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Occurrence and biological impacts of fishing gear and other marine debris in the Florida Keys

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Fishing constitutes one of the most significant threats to marine biodiversity and ecosystem function, documented by a growing body of information on the numerous impacts to populations, community structure, and habitats (Dayton *et al*., 1995; Roberts, 1995; Jennings and Polunin, 1996). Besides the more obvious effects on species population structure, fishing activities may also reduce the structural complexity of habitats or cause corresponding changes in ecological processes such as competition and predation (Russ, 1991; Jones and Syms, 1998; Auster and Langton, 1999). These patterns are most obvious in areas where explosives, poisons, or other destructive fishing methods are used (Hatcher *et al*., 1989). However, ecological effects can be expected in any area where traps, mobile fishing gear such as trawls, and potentially, even large numbers of recreational fishers operate (Russ, 1991; Jennings and Lock, 1996).

The Florida Keys (Monroe County, Florida) have a long history of commercial and recreational fisheries that target a great diversity of fish and invertebrate species using a multitude of gears (Tilmant, 1989; Bohnsack *et al*., 1994). In terms of volume of seafood landed, the Florida Keys is the most important area in the state in landings, dockside value, and numbers of commercial fishing vessels, especially for highly valued invertebrate fisheries (Adams, 1992). There are also significant, but largely undocumented effects of tens of thousands of recreational fishers (Davis, 1977), who target hundreds of species using mostly hook-and-line and spear guns (Bohnsack *et al*., 1994). Baseline data on fishing gear and other marine debris were collected as part of a larger assessment of benthic community structure in the Florida Keys National Marine Sanctuary, a large (9,500 km^2) marine protected area bordering three national parks in southern Florida (Figure 1). These data are particularly timely because this coastal ecosystem continues to experience a growing number of recreational fishers, and both commercial and recreational fishers exploit hundreds of invertebrates and fish species (Bohnsack *et al*., 1994; Ault *et al*., 1998). This study addressed several issues on marine debris occurrence in shallow-water coral reef and hard-bottom habitats. First, what is the spatial extent and frequency of remnant fishing gear at multiple spatial scales in the Florida Keys? Secondly, what factors, such as habitat type (depth) or management regime (closed or open to fishing) affect the spatial variability of marine debris occurrence? Thirdly, what are the biological impacts of marine debris, especially from remnant commercial and recreational fishing gear, on reef biota such as hard corals and sponges?

Forty-five sites were surveyed southwest of Key West to Big Pine Shoal in the lower Keys region of the Sanctuary, spanning 60 km from southwest to northeast and 12 km from nearshore to offshore (Figure 1). Sites were visited between July and August 2000 and were selected using a two-stage, stratified random sampling design (Cochran, 1977; Ault *et al*., 1999). Five of the 23 no-fishing zones (designated as Sanctuary Preservation Areas, Research Only Areas, and Ecological Reserves) in the Sanctuary were surveyed (indicated in Figure 1). Based on the spatial distribution of coral reef habitat types (FDEP,

1998) and the depth limits of the zones, the following habitat strata were sampled: nearshore hard-bottom, mid-channel patch reef, offshore isolated patch reef, offshore aggregate patch reef, back reef and rubble/hard-bottom matrix, shallow fore reef (4-7 m depth), and deeper fore reef (8-12 m) (Table 1). Two random sites were sampled in each no-fishing zone, within a particular habitat stratum that consisted of pre-designated 200 m x 200 m areas randomly selected from a grid constructed using a geographic information system. Reference sites were randomly assigned by habitat type (according to FDEP 1998 data). Preliminary data on debris density were not available, thus sample allocation was based on the spatial distribution of hard-bottom habitats and the amount of funded field days. At each site, four random sampling points using differential GPS were located. At each GPS point, one 25 m transect was deployed, typically from inshore to offshore (total of 4 transects per 200 m x 200 m site). Marine debris were surveyed by searching an area 1 m out from each transect side. The transect dimensions were selected to maximize the area sampled given the number of personnel available and the number of other variables measured during the study (Miller *et al*., 2001). The type of gear, dimensions (length, width, height), and numbers of sessile invertebrates impacted (touched and/or scarred) were noted. Surveys employed plastic slates, transect reels, and a meter stick.

