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Microplastic ingestion by coral as a function of the interaction between calyx and microplastic size

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Abstract

Coral reefs have been heavily impacted by anthropogenic stressors, such as global warming, ocean acidification, sedimentation, and nutrients. Recently, microplastics (MP) have emerged as another potential stressor that may also cause adverse impacts to coral. MP ingestion by scleractinian coral among four species, *Acropora cervicornis*, *Montastraea cavernosa*, *Orbicella faveolata*, and *Pseudodiploria clivosa,* was used to identify the relationship between calyx and MP size as it pertains to active coral ingestion. A range of MP sizes (0.231–2.60 mm) were offered to the coral species across a wide range of calyx sizes (1.33–4.84 mm). Laboratory data showed that as the mean calyx size increased, so too did the mean percent of ingestion with increasing MP size. From laboratory data, a logistic model was developed to extrapolate the range of MP sizes that can be actively ingested by coral species based on calyx size. The data and model presented here offer the first predictive approach that can be used to determine the range of MP sizes that have a high likelihood of being actively ingested by coral of various sizes, thus offering insight to possible impacts on scleractinian coral.

Graphical Abstract

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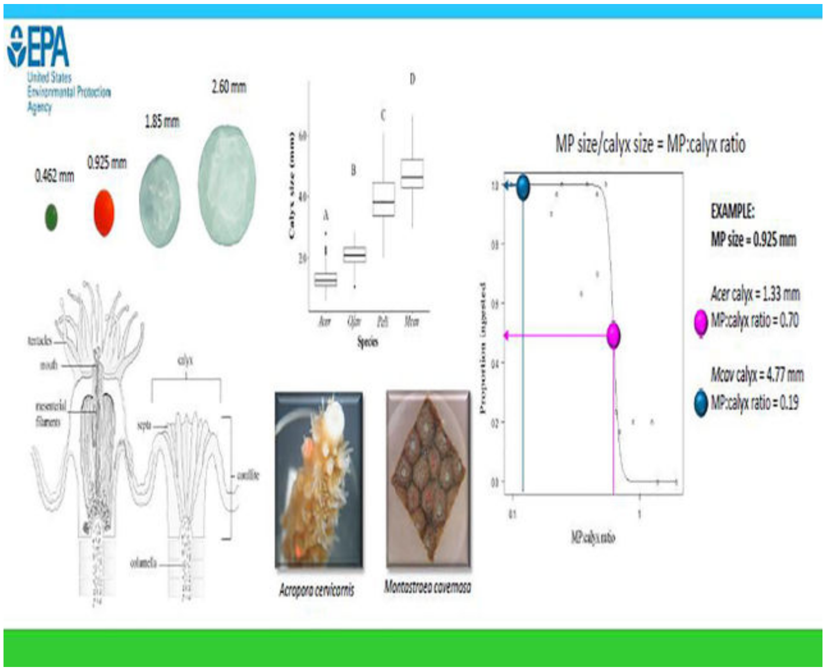
CRediT (Contributor Roles Taxonomy) author statement

Cheryl Hankins – Conceptualization, methodology, validation, investigation, writing – original draft Sandy Raimondo – Methodology, software, validation, formal analysis, writing – review & editing Danielle Lasseigne – Software, formal analysis, investigation, writing – review & editing



Keywords

microplastic; coral; polyp; ingestion; model

1. Introduction

Plastic pollution in the environment is an emerging concern due to its ubiquity and its potential to adversely impact wildlife (Rochman et al., 2016, Law, 2017, Li et al., 2020, Huang et al. 2021a). In 2016, 335 million tons of plastic were produced (Plastics Europe, 2017) and upwards of 23 million metric tons entered aquatic habitats that year (Borelle et al., 2020). In the marine environment, microplastics (MP) (plastics <5 mm) have been found in nearly all habitats, including polar ice and deep-sea habitats (Jamieson et al., 2019, Kanhai et al., 2019, Kelly et al., 2020, Tekman et al., 2020). As MPs enter the marine environment, their hydrophobic surface attracts microbes that may colonize their surface resulting in a reduction of buoyancy and settling in the water column (Zettler et al., 2013, Kaiser et al., 2017, Wright et al., 2020). Sessile benthic organisms, such as coral, live attached to hardbottom substrata and are at risk of exposure to microplastics and the microbes attached to their surface.

