site-selection protocols remained as described above except that the transect start point was established in available coral reef habitat nearest the grid cell center. Tow direction was set to include as much coral reef as possible in each randomly selected grid cell. Tow direction was altered as necessary following the GPS and depth sounder in order to maximize the inclusion of coral reef in our surveys. Tow protocols and subsequent data summarization were as described above for the random surveys.

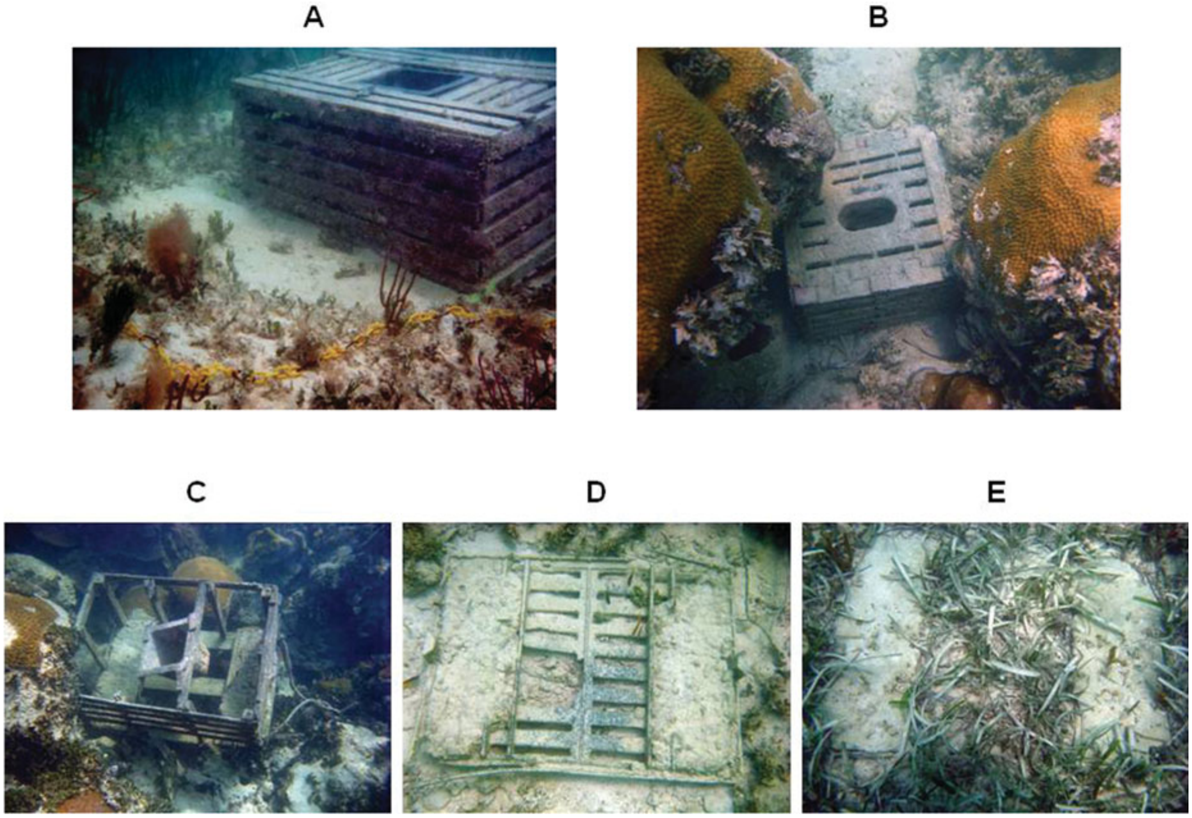

FIGURE 2. (**A**) Spiny lobster ghost trap, (**B**) stone crab ghost trap, and various stages of lobster trap degradation that were categorized as nonfishing traps: (**C**) intact trap bottom with wood framing, (**D**) intact plastic trap bottom, and (**E**) paired concrete ballast slabs.

Data Analysis

Transect data (debris density) was scaled to per-hectare values. Generalized linear models, which do not require the assumptions of normality or homogeneity of variance, were used to analyze the data, because our dependent (response) variable, debris density, did not follow a normal distribution or have constant variance, which is typical of count and abundance data. We used a negative binomial regression (PROC GENMOD, SAS 2002) to initially model the full set of data (random and coral-specific tows combined) from the three Atlantic Ocean trap-use zones and test for differences in debris density between the two survey types (irrespective of trap-use zone) for total debris and the two general categories, trap and nontrap. Likelihood ratio chi-square tests from the negative binomial regression indicated that a model containing survey type did not offer significant improvement over a null model without predictors for trap debris, nontrap debris, or all debris combined ($P = 0.5867$, 0.3225, and 0.3989, respectively; Table 1). Therefore, to increase our sample size for estimates of debris abundance, percentage composition, and density means and variances, we pooled the data from the random and coral reef surveys for each trap-use zone in the Atlantic Ocean.

