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Spatial Distribution of Lost Fishing Gear on Fished and Protected Offshore Reefs in the Florida Keys National Marine Sanctuary

MARK CHIAPPONE[1,3], DIONE W. SWANSON[2], STEVEN L. MILLER[1], AND HELGA DIENES[1]

[1]*Center for Marine Science and NOAA's National Undersea Research Center, University of North Carolina at Wilmington, 515 Caribbean Drive, Key Largo, FL 33037, USA;* [2]*Division of Marine Biology and Fisheries, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA;* [3]*Corresponding author: chiapponem@uncwil.edu.*

ABSTRACT.—**Despite a long history of intensive fishing, information on the spatial extent and biological impacts of fishing gear is lacking in the Florida Keys. We studied spatial distribution, density, and length of lost fishing gear and other non-fishing-related debris at 63 shallow-water (< 8 m) sites. The sites comprised high-relief spur and groove and low-relief hard-bottom habitats; three geographic regions; and three types of management areas: open to fishing, restricted to catch and release fishing by trolling only, and no fishing. Three-hundred pieces of lost fishing gear and other debris were removed from 25,200 m^2 of benthic habitat. Lost hook-and-line gear was the most prominent debris (87%). No significant differences in mean debris densities were detected between habitats studied or among geographic regions. Mean densities of lost hook-and-line gear, lobster trap gear, and total debris were similar among the three management area types in high-relief spur and groove, while lost hook-and-line gear and total debris were significantly greater in no-fishing zones compared to fished areas in low-relief hard-bottom. In designated no-fishing zones, lost fishing was spatially pervasive and comprised the majority of marine debris in the habitats surveyed. Some of the lost fishing gear was probably present before the designation of no-fishing zones in 1997; the preponderance of lost gear in these areas may indicate that they attract anglers. Monitoring of lost fishing gear can help to assess compliance and biological impacts in the Florida Keys and the patterns documented highlight the challenge to patrolling a large marine protected area.**

KEYWORDS.—**Fishing, Florida Keys, marine debris, marine reserves, stratified sampling**

INTRODUCTION

Derelict fishing gear can destroy benthic organisms and entangle both benthic and mobile fauna (Chiappone et al. 2002), including endangered species such as sea turtles (Donohue et al. 2001). The loss and disposal of fishing gear is internationally recognized as a major environmental issue (Watling and Norse 1998) and several approaches to reduce debris are advocated (e.g., educational programs, volunteer clean-up efforts, development of plastic-free gear) (Jones 1995). Despite such recognition, the extent and possible effects of lost fishing gear, and other debris, on organisms and ecological processes are still largely unknown (Dayton et al. 1995; Jennings and Polunin 1996). Exceptions to this pattern are several studies evaluating mobile fishing gear impacts to benthic habitat structure (Auster and Langton 1999; Benaka 1999).

Commercial and recreational fishing are economically important in the Florida Keys, targeting an enormous array of fish and invertebrate species using a variety of gear types (Tilmant 1989; Bohnsack et al. 1994). There is concern about possible effects of fishing on the Florida Keys because it has greatly expanded in the last 40 years with the economy largely dependent upon tourism and recreational fishing (Leeworthy and Wiley 1995; Ault et al. 1998; Schittone 2001). Currently, there are over 4,500 registered commercial fishing vessels using crab/lobster traps or hook-and-line. The Florida Keys vessels using traps may deploy over 540,000 lobster traps for spiny lobsters (*Panulirus argus*) and 750,000 traps for stone crabs (*Menippe mercenaria*) per season (DiDomenico 2001). The number of registered recreational vessels in the Florida Keys (Monroe County) increased nearly ten times between 1964 (2,242 vessels) and 1998 (21,336 vessels). While not all of the boats engage in fishing, over 25 million recreational fishing trips were made in Florida in 2000 (43% east coast and 57% west coast) and over 64 million pounds of fish captured recreationally were landed (Ault et al. 2001; NMFS 2001). Recreational fishing is of management concern because of (1) large number of targeted species, (2) multiple access points for vessels, and (3) array of gears used, but mainly because of (4) no limitations on the number of recreational licenses issued (Bohnsack et al. 1994; Harper et al. 2000). Recreational fishing increasingly resembles commercial fishing as technological improvements are adopted leading to increases in effective fishing power (Bohnsack and Ault 1996). Angling dominates recreational fishing in the Florida Keys, with most of the environmental impacts to benthos from lost gear (e.g., monofilament line, fishing wire, leaders, lead sinkers, and hooks). In addition, lobster and stone crab traps are often dislodged and broken during storms (DiDomenico 2001).

Surveys of marine debris have been conducted around the world using a variety of methods such as beach surveys and benthic trawls (Slip and Burton 1991; Hess et al. 1999); however, the present study, using *in situ* underwater observations, was undertaken to document the spatial distribution of lost fishing gear and other marine debris in the Florida Keys National Marine Sanctuary (FKNMS). This study, undertaken as part of an ongoing assessment of the community structure of reefs in the FKNMS (Miller et al. 2002), is a continuation of an assessment of lost fishing gear and its impacts to sessile invertebrates (Chiappone et al. 2002). This documentation is relevant because coastal ecosystems in the Florida Keys continue to experience a growing number of anglers (Schittone 2001) and intensive commercial trap fishing (DiDomenico 2001). However, the spatial distribution of lost fishing gear and its biological impacts to sessile invertebrates and other organisms is poorly documented (Chiappone et al. 2004). This study evaluated the spatial distribution of marine debris on shallow (<8 m), high-relief spur and groove and low-relief hard-bottom habitat types in the FKNMS during 2001. We hypothesized that the mean densities of marine debris, particularly lost fishing gear such as hook-and-line, would be lower in no-fishing zones ("protected" since 1997) compared to fished areas, and that catch and release areas would likely yield similar densities of lost fishing gear compared to fished areas.

Materials and Methods

Study area

The Florida Keys National Marine Sanctuary (FKNMS), created in 1990 to conserve biodiversity and facilitate multiple resource uses, implemented in 1997 a zoning plan and introduced the concept of marine reserves in discrete areas of the Florida Keys, including no-fishing zones and catch and release areas (NOAA 1996; Bohnsack 1997). Twenty-three no-fishing zones (1 to 2 km^2) were created to minimize user group conflicts, protect biodiversity in many best-developed coral reef areas of the FKNMS, and restore density and size structure of overfished species (Bohnsack 1996; Ault et al. 1998). These twenty-three no-fishing zones of high-profile coral reef habitat in the Florida Keys National Marine Sanctuary (FKNMS) (NOAA 1996) were the primary focus of the underwater debris surveys.

The no-fishing zones are designated as Sanctuary Preservation Areas (SPAs), Research Only Areas (ROs), and Ecological Reserves (ERs). SPAs are designed to protect the most sensitive and intensively used, high-relief coral reef habitat from extractive use, including fishing and collecting. These areas include many popular diving reefs and were intended to reduce conflicts between divers and fishers. Access to special-use ROs is limited, as they are intended for research and to assess the effects of diving activities. Ecological Reserves are designed to protect contiguous benthic habitats across the south Florida shelf. With the exception of four zones, all consumptive activities including fishing are prohibited; however, in Sand Key SPA, Sombrero Key SPA, Alligator Reef SPA, Conch Reef SPA (three of which were surveyed in this study), catch and release fishing by trolling is permitted. The majority of the 23 no-fishing zones are located on the offshore reef tract to 15 m depth, with the fore reef environment characterized by high-relief spur and groove topography or low-relief hard-bottom (Chiappone and Sullivan 1997; FDEP 1998).

