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WETLAND POLLUTION

Mangrove Forests of Biscayne Bay, FL, USA may Act as Sinks for Plastic Debris

Melinda Paduani[1] · **Michael Ross**[1] · **Gabriel Odom**[2]

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Abstract
Mangrove forests of Biscayne Bay in southeast Florida, USA can sequester pollutants from freshwater inputs. This "filtering" of water minimizes point source discharges through canals, but mangroves may also play an important role in the cycling of plastic pollution that reaches the Bay. The objectives of this study are to determine: 1) The composition of debris in the Bay's mangroves and 2) How the structure of mangrove forests affects debris distribution. Debris was hypothesized to be more abundant further into the forest due to trapping by vegetation, and mesoplastics (5 mm – 2.5 cm) would be positively correlated to macroplastics (> 2.5 cm) due to fragmentation. Nine transects were surveyed and debris was recorded by size and potential origin. 94.5% of all debris was plastic of which 57.8% were fragments. Negative binomial generalized linear regression was used to relate total plastic and mesoplastic densities to distance from shoreline, elevation, basal area, prop root and pneumatophore cover, and mangrove seedling abundance. Plastic increased with distance from shore and basal area, although the latter was just above the p-value cut-off of 0.05 for mesoplastic (p-value = 0.0513), and was weakly negatively related to prop root coverage. Total plastic was weakly negatively related to red mangrove seedlings and pneumatophore coverage, although these relationships were less clear. Mesoplastic and macroplastic were positively correlated (p-value < 0.05). Selected mangrove forests of Biscayne Bay appear to be sinks for plastic debris, where it accumulates in the interior forest from which it is unlikely to escape.

Keywords Mangrove · Plastic pollution · Marine debris · Coastal wetlands · Management · Plastic sink

Introduction

Despite their relatively small spatial extent globally compared to other ecosystems, the unique structure of mangroves provides many well-documented ecosystem services. These include improvement of water quality, storm buffering, prevention of erosion, and high carbon sequestration (Woodward and Wui 2001; Barbier et al. 2011). However, plastic pollution poses hazards to associated fauna through physical entanglement or blockages, complications from debris ingestion, and transfer of associated chemical pollutants and harmful biological vectors (Gall and Thompson 2015; Naik et al. 2019; Zhang et al. 2022), and it can damage vegetative structures or cause other physiological stress (Viehman et al. 2011; van Bijsterveldt et al. 2021). Smaller plastic particles including microplastics (< 5 mm in size) generated by the fragmentation of larger items have also been highlighted for their potential to bioaccumulate throughout the food web (Wright et al. 2013; Carbery et al. 2018; Campanale et al. 2020). Reliance on commercially important species that spend a part of their life cycles in mangrove nursery habitats of Biscayne Bay, Florida, such as pink shrimp, blue crab, and various estuarine and offshore fish species, presents concerns for the health risks associated with local plastic pollution (Browder et al. 2005; Lourenço et al. 2017; Hughes et al. 2021).

Combined with increasing patterns of habitat conversion, anthropogenic pressures such as pollution can negatively impact other mangrove ecosystem services over time and may impede the mangroves' role in preventing the dispersal of contaminants (Lewis et al. 2011). Fluxes of plastic within mangrove swamps have rarely been studied and little is known about their capacity to retain marine debris

✉ Melinda Paduani
mpadu004@fiu.edu

[1] Department of Earth and Environment, Florida International University, Miami, FL 33199, USA

[2] Department of Biostatistics, Florida International University, Miami, FL 33199, USA

or the many chemical additives, leachates, and adsorbed toxins associated with it (Holmes et al. 2014; Chen et al. 2017; Nguyễn et al. 2020). It has been suggested that vegetated habitats at the interface of marine and terrestrial environments are likely to harbor a substantial proportion of unaccounted plastic not found in the oceans (Brennan et al. 2018; Olivelli et al. 2020). As a result of the complex structure of the mangrove forest floor, it is hypothesized that debris entangled by vegetation remains trapped indefinitely. Surveys of both marine debris and the unique structure of mangrove forests are needed to explain accumulation on shorelines and to predict how they may store debris in various environmental compartments (Cordeiro and Costa 2010; Ivar do Sul et al. 2014; Paduani 2020).

The objectives of the present study are to determine: 1) The composition of debris in the Bay's coastal wetlands and 2) How the unique structure of mangrove forests affects the distribution of plastic debris. Debris was surveyed at nine sites in mangrove forests along transects extending inland from the coastline. Debris was recorded by size as mesoplastic (5 mm – 2.5 cm) and macroplastic (> 2.5 cm). Abundances of total and mesoplastic were regressed against vegetation parameters (basal area, percentage of plots covered by prop roots and pneumatophores, number of red, black, and white mangrove seedlings), distance to shoreline, and elevation by negative binomial generalized linear regression. The relationship between mesoplastics and macroplastics was then analyzed by simple linear regression. It is hypothesized that both total and mesoplastic debris will be more abundant in the interior forest than at the edge due to entrapment in vegetation, and mesoplastics will be positively correlated to the amount of macroplastics as larger items fragment into smaller pieces. This study is one of the first to record and explain debris abundance and distribution in Biscayne Bay's (FL, USA) mangroves.

Study Area

Florida has the greatest expanse of mangroves in the contiguous United States, and the Biscayne Bay Coastal Wetlands in the southeastern corner of the state comprise the highest coverage of mangrove forests on the east coast of Florida. Tall fringe mangroves line the coasts and are exposed to constant tidal flushing, whereas smaller "dwarf" mangroves inhabit interior, freshwater basins that are less frequently exposed to marine influence. The tree species present are *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), and *Laguncularia racemosa* (white mangrove). The vegetative structure of the mangroves creates a complex forest floor. Red mangroves have branching aerial roots, or prop roots, while black and white mangroves display a different form of exposed root system, called pneumatophores, which are finger-like projections from the forest floor. The Bay is also home to busy marinas, cruise ship ports, and shellfish farms (Browder et al. 2005). Thus, the mangroves in this region exist within a range of highly urbanized to intact habitat, albeit even the most isolated forests are crossed by canals, roads, and old mosquito ditches.