Comparisons of the mean frequency of occurrence (number of incidences per 100 m^2) of debris categories and numbers of organisms impacted per 100 m^2 were made among habitat types and between no-fishing zones and reference areas by habitat type. Statistical comparisons of means at the two spatial scales were conducted by calculating confidence intervals (CI) based on the equation CI = mean $\pm t_{[\alpha, df]}$ *standard error, with standard errors estimated by the two-stage, stratified random sampling design (Cochran, 1977). Confidence intervals were adjusted for multiple comparisons using the Bonferroni procedure (Miller, 1981). Goodness of fit procedures using chi-square analyses were employed to test whether the frequency of debris was independent of habitat type and management regime (Zar 1996).

Nine major categories representing 18 individual types of debris items were recorded from 45 sites encompassing 8,040 m^2 (Table 2). Of the 110 debris occurrences, monofilament line (38%), wood from lobster pots (20%), combined fishing weights, leaders, and hooks (16%), and rope from lobster traps (13%) were the most frequently encountered, representing nearly 90% of all debris. Descriptive statistics for rope from lobster pots, monofilament, and wire leaders were generated from estimates of length in the field. The mean length of 14 occurrences of rope was 6.8 ± 1.83 m (mean ± 1 SE), with a range of 0.7 m to 20 m. Of the 42 occurrences of monofilament line, the mean length was 1.0 ± 0.22 m (mean ± 1 SE), with a range of 0.09 m to 7.1 m. Wire leaders were found 17 times within the transects, had an average length of 0.8 ± 0.15 m (mean ± 1 SE) and ranged from 0.13 m to 2 m in length. Total lengths of rope, monofilament line, and wire leaders recorded from all sites were 95.2 m, 43.2 m, and 13.6 m, respectively.

Total debris density was significantly greater (comparison-wise α = 0.002) on aggregate offshore patch reefs compared to nearshore hard-bottom, and the density of debris from lobster traps was significantly greater on aggregate offshore patch reefs compared to nearshore hard-bottom and deeper fore reef strata (Figure 2). Although the average density of hook-and-line gear was 3.4 per 100 m^2 for the shallow fore reef, there was substantial inter-site variability. A disproportionate amount of hook-and-line gear (55.7%) was found on the shallow fore reef (X^2 = 136.7, df = 6, P < 0.001), especially in reference areas, despite only representing 11.1% of the total sampling effort (Figure 3). Similarly, a disproportionate amount of lobster trap debris (57.9% relative to 8.9% of effort allocation), primarily wood slats and rope, was recorded from aggregate offshore patch reefs (X^2 = 127.3, df = 6, P < 0.001), and to a lesser extent on the shallow fore reef (23.7% vs. 11.1% of sample allocation).

Although we expected no-fishing zones to yield lower debris densities, especially for fishing gear, no significant density differences (comparison-wise α = 0.05) for combined debris types, hook-and-line gear, and lobster traps were detected between zones and reference sites by habitat type (Figure 2). Chi-square analysis indicated that, for all habitat types combined, the frequencies of hook-and-line gear ($X^2 = 0.06$, df = 1, P > 0.75) and remnant lobster traps ($X^2 = 0.19$, df = 1, P > 0.50) were not significantly different between no-fishing zones and reference areas. While the frequencies of hook-and-line gear (24 incidences in no-fishing zones, 37 in reference sites) and debris from lobster traps (16 incidences in no-fishing zones, 22 in reference sites) were slightly greater in reference areas, appreciable amounts of debris were recorded from the zones. For example, hook-and-line gear was found 13 times from two sites within Sand Key SPA at 8-12 m depth, or approximately three incidences of gear per 100 m^2. Similarly, hook-and-line gear was recorded from the shallow fore reef of Looe Key SPA seven times from two sites (2 incidences per 100 m^2), with one site yielding six occurrences.

Fifty-four of the 110 occurrences (49%) of marine debris caused tissue abrasion, other damage, and/ or mortality to 161 individuals or colonies of sessile invertebrates, represented by sponges, branching gorgonians, fire coral (*Millepora alcicornis*), scleractinian corals, and the colonial zoanthid *Palythoa mammilosa*. Gorgonians (37%) and sponges (28%) were the most commonly affected, followed by fire coral (19%), scleractinian corals (9%) and colonial zoanthids (8%). No significant differences (comparison-wise error a = 0.002) were detected in the mean number of impacted organisms per 100 m^2 for any of these taxa among habitat strata. Between no-fishing zones and reference sites by habitat type, significant differences (comparison-wise a = 0.05) in mean impact frequency were detected for sponges (mid-channel patch reef zones > reference sites), scleractinian corals (aggregate offshore patch reef zones > reference sites), and colonial zoanthids (mid-channel patch reef zones > reference sites), but not for fire coral or branching gorgonians (Figure 4).

