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Abundance, patterns, and taxa associations of anthropogenic marine debris on reefs in the middle Florida Keys

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The Florida Keys reef tract has rapidly shifted from a structurally complex, hard coral-dominated reef to a less rugose, soft coral-dominated reef. This transition has been facilitated by persistent anthropogenic stressors including recreational and commercial fishing and increased anthropogenic marine debris. During the summers of 2020–2022, benthic censuses were conducted to identify substrate and marine debris composition for 30 reefs in the middle Florida Keys. Inshore reefs contained higher rugosity, coral cover, and marine debris abundance primarily comprised of monofilament and rope from fishing traps. Plastic items (e.g., ropes and monofilament) overall had the highest species diversity. Additionally, marine debris appears to promote turf algae growth on inshore reefs. While it is not yet possible to determine if this pattern of high debris nearshore is due to proximity to onshore debris sources, accumulation due to higher rugosity snagging debris, or increased debris removal efforts offshore, these differences in marine debris types and abundances suggest variability in potential impacts of debris on marine biota on inshore versus offshore reefs. Therefore, the differential use of marine debris by associated biota should be considered in marine debris management practices.

KEYWORDS

marine debris, coral reefs, Florida Keys, biodiversity, taxa interaction

1 Introduction

The Florida reef tract is the largest coral reef system in the continental United States (Finkl and Andrews, 2008; Toth et al., 2018). This archipelago extends approximately 350 km from Key Biscayne to the Dry Tortugas and is comprised of numerous shelf and patch reefs (Toth et al., 2018, Toth et al., 2022). These reefs are habitats for a large variety of reef fishes and invertebrates (McCarthy et al., 2020). Unfortunately, the Florida reef track has undergone severe loss of hard corals due to anthropogenic stressors and climate change (Office of National Marine Sanctuaries, 2011). This decline began in the 1970s with a severe

outbreak of white band disease followed by physical disturbance from hurricanes and algal blooms exacerbated by increased human impact (Dustan, 1977; Precht et al., 2016). Subsequent waves of coral disease, cold snaps, extreme heat, nutrient eutrophication, and local disturbance from boating and commercial fishing have severely limited hard coral recovery (Aronson and Precht, 2001; Manzello, 2015). In general, the Caribbean alone has experienced a loss of percent hard coral cover from nearly 50% in 1970 to less than 5% today (Gardner et al., 2003; Jackson et al., 2014). This loss of hard corals has resulted in the shifting of reef habitats from structurally complex hard coral thickets to structurally simple soft coral and macroalgal fields (Maliao et al., 2008; Donovan et al., 2020). The complex, three-dimensional reefs represent more than 75% of the volume of shelters available to protect benthic fishes and invertebrates (Takada et al., 2007). Thus, it is now uncertain how this decrease in this complexity will affect both macro- and microfauna that rely on the structural intricacies of the reef.

In addition to the decreases in reef structural complexity, there is also an increasing volume of human-made debris on Florida Keys reefs (Miller et al., 2008). The Florida reef tract has accumulated anthropogenic marine debris (henceforth referred to as marine debris) through severe storms, tourism, and accidental and intentional abandonment indicating that much of the marine debris on Florida Keys reefs are locally sourced (Diersing, 2013). One of the most influential influxes of marine debris into the Florida Keys has resulted from lost and abandoned fishing gear. It is estimated that upwards of 100,000 lobster traps are lost each year Keys-wide (Renchen et al., 2021). In the lower Florida Keys alone, 90% of all debris consists of monofilament, wood from lobster pots, rope from lobster traps, fishing weights, leaders, and hooks (Chiappone et al., 2002; Renchen et al., 2021). This marine debris is known to accumulate along ledges and reefs due to winds, currents, and boating activity (Bauer et al., 2008; Uhrin et al., 2014; Renchen et al., 2021). Such loss of fishing gear causes damage to reef communities from breakage, entanglement, laceration, spread of disease, and restriction of sunlight (Lewis et al., 2009; Lamb et al., 2018).