The number of hectares surveyed in each trap-use zone was calculated by multiplying the total number of completed surveys in each zone by 0.8 ha (transect area). The relative amount of each habitat surveyed (percentage of total) within each transect was estimated using the amount of time spent in each habitat divided by the total amount of time spent towing. These percentages were then applied to the transect area (0.8 ha) to yield an estimate of the relative amount of each habitat encountered in each transect. The relative amount of each habitat surveyed (percentage of total) within each trap-use zone was estimated using the amount of time spent in each habitat per zone divided by the total amount of time spent towing in that zone. These percentages were then applied to the total area surveyed per zone to yield an estimate of the relative amount of each habitat encountered in each zone. Abundance and percentage composition of debris items were tabulated for each debris classification as well as the percentage contribution of each type of trap construction material. Total and trap-debris densities across trap-use zones and habitat types were reported as incidences of debris per hectare surveyed.

A negative binomial regression was used to model the effect of trap-use zone and habitat type on debris density for (1) all debris, (2) trap debris, and (3) nontrap debris, followed by pairwise a priori contrasts to identify the source of variation among trap-use zones and habitats. Due to the natural lack of coral reef habitat in the Gulf of Mexico–Florida Bay, data for

TABLE 1. Type-1 likelihood ratio statistics from the negative binomial regression testing for the effect of survey type, trap-use zone, and habitat on debris density.

Source	df	Deviance	Chi-square	*P*-value
Survey type				
Trap debris:				
Intercept		1936.6795		
Survey	1	1936.9596	0.28	0.5967
Nontrap debris:				
Intercept		932.8645		
Survey	1	933.8431	0.98	0.3225
Combined debris:				
Intercept		4762.9235		
Survey	1	4763.6352	0.71	0.3989
Trap-use zone				
Trap debris:				
Intercept		2327.8885		
Zone	5	2352.3047	24.42	0.0002
Nontrap debris:				
Intercept		1151.1817		
Zone	5	1180.9729	29.79	<0.0001
Combined debris:				
Intercept		5750.5668		
Zone	5	5785.7614	35.19	<0.0001
Habitat: Atlantic Ocean				
Trap debris:				
Intercept		17603.0046		
Habitat	4	17631.6873	28.68	<0.0001
Nontrap debris:				
Intercept		8344.6053		
Habitat	4	8383.1244	38.52	<0.0001
Combined debris:				
Intercept		31470.5451		
Habitat	4	31781.5799	41.03	<0.0001
Habitat: Florida Bay				
Trap debris:				
Intercept		1842.0132		
Habitat	3	1846.5927	4.58	0.2053
Nontrap debris:				
Intercept		1178.3592		
Habitat	3	1187.4777	9.12	0.0278
Combined debris:				
Intercept		4092.9380		
Habitat	3	4101.2846	8.35	0.0394

the Atlantic Ocean and Florida Bay were analyzed separately for habitat effects. Mean and SE estimates of debris density, as well as estimated total amount of all trap debris, ghost traps, and nonfishing traps per fishing zone and across the entire sample domain, were computed following the method of Cochran (1963) for a stratified random design (PROC SURVEYMEANS, SAS 2002). The number of ghost traps was estimated only for spiny lobster traps.

RESULTS

All habitats were sampled proportionately by the random surveys (Table 2). Our surveys identified areas designated in the benthic habitat atlas as unknown habitat, but which we identified as dominated by bare sand or macroalgae on sand, a category not designated in the atlas (FWC and NOAA 2000). Seagrass was the most common habitat encountered in the Gulf of Mexico–Florida Bay; habitat types were more equally represented in the Atlantic Ocean (Table 2). Coral reef-specific surveys successfully included a greater percentage of coral reef and increased the accuracy of debris estimates in this less common but highly affected habitat (Table 2). Trap-use zones differed greatly in size, resulting in different percentages of each area being sampled. Atlantic Ocean sites were sampled approximately twice as often as Gulf of Mexico–Florida Bay zones due to the additional targeted sampling of reefs. Transects in the Middle Bay zone numbered only 10, all of them offshore, because some data from the nearshore transects were lost.

Trap debris accounted for the majority of all recorded debris incidences (69.7%; Table 3), with 94% ascribed to the spiny lobster fishery. Trap debris was composed mainly of wood parts (33.0%) followed by concrete and rope (26.5% and 24.0%; Table 3). Metal objects (e.g., beverage cans, pipe, and sheeting) accounted for 29.5% of the nontrap debris, followed by angling gear (15.0%; e.g., monofilament line, wire leaders, weights). The remaining nontrap debris included plastics (12.7%; e.g., bags and PVC), wood (11.5%; i.e., lumber), glass (10.6%), and, to a lesser extent, concrete, anchor rope, wire, rubber, fabric, and paper; two objects were of unknown origin and material (Table 3).