Despite having an antidegradation water quality standard (FAC § 62–302.300), the health of the Bay has declined in recent years. Persistent water quality issues include the loss of seagrass beds and harmful algal blooms (HABs) caused in part by excessive nutrient inputs from fertilizers, septic waste, and lawn trimmings (Biscayne Bay Task Force 2020). Plastic pollution has also been raised as a major concern by local governments. The Comprehensive Everglades Restoration Program seeks to restore the hydrology and water quality of the Bay through various components of the Biscayne Bay and Southeastern Everglades Ecosystem Restoration (BBSEER) project, including redirection of freshwater flows through the mangroves as opposed to localized discharges from canals (U.S. Army Corps of Engineers and South Florida Water Management District 2020). Plastics or trash are not explicitly cited in BBSEER, but considering the pervasiveness of debris collected in clean-ups and accumulated in stormwater systems across South Florida, plastics are an emerging threat to Biscayne Bay.

Formal studies of plastic debris in Biscayne Bay are scarce. Based on community cleanup data, debris appears to be equally abundant across most of the Bay's beaches (Kitayama 2017). Recently, researchers documented polystyrene film microplastics in the waters of adjacent Card Sound and Barnes Sound (Badylak et al. 2021) and polyethylene terephthalate (PET) fibers in beach sediments of Biscayne National Park (Yu et al. 2018). Biofouling of plastics by invertebrates and algae in Biscayne Bay may alter the transport of these plastics and increase exposure of organisms in higher trophic levels (Ye and Andrady 1991).

Organized debris clean-ups around the Bay range from local efforts led by schools to large annual events. However, local reports specifically call for increased efforts to remove debris in this region (National Oceanic and Atmospheric Administration Marine Debris Program 2017; 2020). In the mandated Update to the Retail Bag Report of 2010, Florida clean-up data from the Surfrider Foundation regarding plastic bags, food packaging, and wrappers totaled 19,983 units (545 lb by weight) between 2018–2021, and the Ocean Conservancy documented 22,045 lb between 2018–2020 (Townsend et al. 2021). Despite the prevalence of extensive mangrove forests, a dense human population, and numerous clean-up efforts, the fate of plastics in the Bay's mangrove forests has not been studied.

Methods

Surface Surveys

Stretches of shoreline from the central and southern parts of Biscayne Bay were selected based on the presence of intact, homogenous coastal (fringe) mangrove forest that extended 65 – 95 m inland perpendicular to the shoreline except for transect DE3_1 which extended only 45 m. Transect starting points were created using Google Earth satellite imagery and designated using a random number generator to select a point along each stretch. Transects were separated by at least 50 m. For this pilot study, starting points of survey transects were at least 15 – 20 m away from roadways, canals, and areas where clean-ups are known to occur (Fig. 1). Therefore, debris sampled in the study was most likely deposited from marine sources.

Starting at the coast of a designated shoreline, debris was thoroughly sampled at low tide in plots of 2 ft (0.61 m) radius at 0 m, 5 m, and every 10 m thereafter. Plastic debris was measured at the longest dimension with a ruler and characterized by type and size class (meso: 5 mm – 2.5 cm, macro: > 2.5 cm) according to Lippiatt et al. (2013) and left in place to avoid altering the site in any way. The density and structure of vegetation were also surveyed, including: basal area (local stand cross-sectional area at 1.4 m height, in m^2/ha, captured with an angle gauge, using Basal Area Factor 10 (English units) opening (Grosenbaugh 1952); percent coverage of prop roots and pneumatophores within each plot; and counts of seedlings (1 – 10 cm in basal diameter) by species. Plots