Marine debris accumulation has been well documented to have detrimental and deleterious effects on marine taxa (Moore, 2008; Rochman et al., 2016); however, few studies indicate alternative uses of marine debris by cryptic reef taxa (Katsanevakis et al., 2007; De Carvalho-Souza et al., 2018; Teng et al., 2023). As of 2020, over 900 marine species were documented to interact with marine debris (Kühn and van Franeker, 2020). Of that, 701 species were documented to have ingested marine debris, and 354 species experienced entanglement (Kühn and van Franeker, 2020). It is estimated that at least 17% of species documented to have interactions with marine debris also appear on the International Union for Conservation of Nature Red List (Gall and Thompson, 2015). However, the full scope to which marine species are interacting with the debris is unclear. Oftentimes, marine debris uses such as refuge, homing dens, and substrate by marine taxa go unreported.

Human-made structures have long been used to promote biodiversity for fishing success and recruitment of spiny lobster *Panulirus argus* for Caribbean fishermen (Lee et al., 2018; Ross

et al., 2022). Casitas, for example, are illegally placed low-lying structures that vary in material composition and structure. Ross et al. (2022) found that casitas, while they may be artificial, increase the biodiversity of fishes and mobile invertebrates and mimic the effects of naturally occurring coral heads. While some uses of marine debris may be seen as having positive influences on marine biota as habitat, currently, there is a lack of “positive” and net neutral interaction data to fully assess long-term effects and management. Furthermore, Katsanevakis et al. (2007) suggest that “positive” interactions with marine debris may be short-lived as artificial structures may promote predation and decreased survival rates. While studies of predation and survival rates of organisms on marine debris are not yet prominent, Komyakova et al. (2021) note that poorly designed artificial reefs could serve as ecological traps and increase mortality rates of inhabiting species as Katsanevakis et al. (2007) suggest. Such conclusions may directly contradict the use of man-made materials as artificial reefs and the non-removal of marine debris overgrown by biota (Donohue et al., 2001; Smith and Edgar, 2014).

Here, we conducted a 3-year survey of benthic marine debris on reefs in the middle Florida Keys. This study provides an analysis of the influence of structural complexity and community composition on marine debris. First, we hypothesize that marine debris abundance is related to reef rugosity and predict that debris concentration would increase with an increase in reef structural complexity (rugosity) and that this difference would be most noticeable between reefs inshore versus those farther from shore. Second, we hypothesize that most marine debris is from recreational and commercial fishing sources and predict that derelict fishing gear comprised of lobster traps and trap debris would be uniformly distributed regardless of distance from shore. Third, given that most marine debris come from similar sources, we expect the distribution of marine debris material types to be similar inshore to offshore. Fourth, we hypothesize that the taxa community associated with marine debris differs by material type independent of distance from shore. By understanding the patterns of marine debris distribution, material types, and associations with marine fauna, we hope to expand our understanding of the costs and benefits of marine debris removal in the middle Florida Keys.

2 Methods

2.1 Study sites

Permitted research was conducted on 15 paired reef sites in the Florida Keys National Marine Sanctuary (FKNMS; 24.7°N, 80.8°W) from Islamorada to Marathon (Figure 1). Each of the paired reef sites is approximately 500 m from each other and over 1,000 m from the nearest adjacent site of paired reefs. Previous research was conducted on these sites examining reef substrate, rugosity, and reef fish behavior over the last 12 years (Smith et al., 2018, Smith et al., 2019; Noonan and Childress, 2020). None of the 15 locations occurred in Special Preservation Areas. Seven of the paired reefs were considered inshore (3–8 m depth, within 4 km from shore)

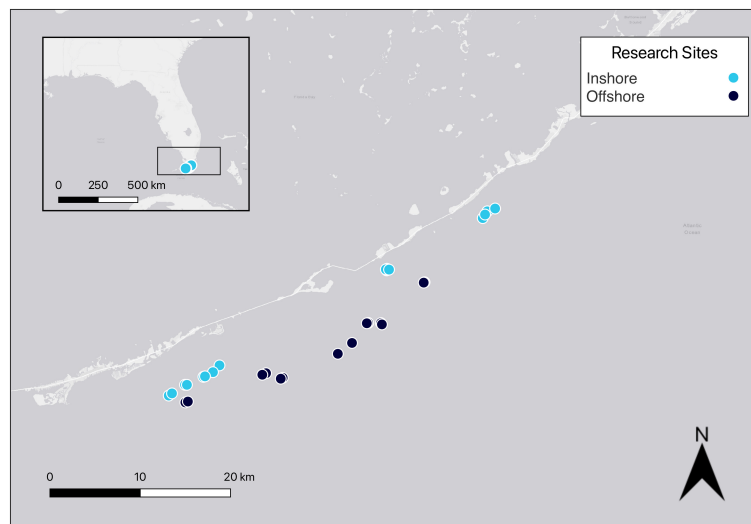


FIGURE 1

Map of 30 reef locations in the middle Florida Keys. Marine debris, substrate cover, and rugosity were measured at each of the inshore and offshore locations. Map generated using QGIS version 3.32.3-Lima (QGIS.org, 2023).

