# Marine debris knows no boundaries: Characteristics of debris accumulation in marine protected areas of the Florida Keys

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## Abstract

Marine debris is a persistent and pervasive threat worldwide including inside marine protected areas (MPAs). To assess marine debris accumulation rates and potential impacts, we counted and evaluated trap, non-trap fishing gear, and non-fishing debris in unprotected areas and MPAs with different management boundary regulations in the Florida Keys (USA). Analyses identified that neither MPA type nor size were strong drivers of debris density and that debris densities were not statistically different between unprotected areas and MPAs. Non-fishing and non-trap fishing gear debris densities were potentially related to unexplored local differences in human behavior, while trap debris density was likely associated with oceanographic forces that transported traps into the MPAs. Overall, our results suggested that the drivers of marine debris accumulation for each debris category were different and may vary with each individual MPA, and that marine debris is not constrained by MPA boundaries.

*Keywords:* Submerged marine debris, Marine protected areas, Florida Keys, Fishing gear debris, Coral reef habitat

## 1. Introduction

Marine protected areas (MPAs) are spatially designated areas created to reduce the exploitation of resources and habitat degradation (Agardy et al., 2011; Jentoft et al., 2011) by limiting or prohibiting the entrance of resource users or specific activities (Fox et al., 2012). MPAs face an ever-growing list of pressures that threaten to undermine their success; one of the pervasive and persistent threats is the accumulation of marine debris inside MPA boundaries (Chiappone et al., 2004; Smith and Edgar, 2014; Luna-Jorquera et al., 2019; Renzi et al., 2019). The National Oceanic and Atmospheric Administration (NOAA) and the United States Coast Guard define marine debris as “any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment” (Marine Debris Research, Prevention, and Reduction Act, 2009). The accumulation of debris inside the boundaries of MPAs threatens the protections that MPAs are intended to provide and is a management challenge that transcends marine spatial boundary management.

A mosaic of MPAs with differing management structures, establishment dates, and conservation objectives have been developed to protect marine resources throughout the Florida Keys. All these MPAs are within the Florida Keys National Marine Sanctuary (FKNMS), but responsibility for conservation of their natural resources also lies with additional agencies that have different jurisdictions, management goals, and regulatory capacity. Coral reef protection is a primary goal of many of these MPAs, but some of the reefs are also important for commercial and recreational fishing — including trap fishing for lobster and stone crab and other water-based activities such as snorkeling and scuba diving (ONMS 2011). The health of many marine resources, particularly coral reefs, has been in decline for decades because of a wide variety of stressors. These stressors include regional-scale factors, such as declining water quality, hurricanes, and bleaching and coral disease, as well as localized factors such as excessive nutrients from stormwater and wastewater (ONMS, 2011; Ruzicka et al., 2013; Kenkel et al., 2015).

Different studies show that marine debris is prevalent throughout the Keys (Uhrin et al., 2014), including within the boundaries of MPAs (Chiappone et al., 2004). Lobster trap and hook-and-line fishing gears were the predominant categories of debris observed (Uhrin et al., 2014). Many negative impacts are associated with marine debris, including wildlife entanglement and ingestion (Laist, 1997; Derraik, 2002; Adimey et al., 2014), habitat damage (Chiappone et al., 2002; Lewis et al., 2009), spread of invasive species (Rech et al., 2016; Miralles et al., 2018), loss of aesthetics (Somerville et al., 2003; Krelling et al., 2017) and effects on human health (Campbell et al., 2016; Barboza et al., 2018). If left unaddressed, marine debris in MPAs could further degrade coral reef health and undermine conservation goals.

Marine debris has been documented in Florida Keys MPAs, but previous research has not addressed the effectiveness of MPA boundaries for managing marine debris. While MPAs may have the ability to reduce discrete, localized pressures, they may not be able to effectively address the accumulation of marine debris when the sources and transport of marine debris occur at scales greater than the size of the MPAs themselves (Nelms et al., 2020). Identifying the category, abundance, and distribution of marine debris in MPAs is essential for developing strategies to reduce marine debris within their boundaries and for evaluating the overall success of these protected areas at achieving their conservation goals. Here, we examine submerged marine debris in three types of MPAs in the Florida Keys that use various combinations of buoys or navigational charts to mark their boundaries, with the goal of understanding debris densities and distributions in the context of MPA boundary management. We hypothesized that marine debris densities would be lower in MPAs, particularly those with marked boundaries, than in control areas. To our knowledge, this is the first study to provide detailed information of debris and coral habitat interactions relative to different types of MPA boundary identification. The information provided in the present study provides essential information on marine debris abundance and distribution patterns within an MPA system that is relevant to future MPA design and management.

## 2. Methods

### 2.1 Study area and sampling design

The Florida Keys archipelago extends from the southern tip of Florida, from Key Biscayne to the Dry Tortugas. The third largest barrier reef in the world, the Florida reef tract lies adjacent to the archipelago (Finkl et al., 2008). The islands and reef tract are encompassed by the Florida Keys National Marine Sanctuary (FKNMS), which contains a mosaic of several types of MPAs that are managed by multiple government entities for varied conservation goals.

### 2.1.1 Marine debris survey sites

Three types of MPA were evaluated in this study, the FKNMS's Sanctuary Preservation Areas (SPAs), John Pennekamp Coral Reef State Park's Lobster Exclusion Zones (PLEZs), and National Marine Fisheries Service's Spiny Lobster Closed Areas (SLCAs). These MPAs all contain coral reef habitat and prohibit the use of spiny lobster traps within their boundaries but have different methods of boundary marking (see Renchen et al., 2018). We stratified our sampling of these MPAs into two regions (Upper Keys and Middle/Lower Keys; Fig. 1).

Eighteen FKNMS SPAs (average size = 0.92 $km^2$ ± 0.29 $km^2$) are distributed throughout Florida Keys waters and encompass a total area of approximately 17 $km^2$. We sampled all SPAs; 12 were in our Upper Keys study region, and 6 were in the Middle/Lower Keys region. These SPAs protect shallow coral reef habitats, such as patch reef and spur and groove habitats, and include some of the Florida Keys most heavily used coral reefs (ONMS, 1997; ONMS, 2019). The SPA boundaries are physically marked on the water with buoys, their boundary information is available on navigation charts, and all types of fishing activity except for trolling and bait fishing in a select few sites are prohibited (ONMS, 2007). These areas were established in 1997 and have the longest history of fishing prohibition among the MPAs we evaluated.

There are eight PLEZs (average size = 1.51 $km^2$ ± 0.53 $km^2$), which are located only in the Upper Keys region, encompassing a total area of approximately 12 $km^2$ (Fig. 1). We sampled all eight PLEZs. These areas are also referred to as Coral Formation Areas in other sources (68B-24.0065, Florida Administrative Code). The PLEZ boundaries are physically marked with buoys, but boundary information is not available on navigation charts. Although recreational hook-and-line fishing is permitted in these

PLEZs, commercial and recreational lobster fishing is prohibited within their boundaries. The PLEZs were established in 1993, but their boundaries were not marked until 2001, and they have since changed.

The SLCAs were established in 2012 (n = 60, average size = 0.25 $km^2$ ± 0.04 $km^2$) and are distributed throughout Florida Keys waters, encompassing a total area of approximately 15 $km^2$. A random subset of SLCAs were sampled in both regions (n = 9 Upper Keys, n = 9 Middle/Lower Keys). The SLCAs were established to protect two Endangered Species Act (ESA) listed coral species, staghorn (*Acropora cervicornis,* Lamarck, 1816) and elkhorn (*Acropora palmata*, Lamarck, 1816) coral from spiny lobster trap fishing (Gulf of Mexico and South Atlantic Fishery Management Councils, 2012; GMFMC, 2014). The use of spiny lobster traps is prohibited in the SLCAs. SLCA boundaries are not physically marked, and boundary information is not available on navigation charts; however, all commercial lobster fishermen were provided the boundary and regulatory information for these areas in late 2014 (Renchen et al., 2018).