Previous regional classifications of the Florida Keys marine environment (Shinn et al. 1989; Ginsburg and Shinn 1993) were modified accordingly for the present study to evaluate potential regional differences in the spatial distribution of lost fishing gear. Ginsburg and Shinn (1993) defined three regions in the Florida Keys as follows based upon the size and orientation of the Pleistocene islands and the distribution of patch reefs and offshore bank-barrier reefs: (1) upper Florida Keys (Hen and Chickens or Plantation Key north), (2) middle Florida Keys from Upper Matecumbe (including Alligator) to Big Pine Key, and (3) lower Florida Keys (west of Big Pine Key). Shinn et al. (1989) defined these regions as upper (Miami to Molasses Reef), middle (Molasses to Marker G), and lower Keys (west of Marker G), while FDEP (1998) divided the Florida Keys into upper (Northern Key Largo to Upper Matecumbe), middle Florida Keys from Upper Matecumbe to Pigeon Key, and lower Florida Keys from Little Duck Key to the Dry Tortugas. Our regional classification differs from that of Ginsburg and Shinn (19933) only in the division between the upper and middle Keys regions, in which our division occurs southwest of Molasses Reef (between Pickles and Conch Reef), reflecting the absence of shallow spur and groove development further southwest (except for Sombrero Key) until the lower Keys region (Fig. 1).

Survey methods

Sixty-three sites were surveyed southwest of Key West to northern Key Largo, during June to September 2001, over 200 km of the offshore reef tract in the Florida Keys National Marine Sanctuary (FKNMS) (Fig. 1). Two habitat types (high-relief spur and groove and low-relief hard-bottom) were selected for sampling based upon their prevalence in the study area and their inclusion within the FKNMS no-fishing zones described above (Table 1). The sampling effort encompassed 25,200 m^2 (i.e., 2.52 ha) of benthic habitat from 1-7 m depth. Thirty-four sites (54%) were of spur and groove topography and 29 sites (46%) were low-relief hard-bottom (Table 1). Ten of the 23 FKNMS no-fishing zones were sampled during this study: 8 sanctuary preservation areas (SPAs, average of 0.82 km^2 in area, range of 0.16 to 3.27 km^2); 1 special-use zone (Eastern Sambo Research Only Area); and 1 ecological reserve (Western Sambo, 31 km^2) (Fig. 1). Out of 10 no-fishing zones sampled, 7 prohibit fishing, while 3 (Sand Key SPA, Sombrero Key SPA, and Conch Reef SPA) allow catch and release fishing by trolling (Table 1).

This spatially intensive study employed a two-stage stratified random survey design (Cochran 1977; Ault et al. 1999) to optimize sampling effort and to choose sampling locations to determine density of lost fishing gear and other marine debris. The sampling domain, limited to coral reef and hard-bottom habitats on the Atlantic side of the Florida Keys from northern Key Largo to southwest of Key West (Fig. 1), was partitioned into unique habitat strata based on geographic location and benthic habitat characteristics, using information provided by Florida Department of Environmental Protection (FDEP) habitat maps for the FKNMS (FDEP 1998). The sampling domain was overlain in a Geographic Information System, with a grid of 200 m × 200 m blocks, called sites, which were the primary sample units. Sites containing either high-relief spur and groove or low-relief hard-bottom habitat were assigned unique numbers and randomly selected for sampling from a discrete uniform probability distribution to ensure that each site had equal selection probability. The sampling effort was determined by the availability of the two habitat types selected for the study

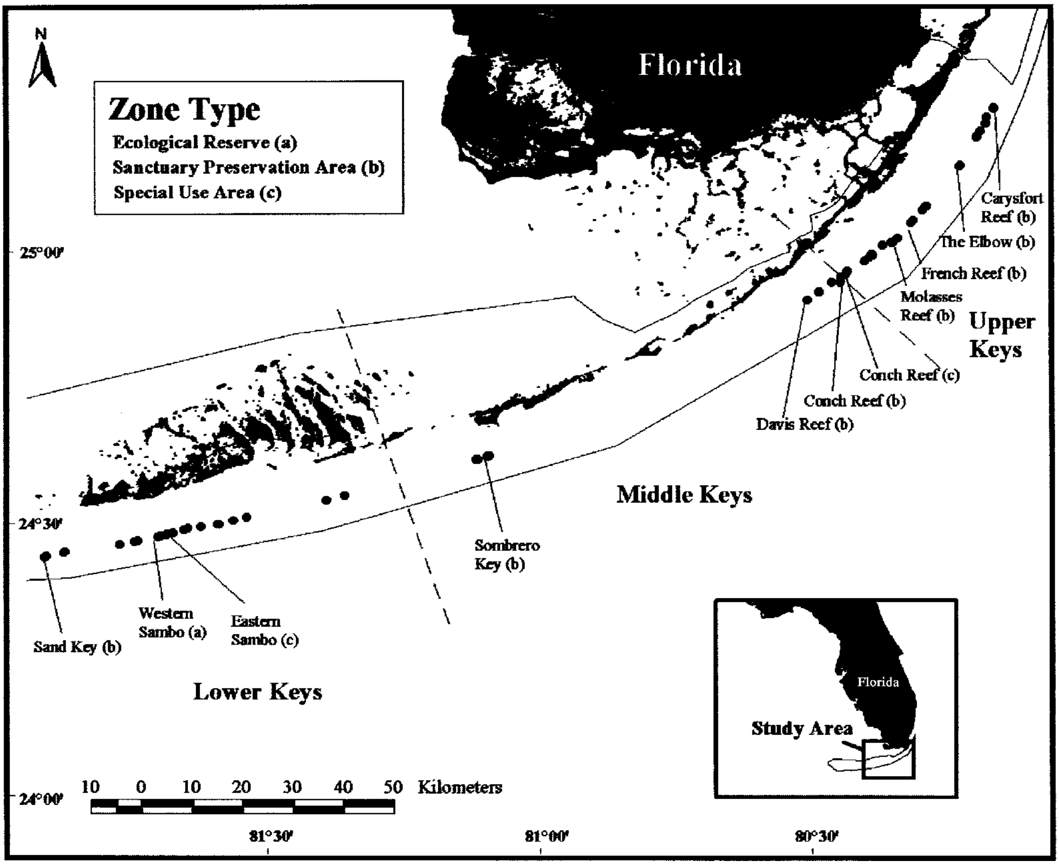

FIG. 1. Sampling locations for lost fishing gear and other marine debris in the Florida Keys National Marine Sanctuary (FKNMS) during June-September 2001. Black dots (•) represent individual survey sites and zone types represent different name designations for no-fishing zones in the FKNMS. Note that catch and release fishing by trolling is currently permitted at Sand Key, Sombrero Key, and Conch Reef.

and the distribution of the FKNMS no-fishing zones (Miller et al. 2002). No-fishing zones are concentrated in particular habitat types; thus, the sampling was largely concentrated in high-relief spur and groove topography in the upper and lower Keys (Table 1). Despite the relatively small sizes of most of the zones, the random allocation of two replicate sites within each zone for a particular habitat type was possible. Second-stage sample units (transect stations) were then randomly positioned in each primary unit (site) as described below.