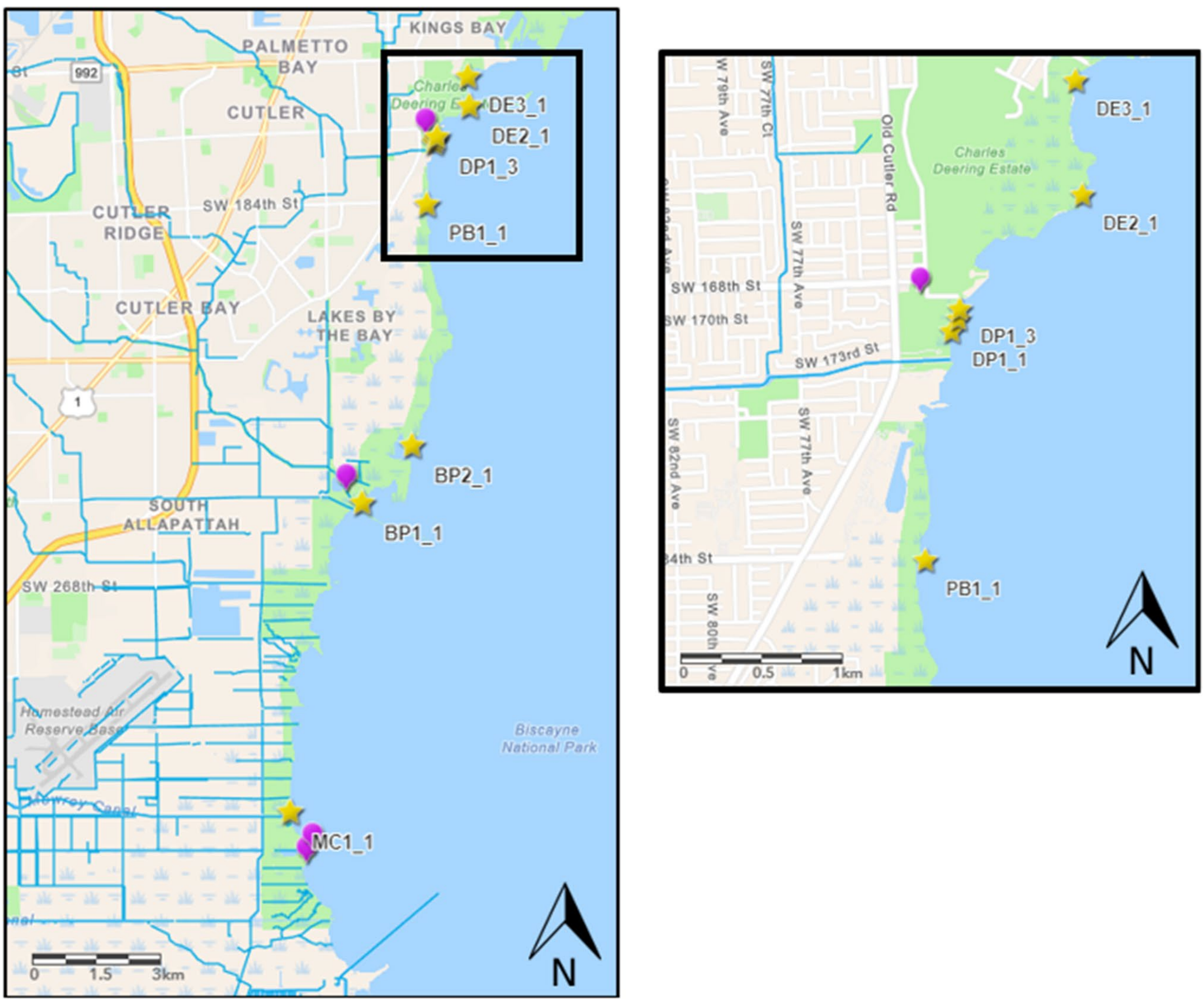

Fig. 1 Transect locations (yellow stars) in relation to canals and major cleanup sites (purple markers). Inset shows a close-up of northern transect locations

at 0 m were excluded from basal area measurements as most of the sample area was open water. GPS coordinates were recorded for each plot. Surveys began in December 2018 and concluded in June 2019. Debris and vegetation were surveyed along each transect once.

Transects were revisited from March to July 2021 and relative elevations were measured to capture changes in slope along each transect. Elevations were recorded every 5 m using an autolevel and two stadia rods (Nikon automatic level AS-2), each starting with a point nearest the coast with a measurable water depth. Front and backshot pairs were recorded from at least two different positions to ensure accuracy ± 2 mm. Referencing the predicted water height for the date and time that water depth was measured during the surveys, relative elevations were converted to real surface elevations using the Mean Sea Level (MSL) datum for the Cutler Biscayne Bay tidal station ("Tide Predictions - NOAA Tides & Currents", n.d.).

Statistical Analyses

Due to the nature of the dependent variables (integers) and overdispersion of the data, negative binomial generalized linear regression models (nbGLMs) were used to analyze relationships between plastic abundance and predictor variables. Separate models were fit for total plastics (mesoplastic + macroplastic) and mesoplastics alone. Counts of plastic abundance were each regressed against all independent variables: distance from the shoreline (starting at 0 m), surface elevation (using the Mean Sea Level datum), estimated coverage of prop roots and pneumatophores (%), counts of red and black/white seedlings, and local estimates of basal area.

Regression models were then systematically reduced to significant models (p-value < 0.05) by backwards stepwise regression. For mesoplastics, the nbGLM was also compared to Poisson, hurdle, and zero-inflated models to try to account for the relatively high frequency of zeros (see Supplementary Information). Finally, macroplastics were regressed against mesoplastics in a simple linear regression to determine if the presence of large debris had any relation to the presence of smaller debris. All analyses and graphs were generated using R software version 3.6.2 (R Development Core Team 2019). Negative binomial generalized linear regressions were run using the "glm.nb" function of the MASS package (Venables and Ripley 2002), hurdle and zero-inflated models were run with the "hurdle" and "zeroinfl" functions of the PSCL package (Zeileis et al. 2008; Jackman 2024), and Pseudo-R^2 values and likelihood ratio chi-square tests were calculated using the "nagelkerke" function of the rcompanion package (Mangiafico 2023).

Results

Debris Composition

A total of 1646 debris items were counted. Across all sites, plastic constituted 94.5% of all debris materials surveyed. Because of the negligible percentage of other debris materials, plastic was the only material analyzed further here. In total, 1555 plastic items were counted (an average of 19.7 ± 21.2 items), or 17.1 items per square meter across all sites (78 plots) ranging from 6.20 total items per square meter at BP1_1 to 40.0 total items per square meter at DP1_3. About 75% of all plastic was in the macroplastic class (> 2.5 cm). Figure 2a shows the average plastic density according to size class at each distance, and Figure S1 (Supplementary Information) shows the distribution of total debris at each transect. Most debris was hard plastic in both size categories, whereas film was the second most abundant for macroplastics and third most abundant by a narrow margin in the mesoplastic category (Fig. 2b).

Most items were fragments of unknown origin (57.8%) followed by the second most frequently observed item type, plastic caps and lids (11.1%), and third most observed were food wrappers (7.3%). In terms of intact items, bags were the next most abundant at 6.3% of total plastic debris. Aggregated into similar categories based on likely origin of each intact item, food-related items were the most common (Fig. 3). Bottle caps were not distinguished between beverage or non-beverage containers, nor were plastic bags that were potentially used for emergency water supplies or other less obvious food storage bags cataloged apart from non-beverage/food bags, thus the results of the "food-related" category are an underestimate. A breakdown of the items placed into each aggregated category is provided in the Supplementary Information (Table S1).

Modeling Plastic Abundance with Physical Predictors

Most sites (7 of 9, with the exception of BP1_1 and DE3_1) are characterized by a typical steep increase in slope at the forest edge followed by a more gradual increase until the fringe mangrove surface asymptotes at about Mean High Water (MHW) (Fig. 4a). Deposits of both macro and meso-sized debris are most abundant at the elevation where MHW is reached (between 0 m and 0.25 m; Fig. 4b). The BP1_1 site had extensive downed trees and coarse woody debris, likely causing the abrupt dip in relative elevation around 35 – 55 m. At PB1_1, a shallow creek (~ 60 cm depth a few hours before high