and eight of the paired reefs were considered offshore (5–10 m depth, >8 km from shore). All reefs were monitored once each year in the summer (May–July) of 2020, 2021, and 2022.

2.2 Reef benthic community and rugosity census

Reefs were censused on SCUBA using a 50 m transect line that ran parallel to the primary axis of the reef and four 30 m transects that laid perpendicular crossing at distances of 10, 20, 30, and 40 m, creating a 50 m × 30 m grid (Noonan and Childress, 2020; Noonan et al., 2021). Rugosity was measured using a chain and tape method (Risk, 1972; Luckhurst and Luckhurst, 1978; Noonan et al., 2021) taking three measurements on each of the four perpendicular transects. Rugosity measurements ($n = 12$) were averaged for the overall rugosity of each reef. To estimate the benthic community composition, divers took digital photographs of 50 cm × 50 cm areas of substrate on each side of the 50 m transect for the 0, 10, 20, 30, 40, and 50 m ($n = 12$ per reef). Photographs were analyzed for percent cover using 25 randomly placed points per picture using Coral Point Count with Excel extension V4.1 (Kohler and Gill, 2006).

2.3 Reef debris census

Using the 50 m × 30 m transect grid, a U-shaped diver search pattern began starting at the zero end of the first 30 m creating a 30 m × 30 m census area. All anthropogenic marine debris found within the 900 m² area was recorded and mapped using XY-coordinate notation. Marine debris observed were grouped into nine material types including plastic, mixed, wood, metal, concrete,

glass, cloth, paper, and other. Materials grouped into “other” included items that were hard to identify (i.e., due to biofouling). Mapping included identifying the material of debris and taxa–debris interactions using predetermined codes adapted from De Carvalho-Souza et al. (2018) (Figure 2). Specifically, interactions were categorized as catches in derelict fishing gear (CDFG), use of debris as a mobile home (MH), debris covering or smothering an organism (COV/SMO), entrapment or entanglement within debris (ENT), use of debris as refuge (RF), and use of debris as substrate (S). Catches in fishing gear and use of debris as a mobile home were not observed and therefore were not included in the current study. In the current study, entanglement (ENT) also included instances of rubbing and abrasion. Spatially calibrated photos of all debris were used to further identify organisms associated with debris. Mapping included little to no disturbance of debris; therefore, only marine taxa interacting with exposed parts of debris were identified. Taxa associations were counted based on the presence/absence of each marine debris item found.

2.4 Data analysis

Principal component analyses (PCAs) were used to characterize the differences between inshore and offshore reef substrate composition and concentration of marine debris by material type. Welch two-sample *t*-tests were used to determine differences in the prevalence of marine debris material type by inshore and offshore reefs. Reef substrate composition, depth, distance, and total marine debris abundance were characterized using a Spearman rank correlation analysis. The Spearman rank correlation analysis and principal coordinate analysis (PCoA) were constructed using Bray–Curtis dissimilarity indices to assess relationships between percent substrate cover, distance