Likelihood ratio chi-square tests from the negative binomial regression model resulted in a significant fit to the data, indicating that debris density was dependent upon trap-use zone for trap debris, nontrap debris, and all debris combined ($P = 0.0002$, <0.0001, and <0.0001, respectively; Table 1; Figure 3). In general, the Upper Keys and Middle Ocean tended to have higher debris density (Figure 3). The lower debris density observed in the Middle Bay may be an artifact of the missing nearshore observations; nevertheless, it appears likely that debris density was lower in the Middle Bay and Lower Bay (Figure 3). The type and proportion of debris was similar across zones with the exception that nontrap debris was very rare in the Middle Bay (Figure 4). The majority of trap debris incidences across zones involved wood parts, nonfishing traps, and rope (Figure 4).

In the Atlantic Ocean, likelihood ratio chi-square tests from the negative binomial regression model resulted in a significant fit to the data, indicating that debris density was also dependent upon habitat type for trap debris, nontrap debris, and the two combined (all $P < 0.0001$; Table 1; Figure 5). In general, macroalgae habitat in the Atlantic Ocean had the lowest debris

TABLE 2. Summary of the proportion of habitat surveyed during random and reef-specific towed-diver transects conducted in the Florida Keys National Marine Sanctuary as well as the proportion of habitat existing in our study area as determined from the benthic habitats component of the Florida Keys atlas (FWC and NOAA 2000).

Source	Area surveyed (ha)	Seagrass (%)	Bare (%)	Hardbottom (%)	Coral (%)	Algae (%)	Unknown (%)
Random tow	76.8	49.6	23.5	15.7	6.6	6.4	0
Reef tow	44.0	0.7	18.7	19.8	59.6	1.2	0
Benthic atlas	361,770	59.1	1.9	21.7	5.1	0	12.3
Use zone:							
Upper Bay	11.2	69.8	7.7	12.4	0.0	10.1	0
Middle Bay	7.2	99.0	0.0	0.0	0.0	1.0	0
Lower Bay	16.8	53.6	18.7	19.9	0.0	7.7	0
Upper Ocean	29.6	22.0	22.1	19.0	35.1	1.8	0
Middle Ocean	29.6	16.7	30.4	17.9	32.9	2.0	0
Lower Ocean	26.4	11.4	25.4	18.4	38.0	6.7	0

density, closely followed by seagrass (Figure 5); bare substrates had the highest amount of debris (Figure 5). Debris density in coral was similar to both bare substrates and hardbottom, while hardbottom was consistently lower than bare substrates. For trap debris, hardbottom was similar to seagrass (Figure 5). In Florida Bay, likelihood ratio chi-square tests from the negative binomial regression model did not result in a significant fit for trap debris indicating that overall, trap debris density was not

TABLE 3. Frequency and proportion of all debris as well as the material composition (percent occurrence) of trap debris encountered in the Florida Keys National Marine Sanctuary during towed-diver surveys.

Debris type	Frequency	Percent of grand total[a]	Percent of nontrap total
Frequency and proportion of debris			
Trap-generated	982	69.7	
Metal	126	9.0	29.5
Hook-and-line	64	4.6	15.0
Plastic	54	3.8	12.7
Lumber	49	3.5	11.5
Glass	45	3.2	10.6
Concrete	32	2.3	7.5
Anchor rope	27	1.9	6.3
Wire	9	0.6	2.1
Rubber	8	0.6	1.9
Fabric	8	0.6	1.9
Paper	2	0.1	0.5
Unknown	2	0.1	0.5
Total	1,408	100	100
Composition of trap debris			
Wood		33.0	
Concrete		26.5	
Rope		24.0	
Plastic		11.8	
Wire		4.5	
Polystyrene foam		0.2	

[a]Percent of trap-generated total in the case of the composition of trap debris.