Within each site, four sampling stations were located using differential Global Positioning System. At each of the four stations per site, two replicate 25 m transects were deployed from inshore to offshore. At sites with spur and groove topography, divers oriented transects along the tops of the spurs and not in sand grooves. Lost fishing gear and other marine debris (Table 2) were surveyed by divers searching an area 1 m out from each transect side, yielding a sample area of 100 m^2 per station (i.e., 400 m^2 per site). The transect dimensions were selected to maximize the area sampled, given the number of personnel available and other variables monitored in the assessment program (Miller et al. 2002). The type of marine debris, dimensions (length, width, and height), numbers of sessile invertebrates damaged (Chiappone et al. 2004), and whether or not the marine debris was possibly recently lost (as determined by biological fouling) were noted.

TABLE 1. Sampling effort for marine debris in the Florida Keys National Marine Sanctuary (FKNMS). Eight 25 m × 2 m transects (100 m^2 per station and 400 m^2 per site) were sampled at each site, with sites defined as 200 m × 200 m cells or blocks on the existing habitat map of the sampling domain. Sampling domain refers to the proportion of habitat area available and effort refers to the proportion of each stratum sampled relative to the total sites available.

Sampling strata	Available sites	Sampling domain (%)	No. sites surveyed	Sampling effort (%)	Sampling area (m^2)
High-relief spur and groove	148	15.42	34	53.97	13,600
Lower Keys Sector	88	9.17	17	26.98	6,800
No-fishing zones	41	4.27	6	9.52	2,400
Catch and release areas	7	0.73	2	3.17	800
Fished areas	40	4.17	9	14.29	3,600
Middle Keys Sector	11	1.15	3	4.76	1,200
Catch and release areas	7	0.73	2	3.17	800
Fished areas	4	0.42	1	1.59	400
Upper Keys Sector	49	5.10	14	22.22	5,600
No-fishing zones	34	3.54	8	12.70	3,200
Fished areas	15	1.56	6	9.52	2,400
Low-relief hard-bottom	812	84.58	29	46.03	11,600
Lower Keys Sector	53	5.52	7	11.11	2,800
Fished areas	48	5.00	7	11.11	2,800
Middle Keys Sector	244	25.42	13	20.63	5,200
No-fishing zones	21	2.19	2	3.17	800
Catch and release areas	6	0.63	2	3.17	800
Fished areas	217	22.60	9	14.29	3,600
Upper Keys Sector	515	53.65	9	14.29	3,600
Fished areas	487	50.73	9	14.29	3,600
Total	960	100.00	63	100.00	25,200

No-fishing zones sampled in high-relief spur and groove were Carysfort/S. Carysfort SPA, Elbow Reef SPA, Molasses Reef SPA, Sombrero Key SPA, Eastern Sambo RO, Western Sambo ER, Eastern Dry Rocks SPA and Sand Key SPA. No-fishing zones sampled in low-relief hard-bottom were Conch Reef SPA and Davis Reef SPA. Note that catch and release fishing by trolling is permitted in three of the no-take zones surveyed listed separately (Sand Key SPA, Sombrero Key SPA and Conch Reef SPA).

Data analysis

Mean densities of lost fishing gear and other marine debris (i.e., pieces of gear or debris per 100 m^2), were compared between habitat types, among geographic regions, and among fully protected no-fishing zones, catch and release areas, and fished areas. Although catch and release areas are designated as no-fishing zones in the FKNMS, mean debris densities were calculated separately for these areas for all statistical comparisons. Fished areas only included areas outside of both no-fishing zones and no-fishing zones allowing catch and release fishing by trolling. Lost debris was partitioned into (1) lost hook-and-line gear, (2) lobster trap gear, (3) other debris, and (4) total debris. Statistical comparisons of mean densities were made by calculating confidence intervals (CI) based on the equation CI = mean ± $t_{[\alpha,df]}$ *standard error, with standard errors estimated by the two-stage, stratified sampling design (Cochran 1977). Confidence intervals were adjusted for multiple comparisons using the Bonferroni procedure (Miller 1981). The experiment-wise error rate was held at α = 0.05 and the comparison-wise error rate was adjusted based on the number of multiple comparisons using the equation: comparison-wise error rate = α/c, where c = k (k-1)/2 and k = number of comparisons.

RESULTS

Transect surveys yielded 298 occurrences of marine debris from the 63 sites (25,200 m^2 of benthic habitat), representing three debris categories (e.g., hook and line gear,

TABLE 2. Frequency of lost fishing gear and other marine debris in the FKNMS sampled during June-September 2001. Values in parentheses for subtotaled categories are the proportions of debris types found in each habitat and management type. For example, 23.07% of all hook-and-line gear was recorded in spur and groove no-fishing zones.

	Spur and groove (34 sites)			Hard-bottom (29 sites)			
Debris type	No-fishing zones (16) (25.40%)	Catch and release (2) (3.17%)	Fished areas (16) (25.40%)	No-fishing zones (2) (3.17%)	Catch and release (2) (3.17%)	Fished areas (25) (39.68%)	Total
Lost hood-and-line gear							
Fishing rod						1	1
Fishing sinker	1					1	2
Fishing wire	27	2	16	3	7	29	84
Fishing wire w/hook		3				8	11
Fishing wire w/leader	4	2	5			1	12
Fishing wire w/sinker	2			1		1	4
Monofilament line	22	9	31	10	4	46	122
Monofilament w/hook	2	3	4	1			10
Monofilament w/leader	1					4	5
Monofilament w/sinker	1	2		1		5	9
Subtotal	60 (23.07%)	21 (8.07%)	56 (21.54%)	16 (6.15%)	11 (4.23%)	96 (36.92%)	260
Lost lobster trap gear							
Rope w or w/o buoy	3	1	6			7	17
Wire grating					1		1
Wooden slats	3					9	12
Subtotal	6 (20.00%)	1 (3.33%)	6 (20.00%)	0 (0%)	1 (3.33%)	16 (53.33%)	30
Other debris types							
Anchor						1	1
Beer bottle					1		1
Bottle cap		1					1
Diving knife						1	1
Diving weight			1				1
Metal pipe	1						1
Nylon bag						1	1
Plastic mesh bag	1						1
Subtotal	2 (25.00%)	1 (12.50%)	1 (12.50%)	0 (0%)	1 (12.50%)	3 (37.50%)	8
All debris categories	68 (22.82%)	23 (7.72%)	63 (21.14%)	16 (5.37%)	13 (4.36%)	115 (38.59%)	298

lobster trap gear and other debris type) and 21 individual debris types or combinations (Table 2) Lost fishing gear and other debris were recorded from 92% of the sites, including all no-fishing zones and catch-and-release areas surveyed in both spur and groove and low-relief hard-bottom habitats. Lost hook-and-line fishing gear was the predominant debris type (260 incidences), representing 87% of all debris, followed by lost lobster trap gear (10%) and other debris (3%). Lost hook-and-line gear was documented at nearly 83% of all sites, including all seven no-fishing zones and the three no-fishing zones allowing catch and release by trolling. The 260 pieces of lost hook-and-line gear were mostly monofilament line (47%) and fishing wire (32%), or combinations of these two debris types with leaders, hooks, and lead sinkers. Most (56%) of the lost hook-and-line gear recovered from spur and groove (56%) and low-relief hard-bottom (63%) was <0.5 or 0.5-1.0 m in length (Fig. 2), but larger (>3.0 m) pieces were also common. Of the 491.07 m of debris pieces recovered, 356.44 m (73%) was lost hook-and-line gear. A total of 126.92 m of lobster trap rope was recorded,