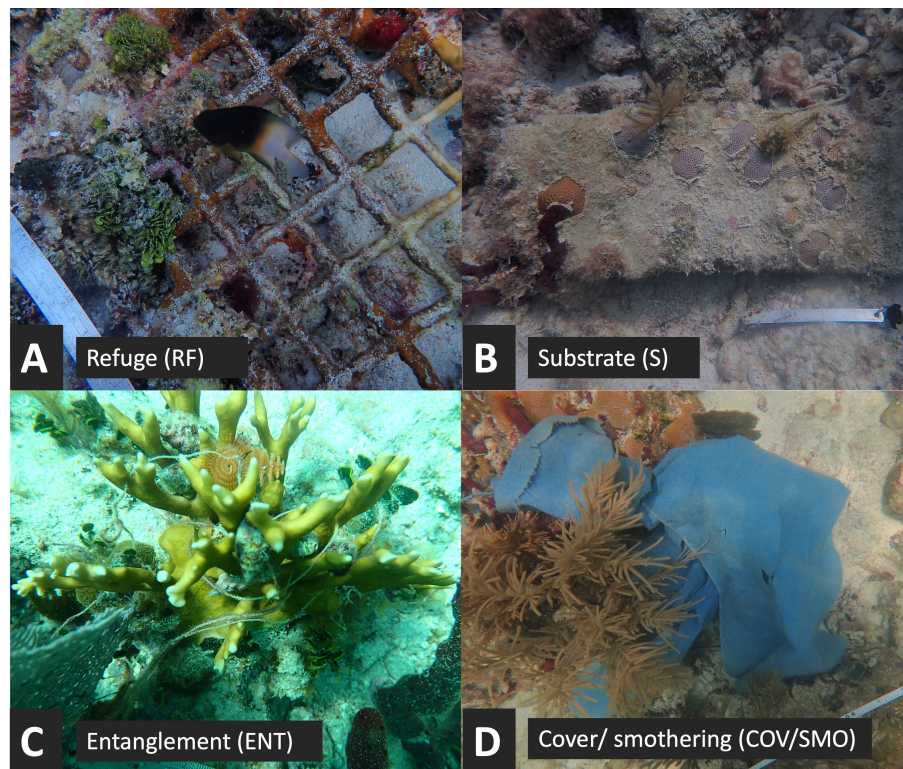


FIGURE 2

Examples of marine taxa interactions with anthropogenic marine debris modified from De Carvalho-Souza et al. (2018). Image (A) (top left) indicates the use of marine debris as a refuge. In this case, the bicolor damselfish is using lobster trap debris as a home. Image (B) (top right) indicates the use of marine debris as substrate such as the use of concrete slabs for coral and sponge growth. Image (C) (bottom left) indicates marine debris (fishing line) being entangled in fire coral. Image (D) (bottom right) shows marine debris (cloth) covering marine organisms such as soft coral.

from shore, reef depth, rugosity, and total marine debris abundance. Richness, Pielou's J' evenness, and Shannon and inverse Simpson's alpha diversity indices for debris-associated taxa were compared by region using Kruskal–Wallis and *post-hoc* Dunn's multiple comparison test with a Holm–Bonferroni multiple comparisons correction to identify areas of significance. Debris-related taxa were identified and assessed based on overall influence (positive, negative, neutral) on the reef community inshore and offshore. Influences were determined based on systematic literature searches for each taxonomic group. Positive associations were defined by having an overall net-positive influence on reef health such as reef builders or herbivores to assist in mitigating macroalgal overgrowth. Net-negative influences included taxa groups that are currently recognized as decreasing the overall health of positive organisms, such as parasites, macroalgae, corallivores, and invasives, whereas neutral influences were determined either by a group having both positive and negative influences that canceled out or having a lack of evidence for either positive or negative influences. Percent occurrence rates were estimated using abundances from the presence/absence of taxa found in marine debris in the current study. A 10% occurrence cutoff was used to assess which organisms may have the biggest impact on the surrounding reef community. All analyses and figures were

performed using RStudio[®] 2022.07.1 Build 554 (Oksanen et al., 2022; R Core Team, 2023).

3 Results

3.1 Increased rugosity is associated with higher rates of marine debris

Inshore and offshore reefs in the middle Florida Keys differ in substrate composition as evidenced by distinct clustering using PCA including distance from shore, depth, rugosity, and benthic substrate cover (Figure 3). Inshore reefs are shallow with high Scleractinia (hard coral) cover and low Alcyonacea (soft coral) cover leading to higher rugosity. Offshore reefs are deeper with low hard coral cover and high soft coral cover leading to lower rugosity.

Spearman rank correlation strongly indicated that reef rugosity is positively influenced by percent Scleractinia (hard coral) and percent Corallinales (calcareous algae) (Spearman's $r = 0.8$, p -value < 0.001, Figure 4). Spearman rank correlations greater than 0.5 or less than -0.5 indicated significant positive or negative correlations, respectively. Percent Alcyonacea and turf alga also exhibited an inverse relationship with rugosity (Spearman's $r = -0.6$, p -value = 0.044 and Spearman's $r = -0.8$,

across both inshore and offshore reefs (Supplementary Figure S3). Non-fishing-related debris density averaged 2.1 (SE \pm 0.4) per site inshore and 1 (SE \pm 0.4) piece per site offshore. Non-fishing-related debris made up approximately 13.8% of all debris inshore and 8.0% of all debris found on offshore sites. All ranges for debris items by region are listed in Supplementary Table S1.