A total of 18 control sites (n = 9 per region) were established to compare debris densities in sites that were not protected and that were open to all types of legal fishing activity. Control site size (0.26 $km^2$) was selected based on the median size of the three types of MPAs evaluated in this study. Control site locations were randomly generated in ESRI ArcGIS v. 10.1 using the FWC-FWRI Unified Florida Reef Map Layer v1.2, Class Lv0. Class Lv0 allowed for the selection of coral reef and hardbottom habitat on the Atlantic side of the Florida Keys. Prior to establishment, control sites were ground-truthed, and the presence of coral reef and hardbottom habitat was verified by divers.

### *2.2 Transect allocation*

The number of transects allocated to each MPA or control area was based on the relative size of the MPAs (0.05 km$^2$ to 4.68 km$^2$). The control sites and SLCAs received three transects per area while the SPAs and PLEZs received six transects per area (Table 1). Though the control sites and SLCAs received fewer transects than SPAs and PLEZs, these sites were smaller thus a greater proportion of the total area available was sampled making the proportions of total area sampled at each site similar to those sampled in the larger MPAs. Transects were 100 m long by 15 m wide, encompassing a total area of 1500 m$^2$. All transects were at least 100 m apart and 100 m from boundary corners to reduce potential confounding effects of sampling multiple boundaries on the same transect. The assignment of all transect locations was conducted using ESRI ArcGIS v. 10.1.

Two types of transects were allocated to the larger MPAs (SPAs and PLEZs): transects that began at the management boundaries (i.e., edge transects, $n = 3$ per site) and transects that were randomly placed away from the management boundaries of the MPAs (i.e., random transects, $n = 3$ per site), for a total of six transects per site (Table 1). The controls and most of the SLCAs were not large enough to accommodate six transects without overlapping; thus, only three transects were used in these areas. The SLCAs received three edge transects per area, while the controls received three random transects per area because they did not have a management boundary (Table 1).

For each MPA type that received edge transects (SPAs, PLEZs, SLCAs), three sides of the boundary were randomly selected. For each of these three sides, one transect starting location was randomly generated; transects were at least 100 m apart and 100 m from boundary corners. The directional bearing of each edge transect was perpendicular to the MPA boundary.

For controls and MPAs receiving random transects (SPAs, PLEZs), three transect starting locations were randomly generated at least 100 m inside the MPA boundary and at least 100 m away from other transects. The directional bearing of each transect was also randomly generated. One PLEZ (Three Sisters South) was too small to accommodate all six transects and instead received three randomly placed transects, although these transects were less than 100 m apart from each other and from the boundary corners.

### *2.2.2 Data collection*

Data collection was conducted underwater by scuba divers from April through July 2015. Data were recorded outside of lobster season (August 6 – March 31) and near the end of stone crab season (October 15 – May 1). For each transect we identified and recorded the category of marine debris, its location along the transect, the habitat the debris was observed in, and any debris interactions with marine species. Debris was recorded as interacting with sessile invertebrates if the debris was observed physically touching (i.e., wrapped around, resting upon) an individual sessile invertebrate colony. We also recorded the distribution of habitat types and locations of habitat changes along each transect. All debris was then grouped by category. Debris and habitat categories were developed *a priori* based on the results of previous marine debris survey efforts conducted in the Florida Keys (Chiappone et al., 2004; Uhrin et al., 2014). Debris was categorized as either “trap debris” related to the spiny lobster trap fishery or to the stone crab trap fishery or was categorized into the more general category of “non-trap fishing debris,” which included other non-trap-related fishing items such as such as monofilament, tackle, lobster hand-nets, etc. Trap debris parts related to the trap frame (throats, wood slats, wire, lids), concrete ballast (concrete slabs used to weigh traps down), as well as partial and intact traps, were identified as belonging to either the spiny lobster fishery or to the stone crab trap fishery (Fig. 2). All debris not identified as fishing gear was labeled as “non-fishing debris” and included items such as plastic, glass, aluminum cans, plastic bags, metal, lumber, snorkel gear, etc. (Fig. 2).

Although all MPAs were located in what is generally considered coral reef habitat, we also recorded changes in habitat along each transect. Divers categorized habitat as coral reef, hardbottom, sand, or seagrass. Transects were not stratified based on the habitat present; therefore, the fine-scale habitats were not sampled equally. The fine-scale habitat data were used only for the purposes of measuring the distance coral reef habitat was from MPA boundaries and to identify the habitat where debris accumulated and debris location relative to the edges of coral reef habitat.

### *2.3 Data analyses*

#### *2.3.1 Analysis of debris counts*

Generalized linear mixed models (GLMMs) were used to examine differences in debris counts for multiple analyses each with different fixed effects. For all analyses, each debris category (trap, non-trap fishing, non-fishing) was examined separately. We first examined whether there were differences in debris counts in MPAs that contained both edge and random transects (SPAs and PLEZs). In all cases, the GLMMs assumed a negative binomial distribution and log-link function. Transect type (edge or random) and MPA type (SPA or PLEZ) were included as fixed effects; an interaction term between transect type and MPA type and a random effect of site (individual areas) were also included. These GLMMs suggested that debris count was not influenced by transect type in SPAs or PLEZs for all debris types as the 95% confidence intervals for each parameter estimate overlapped zero (Table S1); therefore, the data for edge and random transects were combined for SPAs and PLEZs, respectively. GLMMs assuming a negative binomial distribution and log-link function were then used to examine differences in debris counts by MPA type, where MPA type (control, PLEZ, SLCA, SPA) was included as a fixed effect, and site was included as a random effect for each debris category.

For all analyses, inferences were based on the effect sizes of parameter estimates and their 95% confidence intervals (CI). Parameter estimates for covariates included in the GLMMs were considered strongly influential if the 95% CI of parameter estimates did not contain zero. In these cases, pairwise comparisons were performed using the ratio of estimated marginal means. Pairwise comparisons of different observations were considered significantly different if the 95% CI of the ratio of estimated marginal means did not contain one. All analyses were conducted using the glmmTMB package (Brooks et al., 2017) and the fit of each model was evaluated by conducting residual diagnostics using the DHARMa package (Hartig, 2020) in R v. 3.6.2 (R Core Team, 2019).

### *2.3.2 Characterization of FKNMS SPAs*

FKNMS SPAs were the only type of MPA with both nearshore and offshore protected areas that contained different types of coral reef structure. Therefore, the

FKNMS SPAs were further categorized into the variable “reef type” that identified SPAs by the predominant type of reef structure present: nearshore-patch reefs, offshore patch reefs, or offshore continuous reefs. For each debris category, GLMMs assuming a negative binomial distribution and log-link function were used to examine differences in debris counts by reef type, where reef type was a fixed effect and individual site was a random effect.