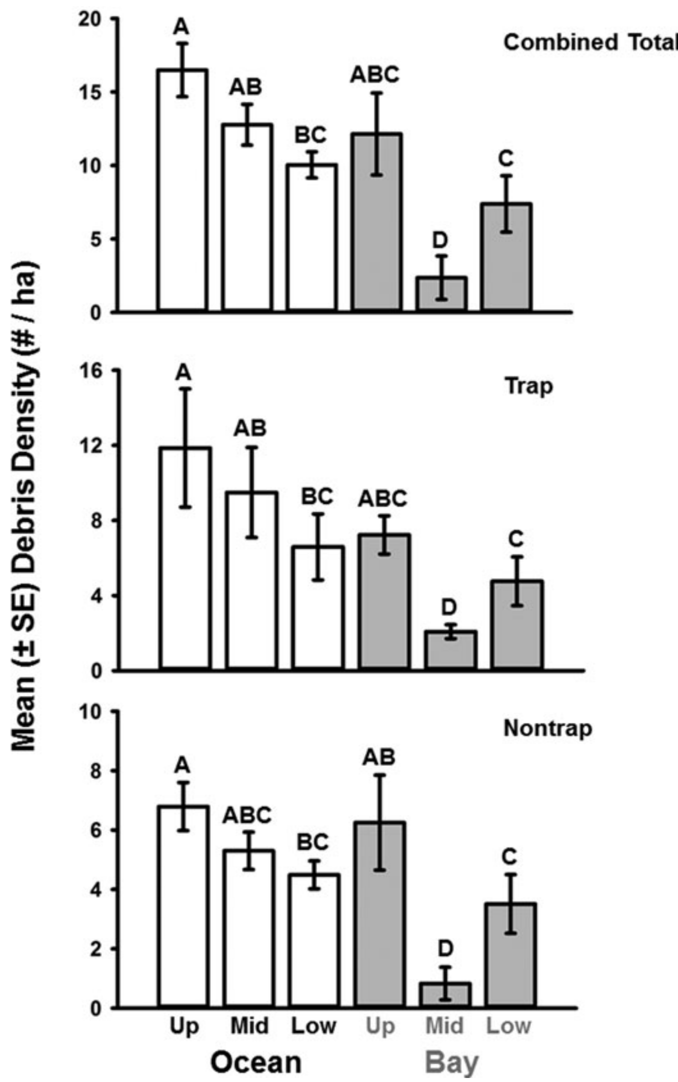

FIGURE 3. Mean (±SE) debris density (number of incidences per hectare) in each trap-use zone for total debris (top panel), trap debris (middle panel), and nontrap debris (bottom panel). Means with the same letter designation are not significantly different at $\alpha = 0.05$.

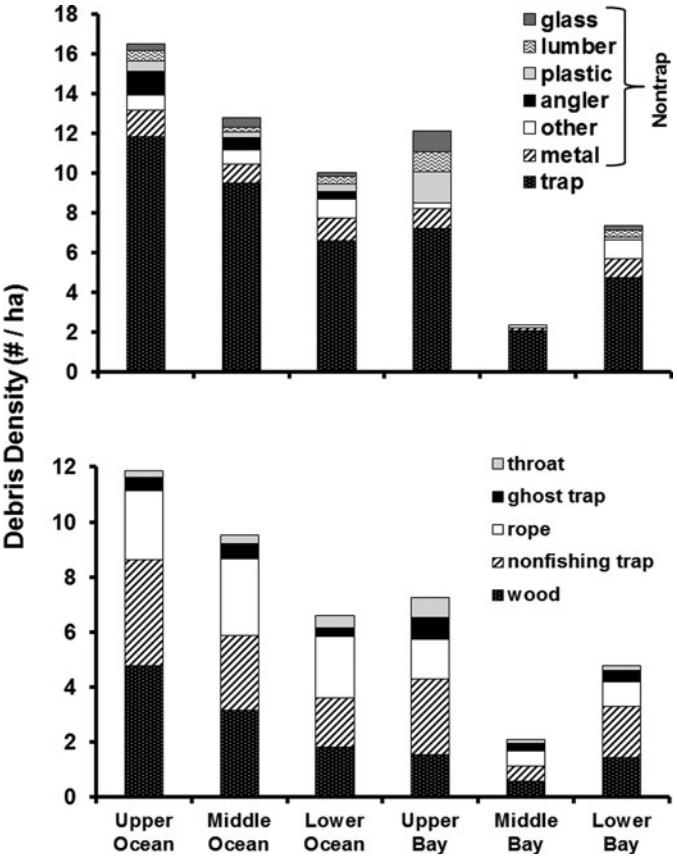

FIGURE 4. Density (number of incidences of debris per hectare of zone) of total debris by category (top panel) and trap debris by stages of degradation (bottom panel) across trap-use zones surveyed during towed-diver transects in the Florida Keys National Marine Sanctuary. Debris items representing less than 10% of nontrap debris were pooled as other (white bars) and included concrete, wire, rubber, paper, fabric, and items of unknown origin (Table 3).

dependent upon habitat type in Florida Bay ($P = 0.2053$; Table 1; Figure 5). However, debris density was dependent upon habitat type for nontrap debris and the combined total ($P = 0.0278$ and 0.0394, respectively; Table 1; Figure 5). Macroalgae and seagrass generally had similar lower debris densities (Figure 5). For total debris, macroalgae was also similar to hardbottom and bare substrates (Figure 5). For the combined total, hardbottom, bare substrates, and macroalgae were similar as were hardbottom, macroalgae, and seagrass (Figure 5). Type and proportion of debris were similar across habitats (Figure 6). Debris from traps accounted for 62.5–78.2% of all debris encountered in every habitat, with wood parts, nonfishing traps, and rope contributing in nearly equal amounts (Figure 6).