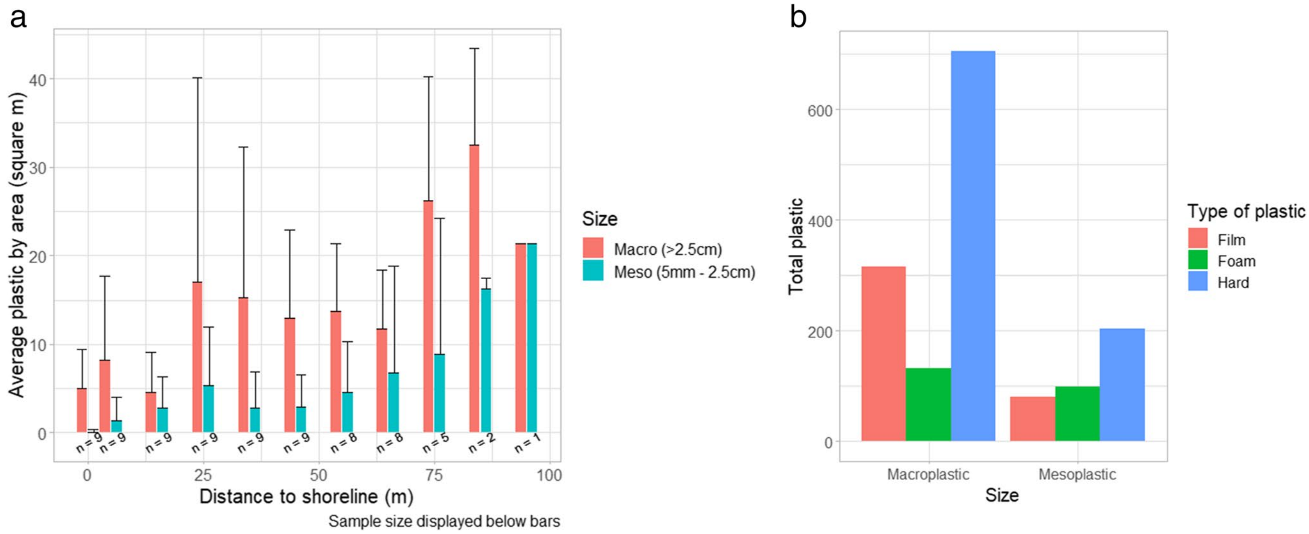

Fig. 2 **a** Average macro- and mesoplastic items at each distance per square meter with upper error bars and **b** Total abundance of plastic debris by type within each size class

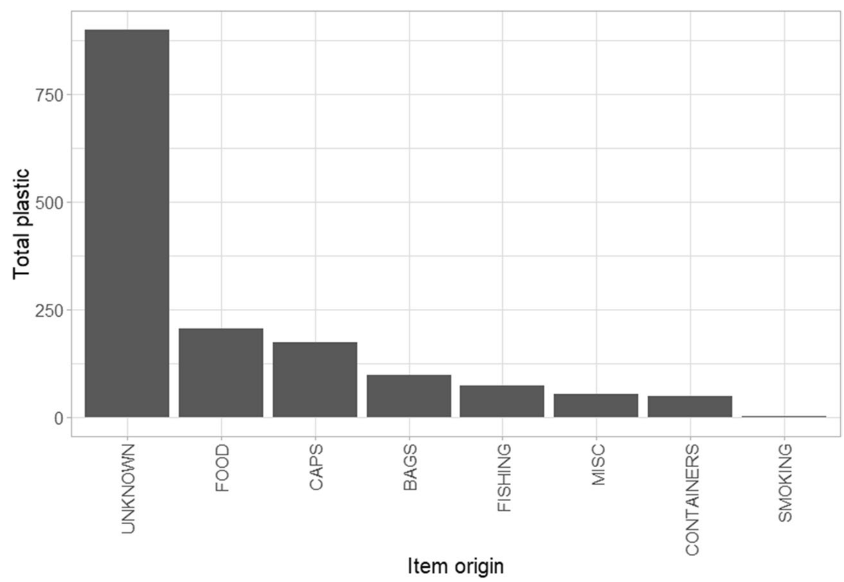

Fig. 3 Total abundance of plastics categorized by item origin

tide) ran parallel to the coastline at 15 m. The DE3_1 site was narrower in mangrove cover than the rest of the sites where the backshore increased rapidly and unevenly in elevation due to the emergence of limestone outcrops, and beyond 45 m the habitat changed to open grasses and shrubs.

Total Plastic

Negative binomial generalized linear models (nbGLM) for predicting total plastic abundance were tested. Graphs of data residuals showed that the residuals were homoscedastic but deviated from a normal distribution (Figure S2). For this reason, the model results cannot be extrapolated to the entire Biscayne Bay shoreline and must be interpreted within the bounds of the study area. The variables in the reduced model shown in Eq. 1 (Distance = distance from shoreline, BA = Basal area, Red = number of red mangrove seedlings, Prop = prop root coverage, Pneum = pneumatophore coverage) were significant when the other variables were in the model as identified by backwards stepwise regression (p-values < 0.05, Pseudo-$R_{\text{Cragg and Uhler}}{}^{2} = 0.428$). Pseudo-$R^2$ values are used to express the improvement of adding predictors to a regression model over the null model. This measure is relevant for regression models that do not use the ordinary least squares (OLS) method, including negative binomial

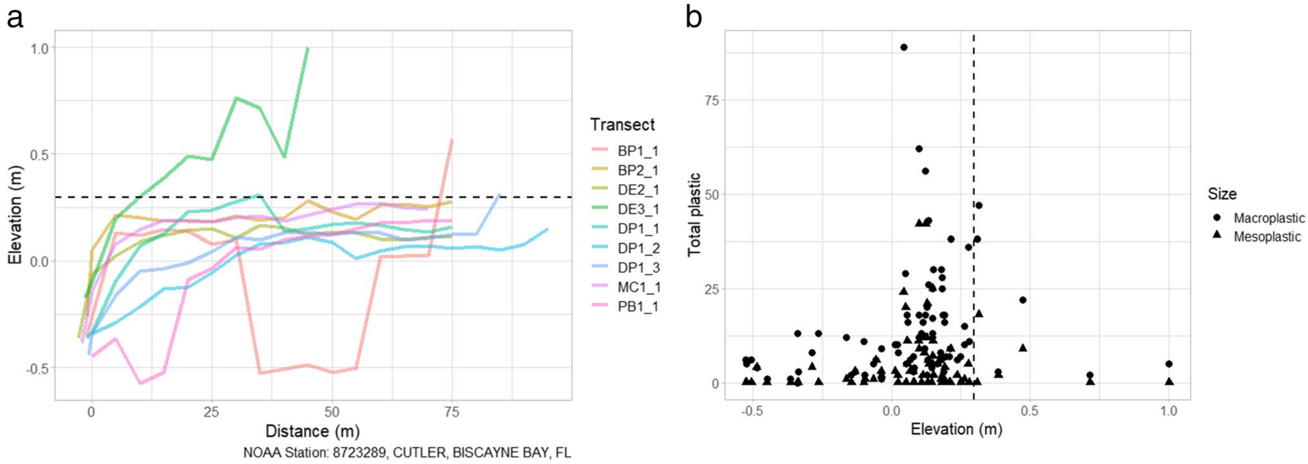

Fig. 4 **a** Elevations of each transect relative to the Mean Sea Level Datum as a function of distance with Mean High Water (MHW) marked by a horizontal dashed line and **b** Abundance of macroplastics and mesoplastics as functions of elevation with Mean High Water (MHW) marked by a vertical dashed line

regressions. However, it should be noted that various equations for calculating pseudo-R^2 values exist ("FAQ: What are pseudo R-squareds?," n.d.), so they should be compared with caution.