### *2.3.3 Spatial distribution of debris relative to coral reef habitat*

The spatial distribution of each debris category was examined relative to coral reef habitat. Transects containing at least one patch of coral reef habitat were used to examine fine-scale distributions of debris relative to the edges of coral reef habitat. This examination excluded transects that were entirely comprised of coral reef habitat or that did not contain this habitat, as we were specifically interested in understanding how the structure of the coral reef edge might affect debris accumulation. The distance of each piece of debris to the nearest coral reef habitat edge within the transect was calculated. Each piece of debris was categorized as being inside or outside of coral reef habitat. Because transect locations were randomly placed without regard to changes in habitat, the areas closer to coral reef habitat would inherently be sampled at a higher frequency. To account for differences in sampling effort, the transects were divided into 10-m sampling bins. Debris counts were then normalized by dividing the debris counts within each sampling bin by the percentage of times each sampling bin was encountered. Because of the rarity of observations 50-100 m from coral reef habitat, these bins were condensed into a single bin for each debris category.

### *2.3.4 Distance from MPA boundaries to coral reef habitat*

Edge transects that contained any amount of coral reef habitat were used to examine the distance of coral reef habitat within a MPA to its boundaries. The distance at which coral reef habitat first occurred was recorded as the distance from the MPA boundary. The frequency distribution of these first encounters with coral reef habitat in terms of distance from MPA boundaries was expressed as the cumulative percentage of distances that were observed in each 1-m interval from 0 to 100 m of each transect.

### *2.3.5 MPA area size*

GLMs were used to examine the influence of MPA area size (ha) on debris density. Debris densities per transect were converted from $m^2$ to ha and averaged to produce a debris density per site for each debris category. The GLMs assumed a Tweedie distribution and log-link function with the fixed effect of MPA size. The GLMs and their results were evaluated using the same methods described in section 2.3.1.

## **3. Results**

### *3.1 Debris characterization and the influence of MPA type*

### *3.1.1 Trap debris*

Trap debris was the most abundant category of debris observed in all MPA types (Fig. 3), accounting for 55.4% of all debris observed in this study. Trap debris was observed in all SPAs and PLEZs and in all but one site for both controls and SLCAs (Table S2). Partial and intact trap parts were identified as belonging to either the spiny lobster fishery or to the stone crab trap fishery. Of these parts, 99.3% were attributed to the spiny lobster trap fishery, while the remaining 0.7% were attributed to the stone crab trap fishery. Trap rope that was not attached to identifiable trap parts was not differentiated between the spiny lobster and stone crab fisheries because rope could not be assigned to a specific fishery. Manufactured materials, particularly those made of plastic (e.g., trap rope, trap throats, plastic coated wire frame) made up approximately 45% of all trap debris.

There were generally lower densities of trap debris in MPAs than in control areas as indicated by the negative parameter estimates for each MPA type (Table S3, Fig. 4A). MPA type did not strongly influence trap debris density, as the ratios of estimated marginal means were relatively close to one and the 95% CIs overlapped one for all pairwise comparisons (Fig 4B). Trap debris densities were less in those MPAs with marked boundaries (SPAs, PLEZs) than in those with unmarked boundaries (SLCAs). In general, trap debris densities decreased as MPA area size increased; however, the parameter estimate was relatively small and the confidence intervals included zero, suggesting that this was not a strong predictor of trap debris density (GLM: df =4, β = -0.002, SE = 0.001, lower 95% CI = –0.004, Upper 95% CI = 0.001).

### *3.1.2 Non-trap fishing debris*

Non-trap fishing debris (e.g., monofilament line, wire leaders, hooks, lobster hand-nets, etc.) was the third most abundant category of debris observed in MPAs (second most abundant is discussed in 3.1.3), accounting for 15.9% of all debris observed in this study. Non-trap fishing debris was observed in 44.4% of control sites, 87.5% of PLEZs, 44.4% of SLCAs, and 88.8% of SPAs. Monofilament line comprised the majority of non-trap fishing debris in each MPA type, followed by terminal-tackle items such as wire leaders, hooks, and weights, and less prevalent fishing gear such as pole spears and lobster hand-nets (Fig. 3). All non-trap fishing debris was comprised of persistent manufactured materials (e.g., plastic and/or metal).

There were generally greater densities of non-trap fishing debris in MPAs than controls as indicated by the positive parameter estimates (Table S3, Fig 4A); however, MPA type did not strongly influence non-trap fishing debris density as the ratios of estimated marginal means were relatively close to one and the 95% CIs overlapped one for all pairwise comparisons (Fig. 4C). The density of non-trap fishing debris also decreased as MPA area size increased, but the parameter estimate was relatively small and the 95% CIs included zero suggesting that this was not strong predictor of its density (GLM: df = 4, $\beta = -0.002$, SE = 0.002, lower 95% CI = –0.006, Upper 95% CI =0.001).

### *3.1.3 Non-fishing debris*

Non-fishing debris (i.e., not from traps or fishing gear) was the second most abundant category of debris in MPAs, accounting for 28.7% of all debris observed in this study. Non-fishing debris was observed in 61.1% of control sites, 75.0% of PLEZs, 83.3% of SLCAs, and 100.0% of SPAs. Non-fishing debris was comprised of a variety of materials, but the majority were glass, plastic, or metal (Fig. 3). Within these material types, much of the debris could further be categorized as consumer debris items. On average, 85.8% ± 0.1% of glass was glass bottles, 14.5% ± 0.1% of metal was aluminum cans, and 60.8 % ± 0.1% of plastic was plastic bags or bottles. Of these consumer-type debris items, 52.7% were observed in SPAs, 17.6% in PLEZs, and 14.9% in both the Controls and SLCAs. A total of 82.0% of all other debris was comprised of manufactured materials (e.g., metal, plastic, glass, rubber).

The greatest densities of non-fishing debris were observed in SPAs (Table S3, Fig. 4A); however, MPA type was considered influential only when comparing SPAs with PLEZs as this was the only comparison in which the 95% CI of the ratio of estimated marginal means did not overlap one (Fig. 4D). It appears that controls had lower densities of other debris than SPAs, but because the 95% CI narrowly overlaps one, these results were weak. The density of other debris decreased as MPA area size increased, but the parameter estimate was relatively small and the confidence intervals included zero, suggesting that this was not a strong predictor of fishing debris density (GLM: df = 4, $\beta$ = -0.002, SE = 0.002, lower 95% CI = –0.005, Upper 95% CI =0.001).

### *3.2 Debris density by SPA reef type*

In SPAs, debris densities generally declined with increasing distance from shore, which coincided with the coral reef structure change from nearshore patch reefs, closest to shore, to offshore patch reefs, and to continuous reef tract furthest from shore (Table S4, Fig. 5A). Parameter estimates and their associated 95% CIs which did not contain zero suggested that all debris categories were influenced by SPA reef type (Supplementary Material Table 4). Further examination of the ratios of estimated marginal means however indicated that the influence of SPA reef type on debris densities was weak in most cases as the 95% CIs overlapped one. Both trap and non-fishing debris densities were influenced by SPAs characterized as nearshore patch reefs (NPR) and offshore continuous reefs (OCR) with greater densities occurring in the nearshore patch reefs (Fig. 5B, 5D). Although similar densities of non-fishing debris were also observed in SPAs characterized as NPR and offshore patch reefs (OPR), they were not statistically different. In contrast, the influence of SPA reef type on non-trap fishing debris was weak, as the 95% CIs for all contrasts of estimated marginal means ratios abutted or completely intersected one (Fig. 5C). Overall, debris densities were highly variable and one nearshore patch reef SPA, Cheeca Rocks, accounted for 18.5%, 23.1%, and 20.0% of the trap, non-trap fishing, and non-fishing debris items, respectively, observed in all SPAs.