Debris types causing the greatest degree of damage were hook-and-line gear (68%), especially monofilament line (58%), followed by debris from lobster traps (26%), especially rope (21%). Hook-and-line gear accounted for the majority of damage to branching gorgonians (69%), fire coral (83%), sponges (64%), and colonial zoanthids (77%) (Figure 5). Remnant lobster traps were also important, accounting for 64% of the stony corals impacted, 22% of gorgonians, and 29% of sponges. The frequency of impacts for all debris types ($X^2 = 49.3$, df = 4, P < 0.001) and hook-and-line gear ($X^2 = 38.7$, df = 4, P < 0.001) were not equivalent among the invertebrate taxa. In particular, branching gorgonians and sponges were disproportionately more affected than other biota, while scleractinian corals and colonial zoanthids were less so. While the frequency of lobster trap impacts differed among the taxa, they were more equally impacted relative to hook-and-line gear ($X^2 = 10.9$, df = 4, 0.05 < P < 0.025), which caused disproportionately more damage to gorgonians and sponges.

Considering the intensive commercial fishing effort and the significant increases in registered recreational boats and angler days in the Florida Keys (Bohnsack *et al*., 1994), patterns in the distribution and frequency of marine debris recorded during this study, especially remnant fishing gear, are not surprising. However, this is the first study we are aware of in the Florida Keys that also attempted to document potential biological impacts to subtidal organisms from marine debris, with comparisons made among multiple coral reef habitat types and between no-fishing zones and reference areas. Although 18 different debris items were recorded, hook-and-line gear, especially monofilament line, and remnant lobster traps, especially buoy lines, were the predominant debris items and were differentially apportioned to where fishing effort is concentrated for reef fishes and spiny lobster, respectively. That is, hook-and-line gear was most common in both shallow and deeper fore reef areas further offshore, while lobster trap debris was most abundant on offshore and mid-channel patch reefs located between the shoreline and the offshore fore reef. Not unexpectedly, debris density, particularly hook-and-line gear, was very low or absent from nearshore hard-bottom, mid-channel patch reef, and back reef habitats. We initially assumed that, independent of habitat type, the mean density of debris, especially fishing gear, would be lower in no-fishing zones "protected" since 1997 compared to reference areas. However, no significant density differences for combined debris, hook-and-line gear, and lobster traps were detected. There are several possible explanations for these patterns. First, non-compliance may have occurred in some of the no-fishing zones sampled, especially on the fore reef where hook-and-line gear was relatively common. Second, and specific to remnant lobster trap gear, it is possible that storms or other factors distributed ropes and wooden slats from the traps. Since lobster traps are most commonly deployed in seagrass beds, with some deployed on the periphery of patch reefs, wave action from storms could have transported trap components elsewhere. It is quite likely, for example, that Hurricane Georges during 1998 resulted in the destruction and transport of numerous lobster traps. Third, and plausible for both hook-and-line gear and lobster traps, the gear encountered in 2000 could have been remnant debris prior to 1997. Qualitative observations concerning whether debris is recent or heavily fouled with organisms should be incorporated into future surveys.

To put the study results into perspective, it is worth noting that there has been a concerted effort on the part of the FKNMS, non-governmental institutions (The Nature Conservancy and The Bacardi Foundation), and dive operators to organize and conduct an annual volunteer reef cleanup effort (Adopt-a-Reef Program) in the Florida Keys since 1994 (M. Enstrom, The Nature Conservancy, personal communication). The program targets recreational divers and provides data placards for recording debris collected at designated locations, usually popular dive sites, coordinated through local dive shops. The types of data collected include date and location of the cleanup, diver name, bottom time, number of trash bags filled, a rank-order of the five most important debris items, and an estimated biomass of debris collected. From 1994 to 2000, 866 divers collected nearly 7,500 kg of debris, with hook-and-line gear, aluminum cans, plastic, cardboard, wood, and rope from lobster pots constituting the most common items. These are similar to results from the present study, the exception being the predominance of remnant lobster traps in our surveys due to the inclusion of offshore patch reefs. Despite 16 volunteer dives at Looe Key SPA comprising 13 hours of bottom time during 1999, hook-and-line debris was not recorded, even though this was the same general area as our 2000 surveys. In contrast, we recorded six incidences of hook-and-line gear (mean of 3 incidences per 100 m^2) from the central fore reef area of this site. This pattern may reflect differences in specific locations surveyed, intensity of searches per unit area for debris (i.e. roving diver versus small strip transects), or non-compliance with regulations. Similar explanations are plausible for Sand Key SPA. Despite its designation as a no-fishing zone, hook-and-line gear was found an average of 3.3 times per 100 m^2 on the deeper fore reef. We are not aware of volunteer cleanup efforts at this site, so this result may reflect remnant gear prior to zone creation or to non-compliance.