$$y = exp(2.49 + 0.0184 \times \mathbf{Distance} + 0.947 \times \sqrt{\boldsymbol{BA}} - 0.0159 \times \mathbf{Prop} - 0.00728 \times \mathbf{Pneum} - 0.0142 \times \mathbf{Red}) + \varepsilon \quad (1)$$

Spearman correlations among all environmental variables included in the model were ≤ 0.6 (Table S2) and VIFs for each regressor were below 2, so multicollinearity was not a concern. Six outliers were identified with the influence.measures() function in R. However, surveys of debris in other habitats have also shown highly variable abundances even along the same shoreline (Moreira et al. 2016; Terzi and Seyhan 2017), so the outliers were retained in the dataset. More details on the fitted model are provided in Table S3.

Total plastic abundance was found to be positively related to distance from shoreline and square-root transformed basal area (Figs. 5a and b). Notably, basal area reaches a peak at about 25 m from the shoreline, corresponding to the point where MHW is reached (Fig. 5c). Total plastic was weakly negatively related to prop root coverage, pneumatophore coverage, and red mangrove seedling abundance (Figs. 5d-f). Red mangrove seedlings and prop roots are most prevalent between 0 and 15 m, followed by an increase in pneumatophores toward the middle of the transects which reflects the appearance of black and white mangroves (Figure S3).

Post-Hoc: Mesoplastic Only

The mesoplastic size class was selected for further analyses because smaller plastics present unique environmental risks compared to larger ones and smaller sizes are known to be the most abundant in the environment (Filella 2015). Therefore, the prevalence and distribution of smaller plastics are of special interest. This size fraction was also surveyed with finite lower and upper size bounds (5 mm – 2.5 cm) which is conducive for comparability with other studies.

A negative binomial model for mesoplastic (Eq. 2) was again fit by backwards stepwise regression. VIFs for all variables were below 2 so multicollinearity was again not an issue. Three outliers were detected with the influence.measures() function but were kept in the model (p-values < 0.05, Pseudo-$R_{\text{Cragg and Uhler}}^2 = 0.292$). Basal area was borderline in significance (p-value = 0.0513) displaying a positive relationship with mesoplastics. Additional statistics are presented in Table S4, and partial plots are shown in Figure S4.

$$y = exp(-0.320 + 0.0344 \times \mathbf{Distance} + 1.88 \times \sqrt{\boldsymbol{BA}} - 0.0291 \times \mathbf{Prop}) + \varepsilon \quad (2)$$

Since mesoplastic abundance is a component of total abundance, the model for mesoplastic is not independent, and therefore the coefficients and p-values of this post-hoc model are interpreted with caution. Deviations from normality and non-heteroscedasticity of residuals (Figure S5) could be due to a small sample size and the fact that meso-sized debris was much less common overall (only 25% of total debris) than the macroplastic fraction, contrary to trends described by Filella (2015).

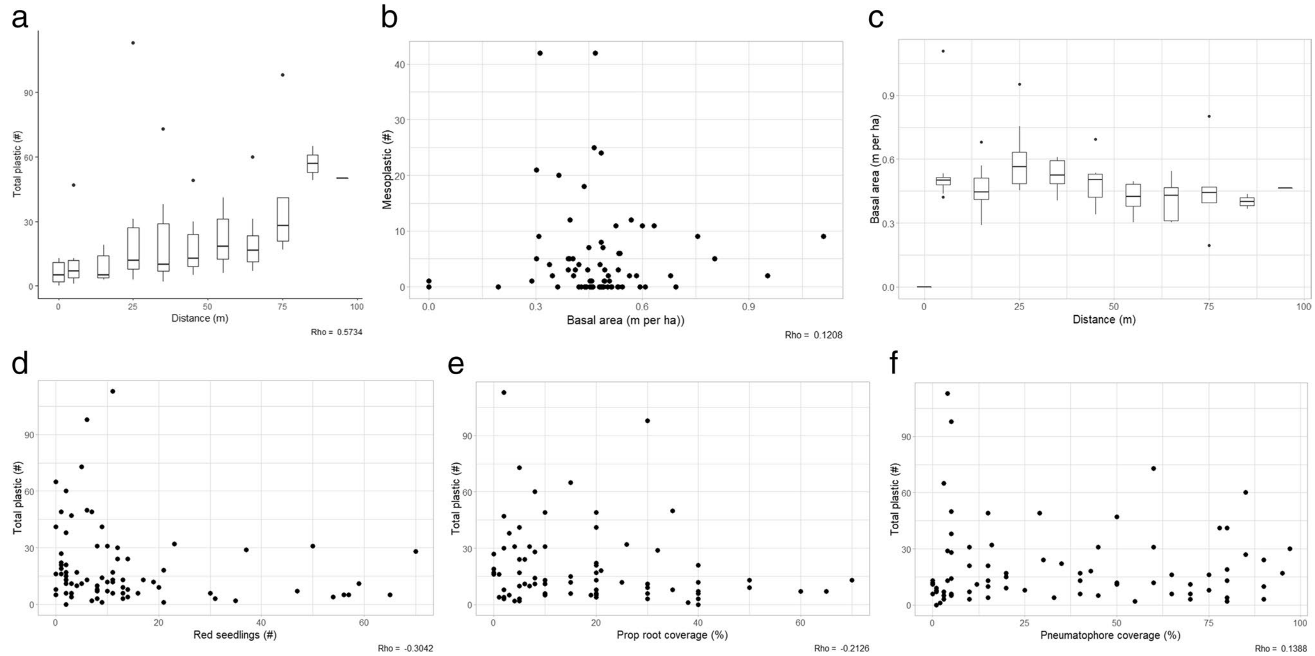

Fig. 5 Partial plots of total plastic as functions of: **a** Distance, **b** Square-root transformed basal area, **d** Red seedlings, **e** Prop root coverage, and **f** Pneumatophore coverage with Spearman correlations, and **c** Basal area as a function of distance

There appears to be a higher frequency of "zero" counts compared to all other counts. To address this issue, various models were fit for mesoplastics using the same significant variables, and diagnostics were compared to the negative binomial ("NB") model (Table S5). Models included Poisson, negative binomial hurdle ("Hurdle-NB"), and two zero-inflated models (one with a negative binomial distribution, "ZINB", and one with a Poisson distribution, "ZIP").