### *3.3 Spatial distribution of debris relative to coral reef habitat*

Debris density was greatest at the edge of coral reef habitat and decreased as the distance from the edge increased (Fig. 6). A total of 88 transects from 43 sites contained patches of coral reef habitat. We were able to examine the spatial distribution of debris relative to coral reef habitat on 73 of these transects; debris was not observed on 15 transects. Debris from all three categories tended to accumulate in coral reef habitat, particularly near the edges (Fig. 6), with 81.9% of non-trap fishing debris, 61.8% of trap debris, and 66.3% of non-fishing debris observed in coral reef habitat. Of the debris observed in coral reef habitat, 35.6% of non-trap fishing, 41.8% of trap, and 47.4% of non-fishing debris were observed within 10 m of the coral habitat edge.

### *3.4 Distance from MPA boundaries to coral reef habitat*

A total of 70 edge transects, which were perpendicular to MPA boundaries, contained coral reef habitat and provided an opportunity to examine the distance of this habitat from MPA boundaries (Fig. 7). MPA boundaries intersected coral reef habitat on 55.7% of these transects, meaning the distance to coral reef habitat was zero meters. Coral reef habitat was first encountered within 25 m of the MPA boundary for 71.4%, 67.7%, and 72.4% of transects from PLEZs, SLCAs, and SPAs, respectively. The average distance from the MPA boundary to coral reef habitat was 21.3 m ± 13.2 m, 29.1 m ± 6.8 m, and 18.2 m ± 5.4 m for PLEZs, SLCAs, and SPAs, respectively.

### *3.5 Debris interactions with sessile invertebrates*

We observed a total of 48 pieces of debris interacting with sessile invertebrates, including hard and soft corals and sponges (Table S5). Of these interactions, 60.4% occurred with trap debris, 29.2% with non-trap fishing debris, and 10.4 % with non-fishing debris. The majority (79.3%) of trap debris interactions occurred with trap rope, while most non-trap fishing gear interactions occurred with monofilament line (85.7%). More than half of debris interactions were observed with hard corals (58.3%), including species listed as threatened under the ESA, *Acropora cervicornis* (Lamarck, 1816), *Orbicella annularis* (Ellis and Solander, 1786), *Orbicella faveolata* (Ellis and Solander, 1786), and *Orbicella franksi* (Gregory, 1895) (Endangered and Threatened Wildlife and Plants Final Listing, 2014). Similar numbers of debris interactions with sessile invertebrates were observed among MPA types with 35.4%, 25.4%, 22.9%, and 16.7% of the interactions observed in SLCAs, SPAs, Controls, and PLEZs, respectively.

## 4 Discussion

The marine protected areas that we evaluated were designed to provide protection to marine resources, specifically coral reef habitat, using spatial management of specific resource user activities. Our study demonstrates that all types of marine debris we evaluated are prevalent throughout Florida Keys MPAs. While there are some idiosyncratic trends associated with each debris and MPA type, these protected areas are generally exposed to similar levels of debris accumulation as control areas that are not protected. Overall, our results suggest that marine debris is not constrained by MPA boundary management regulations.

Lobster trap fishing is prohibited in all the MPAs we evaluated, yet it was the most abundant category of debris observed. Although all MPAs generally had lower trap debris densities than control areas, there was no statistical difference in densities between MPAs and controls. It was not surprising that trap debris was the most abundant category of debris observed or that it was observed within the boundaries of MPAs. Previous studies have documented the pervasiveness of trap debris throughout the Florida Keys (Uhrin et al., 2014), including inside the boundaries of SPAs (Chiappone et al., 2002; Chiappone et al., 2004). The waters surrounding the Florida Keys are the primary fishing grounds of the spiny lobster fishery, where approximately 457,000 traps were used in the 2020-21 fishing season (FWC unpublished data). Previous research evaluating lobster trap fisher compliance with MPA regulations in the Florida Keys indicated that lobster trap fishers tend to fish along the boundaries of marked MPAs (SPAs, PLEZs) and often do not avoid the unmarked SLCAs (Renchen et al., 2018). Even though most lobster trap fishers tend to fish in sand, seagrass, and hardbottom habitats rather than coral (Matthews and Uhrin, 2009; Lewis et al., 2009), the greatest densities of trap debris observed in this study and others were in coral reef habitat (Uhrin et al., 2014).

Our study’s observation that trap debris was disproportionately more abundant near the edges of coral reef habitat suggests that trap debris accumulation at the reef edges may be due to high winds that move traps until stopped by rugose bottom features. Lewis et al. (2009) demonstrated the ability of a moderate breeze (7.72 m/s) to move traps, and a strong breeze (Beaufort scale 11.32 m/s – 13.89 m/s) or tropical disturbances can move traps hundreds of meters, after which, traps and trap debris were often observed resting in coral reef habitat. This is a concern because trap debris from our study accounted for the greatest number of interactions with corals relative to other types of debris, which have the potential to dislodge or damage hard and soft corals, as well as sponges (Chiappone et al., 2005; Lewis et al., 2009). Additionally, damage to corals may include tissue abrasions that facilitate the transmission of coral disease by providing an entry point for pathogens (Lamb et al. 2015). Although coral disease is not a new stressor to corals in the Florida Keys, the recent, unprecedented widespread mortality associated with stony coral tissue loss disease (SCTLD) (Muller et al., 2020) highlights the need for reducing potential sources of physical injury to corals. The SLCAs were specifically developed to protect two threatened coral species, *Acropora cervicornis* and *Acropora palmata*, from physical harm caused by lobster trap fishing (Gulf of Mexico and South Atlantic Fishery Management Councils, 2012; Gulf of Mexico Fishery Management Council, 2014). However, given the relatively equal amount of trap debris in SLCAs compared to other MPAs that have greater levels of compliance with trap prohibitions (SPAs, PLEZs) (Renchen et al., 2018), this suggests SLCAs are not providing sufficient protection to threatened corals. It is likely that wind transport of traps and trap debris was the primary cause of trap debris in MPAs. Our observations of the distance of coral reef habitat from MPA boundaries, combined with debris observations near the center of MPAs, suggest that these areas may not have large enough buffers to protect coral reef habitat from the movement of trap debris into these areas, especially if traps are fished along the boundaries or strong winds occur.

The vast majority of non-trap fishing debris we observed was monofilament line and tackle. All fishing is prohibited in SPAs (except for the limited catch-and-release trolling and bait fishing in select SPAs), but hook-and-line fishing is permitted in the control sites and other MPAs that we evaluated (SLCAs and PLEZs). Although MPA type was not an influential driver of non-trap fishing debris density, densities were greatest in the SLCAs and SPAs. Further, there were similar amounts of non-trap fishing debris in the SPAs, where fishing is prohibited, as there were in the SLCAs, where fishing is allowed. Chiappone et al. (2004) also found that monofilament and tackle were prevalent in SPAs and in densities similar to those observed in areas open to fishing. The SPAs were established in 1997, and while the fishing gear we observed could have persisted since then, it is more likely that it was present as a result of more recent noncompliance by resource users as these areas are often targeted for marine debris clean-ups (ONMS, 2019). Non-trap fishing gear was often observed entangled with hard and soft corals, and our evaluation of its distance from coral reef habitat indicated that it was most prevalent in coral reef habitat near the reef edge, with very few observations outside coral reef habitat. Aerial surveys of boater activity in the Florida Keys indicated that recreational hook-and-line fishing was typically concentrated over coral reef habitat (Matthews et al., 2018). Similar trends were observed in ledge habitats (also known as live bottom) in Grays Reef National Marine Sanctuary (Bauer et al., 2008). Although ledges are not considered coral reef habitat, they are similar in that they are structurally complex and covered by sessile fauna including hard and soft corals. Incidences of hook-and-line fishing gear debris were greatest in these ledge habitats, especially at high-relief ledges. High-relief ledges have more fish and thus attract more fishers, presumably resulting in more opportunities to lose fishing gear (Bauer et al., 2008). Monofilament easily snags and entangles in rugose habitats, and observations of partial or whole coral colony mortality have been documented in corals with tissue abrasions resulting from entanglement with monofilament (Asoh et al., 2004; Yoshikawa et al., 2004; Chiappone et al., 2005; Smith and Edgar, 2014). More consistent, periodic debris clean-ups and observations of resource-user behavior are needed to better understand how non-trap fishing gear is accumulating in MPAs. Because coral habitat is attractive to both fish and fishers, larger MPA buffers may be needed to prevent the entanglement of non-trap fishing gears with protected coral habitats.