Coral reef habitats are an invaluable resource that provide cultural value and shoreline protection as well as economic benefits from commercial and recreational fisheries, pharmacology, and tourism. The cornerstone of these reef habitats are the scleractinian corals. The skeletons of these coral create a three-dimensional structure that provides habitat for many other reef taxa (Graham and Nash, 2012). The energy needed by coral for growth is obtained from their endosymbiotic, photosynthesizing algae along with exogenous feeding. With respect to their exogenous feeding, coral are suspension feeders, ingesting plankton, both actively and passively, that are entrapped on their tentacles (Figure 1). In addition to plankton, corals can also ingest microplastics (Hall et al. 2015, Hankins et al., 2018, Rotjan et al., 2019, Corona et al., 2020, Hankins et al., 2021), with smaller pieces likely being inadvertently consumed (Hankins et al., 2018, Axworthy and Padilla-Gamiño, 2019). Ingested plastics may block the gastrovascular cavity of the coral polyp leaving the polyp feeling satiated or may prevent feeding on nutritious food sources, as has been seen in other taxa (McCauley and Bjornal, 1999, Xu et al., 2017, Egbeocha et al., 2018, Ory et al. 2018, de Barros et al., 2020). While large percentages of ingested MPs (64–92%) will likely be egested (Allen et al., 2017, Hankins et al., 2018, Hankins et al., 2021) by coral polyps, microplastic exposure has been shown to impact feeding, stress response, immune system, coral-host signaling, zooxanthellae photosynthetic performance, growth, and can cause bleaching and tissue necrosis (Chapron et al., 2018, Tang et al., 2018, Axworthy and Padilla-Gamiño, 2019, Reichert et al., 2019, Syakti et al., 2019, Huang et al., 2021, Lanctôt et al., 2020, Hankins et al., 2021, Huang et al. 2021b).

Ingested MPs also have the potential to expose coral to chemical contaminants and disease. Chemicals may include those that are used in plastic production or adsorb to MPs from surrounding water (OECD, 2004, Rochman et al., 2013, Bakir et al., 2014, Mendoza and Jones, 2015). Plastic additives, such as phthalates, are a known endocrine disruptor (Lithner et al., 2011, Hermabessiere et al., 2017) and have been found in coral tissue (Saliu et al., 2019, Montano et al., 2020). Contaminants including polychlorinated biphenyls (PCBs), organochlorines, and metals have all been found on macro- and microplastic surfaces (Mato et al., 2001, Ogata et al., 2009, Ashton et al., 2010, Holmes et at., 2012, Van et al., 2012, Rochman et al., 2013) and can cause a variety of harmful effects in coral such as mortality, reduced photosynthesis, bleaching, and growth declines (Mitchelmore et al., 2007, Bielmyer et al., 2010, Biscéré et al., 2015). Additionally, pathogens such as *Vibrio* spp. and *Hallofoliculina*, have been found on microplastics (Zettler et al., 2013, Goldstein et al., 2014 Kirstein et al., 2016, Li et al., 2019). Two species of *Vibrio*, *V. coralliilyticus* and *V. shiloi*, have been associated with coral diseases (Kushmaro et al., 1996, Ben-Haim et al., 2003). The ciliate *Hallofoliculina* has been linked to skeletal eroding band disease (Antonius and Lispcomb, 2000).

Whether through physical or toxicological mechanisms, there is mounting evidence that microplastics have the potential to negatively affect corals with many studies showing species-specific responses (Mouchi et al. 2019, Reichert et al. 2019, Hierl et al. 2021, Mendrik et al. 2021). However, plastic ingestion has been predicted based on allometric measures such as buccal cavity size and body size (Fueser et al. 2019, Jâms et al. 2020). Here, we hypothesize that active coral microplastic ingestion maybe a function of both MP and calyx size, with calyces being an indicative measure of polyp size. Four coral species, *Acropora cervicornis*, *Montastraea cavernosa*, *Orbicella faveolata*, and *Pseudodiploria clivosa*, were selected based on the varying polyp sizes (Hankins et al., 2018, Hankins et al., 2021). Additionally, *A. cervicornis* and *O. faveolata* were chosen due to their importance as threatened species under the United States' Endangered Species Act which protects imperiled species. The objective of this study was to use ingestion observations from laboratory studies for these four coral species to explore relationships between calyx (i.e., polyp size) and microplastic particle size to improve our understanding of MP ingestion behavior and biomechanics, as well as offer a predictive tool to assess potential effects of MPs on coral.