All models except for the Poisson model predicted close to the number of observed zeros, and NB, Hurdle-NB, and ZINB are very similar in model performance based on log-likelihoods. Since this analysis is a post-hoc model stemming from the total plastic model, the significance of the specific model is less important than the general trends. Plastic between 5 mm and 2.5 cm in size appears to respond to distance from the shoreline, basal area, and prop root coverage in similar ways as the total abundance.

Using Macroplastic as a Predictor for Mesoplastic

It may be intuitive that areas that have more large debris will also be littered with more small-sized debris, either because an area is efficient at trapping all sizes of debris, or smaller plastics become locally generated from the fragmentation of larger items. Some studies of plastic debris have found significant correlations between meso- and macro-sized classes of plastics surveyed in the same area (Lee et al. 2013). This suggests that surveys of larger, easier-to-detect macroplastics could be a useful indicator of smaller plastic particles that are more time- and resource-intensive to survey. To explore the relationship between size classes in this study, macroplastic abundance was regressed against mesoplastic abundance. Residuals of the untransformed model violated normality and constant variance assumptions (Figure S6), so variables were square-root transformed to get closer to normal residual distributions. The resultant model is shown in Eq. 3.

$$y = -0.302 + 0.527 \times \mathbf{Macroplastic} + \varepsilon \tag{3}$$

Details on the improvement of the transformed model over the untransformed model are provided in the Supplementary Material (pg. 7). The final linear model showed a weak, significant positive linear relationship ($F = 34.58$, p-value < 0.01, $R^2 = 0.304$) (Fig. 6). The Spearman's coefficient of correlation between meso- and macroplastics was 0.498. Deviations from constant variance assumptions were still significant, and thus the model cannot be used for statistical inference (Figure S7).

Discussion

Composition

It is not surprising that plastic was the most abundant debris material across all sites. Compared to data reported by the Ocean Conservancy International Coastal Cleanup (ICC),

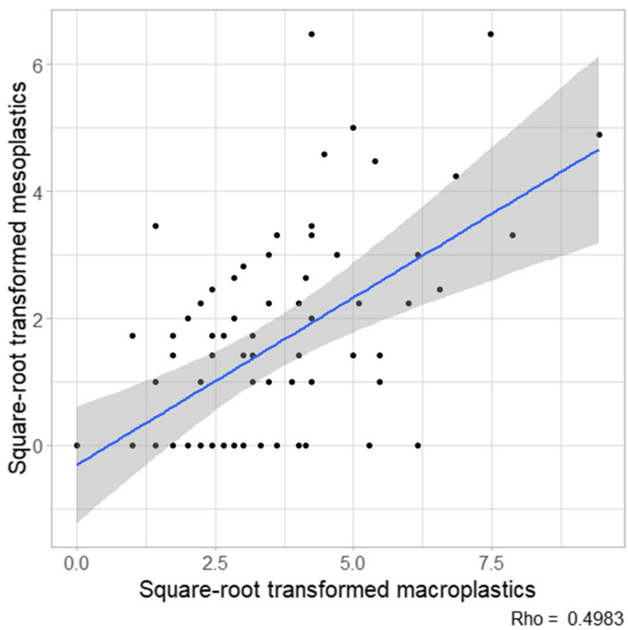

Fig. 6 Counts of mesoplastics plotted against macroplastics with Spearman correlation for the transformed model. Shaded region represents a 99% confidence interval

the prevalence of bottle caps and food wrappers found in the present study aligns with the abundance of these debris items collected in clean-ups across Florida in 2020 (the 2nd and 4th most abundant items by count, respectively; Ocean Conservancy 2021). However, an interesting and unexpected finding was that no cigarette butts were observed in mangrove forests and only a few (13) straws were found across all survey sites, although those two items were the 1st (at ~ 11% of all debris) and 7th (at ~ 4% of all debris) most encountered items in Florida ICC clean-ups in 2020, respectively (Ocean Conservancy 2021). The ICC compiles data from beaches, rivers, lakes, and underwater surveys. This suggests that mangrove habitats may trap a slightly different assemblage of debris compared to other environments. A key difference is in the origin of the debris, e.g. direct littering of cigarette butts on the beach compared to debris from elsewhere washing up in mangrove forests. Therefore, to better protect a variety of vulnerable ecosystems, debris management policies and public outreach campaigns in regions where mangroves are a significant contributor of ecosystem services (such as Florida) should also give special consideration to debris items commonly found in mangrove habitats.

What is apparent from the ICC, the Update to the Retail Bag Report document, and the present survey is that improperly discarded food-related materials are major contributors to marine debris in Florida. Fishing-related debris is also a prevalent category found in Biscayne Bay's mangroves. The Bay is in the jurisdiction of Miami-Dade County (the largest of 67 counties in the State of Florida) where some debris management strategies aimed directly at these common debris categories are currently in effect or have been proposed. Selected examples are summarized in Table 1 below; however, as of the time of writing this article, the three state bills introduced in 2022 have died in various committees. Important to note is that most of these strategies focus on terrestrial (plastic retail bags and films) and marine, offshore (marinas, beaches, coral reefs) environments, but not necessarily other coastal environments like mangrove forests.

The gradient from the urbanized northern part of the Bay to the more isolated, intact mangroves of the southern Bay may be important in predicting how much debris is transported into the mangroves, particularly for locally generated, food-related waste. The proximity of high debris loads closest to human centers is also reported elsewhere (Naidoo et al. 2015; Lourenço et al. 2017; Zhou et al. 2020). However, not all debris is of local origin. Some notable foreign items that were found include small, clear bags labeled from Haiti and Cuba that were later discovered to be water packets that are distributed following disasters or emergencies. There were also Spanish-labeled vinegar bottles that may have been used as cleaning agents on cruise ships. The combination of local and offshore-derived litter highlights the complex interconnectivity and broader socio-economic context of debris deposition in the environment.