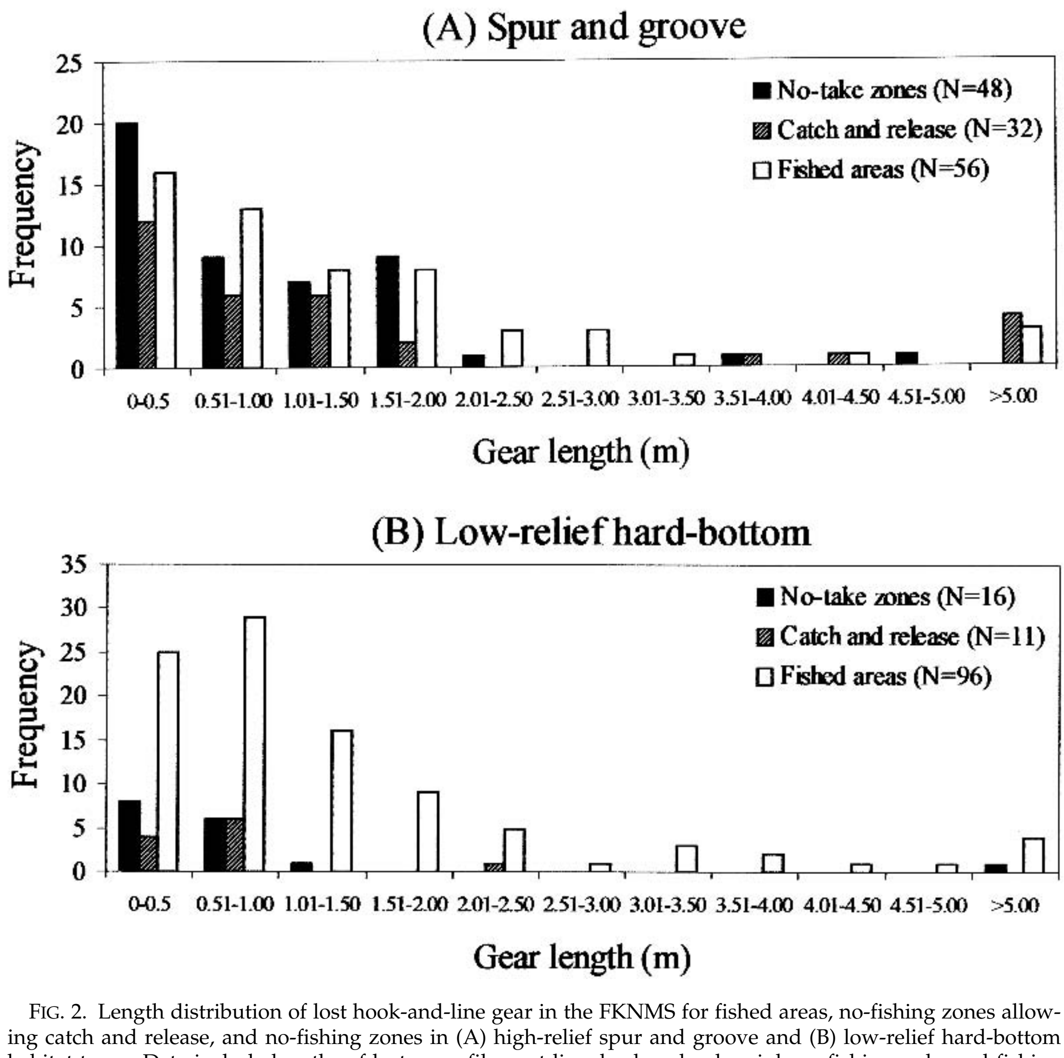

FIG. 2. Length distribution of lost hook-and-line gear in the FKNMS for fished areas, no-fishing zones allowing catch and release, and no-fishing zones in (A) high-relief spur and groove and (B) low-relief hard-bottom habitat types. Data include lengths of lost monofilament line, leaders, hooks, sinkers, fishing rods, and fishing wire.

of which 75% was retrieved from spur and groove and 61% from the lower Keys region. Recovered trap rope pieces ranged from 0.17 to 19.6 m in length.

Mean densities of hook-and-line gear in high-relief spur and groove (1.01 ± 0.14 pieces/100 m^2) and low-relief hard-bottom (1.06 ± 0.19 pieces/100 m^2) were not statistically different ($P > 0.05$) between the two habitat types (Table 3). Mean densities of lost lobster trap gear, other debris, and total debris also did not differ significantly between the two habitats. In both high-relief spur and groove and low-relief hard-bottom, the density of lost hook-and-line fishing gear was approximately eight to 34 times greater than the mean densities of lost lobster trap gear and other debris, respectively (Table 3). Mean (±1 SE) lengths of recovered hook-and-line gear were 1.49 ± 0.20 m in high-relief spur and groove and 1.23 ± 0.13 m in low-relief hard-bottom (Table 4). The average length of lost lobster trap rope was 8.65 ± 1.87 m and 5.30 ± 2.50 m in high-relief spur and groove and low-relief hard-bottom, respectively.

Significant regional variations in lost fishing gear and other marine debris were not detected ($P > 0.0167$), except for significantly greater densities ($P < 0.0167$) of lost lobster trap gear in the lower Keys compared to the middle Keys (Table 3). In the high-relief spur and groove habitat, the middle, upper and lower Keys regions yielded 1.50 incidences/100 m^2, 1.04 incidences/100 m^2 and 0.90 incidences/100 m^2 of lost hook-and-line gear, respectively (Table 3). The relatively high mean density

TABLE 3. Mean (±1 SE) densities (no. per 100 m^2) of lost hook-and-line gear, lobster trap gear, and other marine debris in the FKNMS habitat type, geographic region, and management zone.