2. Material and Methods

Coral morphometric characteristics and ingestion behaviors were measured during laboratory-based experiments using microplastic spheres (MP) of various sizes in four Caribbean coral species: *Monstastraea cavernosa*, *Orbicella faveolata*, *Acropora cervicornis,* and *Pseudodiploria clivosa*. Experimental designs for ingestion experiments are described in detail in Hankins et al. (2018, 2021). In brief, these ingestion experiments were conducted in a 170 L tank containing 120 experimental chambers, made from 5.1 cm (2”) diameter polyvinyl chloride (PVC) pipe cut into ~5 cm lengths. The bottom of the experimental chambers was comprised of 118 µm Nitex® mesh, which was also attached around the circumference of the top of the chamber to ensure MPs remained within each chamber. Experimental chambers contained one fragment. *Monstastraea cavernosa*, *O. faveolata*, and *P. clivosa* fragments (~4 cm^2) sat freely on the bottom of their chamber. *Acropora cervicornis* fragments (3–4 cm length) were glued onto a 2.5 cm diameter polycarbonate disc so that the fragments were oriented vertically in the chamber.

2.1 Calyx size

Each coral polyp resides in its own calyx (Figure 1). To minimize measurement variation and stress to the organism, calyces from deceased laboratory colonies were measured as a proxy for polyp size. The diameter of 100 calyces from each species were measured with dial calipers to the nearest 0.02 mm. Skeletal fragments from the experiments, which ranged in size from 2.5–4.0 cm^2, were used to measure calyces for *M. cavernosa, O. faveolata,* and *P. clivosa*; with five calyces measured from each of 20 fragments for each species. Three large skeletal colonies (approx. 25 cm length × 20 cm width) of *A. cervicornis* from previously deceased culture stock colonies were used to measure calyces, with approximately 33 calyces measured from each colony. These measurements were limited to the calyces of *A. cervicornis* within 12 cm of the apical ends of the branches as these were target areas for fragments used in the Hankins et al. (2018) ingestion experiment. Calyces for *A. cervicornis*, *O. faveolata*, and *M. cavernosa* were measured at their widest diameter. Since the calyces of *P. clivosa* are not prominent and highly irregular, the length of the longest septum was measured to infer calyx size (Figure 1). The distribution of calyx diameters of the four species were assessed for normality using Shapiro test, and the average calyx size among coral species was compared using one-way analysis of variance. Tukey’s post-hoc test was used to determine which groups were significantly different from each other.

2.2 Microplastic ingestion

Five size classes of virgin, fluorescent MP spheres (obtained from Cospheric®) were offered to coral fragments (N=10 fragments per species for each of five MP sphere size classes). All spheres were polyethene and had densities of 1.002 ± 0.0006 g cc^{-1}. The MP median size for each size class used to define treatment levels and were: (1) 0.231 mm (range = 0.212–0.250), (2) 0.462 (range = 0.425–0.500), (3) 0.925 mm (range = 0.850–1.000), (4) 1.85 mm (range = 1.7–2.0), (5) 2.6 mm (range = 2.4–2.8), and (6) a control group not exposed to MPs. To mimic chemical stimuli in coral that may feed predominantly at night, food (5–50 μm Golden Pearls® Brine Shrimp Direct, Ogden, UT) was added to seawater at a concentration of 156 mg/100 mL. The food/seawater mixture was used to apply three MPs of the same size class to a coral fragment's polyps within the experimental chamber using a separate 1 mL transfer pipette for each fragment. One MP sphere was placed in contact with a tentacle from one polyp, such that three polyps from each fragment were fed a single MP each. Each fragment was visually monitored for up to 20 minutes to observe ingestion. MPs not ingested after 20 minutes were removed from the chamber, as described in Hankins et al. (2018, 2021). The proportion of MPs ingested by each fragment was determined from the individual MPs offered to individual polyps of the coral fragment. The control group was supplied with food in the same manner but without MP application.

2.3 Calyx and microplastic size interaction

Preliminary comparison of the proportion of MPs of size classes that were ingested by the four coral species indicated that the probability of MP ingestion may be influenced by an interaction between calyx and MP size. To visualize this relationship, we fit the data to 3-dimensional (3D) polynomial models in which the proportion of MP ingested (dependent variable) was a function of MP size (independent variable 1), and calyx size (independent variable 2). Since we did not have direct calyx size measurements for the specific polyps that ingested MPs in the laboratory experiments, each observation of polyp ingestion was associated with a calyx size that was randomly sampled without replacement from those measured on laboratory skeletons of the respective species. This assumes that: (1) the size of each calyx used in the experiments falls within the measured ranges for each species, and (2) calyx measurement error is normally distributed and approximated by the standard deviation of the measured skeletons.