Methods of fishing that cause habitat modification or damage to benthic organisms represent potentially serious consequences of fishing (Russ, 1991; Benaka, 1999). Although there is increasing recognition of the consequences to benthic habitats from the use of mobile fishing gear (Watling and Norse, 1998; Auster and Langton, 1999) and other destructive fishing practices (Saila *et al*., 1993; Jennings and Polunin, 1996), we are not aware of any studies in the Florida Keys that have evaluated biological impacts from marine debris and specifically fishing gear. Interpretation of the biological impact data is complicated by several factors. Both the debris density and the distribution of sessile invertebrates sampled in this study are related to habitat type, and secondarily by management type. Future efforts need to consider the scaling of debris occurrence with impacts relative to these two factors. For example, it is probable that a coral-dominated reef with a given amount of hook-and-line gear will not be affected in the same way as a gorgonian-sponge dominated reef with the same density of gear. Estimates of the proportion of different taxa impacted by debris relative to total abundance estimates are also useful for placing the debris impact assessment into context. Also, the long-term impacts to biota and the degree of recovery are unknown. For example, we observed several instances where hook-and-line gear, especially monofilament, was overgrown by sponges, and it seems plausible that some debris will be incorporated into the habitat matrix. We also recognize that the future biological assessments would be more useful if data on the severity of each impact (e.g. amount of tissue damage) relative to the size of the organism were collected.

We suggest that future debris surveys in the Florida Keys should compare debris densities between no-fishing zones and reference areas, as well as the impacts to sessile biota and whether fishing gear is relatively recent or biologically fouled. Despite these considerations, results from this study suggest that overall estimates of biological impact from marine debris may be considerable, and such impacts are among a suite of factors that affect the structure and condition of Florida Keys reefs. As visitation and fishing pressure increase in this area, it can be expected that the extent of marine debris and the impacts to organisms will also increase.

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Fig. 1 The lower Keys region of the Florida Keys National Marine Sanctuary, southeastern Florida, with marine debris sampling locations and no-fishing zones (Ecological Reserve, ER and Sanctuary Preservation Areas, SPAs).