3.3 Taxa interactions with marine debris differ based on region and debris type

Debris-associated taxa were comprised primarily of what was considered positive non-excavating sponges and hard corals, negative turf algae, and green and brown macroalgae (Supplementary Table S2). Regardless of marine debris, material type-associated taxa differed in J' evenness by region, inshore and offshore ($\chi^2 = 4.149$, p -value < 0.05 ; Figure 5). However, species richness and alpha diversity indices did not differ significantly (richness: $\chi^2 = 0.130$, p -value = 0.717; Shannon: $\chi^2 = 0.027$, p -value = 0.867; inverse Simpson:

$\chi^2 = 0.292$, p -value = 0.588; Figure 5). Taxa richness and alpha diversity indices significantly differed based on marine debris material type (richness: $\chi^2 = 69.497$, p -value < 0.001 ; Shannon: $\chi^2 = 62.708$, p -value < 0.001 ; inverse Simpson: $\chi^2 = 56.716$, p -value < 0.001 ; J' : $\chi^2 = 28.156$, p -value < 0.001 ; Supplementary Table S3). Furthermore, richness and alpha diversity also differed inshore compared to those of offshore. All diversity indices were significant for inshore taxa driven by taxa associated with plastics (Supplementary Table S4). Plastics overall contained the highest species richness above all other material types (Supplementary Figure S4). For offshore, the evenness of taxa found on wood was significantly different compared to the taxa found on glass (p -value < 0.01). No other offshore diversity association was significant. While the percent cover of turf algae occurring on the inshore reef community was not significant, significantly more turf algae were associated with debris inshore compared to offshore ($\chi^2 = 72.627$, p -value < 0.001 ; Figure 6A). Scleractinia hard corals and calcareous Corallinales taxa occurring on debris were also significantly abundant on inshore reefs ($\chi^2 = 6.130$, p -value < 0.05 ; $\chi^2 = 4.445$, p -value < 0.05 ; Figure 6A).