Using data for all MP size categories, the proportion of MPs ingested by all species displayed a bimodal distribution with only 23 out of 200 observations exhibiting a partial response (0.33 or 0.66, i.e. ingestion of 1 (33%) or 2 (66%) of the three MPs applied) and an even distribution of 0s (N=88) and 1s (N=89). These data were fit to polynomial models of the general form:

$$P_{\text{ingest}} = \text{poly}\left(D_{\text{calyx},} i\right) + \text{poly}\left(D_{\text{MP}}, j\right) + aD_{\text{calyx}} \times D_{\text{MP}} \qquad \text{(EQ 1)}$$

Where P_{ingest} is the proportion of MPs ingested, D_{calyx} and D_{MP} are the diameters of the calyx and MP, respectively, i and j represent the order of the polynomial and ranged from 1 to 4, and $a = 0$ to exclude or $a = 1$ to include an interaction between the two variables. A total of 64 polynomial models were fit to the data using the generalized linear model and poly functions in R studio (version 1.3.959). Of these 64 models, one subset of 32 models was fit using all data which assumed a normal distribution of errors and used the Gaussian family function. The second subset of 32 models excluded partial responses and were fit to a logistic function using a bimodal distribution. Within each subset of 32 models, 16 included the interaction term $D_{\text{calyx}} \times D_{\text{MP}}$ and 16 excluded this interaction (a = 0). The 16 models fit within or with the calyx-MP interaction were polynomials that varied by order, *i*. We set the highest order at 4 based on preliminary visual inspection of the data. The 32 models from each data subset (with or without partial responses) were compared using Akaike Information Criterion (AIC) to identify the best fit model for each data subset, which was then plotted to graphically represent the data in three dimensions.

There were no MPs ingested in the 0.231 mm size category by any coral species. While the models fit from all MP size ranges described above interpolates an increase in proportion ingested of MP spheres between 0.231 and 0.462 mm, it may overfit the data across the modeling space despite low AICs. To view the relationship of ingestion more clearly within the range of MP sizes that were actively ingested, we ran a second set of the 64 models described above using only the data for MP > 0.231 mm.

2.4 Potential ingestion of MP size ranges by coral

To identify the MP size range in which coral of a given calyx size are highly likely to ingest MPs, MP:calyx size ratio was first determined for each species and MP size category. For this analysis, the median size of each MP size category was divided by the average calyx size (N=100) of each coral species such that each coral species and MP size class was reduced to one ratio value. For example, all observations for which *A. cervicornis* (average calyx size = 1.33 mm) was offered an 0.462 mm MP were represented by the MP:calyx size the ratio of 0.35 (0.462 mm/1.33 mm). Similarly, all observations for which *M. cavernosa* (average calyx size 4.77 mm) were offered MPs of the median size 2.60 mm were represented by the ratio 0.54, and so on. Including all species and MP size classes, the MP:calyx size ratios ranged from 0.05 – 1.96. Excluding the smallest MP size class (0.231 mm), the MP:calyx size ratios ranged from 0.1 – 1.96. Visual inspection of the data and results of the 3D modeling described above suggested that lack of ingestion by any coral species observed with the MP 0.231 mm size class were independent of coral size and were excluded from the model fit to these data.

A logistic model with the lower and upper bounds set at 0 and 1, respectively, was fit to the data to describe the relationship between the average proportion of MPs ingested (dependent variable) and the MP:calyx size ratio (independent variable), such that:

$$P_{ingest} = \frac{1}{1 + exp^{b(\log(x) - e)}} \qquad \text{(EQ 2)}$$

Where P_{ingest} is the proportion of MPs ingested at any MP:calyx size ratio, x. The variable e is the model inflection point associated with the 50th percentile and b is the slope of the curve. Using this model, we identify size ranges in which coral of known calyx size are most likely or unlikely to ingest MP of a particular size.