Non-fishing gear debris densities were greatest in SPAs compared to other MPAs and were found in every SPA examined in this study. This suggests that *in situ* deposition, intentional or not, may be a consequence of the concentration of resource users at these sites. The Florida Keys attract 5.5 million tourists annually (ONMS, 2019) and aerial surveys of boating activity in the region suggested that 55% of the dive boats observed in the Florida Keys were observed inside the boundaries of SPAs (Matthews et al., 2018). A potential unintended consequence of designating less than 1% of the FKNMS by area as SPAs (ONMS, 2011) is the concentration of snorkelers and divers in these relatively small areas. While debris could be transported by waves and currents, a large proportion of the non-fishing debris, especially in SPAs, was composed of single-use consumer items such as plastic, glass, and aluminum beverage containers, suggesting that the debris likely originated from resource users at the MPAs. Additional research has indicated that tourism and recreation contribute to increased amounts of marine debris, even in areas that are protected (Wilson and Verlis, 2017; Rodríguez-Rodríguez, 2012). Although it is often assumed that most marine debris originates from land (Kastanevakis, 2008; UNEP, 2009), this may not be the case for submerged debris measured in this study, where considerable amounts of recreational and commercial boating occur (Wilson and Verlis, 2017).

SPA reef type, which combined the location and predominant type of coral reef structure, influenced the densities of trap and non-fishing debris. Trap debris and non-fishing debris densities were approximately three times greater at SPAs classified as nearshore patch reefs, namely Cheeca Rocks. Cheeca Rocks provides a good example of a hot spot for debris accumulation, as all debris categories were elevated at this site. The ease of access and popularity of nearshore SPAs may be a driver of the increased densities of non-fishing debris, particularly consumer debris items such as plastic, glass, and aluminum beverage containers. The nearshore SPAs are also surrounded by popular lobster trap fishing grounds in relatively shallow water that may be more susceptible to wind-driven trap movement (Lewis et al., 2009; Butler and Matthews, 2015). Although we observed very few fully intact traps, the increased trap debris densities are consistent with those described by Butler and Matthews (2015), who indicated that the densities of lost traps were greatest in nearshore waters of the Florida Keys. Boat traffic tends to be greater in nearshore waters, resulting in a greater amount of buoy cutoffs and thus greater densities of lost traps.

Although the MPAs we evaluated were not created to directly address marine debris, the pervasiveness of debris inside their boundaries is a concern from both an ecological and socioeconomic perspective. The health of Florida Keys coral reefs has been steadily declining for decades because of local and global stressors (ONMS, 2011; Ruzicka et al., 2013; Kenkel et al., 2015). Tourism, boating, fishing, diving, and adventure sports rely on a healthy coral reef environment (Leeworthy and Morris, 2010; Matthews et al., 2018). The accumulation of debris could further exacerbate the deteriorating health of this already compromised ecosystem. That MPA size was not an influential predictor of debris densities and MPA boundaries often intersected coral reef habitat indicates that the current boundary designations of Florida Keys MPAs are not large enough to prevent debris transport inside their boundaries. Also, they may not entirely deter noncompliance with fishing or litter regulations, intentional or not. The behavior, knowledge of fishing and littering regulations, and low experience levels of resource users in MPAs may drive debris accumulation in MPAs, particularly for non-trap fishing gears and non-fishing debris.

The three categories of debris identified in MPAs accumulate from independent sources and causes. The majority of trap debris likely originates outside of MPAs and is transported into the protected areas by strong winds. The relatively small size of MPAs in the Florida Keys, whose boundaries intersect coral reef habitat, and the concentration of traps fished near MPA boundaries may exacerbate the transport of those traps into MPAs. Although we did not directly assess boat densities, human behavior, and the concentration of boaters in SPAs, it is likely that they contributed to the increased densities of non-fishing debris in these MPAs. The uniform distribution of non-trap fishing debris across all MPAs and control areas regardless of fishing prohibition suggests that non-trap fishing debris is also likely tied to human behavior. MPA managers may need to evaluate resource user behavior to identify other means for increasing compliance and reducing marine debris. This could include increasing the frequency of marine debris clean-ups and monitoring to determine the rates of accumulation, and intense periods of on-the-water surveillance to understand how non-trap debris enters the water as well as how the number of resource users influences debris deposition. Policy interventions at a scale much broader than MPA management alone have the potential to reduce the amounts of debris entering MPA boundaries.

To reduce marine debris in MPAs the source of the materials and the circumstances that cause them to become marine debris need to be addressed. Trap debris and the rope used with lobster traps is being reduced as part of the spiny lobster trap certificate program (68E-18.007, Florida Administrative Code). This program assigns a single certificate to each trap and reduces the number of certificates available to the fishery annually until 400,000 certificates are left. Although the rate of reduction is less than 1% each year (FWC unpublished data), continued reduction of the number of traps directly addresses the potential number of traps that could become debris associated with loss and movement into MPAs during tropical disturbances. The size of MPAs in this study were relatively small relative to the distance traps move during tropical disturbances. Larger MPAs would presumably reduce the effects of traps fished near MPA boundaries impacting the interior of the MPAs. Introduction of ropeless and stationary fishing gear like casitas is an alternative that now dominates lobster fisheries in the Caribbean (Cruz and Adriano, 2001; Méndez-Medina et al., 2015, Gittens and Butler, 2018) and might also work in Florida. Non-trap fishing debris is more problematic. Regulations already prohibit fishing in several of the MPAs examined and additional regulations would likely be redundant and not change the behavior of the people fishing in the MPAs. Technological innovations to introduce biodegradable fishing line have not been readily accepted by fishers and currently do not seem practical. Non-fishing debris, such as single-use consumer items were likely a result of *in situ* deposition. Reduction of nondegradable packaging materials and onboard waste disposal containers on boats are relatively easy technical options. Increased availability of specialized waste receptacles for use on boats in concert with marine debris education at targeted locations like dive shops and marinas is recommended to reach the boating community at locations and on popular boating days when they most commonly visit MPAs in the Florida Keys. Accountability of marine debris in these already pressured MPAs falls upon every visitor and resident, as well as fisheries and MPA managers. Increased efforts to reduce the volume of both fishing and non-fishing marine debris have the potential to benefit all those who value the waters of the Florida Keys.

## Acknowledgments

This research was supported by funds from the NOAA Coral Reef Conservation Fund that were awarded through the National Fish and Wildlife Foundation (Project no. 0302.14.043840). All field work was conducted under permits from FKNMS (Permit no. FKNMS-2014-137) and John Pennekamp State Park (Permit no. 10081425). We would like to thank J. Renchen, J. Hunt, and our anonymous reviewers for providing valuable input on earlier versions of this manuscript. We are grateful for field assistance from E. Hart, M. Beaton, J. Kidney, J. Renchen. K. Maxwell, D. Eaken, and B. Reckenbeil. We also thank C. Shea for statistical analysis guidance.