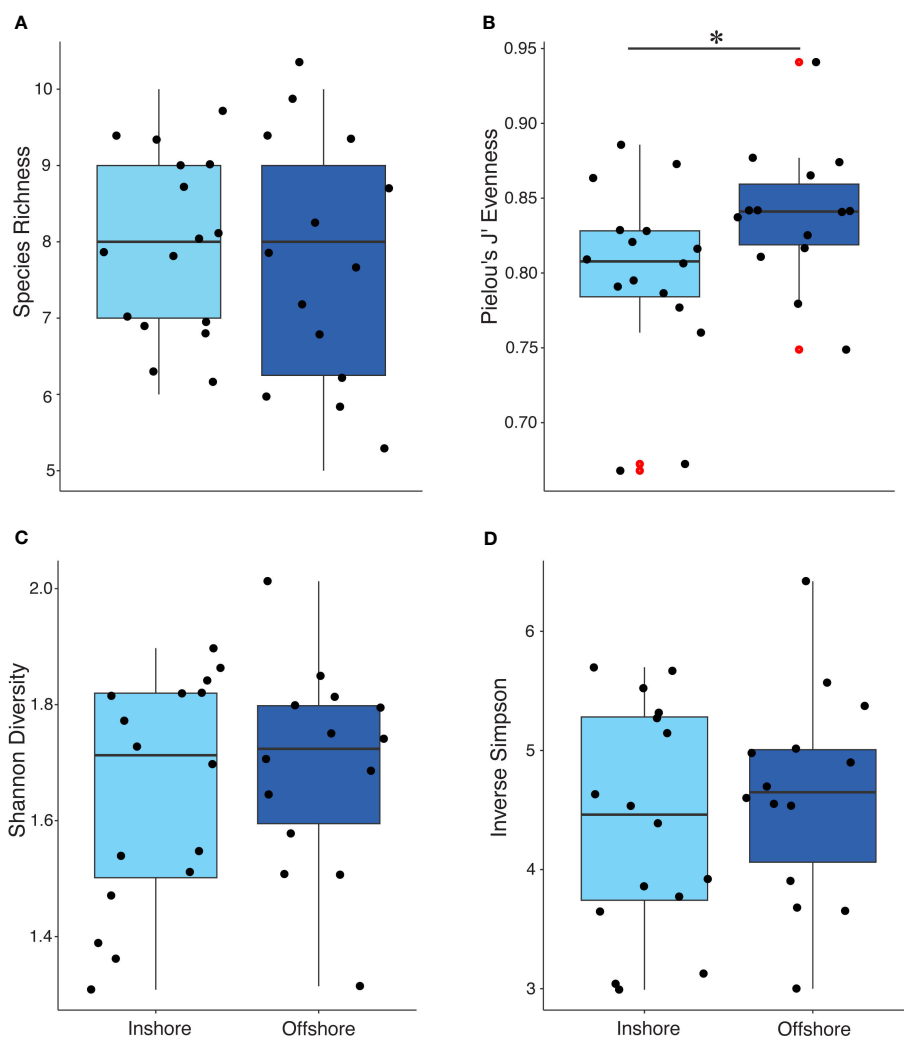


FIGURE 5
Jittered box plots of taxa richness (A), Pielou's J' evenness (B), and alpha diversities; Shannon (C) and inverse Simpson (D) for inshore versus offshore reef locations. Red dots indicate outliers in the data. Only evenness was significant ($p < 0.05$) indicated by the bar and asterisk (B).