The mean number of ghost traps per transect was 0.1645 (SE = 0.0024) (approximately 0.2 ghost traps/ha), or an estimated 85,548 (SD = 23,387) total ghost traps when this value is applied to the entire study area, which notably excludes regions west of Key West (Table 4). For nonfishing traps, the mean per transect was 2.0311 (SE = 0.2402) (approximately 2.5 nonfishing traps/ha), or an estimated 1,056,129 (SD = 124,919) nonfishing traps within the study area (Table 4).

DISCUSSION

The bulk of submerged marine debris observed in the Florida Keys National Marine Sanctuary originated in commercial trap fisheries, primarily the spiny lobster fishery. Our study area represented the most heavily fished portion of the sanctuary (Sheridan et al. 2003). We estimated that ∼18% of the traps used annually in the lobster fishery were ghost fishing when the season was closed, consistent with results from mail surveys of commercial fishers who reported trap loss for non-hurricane years (Matthews and Uhrin 2009). Our estimate of the number of lost traps was potentially affected by Tropical Storm Ernesto in August 2006. This relatively weak tropical storm with 65 km/h sustained winds crossed the Upper Ocean trap-use zone, but no particular effects on the lobster fishery were reported. Our observation of approximately 85,000 ghost-fishing traps likely represents a typical condition in the fishery.

It is difficult to evaluate our estimate that more than 1 million derelict traps were in the sanctuary. Given the persistence of concrete and plastic trap parts, trap debris from multiple years was likely included, and some of the debris would have been the result of loss due to previous tropical weather systems. Additionally, for most of the fishery's history, old or broken traps were intentionally disposed of at sea and this practice was not

TABLE 4. Mean (SE) number of spiny lobster ghost traps and nonfishing traps per 0.8-ha transect, as well as estimates of the total number of ghost traps and nonfishing traps, by trap-use zone, throughout the sample domain.

Use zone	Mean (SE) number of ghost traps per transect	Estimated total number of ghost traps	Mean (SE) number of nonfishing traps per transect	Estimated total number of nonfishing traps
Lower Bay	0.0476 (0.0476)	6,467	1.8095 (0.6459)	245,763
Lower Ocean	0.2121 (0.0843)	16,795	1.6667 (0.3158)	131,959
Middle Bay	0 (0)	0	0.6667 (0.3727)	74,788
Middle Ocean	0.4054 (0.1421)	24,678	2.6216 (0.4844)	159,582
Upper Bay	0.0714 (0.0714)	1,462	2.8571 (0.8374)	58,476
Upper Ocean	0.3243 (0.1977)	36,146	3.4594 (0.4594)	385,559
Overall	0.1645 (0.0024)	85,548 (SD = 23,387)	2.0311 (0.2402)	1,056,127 (SD = 124,919)