Strata/site location (no. sites)	Lost hood-and-line gear	Lost lobster trap gear	Other marine debris	Total marine debris
High-relief spur and groove (34)	1.01 ± 0.14	0.12 ± 0.03	0.03 ± 0.01	1.15 ± 0.14
Lower Keys Sector (17)	0.90 ± 0.20	0.18 ± 0.05	0.04 ± 0.02	1.12 ± 0.22
No-fishing zones (6)	0.81 ± 0.29	0.22 ± 0.07	0.06 ± 0.04	1.09 ± 0.32
Eastern Dry Rocks SPA (2)	1.75 ± 0.95	0.38 ± 0.14	0 ± 0	2.13 ± 1.03
Western Sambo ER (2)	0.25 ± 0.07	0 ± 0	0.13 ± 0.13	0.38 ± 0.14
Eastern Sambo RO (2)	0.50 ± 0.26	0.38 ± 0.15	0.13 ± 0.13	1.00 ± 0.46
Catch and release areas (2)	0.75 ± 0.37	0.13 ± 0.12	0 ± 0	0.88 ± 0.31
Sand Key SPA (2)	0.75 ± 0.37	0.13 ± 0.12	0 ± 0	0.88 ± 0.31
Fished areas (9)	0.97 ± 0.29	0.14 ± 0.06	0.03 ± 0.03	1.14 ± 0.30
Middle Keys Sector (3)	1.50 ± 0.61	0 ± 0	0.08 ± 0.08	1.58 ± 0.69
Catch and release areas (2)	1.88 ± 0.85	0 ± 0	0.13 ± 0.13	2.00 ± 0.98
Sombrero Key SPA (2)	1.88 ± 0.85	0 ± 0	0.13 ± 0.13	2.00 ± 0.98
Fished areas (1)	0.75 ± 0.48	0 ± 0	0 ± 0	0.75 ± 0.48
Upper Keys Sector (14)	1.04 ± 0.19	0.07 ± 0.05	0 ± 0	1.11 ± 0.18
No-fishing zones (8)	1.25 ± 0.27	0 ± 0	0 ± 0	1.25 ± 0.27
Molasses Reef SPA (2)	2.38 ± 0.57	0 ± 0	0 ± 0	2.38 ± 0.57
Elbow Reef SPA (2)	0.75 ± 0.17	0 ± 0	0 ± 0	0.75 ± 0.17
Carysfort Reef SPA (4)	0.94 ± 0.24	0 ± 0	0 ± 0	0.94 ± 0.24
Fished areas (6)	0.75 ± 0.26	0.17 ± 0.10	0 ± 0	0.92 ± 0.25
Low-relief hard-bottom (29)	1.06 ± 0.19	0.12 ± 0.03	0.03 ± 0.03	1.22 ± 0.20
Lower Keys Sector (7)	0.64 ± 0.47	0.21 ± 0.10	0 ± 0	0.86 ± 0.55
Fished areas (7)	0.64 ± 0.47	0.21 ± 0.10	0 ± 0	0.86 ± 0.55
Middle Keys Sector (13)	1.17 ± 0.19	0.10 ± 0.04	0.04 ± 0.03	1.31 ± 0.18
No-fishing zones (2)	2.00 ± 0.35	0 ± 0	0 ± 0	2.00 ± 0.35
Davis Reef SPA (2)	2.00 ± 0.35	0 ± 0	0 ± 0	2.00 ± 0.35
Catch and release areas (2)	1.38 ± 0.49	0.13 ± 0.12	0.13 ± 0.13	1.63 ± 0.54
Conch Reef SPA	1.38 ± 0.49	0.13 ± 0.12	0.13 ± 0.13	1.63 ± 0.54
Fished areas (9)	0.94 ± 0.23	0.11 ± 0.06	0.03 ± 0.03	1.08 ± 0.21
Upper Keys Sector (9)	1.22 ± 0.42	0.08 ± 0.04	0.06 ± 0.04	1.36 ± 0.43
Fished areas (9)	1.22 ± 0.42	0.08 ± 0.04	0.06 ± 0.04	1.36 ± 0.43

TABLE 4. Mean (±1 SE) and total lengths (m) of lost hook-and-line gear categories (monofilament, wire, leaders, hooks, weights, rods) and lost lobster trap rope in the FKNMS by habitat type, geographic region, and management zone.

	Lost hook-and-line gear			Lost lobster trap rope		
Strata/site location (no. sites)	N	Mean (SE)	Total (m)	N	Mean (SE)	Total (m)
High-relief spur and groove (34)	137	1.49 ± 0.20	204.42	11	8.65 ± 1.87	95.14
Lower Keys Sector (17)	61	1.41 ± 0.27	86.10	9	8.62 ± 1.96	77.58
No-fishing zones (8)	20	0.87 ± 0.20	17.37	3	5.78 ± 2.60	17.35
Eastern Dry Rocks SPA (2)	14	0.58 ± 0.10	8.08	3	5.78 ± 2.60	17.35
Western Sambo ER (2)	2	1.20 ± 0.55	2.40			
Eastern Sambo RO (2)	4	1.72 ± 0.81	6.89			
Catch and release areas (2)	6	2.91 ± 1.17	17.44	1	5.80	5.80
Sand Key SPA (2)	6	2.91 ± 1.17	17.44	1	5.80	5.80
Fished areas (9)	35	1.47 ± 0.39	51.29	5	10.89 ± 1.33	54.43
Middle Keys Sector	18	3.05 ± 1.08	54.94			
Catch and release areas (2)	15	2.32 ± 0.82	34.74			
Sombrero Key SPA (2)	15	2.32 ± 0.82	34.74			
Fished areas	3	6.73 ± 5.32	20.20			
Upper Keys Sector	58	1.09 ± 0.14	63.38	2	8.78 ± 7.43	17.56
No-fishing zones	40	0.94 ± 0.13	37.75			
Molasses Reef SPA (2)	19	0.59 ± 0.12	11.20			
Elbow Reef SPA (2)	6	0.95 ± 0.26	5.69			
Carysfort Reef SPA (4)	15	1.39 ± 0.27	20.86			
Fished areas (6)	18	1.42 ± 0.33	25.63	2	8.78 ± 7.43	17.56
Low-relief hard-bottom (29)	123	1.23 ± 0.13	152.02	6	5.30 ± 2.50	31.78
Lower Keys Sector (7)	18	1.24 ± 0.20	22.35	4	7.19 ± 3.45	28.77
Fished areas (7)	18	1.24 ± 0.20	22.35	4	7.19 ± 3.45	28.77
Middle Keys Sector (13)	61	0.99 ± 0.16	60.51	1	0.61	0.61
No-fishing zones (2)	16	0.86 ± 0.35	13.74			
Davis Reef SPA (2)	16	0.86 ± 0.35	13.74			
Catch and release areas (2)	11	0.71 ± 0.16	7.86			
Conch Reef SPA (2)	11	0.71 ± 0.16	7.86			
Fished areas (9)	34	1.35 ± 0.23	38.91	1	0.61	0.61
Upper Keys Sector (9)	44	1.55 ± 0.26	68.83	1	2.40	2.40
Fished areas (9)	44	1.55 ± 0.26	68.83	1	2.40	2.40

of debris in the middle Keys was mostly due to the localized occurrence of lost hook-and-line gear in Sombrero Key SPA, a no-fishing zone allowing catch and release fishing by trolling. Subsequent analyses evaluating debris densities among management zones did not discriminate geographic regions due to the lack of regional variability detected.

Spatial patterns in mean densities of marine debris indicated relatively similar densities among no-fishing zones, catch and release areas, and fished areas for both habitat types (Table 3). Four of the six no-fishing zones surveyed in high-relief spur and groove yielded relatively high densities (0.75 pieces or more/100 m^2) of lost hook-and-line gear (Table 3). All three catch and release areas also yielded relatively high mean densities (0.75 or more pieces/100 m^2) of lost hook-and-line gear. Most no-fishing zones and catch and release areas thus yielded similar or greater densities of lost hook-and-line gear compared to fished areas (Fig. 3A). Statistical comparisons of the means indicated that no-fishing zones and catch and release areas yielded similar ($P > 0.05$) densities of both hook-and-line gear and lobster trap gear compared to fished areas (Table 5).