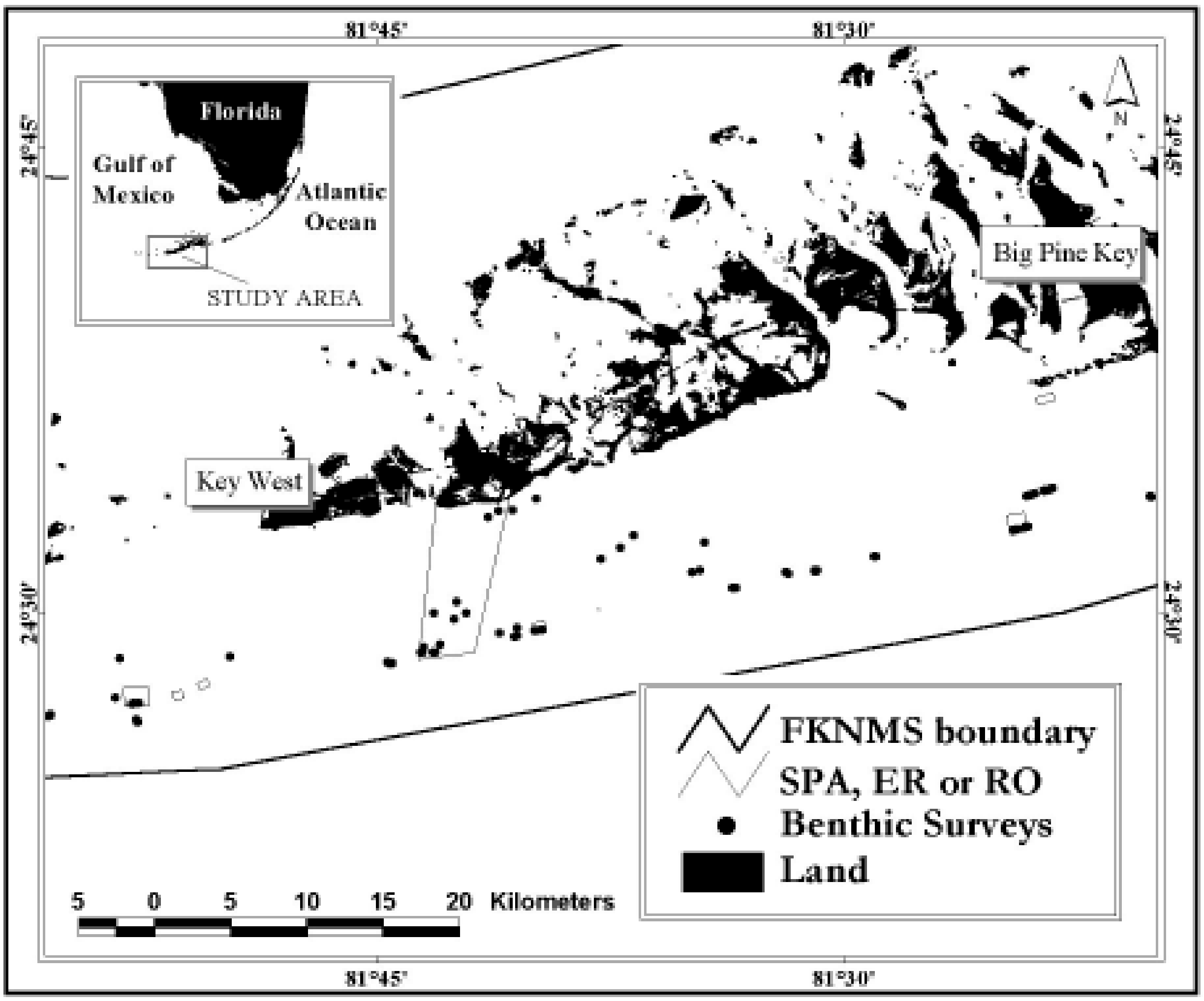

Fig. 2 Mean frequency (± 95% CI) of combined debris types, combined hook-and-line gear, and combined lobster trap debris per 100 m^2 in the Florida Keys between no-fishing zones (NTZ, open circles) and reference areas (REF, filled circles) by habitat type. Habitat types are arranged from inshore to offshore along the x-axis, with the number of sites sampled in each stratum in parentheses.