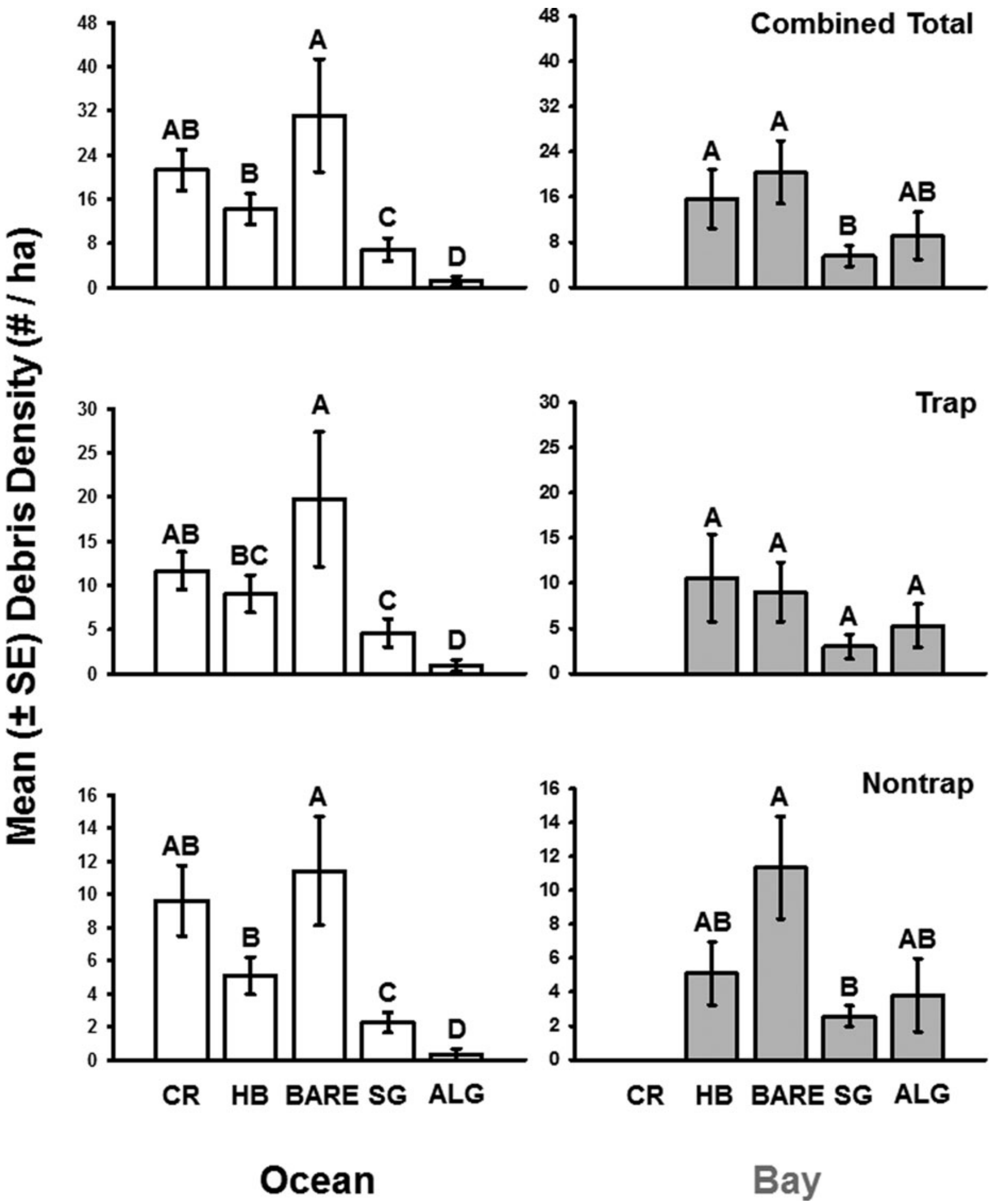

FIGURE 5. Mean (±SE) debris density (number of incidences per hectare) in each habitat for total debris (top panels), trap debris (middle panels), and nontrap debris (bottom panels). Means with the same letter designation are not significantly different at $\alpha = 0.05$. CR = coral, HB = hardbottom, BARE = bare substrates, SG = seagrass, ALG = macroalgae.

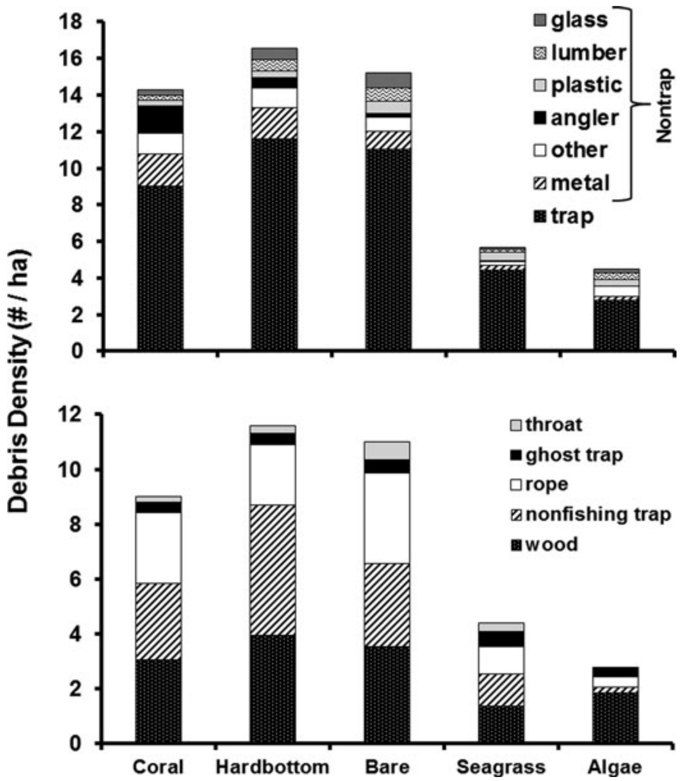

FIGURE 6. Density (number of incidences of debris per hectare of habitat) of total debris by category (top panel) and trap debris by stages of degradation (bottom panel) across trap-use zones surveyed during towed-diver transects in the Florida Keys National Marine Sanctuary. Data from the Atlantic Ocean and Florida Bay are combined. Debris items representing less than 10% of nontrap debris were pooled as other (white bars) and included concrete, wire, rubber, paper, fabric, and items of unknown origin (Table 3).