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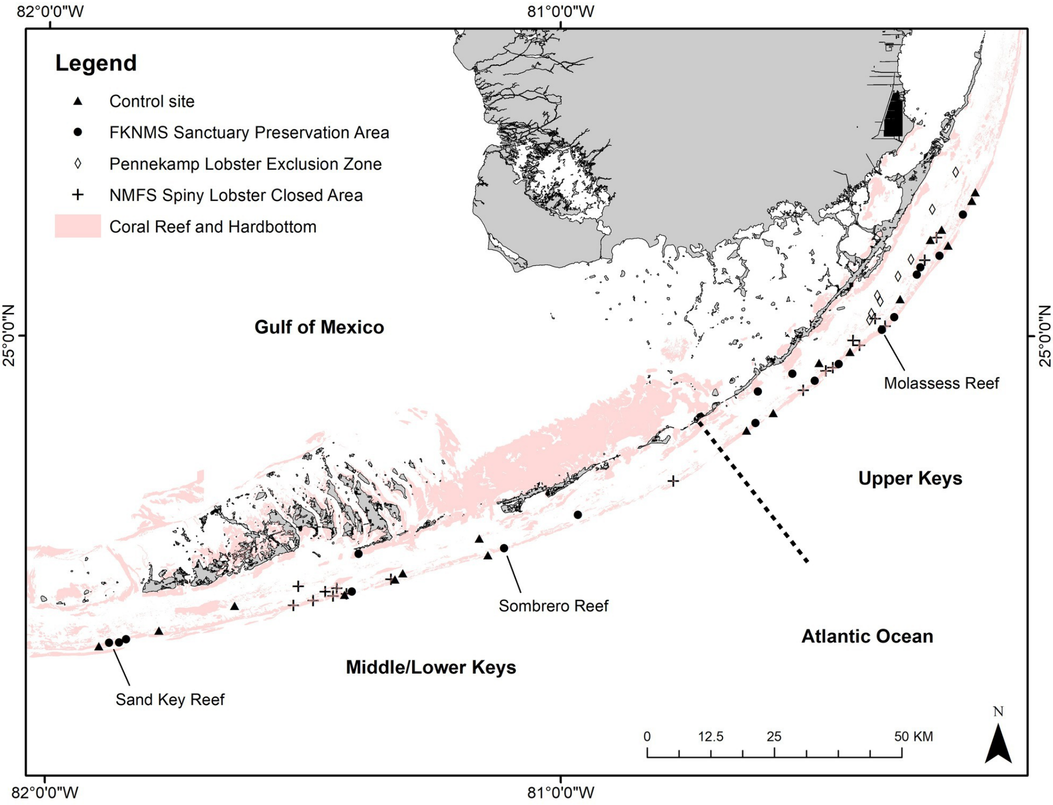
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◊ Pennekamp Lobster Exclusion Zone
+ NMFS Spiny Lobster Closed Area
Coral Reef and Hardbottom
Gulf of Mexico
Molassess Reef
Upper Keys
Sombrero Reef
Atlantic Ocean
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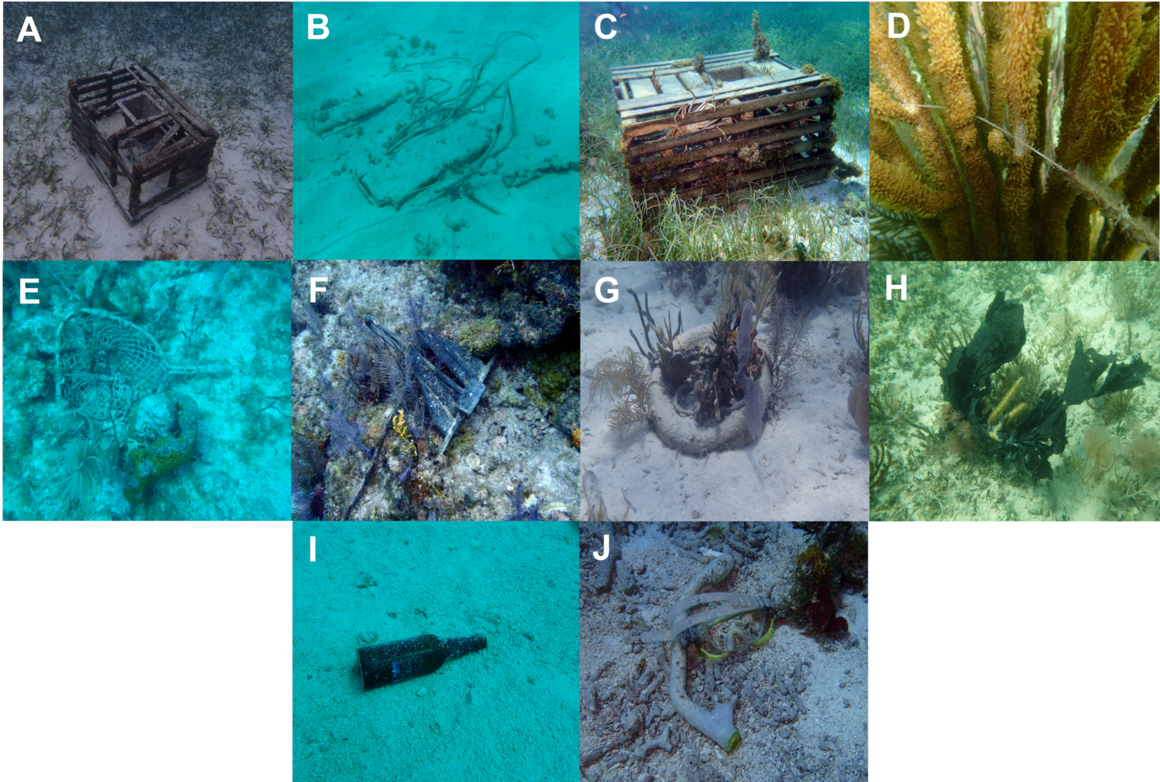
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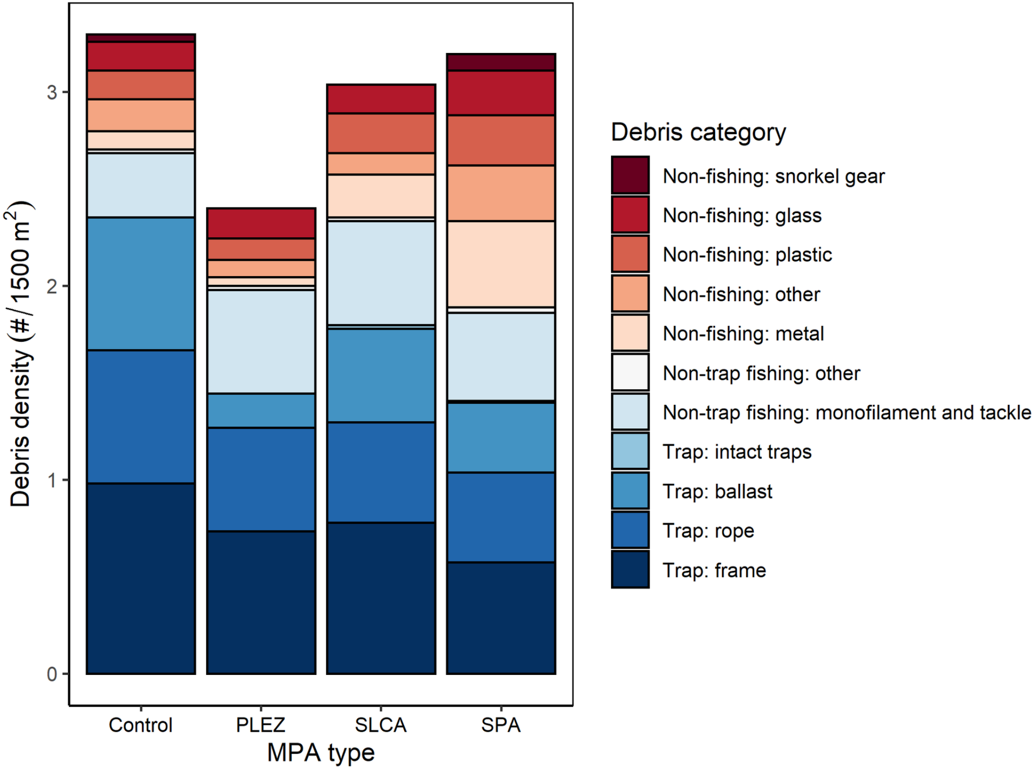
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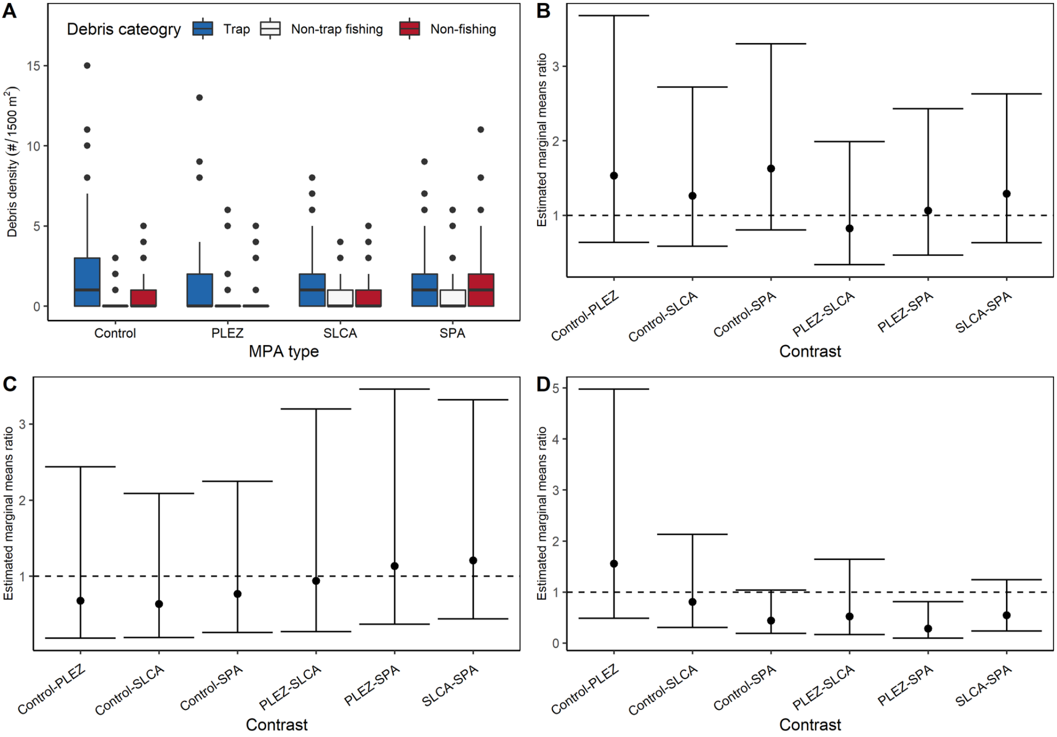
Non-fishing: plastic