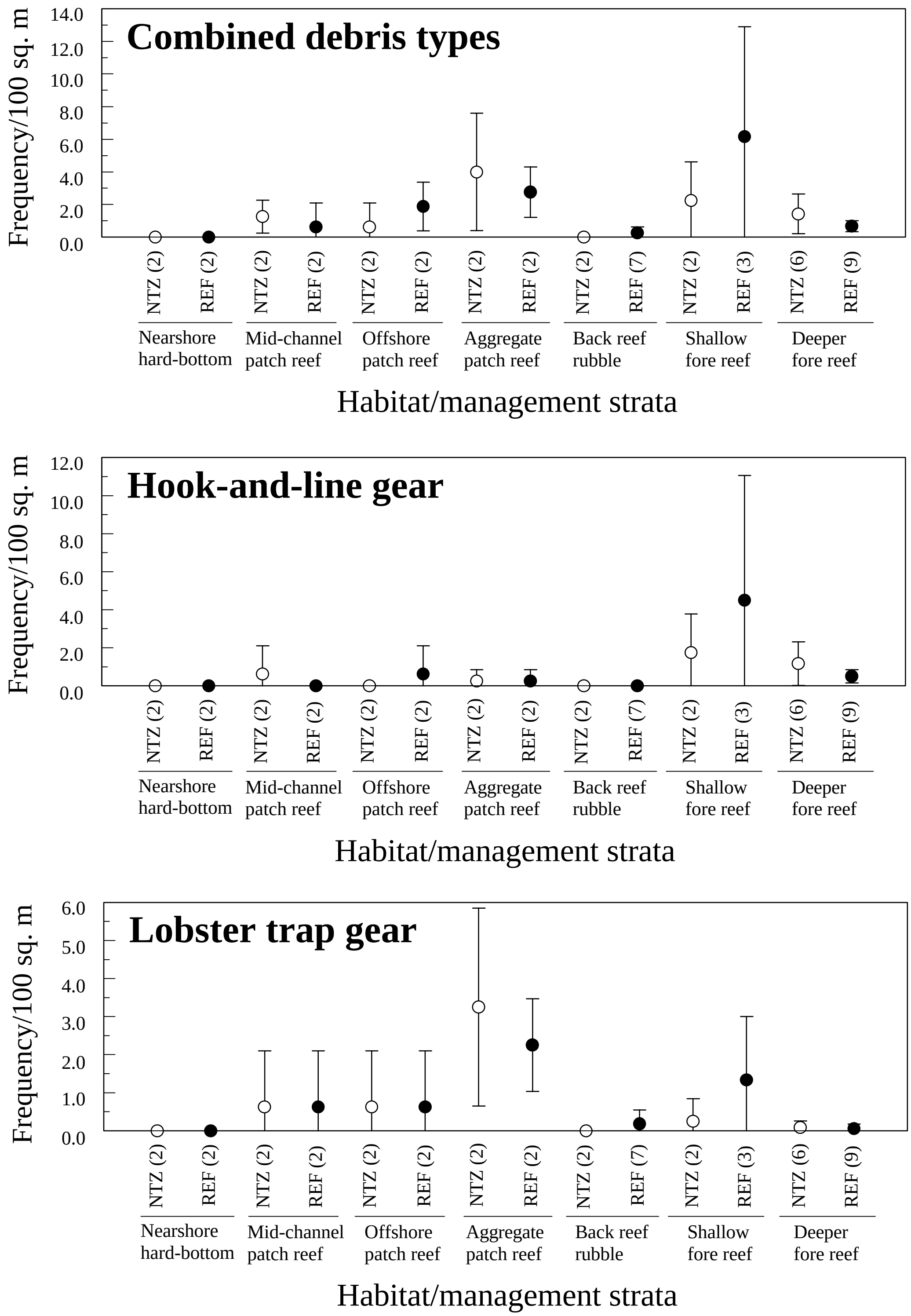

Fig. 3 Proportion of recreational hook-and-line gear and commercial lobster trap debris by benthic habitat type and management zone relative to sampling allocation (number of sites).

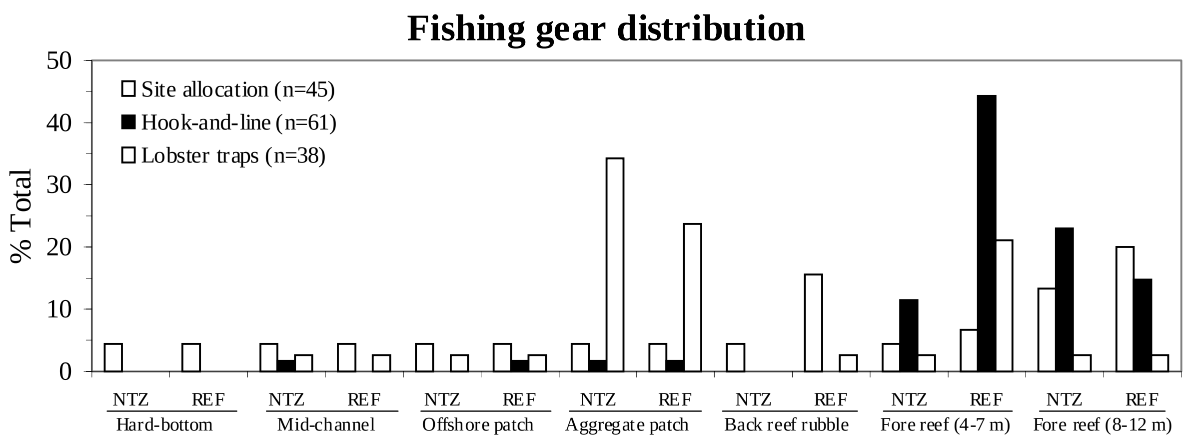

Fig. 4 Mean frequency (± 95% CI) of biological impacts per 100 m² for combined invertebrate taxa, sponges, and gorgonians in the Florida Keys by benthic habitat type and inside (NTZ) and outside (REF) of no-fishing zones. Numbers of sites sampled in each stratum are in parentheses.