Contrary to trends described by Filella (2015) and Lee et al. (2013), macroplastics were much more abundant than mesoplastics within Biscayne Bay's mangrove forests. A lack of significant relationships between most variables and mesoplastics may suggest that these smaller plastics are more mobile and can more easily be removed from the forest, partially explaining the overall low ratio of meso- to macroplastics. Because of the small size of their lower limit (5 mm) and presence of leaf litter in some plots, the potential that some mesoplastics were missed during surveying cannot be excluded. However, undercounting is not expected to be a major factor as only debris on the exposed surface of the forest floor was considered for both size classes. The fact that the majority of surveyed plastics were fragments of unidentified origin was expected as plastic litter becomes degraded by exposure to the elements (Sun et al. 2020). It is impossible from the present study to determine if these fragments were generated from larger items in the mangrove forest, if they entered the system as fragments, or how old those fragments were to begin with.

An interesting consideration raised by Martin et al. (2019) is that the density of debris per unit area in mangroves was similar to that found on beaches around the Red Sea, but the debris items were larger in mangroves. This raises the question of whether mangrove forests are simply more efficient at trapping large debris than smaller debris, or are sheltered conditions in forests preserving intact plastics longer than on beaches? The latter may be supported in that reduced wave

Table 1 Selected examples of local (southeast Florida) and statewide management strategies pertaining to food- and fishing-related debris items

Program or legislation	Summary	Reference
W.R.A.P. (Wrap Recycling Action Plan) Campaign	Since 2019, Florida Dept. of Environmental Protection (FDEP) partnership with the Flexible Film Recycling Group for retail bag & plastic film recycling	("The Wrap Recycling Action Program," n.d.)
Florida Clean Marina and Clean Boater Programs	Voluntary certifications through inspections and/or online courses including but not limited to recycling and proper disposal of boat-related debris	("Clean Boating Programs | Florida Department of Environmental Protection," n.d.)
Southeast Florida's Marine Debris Reporting and Removal Program	Since 2008, regional collaboration between FDEP, Florida Fish and Wildlife Conservation Commission (FWC), and Palm Beach County Reef Rescue (PBCRR) for marine debris reporting & organizing underwater clean-ups	("Southeast Florida Marine Debris Reporting and Removal Program | Florida Department of Environmental Protection," n.d.)
Plastic Free 305 program	Authorizes a voluntary certification program recognizing Miami-Dade County businesses that reduce their use of single-use plastics, packaging, etc	("Plastic Free 305," n.d.)
Coral Gables Green Businesses Certification Program	Voluntary certification program recognizing Coral Gables businesses that reduce their use of single-use plastics, packaging, etc	("City of Coral Gables—Green Business," n.d.)
HB 1145 / SB 1580: Regulation of Single-use Plastic Products	Authorizes certain coastal communities to establish pilot programs to regulate single-use plastic products (Died in Environment, Agriculture & Flooding Subcommittee)	(Regulation of Single-use Plastic Products 2022)
HB 6063 / SB 320: Preemption of Recyclable and Polystyrene Materials	Removes both the preemption of local laws regarding the regulation of auxiliary containers, wrappings, or disposable plastic bags and preemption of local laws regarding the use or sale of polystyrene products to the Department of Agriculture and Consumer Services, etc. (Died in Regulatory Reform Subcommittee)	(Preemption of Recyclable and Polystyrene Materials 2022)
SB 1900 / HB 6113: Preemption to the State	Contains provisions to remove the prohibition of local laws relating to the regulation of auxiliary containers, wrappings, and disposable plastic bags and repeal preemption of local laws regarding the use or sale of polystyrene products to the Department of Agriculture and Consumer Services (Died in Community Affairs)	(Preemption to the State 2022)

energy, lower exposure to UV radiation, and temperature modulation in submerged or buried conditions have been observed to reduce plastic degradation rates in laboratory experiments (Albertsson and Karlsson 1988; Andrady 2011; Sun et al. 2020). Mangrove-associated microbiota have displayed the ability to degrade debris into smaller fragments (Deng et al. 2021), but accumulation of large plastics outpaces this process. Understanding degradation dynamics under wetland conditions and distinguishing the origin of fragmented plastics, whether they are already degraded in circulation or are generated from larger plastics in situ, will provide better understanding of the role of mangrove forests in the storage of debris (Mohamed Nor and Obbard 2014).

Distribution

Few other studies have employed a comparable transect survey. The overall density of debris counted here (17.1 total items/m^2) was less than Yin et al. (2019) who also surveyed an urban mangrove strand, finding 21.9 items/m^2, but more than (Debrot et al. 2013) who reported 11.8 items/m^2 along a gradient from mangrove back vegetation to beach coastline. Luo et al. (2022) found an average of 1.45 ± 0.38 items/m^2 across all transects but also distinguished between seaward zones (0.47 ± 0.09 items/m^2) and landward zones (2.99 ± 0.85 items/m^2). On an areal basis, abundances of plastic debris tend to vary widely within global mangrove forests, ranging from 0.66 ± 0.18 items/m^2 to 78.3 ± 15.1 items/m^2 (Paduani 2020).

Satellite images of the study area exhibit a distinct band of taller trees at around 25 m from shore, matching the observed peak in basal area at this distance (Fig. 5c). Perhaps this band of taller, densely aggregated trees occurs where sediment has built up due to dramatic reduction in water velocity incoming from Biscayne Bay at this first peak in elevation, allowing fine sediments to deposit and begin forming a plateau. The fringe zone (coastal edge) of intertidal wetlands has been documented to produce a self-preserving or positive feedback between reduced water velocity and increased elevation through soil accretion (Robertson et al. 1992; van Proosdij et al. 2006; Mudd et al. 2010). This zone of the greatest basal area might act as a wall that traps debris as the water level falls with the outgoing tide (Ivar do Sul et al. 2014; but see Riascos et al. 2019).

The presence of vegetative structures in the understory was hypothesized to trap more debris than areas of bare forest floor, and some plastics were observed to be strewn over or wrapped around vegetation, particularly between 0 and 25 m where prop roots and red seedlings are the most prevalent (Figure S3). However, in contrast to other authors who found that debris abundance was positively correlated to pneumatophores (Govender et al. 2020) and prop roots (Cordeiro and Costa 2010), the relationship of total plastic with these structures as well as the number of red mangrove seedlings was less clear in the present study. Vegetation interacts with elevation, distance from shoreline, and asymmetrical tidal flows in wetlands such that their individual effects on plastic distribution may be inseparable. When considering other conditions along the distance gradient, understory vegetation may indirectly reinforce the overall debris-trapping effect of the basal area “wall” near the forest edge.