In the low-relief hard-bottom habitat, one no-fishing zone (Davis Reef SPA), one catch and release area (Conch Reef SPA), and 25 fished areas throughout the Florida

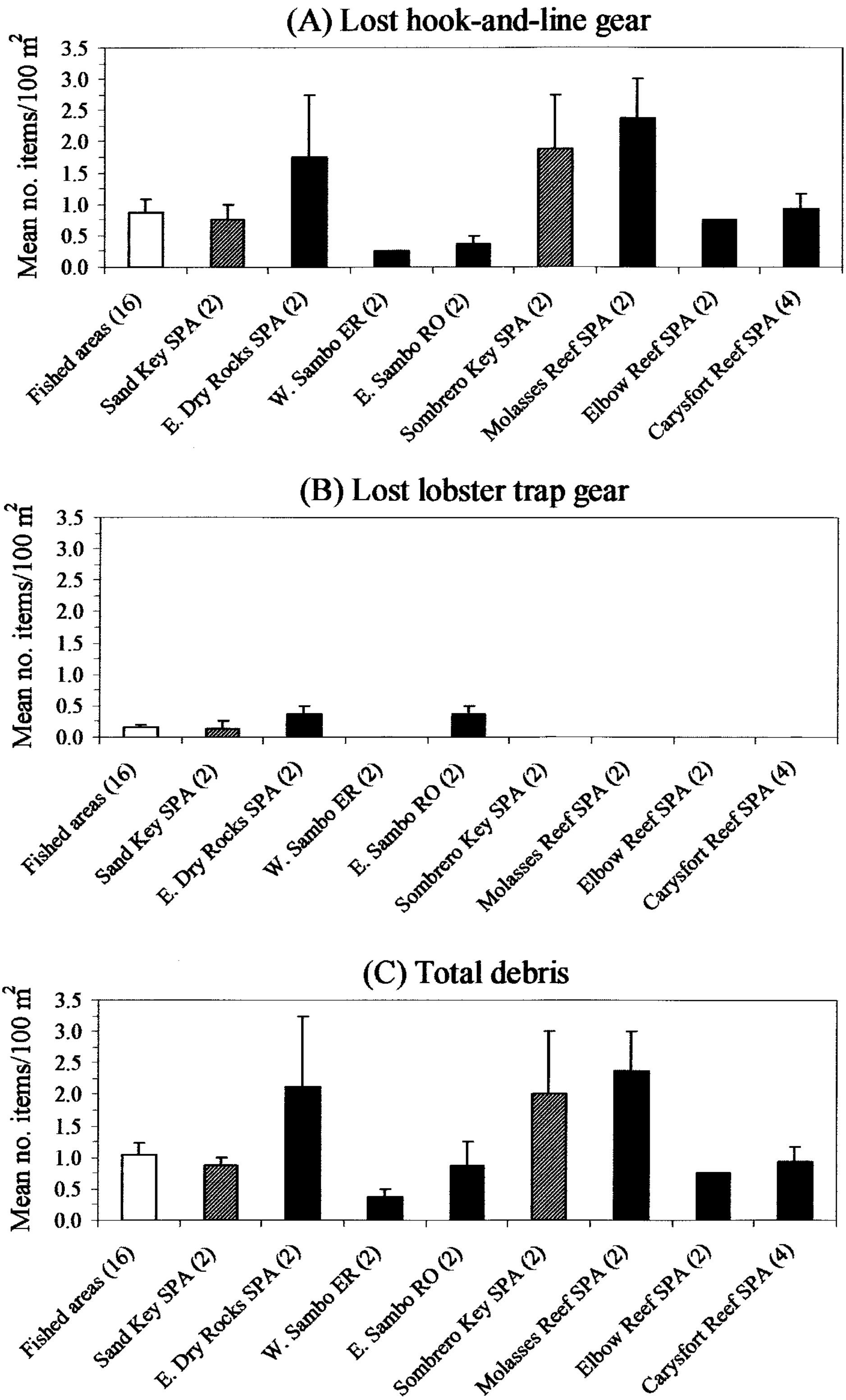

FIG. 3. Mean (+ 1 SE) densities (no. per 100 m^2) of (A) lost hook-and-line gear, (B) lost lobster trap gear, and (C) total marine debris among fished areas (open bars), no-fishing zones allowing catch and release (striped bars), and no-fishing zones (filled bars) in high-relief spur and groove. In parentheses are numbers of sites.

TABLE 5. Mean (±1 SE) densities (no. per 100 m^2) of lost hook-and-line gear, lobster trap gear, and other marine debris in no-fishing zones, catch and release areas, and fished areas for high-relief spur and groove and low-relief hard-bottom in the FKNMS.

Habitat type	Debris category	No-fishing zones	Catch and release areas	Fished areas
High-relief spur and groove	Lost lobster trap gear	0.11 ± 0.05	0.06 ± 0.06	0.14 ± 0.06
	Lost hook-and-line gear	1.05 ± 0.24	1.31 ± 0.49	0.88 ± 0.20
	Other debris	0.04 ± 0.02	0.06 ± 0.06	0.02 ± 0.02
	Total debris	1.20 ± 0.25	1.44 ± 0.52	1.03 ± 0.20
Low-relief hard-bottom	Lost lobster trap gear**	0.00 ± 0.00	0.13 ± 0.13	0.13 ± 0.04
	Lost hook-and-line gear**	2.00 ± 0.00	1.38 ± 0.38	0.96 ± 0.21
	Other debris	0.00 ± 0.00	0.13 ± 0.13	0.03 ± 0.02
	Total debris**	2.00 ± 0.00	1.63 ± 0.38	1.12 ± 0.23

** = significant differences in mean debris density among the three management areas surveyed.

Keys (Table 3) indicated significantly different densities ($P < 0.0167$) of lost hook-and-line gear and lobster trap gear among the three management zone types. Similar to spur and groove, no-fishing zones and catch and release areas yielded greater densities of lost fishing gear and other marine debris compared to fished areas (Fig. 4). The mean density of lost hook-and-line gear and total debris were significantly greater ($P < 0.0167$) in no-fishing zones compared to fished areas (Table 5). In contrast, the mean density of lost lobster trap gear was significantly greater ($P < 0.0167$) in fished areas compared to no-fishing zones.

DISCUSSION

Hook-and-line fishing gear is ubiquitous on the Florida Keys shallow platform mar-

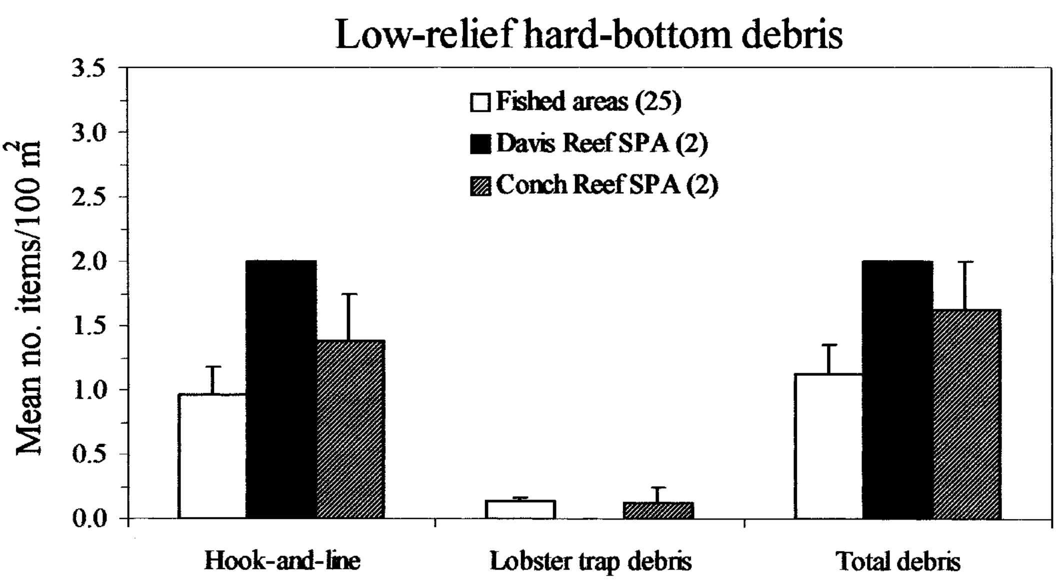

FIG. 4. Mean (+1 SE) densities (no. per 100 m^2) of lost hook-and-line gear, lobster trap gear, and total marine debris among fished areas, no-fishing zones (Davis Reef SPA), and no-fishing zones allowing catch and release (Conch Reef SPA) in low-relief hard-bottom habitat. In parentheses are numbers of sites.