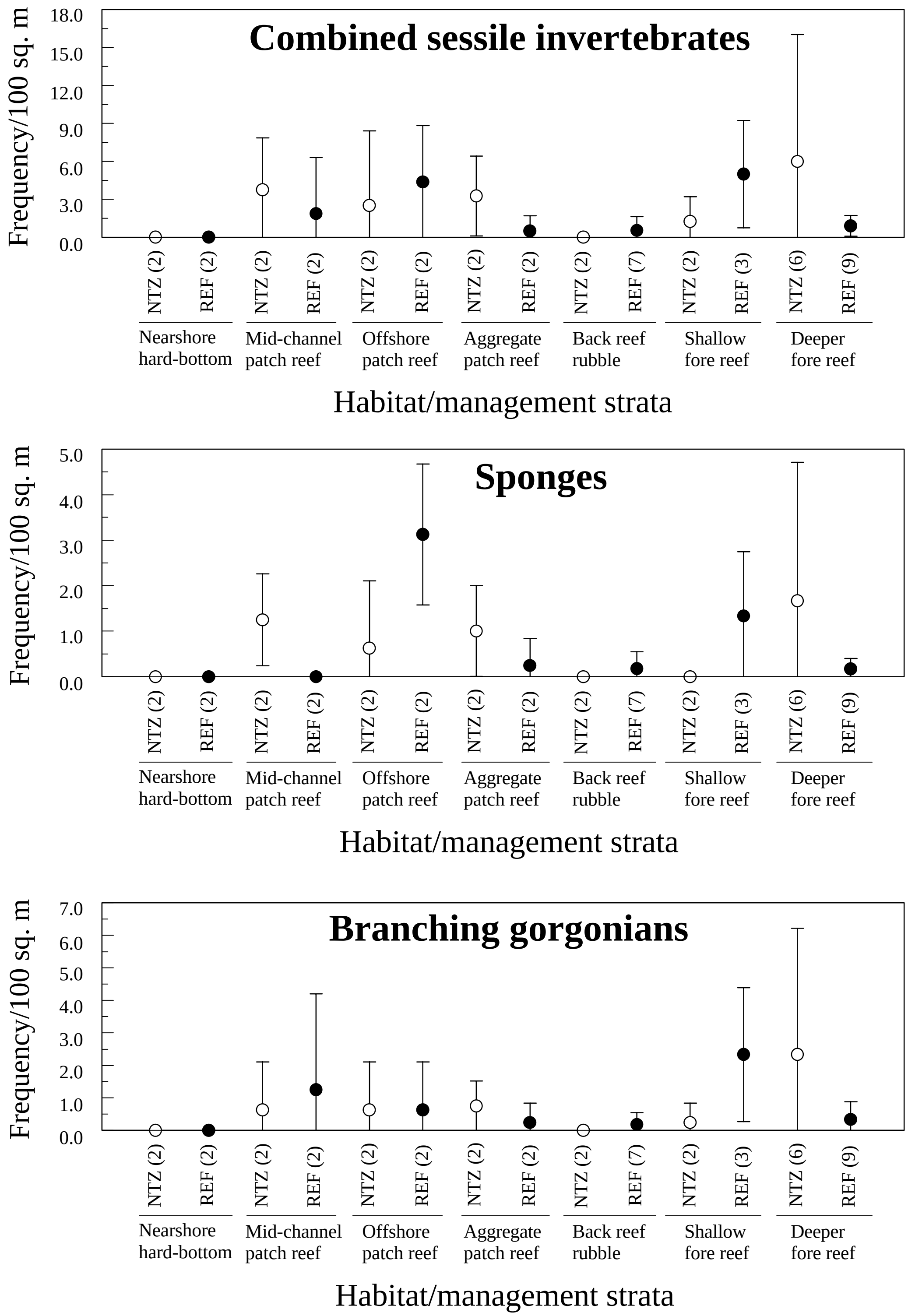

Fig. 5 Frequency of biological impacts to invertebrates by fishing gear and other debris in the Florida Keys.