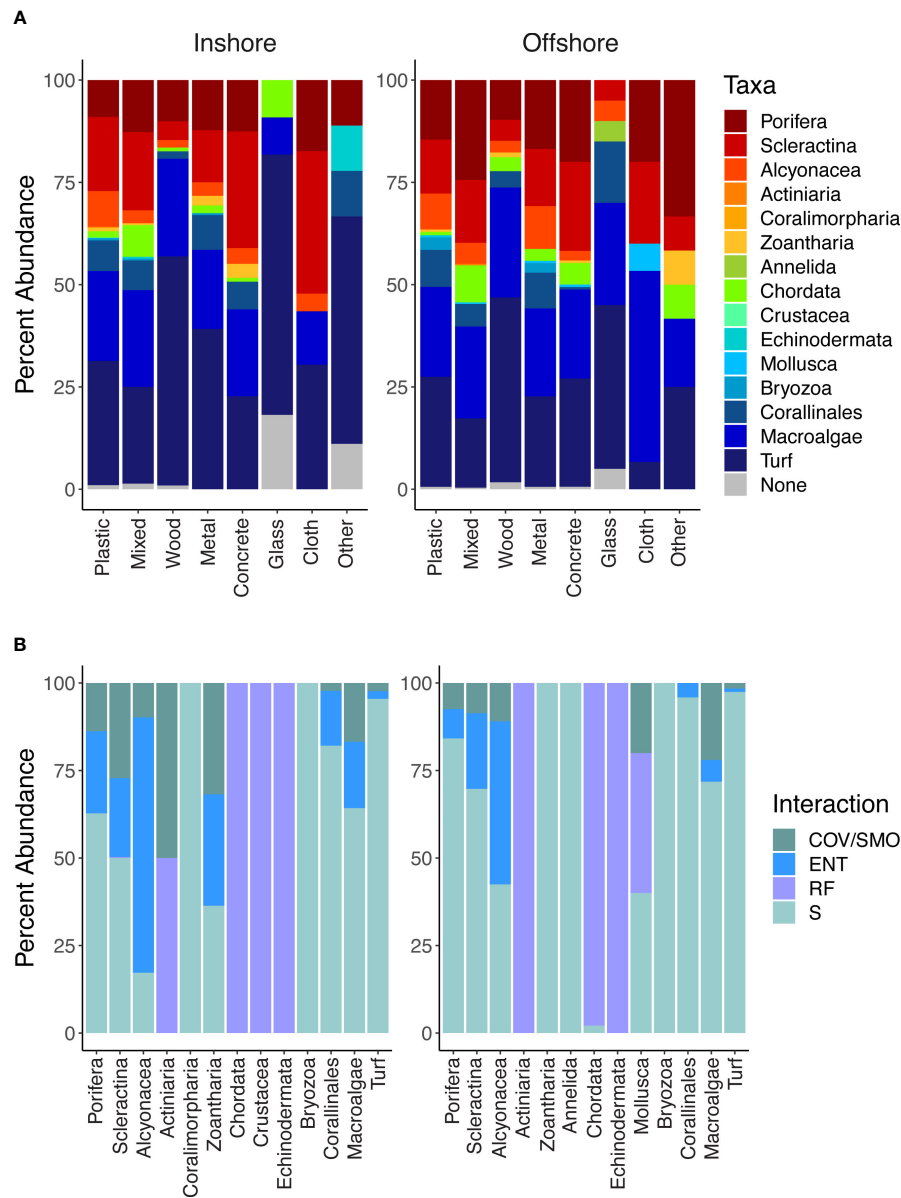


FIGURE 6

(A) Stacked bar graph demonstrating the percent abundance of taxa associated with anthropogenic marine debris by material type for inshore and offshore reefs. Taxa were identified based on the presence/absence for each piece of marine debris observed *in situ*. (B) Stacked bar graph demonstrating the percent interaction type for each identified taxon for inshore and offshore locations. Interactions included cover and smothering (COV/SMO), entanglement and abrasion (ENT), refuge (RF), and substrate (S).

Taxa interactions with marine debris were categorized as covering and/or smothering (COV/SMO), refuge (RF), substrate (S), and entanglements or entrapments (ENT). Mobile organisms such as chordates used all materials as a form of shelter or refuge except for cloth and paper (Figure 6B). However, sessile zoanths preferred concrete and our “other” material category. Taxa also significantly differed by their interaction with debris ($\chi^2 = 3054.7$, p -value < 0.001). Alcyonacea (soft corals) while noted to interact with most all marine debris material types observed, most of the interactions involved entanglements.

4 Discussion

Anthropogenic marine debris has been documented worldwide, and the Florida Keys National Marine Sanctuary is no exception (Raimondo et al., 2024). This anthropogenic disturbance is in juxtaposition with changes in climate and ecosystem shifts (Ford et al., 2022; Thirukanthan et al., 2023). Over the last decades, we have seen a melting of reef structures from diverse structural complexities to flatter less diverse reefs (Hughes, 1994; Donovan et al., 2020). This altered coral reef ecosystem, in conjunction with increased marine

debris, introduces shifts from natural to artificial structures. In addition, the use of coral reefs by humans for nutrition, medicines, safe shores, and recreation and changes in climate add a significant influx of debris (Ford et al., 2022; Thirukanthan et al., 2023). For example, recreational and commercial fishing is responsible for creating the highest types of debris on the adjacent reef environment in the Florida Keys (Uhrin et al., 2014; Renchen et al., 2021). What is not known in full is the distribution and use of marine debris by marine organisms. Our study has identified patterns of marine debris distribution regarding the naturally occurring benthic community on 30 reef locations in the middle Florida Keys. The highest abundance of debris occurred on shallow, inshore reefs associated with higher rugosity, coral cover, and calcareous algae (Corallinales). These inshore reefs contain massive *Siderastrea siderea* and *Orbicella* spp. boulder corals that provide habitat for recreational game fish and become a sink for recreational fishing and trap debris that is moved by wind and current (Lewis et al., 2009).

We observed that the primary marine debris material types found on inshore reefs were plastics and metals from fishing gear suggesting that these are locally derived and may indicate a difference in recreational use of inshore reefs versus offshore reefs. This observation warrants further investigation as metal was represented by leader line and wire and much of the plastic materials consisted of monofilament fishing line and nylon and polypropylene rope. Increased monofilament and leaders could suggest that inshore reefs experience higher recreational hook and line fishing pressure or that the increased reef complexity results in more entangled or caught lines than the less rugose offshore reefs. The same could be said for rope from fishing traps as cut lines may find their way entangled in a more complex structure. An alternative explanation for this increased abundance of marine debris inshore could be related to marine debris removal activities by local dive shops. Based on interviews with commercial dive shops in the Florida Keys, many focus on offshore reefs due to clearer visibility and the belief that more debris is found deeper and along the continuous reef track (not published). This does not appear to be the case for our middle Keys reefs for which very few marine debris removal activities, either inshore or offshore, have been conducted based on the PADI Aware Foundation Dive Against Debris database (PADI AWARE Foundation, 2022).