gin, even within no-fishing zones protected from fishing since 1997. Results from 2001 are consistent with an earlier (2000) pilot study (Chiappone et al. 2002), illustrating widespread distribution of lost fishing gear, even within FKNMS no-fishing zones. This is not surprising, given the large amount of fishing areas in the Florida Keys, the cumulative properties of lost gear, and the limited number of personnel available to patrol a large marine protected area (Causey 1995). In an earlier study, we found that lost hook-and-line gear was the most prevalent debris type encountered, with gorgonians, sponges, and milleporid hydrocorals as the most commonly damaged sessile invertebrates (Chiappone et al. 2002). Results are limited, however, since measures of the rate at which new debris appears at sites were not available (e.g. after reef clean-up efforts), nor do we know how quickly derelict fishing gear disappeared from sites (e.g. disintegration rates assumed to be slow for stainless steel and synthetic materials). Estimates of the proportion of hook-and-line gear attributable to commercial versus recreational fishing are also unknown.

The most significant finding from this study concerned the spatial distribution and density of hook-and-line gear among FKNMS no-fishing zones, catch and release areas, and fished areas in shallow spur and groove and low-relief hard-bottom habitat types. We hypothesized that the mean densities of marine debris, particularly lost fishing gear such as hook-and-line, would be lower in no-fishing zones ("protected" since 1997) compared to fished areas, and that catch and release areas would likely yield similar densities of lost fishing gear compared to fished areas. These hypotheses were partially supported by the data, as the three catch and release areas surveyed yielded statistically similar mean densities of lost hook-and-gear (i.e., the predominant debris type) compared to fished areas. This is not unexpected, as no-take zones allowing catch and release fishing by trolling and fished areas both allow for hook-and-line fishing. However, most no-fishing zones, in both habitat types surveyed, yielded similar or greater densities of lost fishing gear than fished areas. Patterns in the distribution and density of lost lobster trap gear, however, differed from those for hook-and-line gear. It is plausible that a significant proportion of the lobster trap debris recovered from many spur and groove sites was distributed from neighboring habitats by previous storms, as the shallow fore reef is not a predominant area for deploying lobster traps (DiDomenico 2001).

Several factors may explain the relatively high densities of lost hook-and-line gear in FKNMS no-fishing zones. One explanation is that some level of non-compliance occurs in the FKNMS no-fishing zones, possibly because both the no-fishing zones and catch and release areas attract prospective anglers. Many of the sites surveyed are "named" reefs and are well demarcated. It is also possible that much of the lost fishing gear found within these areas was lost prior to the implementation of the "protected" zones in 1997. For example, most of the recovered fishing gear was biologically fouled, and while most of the fouled fishing gear was covered with crustose coralline algae and algal turfs known to foul new surfaces quickly (Winston et al. 1997), it is likely that some proportion of the fishing gear encountered in our study was lost prior to the 1997 establishment of the FKNMS zones.

Effective resource management requires a system achieving desired levels of compliance with regulations (Causey 1995) which are essential if public confidence in the management of natural resources is to be maintained and the management plan is to achieve the level of the desired effect (Royce 1986). Enforcement and compliance are, perhaps, the most important considerations in the design and implementation of marine reserves. Many attempts to implement fishery management plans in coral reef areas have failed due to non-compliance the human population (McManus 1996). Even relatively moderate levels of poaching may quickly deplete recoveries achieved by protection from fishing (Samoilys 1988; Russ and Alcala 1989; Watson et al. 1997), and affect the rate at which habitats and species may subsequently recover within no-take marine reserves (Jennings 2001). The pattern and distribution of lost hook-and-line fishing gear in the FKNMS indicate that non-compliance, relatively common within the small no-fishing zones, may be facilitated because the size of the FKNMS (>9,500 km^2) represents an enormous challenge to enforcement (i.e., high costs to patrol and monitor human activities). In fact, the FKNMS mainly depends upon interpretive law enforcement—that is, a directed effort at public education and enlistment of the help of user groups such as dive charter operators to report violations (Causey 1995). The problem, however, is further compounded by the thousands of registered recreational vessels in the Florida Keys; many of which are used for fishing, and the increase in the number of visitors, estimated at over four million people annually. The FKNMS zones are well demarcated, with many encompassing the most popular diving locations, and although counter-intuitive, the no-fishing zones may actually attract potential anglers who are not aware of Sanctuary regulations. This problem is likely to continue as tourism, relative to commercial fishing, becomes even more economically important in the Florida Keys (Leeworthy and Wiley 1995; Schittone 2001).

Results from this assessment have several implications for fisheries management and research in the Florida Keys. Careful and quantitative debris surveys may provide an important measure of compliance with no-take management rules in marine protected areas, as long as the survey efforts distinguish new versus old debris, and the type of debris, as presented here. The stratified design used here provides baseline data from which future assessments can be made between fished areas and protected zones to evaluate potential damage that may result from lost fishing gear. Although the impacts of lost hook-and-line gear on sessile coral reef invertebrates appear to be modest, relative to total sessile invertebrate densities (Chiappone et al. 2004), the prevalence of such effects are likely to increase concomitant with expected increases in fishing effort in the Florida Keys. Moreover, there are no data to evaluate the effects of lost fishing gear and other debris on marine organisms from the region (e.g., marine turtles and birds). The long-term impacts to both sessile and mobile biota, and the degree of recovery for benthic organisms and habitats from lost fishing gear effects, are not adequately studied. Hook-and-line gear, especially monofilament line, was commonly overgrown by sponges, and thus it is plausible that some marine debris is incorporated into the habitat matrix. Future studies should consider the magnitude of lost fishing gear impacts relative to the sizes of organisms affected. While the magnitude of tissue loss may not be large per occurrence, it is possible that such impacts may render organisms more susceptible to predation, competitive overgrowth, and disease.

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LITERATURE CITED

Ault, J. S., J. A. Bohnsack, and G. A. Meester. 1998. A retrospective (1979-1996) multispecies assessment of coral reef fish stocks in the Florida Keys. *Fish. Bull.* 96:395-414.

Ault, J. S., G. A. Diaz, S. G. Smith, J. Luo, and J. E. Serafy. 1999. An efficient sampling survey design to estimate pink shrimp population abundance in Biscayne Bay, Florida. *N. Amer. J. Fish. Manage.* 19: 696-712.