discouraged until the sanctuary was designated. The estimate of 1 million derelict traps was clearly an underestimation of the number of traps lost or intentionally disposed of during the 50-year history of the lobster trap fishery, when between 0.5 and 1.0 million traps were used annually (Labisky et al. 1980; Hunt 1994; Milon et al. 1998); therefore, the vast majority of trap debris either decayed, was buried, or was transported from the study area. It seems likely that wood decayed, concrete slabs were buried, and plastic trap parts may have floated away. Although the predominant use of wood in the construction of lobster traps may ameliorate some debris accumulation issues through the eventual degradation and deterioration of wooden parts, preliminary results have shown that simulated lost wood traps remained intact and fishing for as long as 2 years and that wood pieces persisted longer (Matthews et al. 2012).

The Upper Ocean, Middle Ocean, and the Upper Bay had the highest trap debris density. For the Middle Ocean and the Upper Bay this corresponds with the large number of traps used in these zones (Sheridan et al. 2003). For the Upper Ocean, we cannot rule out the influence of Tropical Storm Ernesto, which might have caused some trap loss. The Middle Bay, however, where a large number of traps were also used, had the least amount of trap debris. Less boat traffic was typically observed offshore in the Middle Bay zone, which might have reduced the number of buoy-line cutoffs by boat propellers, compared with the greater boat traffic in the Atlantic Ocean and Upper Bay (authors' personal observation). In the Upper Bay, trap molestation by divers was likely minimal after the first month of the lobster fishing season but more prevalent in all Atlantic Ocean zones because most recreational dive activities after the first few days of the lobster season take place on the oceanside reefs. Our surveys in Middle Bay were limited to softbottom habitats, mainly seagrass, where the lack of hardened structure may render traps less susceptible to movement, entanglement, breakage, and loss. The reduced amount of trap debris in one of the most intensely fished zones and the increased amount of trap debris in one of the less intensely fished zones suggest that trap loss caused by forces outside the fishery (e.g., cut ropes by recreational boats) and habitat-mediated accumulation may play a more critical role than direct gear loss in the distribution of debris across the sanctuary.

Trap debris density in hardbottom, bare substrate, and coral reef habitats was consistent with that in previous studies. When we combine our trap debris density estimates for coral reef and hardbottom habitats (10.0 incidences of debris per hectare) to correspond with the habitat classification method of Chiappone et al. (2004), our survey estimates were similar to the 12.6 pieces of debris per hectare reported by those authors. However, trap debris densities of 69.2 items per hectare reported by Miller et al. (2008) greatly exceeded those in our study and previous studies. Interestingly, the percentage of trap debris on coral reef and hardbottom reported by Chiappone et al. (2002, 2004) and Miller et al. (2008) was markedly less (34.5%, 10.1%, and 35%, respectively) than that reported here (51.9%) and those authors did not report any observations of intact traps. Our method of habitat classification may explain why our estimates of trap debris density for bare substrate were greater than those reported by Chiappone (2002, 2004) and Miller et al. (2008) and why those for coral reefs were less. In our study, a debris item observed on bare substrate and one observed in a sand pocket embedded in a reef were both recorded as being associated with bare sand. Chiappone (2002, 2004) and Miller et al. (2008) did not distinguish these microhabitats from coral reef habitat in general.

The relatively high accumulation of trap debris on coral-dominated habitats emphasizes the potentially prominent role of wind-driven movement as a vector for redistributing traps in the sanctuary (Uhrin et al. 2005; Lewis et al. 2009). The effects of trap movement and trap loss on coral reefs appear dramatic and additional research appears warranted to evaluate the contribution lost traps have to coral reef health. Traps moving in reef habitat may be abraded and broken from repeated contact with hard coral surfaces (Lewis et al. 2009), and the reef foundation with its complex network of outcroppings, overhangs, cracks, and crevices offers many opportunities for debris entanglement. The presence of upright and branching reef organisms (e.g., hard corals, gorgonians, sponges) might have facilitated debris entrapment in this habitat. Although hardbottom habitats in the sanctuary do not exhibit the highly variable relief and associated microtopography characteristic of reefs, debris accumulation occurs because of the presence of many gorgonian and sponge species (Bauer et al. 2008). Additional research is required to identify whether trap modifications to buoys, ropes, or ballast or increased use of wire would reduce trap drag in currents and wind-driven movement leading to reduced trap movement and debris accumulation on reefs.