3. Results

3.1 Calyx size

Coral calyx size was significantly different among all species (ANOVA, df=3, F=760.7, $p<0.00$) (Figure 2), with *A. cervicornis* having the smallest mean calyx (1.33 mm, SD=0.39) and *M. cavernosa* having the largest mean calyx (4.77 mm, SD=0.73). The mean calyx size for *O. faveolata* and *P. clivosa* was 2.08 mm (SD=0.36) and 3.96 mm (SD=0.89), respectively.

3.2 Microplastic Ingestion

Of the five MP size classes provided to coral fragments, none of the species ingested the 0.231 mm size class. Proportion of MPs ingested by the different coral species suggests a relationship between calyx size and MP size (Table 1). The coral species with the smallest average calyx size, *A. cervicornis,* did not ingest the two largest size classes, 1.85 mm or 2.60 mm, while the largest coral (*M. cavernosa*) ingested ≥90% of all MP size classes >0.231mm. The two intermediate coral species displayed intermediate ingestion rates that further demonstrate an increasing proportion of larger MPs ingested with increasing calyx size (Table 1).

3.3 Calyx and microplastic size interaction

Of the 64 models fit to the dataset that included all the MP sizes with (N=32) and without (N=32) partial responses, the best fit model based on AIC was a fourth-order polynomial fit to the Gaussian family of the form: $P_{ingest} = -2.58 + 0.25\ D_{calyx} + 12.99\ D_{MP} - 0.03\ D_{calyx}^2 - 17.98\ D_{MP}^2 + 9.16\ D_{MP}^3 - 1.56\ D_{MP}^4 + 0.09\ D_{calyx} * D_{MP}$ (Figure 3a; $R^2 = .72$, $p < 0.001$, AIC = 35.7). Of the 64 models fit to the data that excluded the smallest MP size of 0.231 mm, the best fit model was a quadratic equation fit to the Gaussian family of the form $P_{ingest} = 0.47 + 0.35\ D_{calyx} - 0.50\ D_{MP} - 0.04\ D_{calyx}^2 + 0.08\ D_{calyx} * D_{MP}$ (Figure 3b; $R^2 = 0.62$, $p < 0.001$, AIC = 56.6). Both models included partial response data and had significant interactions between D_{calyx} and D_{MP}.

3.4 Potential coral ingestion of MP size ranges

The logistic model relating the proportion of MPs ingested to MP:calyx size ratios is depicted in Figure 4. The slope, *b*, was estimated at 18.73 and the variable *e* was 0.62 (EQ 2). In general, and when excluding MP = 0.231 mm, the proportion of MPs ingested decreases with increasing MP:calyx size ratio. This model identifies the upper limit of MP sizes that are ingested by coral of varying sizes at a given rate of ingestion, represented as the proportion of MP ingested, and can be used to determined MP sizes that are likely to be actively ingested by coral of a given size (Table 2). The MP:calyx size ratios for which MPs have a high likelihood of being ingested by a coral polyp are represented by proportion of ingested MP ≥ 0.75. Conversely, MPs have a low likelihood of being ingested by a coral polyp when MP:calyx size ratios are associated with low ingestion rate (proportion ingested = 0.1–0.25).

To demonstrate this utility and estimate upper MP size limits for the species used in the present study, the MP sizes associated with ingestion rates of 0.10, 0.25, 0.50, 0.75, and 0.90 are determined by multiplying the average calyx size for each species by the MP:calyx size ratio estimated for each ingestion rate provided in Table 2. For *A. cervicornis*, the species with the smallest calyx, MPs of ≤ 0.78 mm are highly likely to be actively ingested, where MP > 0.88 mm are unlikely to be ingested. This is supported by the average rate of ingestion for this species listed in Table 1, in which 63% of 0.462 mm MP were ingested and 17% of 0.925 mm MP were ingested. For *M. cavernosa*, Table 3 identifies MP < 2.81

mm with a high likelihood of ingestion, which is demonstrated by ≥90% ingestion of MP 0.462 – 0.260mm for this species (Table 2). Based on the modeled ratios, MPs ≥3.16 mm are unlikely to be ingested by *M. cavernosa*, MPs < 2.98 mm have a moderate likelihood of ingestion, and MPs < 2.81 mm are highly likely to be ingested.