Non-fishing: other
Non-fishing: metal
Non-trap fishing: other
Non-trap fishing: monofilament and tackle
Trap: intact traps
Trap: ballast
Trap: rope
Trap: frame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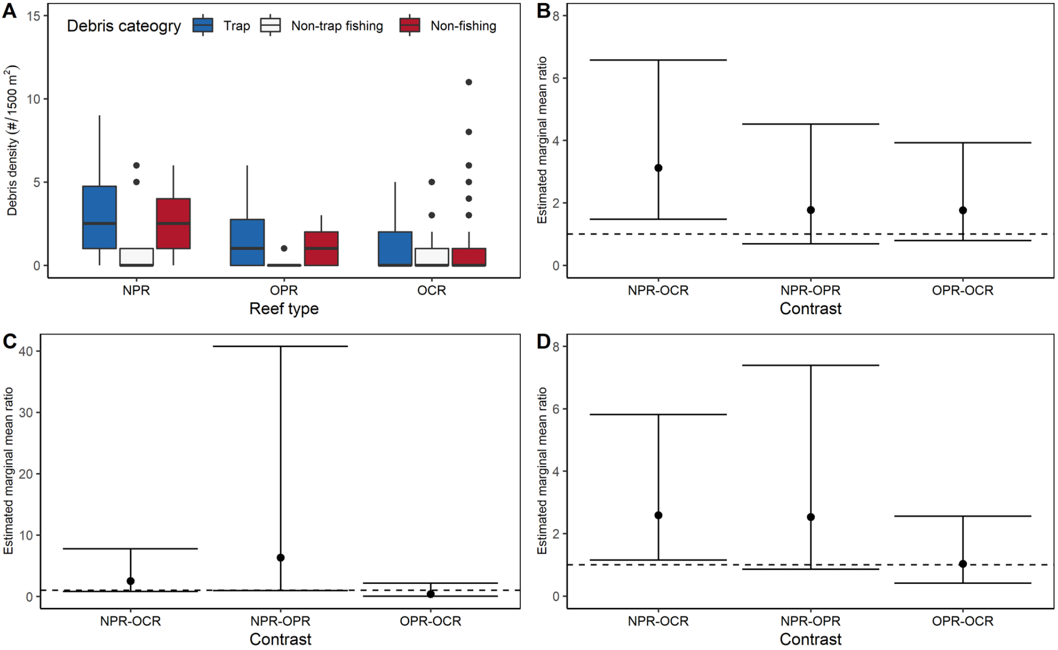
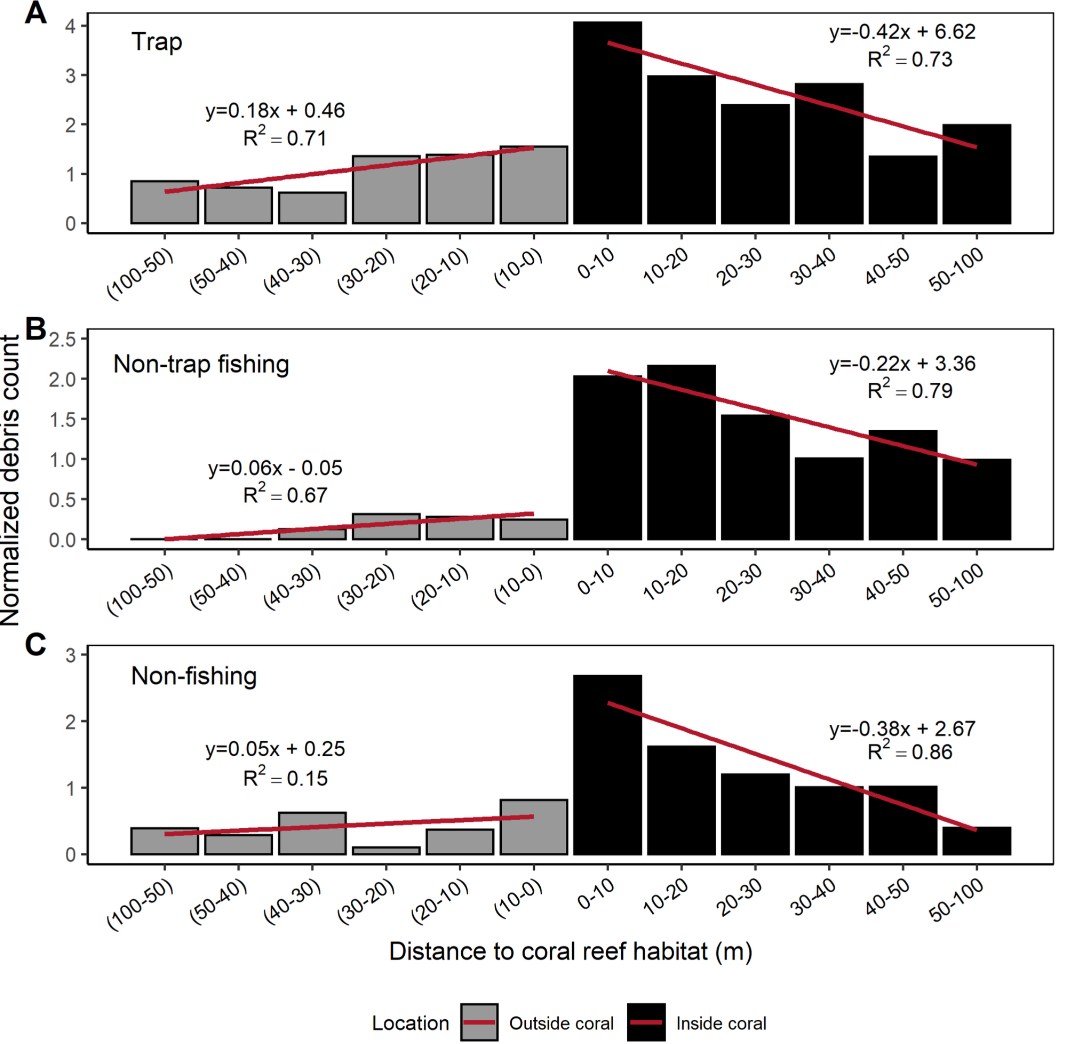
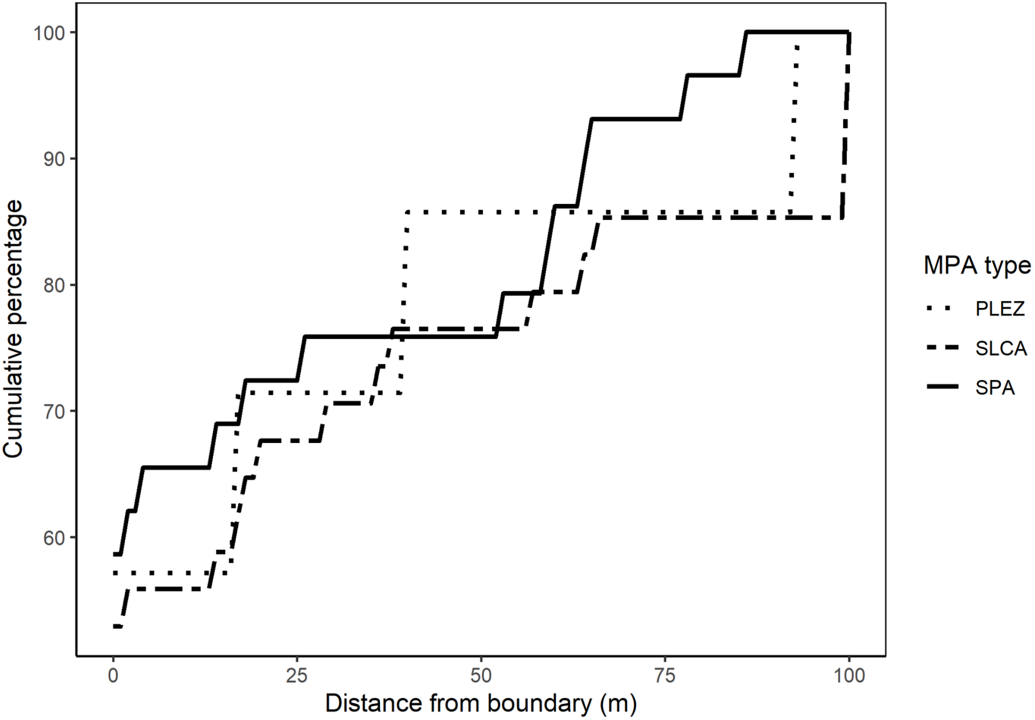
Control-SPA
PLEZ-SLCA
PLEZ-SPA
SLCA-SPA
Contrast
C
Estimated marginal means ratio
1
2
3
Control-PLEZ
Control-SLCA
Control-SPA
PLEZ-SLCA
PLEZ-SPA
SLCA-SPA
Contrast
D
Estimated marginal means ratio
0
1
2
3
4
5
Control-PLEZ
Control-SLCA
Control-SPA
PLEZ-SLCA
PLEZ-SPA
SLCA-SPA
Contrast