Ault, J.S., S. G. Smith, J. Luo, G. A. Meester, J. A. Bohnsack, and S. L. Miller. 2001. *Baseline multispecies coral reef fish stock assessments for the Dry Tortu-*

gas. Miami, Florida: University of Miami, Rosenstiel School of Marine and Atmospheric Science.

Auster, P. J., and R. W. Langton. 1999. The effects of fishing on fish habitat. In *Fish habitat: essential fish habitat and rehabilitation*, ed. L. R. Benaka, 150-187. Bethesda, Maryland: AFS Symposium 22.

Benaka, L. R. (Ed.). 1999. *Fish habitat: essential fish habitat and rehabilitation*. Bethesda, Maryland: AFS Symposium 22.

Bohnsack, J. A. 1996. Marine reserves, zoning, and the future of fishery management. *Fisheries* 21:14-16.

Bohnsack, J. A. 1997. Consensus development and the use of marine reserves in the Florida Keys, U.S.A. *Proc. 8th Intl. Coral Reef Symp*. 2:1927-1930.

Bohnsack, J. A., and J. S. Ault. 1996. Management strategies to conserve marine biodiversity. *Oceanography* 9:73-82.

Bohnsack, J. A., D. E. Harper, and D. B. McClellan. 1994. Fisheries trends from Monroe County, Florida. *Bull. Mar. Sci*. 54:982-1018.

Causey, B. D. 1995. Enforcement in marine protected areas. In *Marine protected areas: Principles and techniques for management*, ed. S. Gubbay, 119-148. New York: Chapman and Hall.

Chiappone, M., H. Dienes, D. W. Swanson, and S. L. Miller. 2004. Impacts of lost fishing gear on coral reef sessile invertebrates in the Florida Keys National Marine Sanctuary. *Biol. Conserv*. 121:221-230.

Chiappone, M., and K. M. Sullivan. 1997. Rapid assessment of reefs in the Florida Keys: Results from a synoptic survey. *Proc. 8th Int. Coral Reef Symp*. 2:1509-1514.

Chiappone, M., A. White, D. W. Swanson, and S. L. Miller. 2002. Occurrence and biological impacts of fishing gear and other marine debris in the Florida Keys. *Mar. Pollut. Bull*. 44:597-604.

Cochran, W. G. 1977. *Sampling techniques, 3rd edition*. New York: Wiley & Sons.

Dayton, P. K., S. F. Thrush, M.,T. Agardy, and R. J. Hofman. 1995. Environmental effects of marine fishing. *Aquatic Conserv. Mar. Freshwater Ecosyst*. 5: 205-232.

DiDomenico, G. 2001. *Storm trap debris generated from lost and abandoned lobster and stone crab traps in Monroe County*. Marathon, Florida: Environmental Problem Solving Group, Florida Department of Environmental Protection.

Donohue, M., R. Boland, C. Sramek, and G. Antonelis. 2001. Derelict fishing gear in the Northwestern Hawaiian Islands: Diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems. *Mar. Poll. Bull*. 12:1301-1312.

FDEP (Florida Department of Environmental Protection). 1998. *Benthic habitats of the Florida Keys*. St. Petersburg, Florida: FMRI Technical Report TR-4.

Ginsburg, R. N., and E. A. Shinn. 1993. Preferential distribution of reefs in the Florida Reef Tract: The past is the key to the present. In *Proceedings on the colloquium on global aspects of coral reefs: health, hazards, and history*, ed. R.N. Ginsburg, 21-26. Miami, Florida: University of Miami.

Harper, D. E., J. A. Bohnsack, and B. Lockwood. 2000. Recreational fisheries in Biscayne National Park, Florida, 1976-1991. *Mar. Fish. Rev*. 62:8-26.

Hess, N., C. Ribic, and I. Vining. 1999. Benthic marine debris, with an emphasis on fishery-related items, surrounding Kodiak Island, Alaska, 1994-1996. *Mar. Poll. Bull*. 38:885-890.

Jennings, S. 2001. Patterns and prediction of population recovery in marine reserves. *Rev. Fish. Biol. Fisheries* 10:209-231.

Jennings, S., and N. V. C. Polunin. 1996. Impacts of fishing on tropical reef ecosystems. *Ambio* 25:44-49.

Jones, M. 1995. Fishing debris in the Australian Marine Environment. *Mar. Poll. Bull*. 30:25-33

Leeworthy, V. R., and P. C. Wiley. 1995. *Linking the economy and environment of Florida Keys/Florida Bay: Preliminary estimates of tourist/recreational uses of the Florida Keys, July-August 1995.* Silver Spring, Maryland: NOAA/NOS, Office of Ocean Resources Conservation and Assessment.

McManus, J. W. 1996. Social and economic aspects of reef fisheries and their management. In *Reef fisheries*, ed. N. V. C. Polunin and C. M. Roberts, 249-282. New York: Chapman & Hall.

Miller, R. G. 1981. *Simultaneous statistical inference*. New York: Springer-Verlag.

Miller, S. M., D. W. Swanson, and M. Chiappone. 2002. A multiple spatial scale assessment of coral reef and hard-bottom community structure in the Florida Keys National Marine Sanctuary. *Proc. 9th Intl. Coral Reef Symp*. 1:69-74.

NMFS (National Marine Fisheries Service). 2001. National Marine Fisheries Service, Fishery Statistics and Economics Division. Silver Spring, Maryland.

NOAA (National Oceanic and Atmospheric Administration). 1996. *Final management plan/environmental impact statement. Volume II: Development of the management plan: environmental impact statement*. Silver Spring, Maryland: NOS/SRD.

Royce, W. F. 1986. *Fishery development*. New York: Academic Press.

Russ, G. R., and A. C. Alcala. 1989. Effects of intense fishing pressure on an assemblage of coral reef fishes. *Mar. Ecol. Prog. Ser*. 56:13-27.

Samoilys, M. A. 1988. Abundance and species richness of coral reef fish on the Kenyan coast: the effects of protective management and fishing. *Proc. 6th Intl. Coral Reef Symp*. 2:261-266.

Schittone, J. 2001. Tourism vs. commercial fishers: Development and changing use of Key West and Stock Island, Florida. *Ocean Coast. Manage*. 44:15-37.

Shinn, E. A., B. H. Lidz, R. B. Halley, J. H. Hudson, and J. L. Kindinger. 1989. *Reefs of Florida and the Dry Tortugas: Field Trip Guidebook T176*. Washington, D.C.: American Geophysical Union.

Slip, J., and H. Burton. 1991. Accumulation of fishing debris, plastic litter, and other artifacts, on Head- and Macquarie Islands in the Southern Ocean. *Environ. Conserv*. 18:249-254.

Tilmant, J. T. 1989. A history and an overview of recent trends in the fisheries of Florida Bay. *Bull. Mar. Sci*. 44:3-22.

Watling, L., and E. A. Norse. 1998. Disturbance of the seabed by mobile fishing gear: A comparison to forest clearcutting. *Conserv. Biol*. 12:1180-1197.

Watson, M., R. F. G. Ormond, and L. Holliday. 1997. The role of Kenya's marine protected areas in artisanal fisheries management. *Proc. 8th Intl. Coral Reef Symp*. 2:1955-1960.

Winston, J., M. Gregory, and L. Stevens. 1997. Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biogeographical, environmental, and conservation issues. In *Marine debris: Sources, impacts, and solutions*, eds. J. M. Coe and D. B. Rogers, 8197. New York: Springer.