Total marine debris abundance was positively correlated with calcareous red algae which appeared on all debris types and were known to facilitate hard coral settlement (Tebben et al., 2015; Gómez-Lemos et al., 2018; Deinhart et al., 2022). We note that structures such as plastic and concrete allow for the facilitation of hard coral recruitment; however, the duration of sustained growth is currently unknown and warrants further investigation. No correlation of total debris with naturally occurring fleshy macroalgae cover was noted, and thus, this study indicates that while increases in macroalgae have coincided with the shifting of reefs to less structurally complex communities (Maliao et al., 2008; Donovan et al., 2020), marine debris does not seem to be facilitating fleshy macroalgal growth.

The significant presence of calcareous algae, hard corals, and turf on marine debris inshore heavily influenced the significantly lower evenness of taxa inshore versus offshore. However, the

evenness of taxa on offshore debris was higher with only notable differences in communities on wood and glass, with glass containing the least difference in taxa. Due to higher turf cover on offshore reefs compared to inshore reefs, we would expect that marine debris offshore would have more turf present. However, we found that marine debris inshore contained 122% more turf than debris offshore. Turf competes with hard corals for space and accumulates sediments further preventing coral growth (Tebbet and Bellwood, 2019; Brown et al., 2020). Turf algae, if introduced by marine debris at higher than naturally occurring levels, could have cascading effects on coral reef habitats. Such interactions have occurred in the Yellow Sea with the carnivorous anemone *Metridium senile fimbriatum* (Teng et al., 2023).

With decreases in three-dimensional reef structure, studies are showing that various marine organisms are finding habitat among anthropogenic marine debris (De Carvalho-Souza et al., 2018). While deleterious effects are heavily documented (Moore, 2008; Rochman et al., 2016), this study also notes additional taxa–debris interactions as a future opportunity to better understand how marine debris is affecting coral reef communities. For instance, here, we showed that species composition can differ significantly based on the material of the marine debris. This information may inform debris removal efforts for retrieval efficiency and reef health by focusing on materials causing the most risk. We can assume that interactions such as covering/smothering (COV/SMO) and entanglement (ENT) are detrimental to marine life while refuge (RF) and substrate (S) may be beneficial depending on what is utilizing the space. However, the extent to which these interactions are positive, negative, or net-neutral is still unknown, and we encourage future marine debris research to incorporate these elements moving forward. It is estimated that two-thirds of coral reefs are made of hidden nooks and crevices creating homes for many cryptic benthic fishes and invertebrates (Takada et al., 2007; Glynn and Enochs, 2011). Thus, the question remains as to how marine debris is being used by these cryptic species *in situ* and in the long term. While only visually exposed organisms were accounted for in our study, we acknowledge that more cryptic or hidden biota could be utilizing and/or affected by debris that cannot be identified until the debris is disturbed or removed. Therefore, our proportions of organisms covered (COV/SMO) or marine debris used as refuge (RF) may be underestimates and will be further investigated. For instance, the oviposition of fishes on marine debris was not noted in this study but has been raised as an area needing further research by Shruti et al. (2023). Additionally, we note that non-indigenous species such as sun corals, *Tubastrea* spp., which have been previously documented on marine debris in the Florida Keys (Parsons et al., 2023) were not identified in this study and require further investigation to determine the cost and benefits of debris materials as substrate or refuge.

There is strong evidence that high natural structure from massive reef-building corals contributes to reef biodiversity (Alvarez-Filip et al., 2011; Graham and Nash, 2013). Therefore, the concern is that the loss of reef-building corals will lead to a flattening of the reef and a corresponding loss of biodiversity (Alvarez-Filip et al., 2009; van Woesik et al., 2022). This may also elevate the importance of structure from marine debris which may serve as unintentional artificial reefs

attracting the settlement of reef species (Spanier and Almog-Shtayer, 1992; Kiessling et al., 2015). This raises an important question when considering the net benefits of the removal of debris heavily covered in sessile species with a shrinking natural area for settlement. This study serves as a framework to continue the study of marine debris on Florida Keys reefs. Future studies will work to better understand debris patterns on Florida reefs and the potential costs and benefits of debris on cryptic marine biota. Such research will aid in natural resource management and assist in safe marine debris removal for cleaner, healthier reefs.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

TP: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. RS: Data curation, Funding acquisition, Writing – review & editing. MC: Data curation, Funding acquisition, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2024.1412858/full#supplementary-material>

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