A
Debris cateogry
Trap
Non-trap fishing
Non-fishing
Debris density (#/1500 m$^2$)
0
5
10
15
NPR
OPR
OCR
Reef type
B
Estimated marginal mean ratio
0
2
4
6
8
NPR-OCR
NPR-OPR
OPR-OCR
Contrast
C
Estimated marginal mean ratio
0
10
20
30
40
NPR-OCR
NPR-OPR
OPR-OCR
Contrast
D
Estimated marginal mean ratio
0
2
4
6
8
NPR-OCR
NPR-OPR
OPR-OCR
Contrast


A
Trap
y=-0.42x + 6.62
$R^2 = 0.73$
y=0.18x + 0.46
$R^2 = 0.71$
0
1
2
3
4
B
Non-trap fishing
y=-0.22x + 3.36
$R^2 = 0.79$
y=0.06x - 0.05
$R^2 = 0.67$
0.0
0.5
1.0
1.5
2.0
2.5
C
Non-fishing
y=-0.38x + 2.67
$R^2 = 0.86$
y=0.05x + 0.25
$R^2 = 0.15$
0
1
2
3
Normalized debris count
(100-50)
(50-40)
(40-30)
(30-20)
(20-10)
(10-0)
0-10
10-20
20-30
30-40
40-50
50-100
Distance to coral reef habitat (m)
Location
Outside coral
Inside coral



Cumulative percentage
100
90
80
70
60
0
25
50
75
100
Distance from boundary (m)
MPA type
PLEZ
SLCA
SPA

**Table 1**: Summary of the sampling effort completed for each Marine Protected Area (MPA) (PLEZ = Pennekamp Lobster Exclusion Zone, SLCA = Spiny Lobster Closed Area, SPA = Sanctuary Preservation Area) and transect type (edge or random). The number of SPAs and PLEZs sampled per region (Upper or Middle/Lower Keys) is the total number of sites available in each region.

| | Number of sites sampled | | Number of transects per area type | | |
|---|---|---|---|---|---|
| MPA type | Upper Keys | Middle/Lower Keys | Edge | Random | Total number of transects |
| Control | 9 | 9 | N/A | 54 | 54 |
| SLCA | 9 | 9 | 54 | N/A | 54 |
| PLEZ | 8 | N/A | 21 | 24 | 45 |
| SPA | 12 | 6 | 54 | 54 | 108 |
| *Grand total* | *38* | *24* | *129* | *132* | *261* |