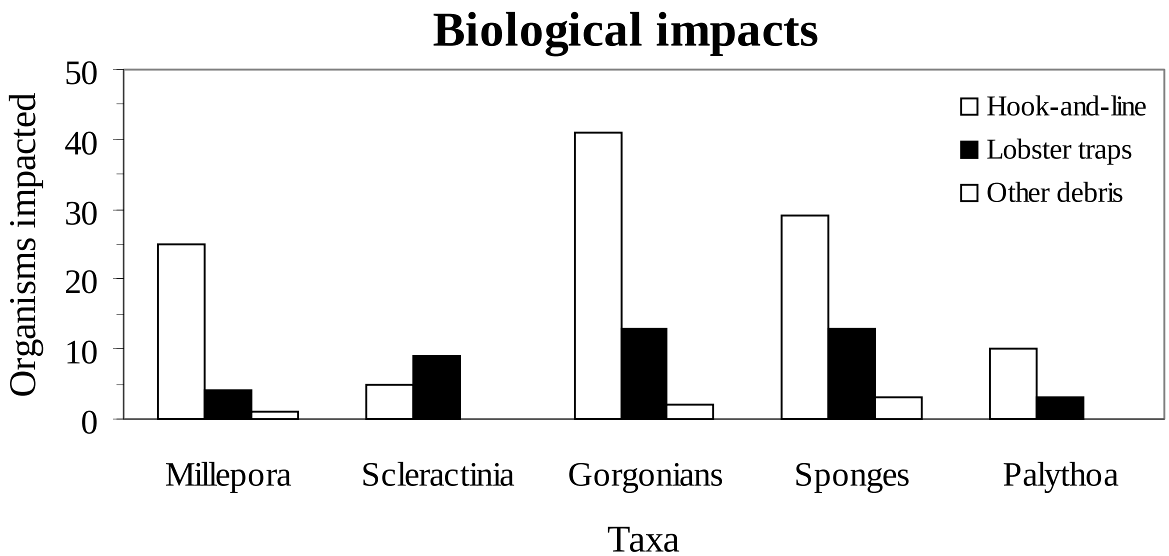

TABLE 1

Sampling effort for fishing gear and other debris in the lower Florida Keys. No-fishing zones are ecological reserves (ER), research only areas (RO), and sanctuary preservation areas (SPA).

Habitat type	Management type	No. sites	No. transects	Area sampled (m^2)
Nearshore hard-bottom	Western Sambo ER	2	8	400
	Reference areas	2	8	400
Mid-channel patch reef	Western Sambo ER	2	8	160
	Reference areas	2	8	160
Offshore patch reef	Western Sambo ER	2	8	160
	Reference areas	2	8	160
Offshore aggregate patch	Looe Key RO	2	8	400
	Reference areas	2	8	400
Back reef rubble	Western Sambo ER	1	4	200
	Sand Key SPA	1	4	200
	Reference areas	7	28	1400
Shallow fore reef (4-7 m)	Looe Key SPA	2	8	400
	Reference areas	3	12	600
Deeper fore reef (8-12 m)	Sand Key SPA	2	8	400
	Western Sambo ER	2	8	400
	Eastern Sambo RO	2	8	400
	Reference areas	9	36	1800
Total		45	180	8040

TABLE 2

Frequency of fishing gear and other marine debris in the lower Florida Keys.

Debris type	Frequency	% of total debris	No. habitats recorded	No. sites recorded
Remnant lobster traps				
Wood	22	20.0	3	7
Rope	14	12.7	4	10
Cement	1	0.9	1	1
Plastic opening to pot	1	0.9	1	1
Hook-and-line gear				
Monofilament line[a]	42	38.2	3	11
Fishing weights, leaders, hooks	18	16.4	4	12
Glass bottles	1	0.9	1	1
Fabric (cloth windsock)	1	0.9	1	1
Plastic				
Band	1	0.9	1	1
Mesh bag	1	0.9	1	1
Aluminum				
Anchor	1	0.9	1	1
Cans	1	1.8	1	1
Can flip-top	1	0.9	1	1
Lead and other metals				
Diving weights	1	0.9	1	1
Bar	1	0.9	1	1
Mesh grating	1	0.9	1	1
Rod	1	0.9	1	1
Boat motor	1	0.9	1	1
Total	110	100.0	5	28

[a]Includes monofilament line with or without attached wire leaders, sinkers, and/or hooks.