Nontrap debris was encountered 25% less often than was trap debris, and nontrap debris items were generally much smaller. The number of nontrap debris items was relatively consistent between zones suggesting that debris accumulation was not proportional to the most proximate likely source, boating activity. Chiappone et al. (2002) and Miller et al. (2008) reported similar trends in surveys conducted in reef and hardbottom habitats from both no-fishing zones and areas open to fishing in the sanctuary, although the contribution of nontrap debris to the total amount of debris encountered was less (11%) than that reported here. Additional research will be necessary to identify the sources and causes of accumulation of nontrap debris.

Although hook-and-line gear is used extensively by recreational fishers near coral reef and hardbottom habitats, we observed fewer pieces of debris from angling gear in the sanctuary than did other studies. Coral reef and hardbottom appeared to accumulate angling gear (1.12 incidences/ha) but to a much lesser extent than previously reported for these habitats in the sanctuary (74.6 pieces/ha: Chiappone et al. 2002; 99.4 items/hectare: Miller et al. 2008). A pattern similar to that in the Florida Keys National Marine Sanctuary was observed at Gray's Reef National Marine Sanctuary where hook-and-line debris was concentrated on ledges where boat density was highest (Bauer et al. 2008). The differences in the contribution of hook-and-line gear between our study and others in the Florida Keys National Marine Sanctuary highlight a possible limitation of the towed-diver technique. Towing restricts movement by survey divers, which prevents longer searches underneath outcroppings and in crevices and limits divers' ability to detect transparent monofilament line and small debris items. In addition, to avoid collision with features of high-relief habitats and other structures and to prevent entanglement in derelict rope, especially in low-visibility situations, divers remained approximately 1 m off the bottom during tows, which also may have inhibited detection of small, transparent debris items like monofilament line.

Considering that the footprint of a spiny lobster trap is 0.6 m^2, our estimates of approximately 1,000,000 lost traps indicate that the affected area is at least 600,000 m^2 (60 ha). Wind-driven movement of traps, which may occur a number of times before a trap becomes completely dismantled or rendered immobile, would greatly increase this area of impact. After the passage of Tropical Storm Barry in 2007, Lewis et al. (2009) reported mean impact areas of 21.27 and 3.12 m^2 for unbuoyed traps (simulating a derelict state) on hardbottom in water 4 and 8 m deep, respectively. If we consider the size of our study area (361,770 ha), the proportion of hardbottom within that area (21.7%), and a combined ghost trap and nonfishing trap density of 5.2 incidences/ha on hardbottom (Figure 6), more than 400,000 traps (ghost and nonfishing combined) could exist on hardbottom in our study area. If we assume one storm event in which each lost trap moved and created an impact area based upon Lewis et al.'s (2009) average range of movement, then the total area of damaged hardbottom could be 127–868 ha.

Lost traps may also continue to catch and confine, often referred to as ghost fishing, both target species and bycatch causing mortality. Ghost fishing is well documented and can be a significant source of mortality in trap fisheries (Breen 1990; Matsuoka et al. 2005). Little data exist on the extent of spiny lobster mortality in derelict traps, but extended trap deployment times, often up to 30 d in Florida, was implicated as a cause of lobster mortality (Hunt et al. 1986; Matthews 2001). Additional research is needed to understand the length of time that a derelict trap continues to fish and to estimate the lobster mortality resulting from derelict traps. Determination of ghost-fishing mortality rates is potentially a component of fishing mortality that could be relevant to stock assessments.

Our study draws attention to the widespread distribution and predominant presence of spiny lobster trap debris in the Florida Keys National Marine Sanctuary where coral and hardbottom habitats appear to act as sinks for debris from spiny lobster traps, despite the reported avoidance of these habitats by lobster fishers. To our knowledge, this is the first study to survey and estimate the number of derelict spiny lobster traps on the seafloor of the sanctuary. Given the large number of traps in the fishery (Milon et al. 1999) and the inability to prevent trap loss, generation of trap debris will likely continue. Removal of submerged trap debris on especially vulnerable coral-dominated habitats (reef and hardbottom), where trap debris densities are high, would mitigate key habitat issues and remove debris from areas in which it accumulates (Martens and Huntington 2012). Retrieval programs, however, are prohibitively expensive (NOAA 2011), and experience suggests that such programs cannot remove debris as fast as it accumulates (Martens and Huntington 2012). Side-scan sonar has been used to detect derelict wire-construction blue crab *Callinectes sapidus* and Dungeness crab *Cancer magister* traps on low-relief, softbottom habitats (i.e., mud, sand, seagrass), leading to effective removal (Havens et al. 2008; June et al. 2010). Recent trials in the U.S. Virgin Islands under a controlled field setting with known trap targets suggest that sonar can detect derelict traps in low- to moderate-relief coral substrates (e.g., sand, colonized pavement, low-relief aggregate reef), but no consistent program exists for the removal of trap debris in coral (Battista et al. 2012).

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