Around 25 m from the shoreline, elevation asymptotes between 0 m and 0.25 m above MSL where MHW is reached (Fig. 4a) which corresponds to the elevation at which debris was most abundant (Fig. 4b). Debris accumulation between MSL and MHW would be expected in the case of debris stranding, similar to that on beaches (Vermeiren et al. 2016). However, the nonsignificance of the elevation variable in both models and continuous increase in debris beyond 25 m indicates that other factors captured by the distance gradient result in accumulation. In wetlands, several properties like water depth and water velocity vary with distance from the shoreline and thus location along this gradient may be important in determining plastic distribution (Mariotti and Fagherazzi 2011; van Proosdij et al. 2006). As the ebb tide drains from the forest, debris brought in by the flood tide may settle where it is too far to get pulled back out of the forest, whereas constant tidal flushing at the mangrove fringe may wash away coastal debris.

Combined with the effect of vegetation along transects, the positive correlation between plastic abundance and distance into the interior forest suggests that these mangrove forests act as effective traps for plastic pollution. Other studies have also identified mangrove forests as plastic debris sinks (Govender et al. 2020; Luo et al. 2021; Luo et al. 2022; Riascos et al. 2019). Martin et al. (2019) found positive relationships between plastic abundance, tree density, and distance into the forest from the coast where debris is unlikely to be recirculated without a massive perturbation. Other forest properties are also being investigated for their effects on plastic accumulation. For example, the abundance of microplastics captured on the surface of mangrove leaves has been shown to vary depending on the distance from shore and the tree’s position in the water column (i.e., submerged vs. non-submerged) (Li et al. 2022). Although complex interactions on the forest floor constrain our ability to address outstanding questions regarding the role of different vegetation structures among studies, overall, dynamic interactions between vegetation and tidal action in the transitional zone of wetlands ultimately result in macroplastic debris accumulation.

The present data are a snapshot in time rather than a reflection of temporal or larger geographic patterns. Other variables that may also be important in these models include debris density and/or volume, plastic polymer type, wind and tidal current direction and velocity, and hydroperiod along each transect. Data for these variables were not available due to time constraints on field sampling (restricted to the duration of low tide and the logistics of sampling in mangrove forests), and tidal/wind current direction and velocity were not available at the scale and locations necessary for this study. Therefore, there are limitations in scaling up these data, and application of the models to the entire region would require additional spatial coverage. A lack of unvegetated wetlands like mudflats in Biscayne Bay precludes direct comparison of these mangrove forests with intertidal "control" habitats. Comparison with adjacent beaches could help to distinguish the role of vegetation from the distance parameter; however, additional factors of direct human disturbance and sediment type would need to be considered. Even considering the limitations of this study, vegetation and other physical parameters tested here may be useful for scaling up estimates of stranded plastic debris in mangrove forests. Improved regional, hydrologic models could also benefit future accumulation studies and, in turn, management of accumulation hot spots in this area as has been done for other water bodies (Critchell and Lambrechts 2016; Isobe et al. 2014; Krelling et al. 2017).

Conclusion

Debris, particularly plastics, was prevalent at all surveyed sites, highlighting the ubiquity of this material. After fragments, plastic food wrappers and bags were the most common debris items, which differed from the ICC's beach cleanup data. With regards to plastic abundance, total plastic and mesoplastic showed weak, positive relationships with distance from the shoreline and basal area (although the latter was borderline in significance for mesoplastics) and relationships with understory vegetation were less clear. Additionally, mesoplastics could be explained based on the abundance of macroplastics by a significant but weak positive linear relationship. Complex interactions along the distance gradient result in increased debris accumulation in the interior forest, suggesting that mangrove forests may be acting as plastic debris sinks (Ivar do Sul et al. 2014; Zhang 2017; Luo et al. 2022) similar to their ability to sequester other pollutants from upstream waters and prevent their deposition into estuaries (Nguyễn et al. 2020).

Mangrove cleanups, while relatively rare, are restricted to the immediate proximity of the shore, and this study provides evidence that the amount of debris collected in these cleanups underestimates how much is actually present in coastal forests due to its spatial variation. Because backshore habitats and intertidal wetlands are likely to retain plastic (Brennan et al. 2018; Olivelli et al. 2020), the loss of these ecosystems to human development, "coastal squeeze" inundation due to sea level rise (Willemsen et al. 2016), and erosion could release significant amounts of plastic into recirculation (Martin et al. 2020; also see Andriolo and Gonçalves 2022). Even in the short-term, the overwhelming prevalence of plastic in the mangrove forests of Biscayne Bay may suggest broader impacts of plastic pollution on water quality in the Bay, as a source of ingested plastics for humans and native fauna, or other ecological impacts such as alteration of soil properties and plant growth (Viehman et al. 2011; Paduani 2020). The ecological, economic, and social dependence of South Florida on Biscayne Bay warrants an integrated plastic debris monitoring program to ensure the health of mangrove wetlands throughout the trophic levels (Luo et al. 2022).

Clean-ups are valuable tools for engaging the community and local governments, and they could form the basis of a formal citizen science plastic monitoring program to build a long-term dataset of plastic pollution in Biscayne Bay (see Miami Plastic Patrol program; Paduani 2021) and elsewhere. However, monitoring and 'damage control' strategies are only one part of the solution to marine debris. Targeting strategic corridors of plastic pollution, such as coastal wetlands, and specific infrastructure like stormwater outfalls and canals is necessary for addressing local debris. In this way, the local "plastic budget", i.e., the amount and transport of plastic pollution into and out of a watershed, could be quantified (Law et al. 2020; Hoellein and Rochman 2021; also see Drummond et al. 2022). A combination of proactive and innovative measures, such as voluntary programs and regulatory mechanisms to address different forms and sources of plastic wastes as hazardous materials (Rochman et al. 2013), should complement ongoing monitoring of plastic debris as a commonly surveyed water quality metric in any coastal ecosystem.

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Data Availability The datasets and R script used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

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