4. Discussion

The results of this study show that the relationship of coral calyx size and MP sizes is an important determinant of potential MP ingestion by coral. The four coral species used in our studies had significantly different calyx sizes and were selected to demonstrate the relationship of coral and MP size across a wide range of calyx sizes. Since coral ingest particulate matter opportunistically, combining species that vary widely in size provides a broader perspective of MP and calyx size interactions; as the species mean calyx size increased, so too did the mean percent of ingestion with increasing MP size (Table 1). The three-dimensional models provide a view of these data as continuous variables, which is more realistic for relationships based on size. The logistic model can be used to estimate the likeliness of an MP size range to be actively ingested by any species of coral within the range of calyx sizes used in this study. The models presented here are caveated by lack of direct measurement of calyces for the polyps used in the study.

Ingestion of MP by coral polyps is analogous to gape size predation seen in many prey-predator interactions for taxa such as fish, whereby ingestion is an opportunistic function of prey size that fits within the predator’s gape. In these cases, smaller prey are more susceptible to a wider range of predation than larger prey, and predators will consume any prey smaller than a maximum size threshold (Sogard, 1997, Urban, 2007). Additionally, there is evidence of allometric relationships between ingested plastic and animal body size when compared across many different taxa (Jâms et al. 2020) as well as within taxa (Fueser at al. 2019). As demonstrated by the results here, coral will actively ingest most microplastic smaller than a maximum size threshold, but not smaller than 0.231 mm. Larger MPs (defined here as >0.925 mm) have less risk of consumption due to the coral’s small mouth gape as shown in *A. cervicornis*, which did not ingest any MPs from the 1.85- or 2.60 mm size classes and had a low likelihood of ingestion compared to the other, larger polyp species tested in this study. While this study demonstrates the maximum MP sizes that would potentially be actively ingested by coral with a particular calyx (i.e., polyp size), there is also a minimum size threshold in which MPs are not actively ingested. The present study identified the 0.231 MP size class as a size that is not actively ingested by any species, however, these data do not specifically identify the lower size threshold at which coral do not ingest MPs. The 3D model presented in Figure 3a interpolates ingestion potential between 0.231 and 0.462 mm; the lower threshold is likely within this size range. Additionally, the lower threshold may be indicative of the MP sizes in which coral passively feed on MPs (Hankins et al., 2018, Axworthy and Padilla-Gamiño, 2019) suggesting that smaller MPs do not elicit a tactile response from the coral tentacles.

Although microplastic ingestion is a function of calyx size for MPs >0.462 mm, MPs could impact corals without being consumed. Corals have been suggested as microplastic “sinks” in the marine environment due to MP adhesion on coral surfaces (Martin et al., 2019, Corona et al., 2020). Martin et al. (2019) investigated MP adhesion on three scleractinian coral species and found that roughly 30% of available MPs attached to the surface in two of the three species. Additionally, Corona et al. (2020) showed that MP adhesion was 40 times greater than ingestion in the mushroom coral, *Danafungia scruposa*. Neither study looked at effects of MP ingestion versus adhesion on coral. Acknowledging that there may be other mechanisms of MP exposure to coral that may cause adverse effects, our study only presents the likelihood of MP ingestion and does not infer impacts.

The models presented here describe MP ingestion potential as a function of the interaction between polyp and MP size. Complex relationships such as these are best visualized in 3-dimensions, but these types of models are at risk of overfitting and are less robust as prediction tools. Additionally, without direct measurements of the individual calyces and MP spheres used in the laboratory studies, we assume a slightly larger measurement error associated with these models. Multiple coral species were combined into one model, because all scleractinian coral have the same anatomy and general feeding behaviors and because phenotypic morphology within a species can vary due to environmental conditions (Foster, 1979, Todd et al., 2002, Erftemeijer et al., 2012). While models are most robust when the measurement error is minimized, the models presented here can describe the interaction of MP and coral polyp size and provide new insights into likelihood of active ingestion of MP by coral. Predictions may be altered with a more continuous distribution design rather than the one conducted in this study that resulted in four categories (0, 33, 66, and 100%). Additionally, it should be noted that some corals are opportunist feeders, therefore, ingestion of prey is often influenced by prey density and flow speeds (Helmuth and Sebens 1993, Sebens et al., 1998, Ferrier-Pages et al., 2003). In this study, we excluded these variables in the application of MPs; therefore, the likelihood of ingestion in field applications should also consider environmental parameters.

Some of the impacts of MPs on coral are species-specific (Mouchi et al., 2019, Reichert et al., 2019, Mendrik et al., 2021), however it is unknown if the responses observed may be attributed to species specificity or a response of the coral based the physical structure of its polyp size. As previously mentioned, without measurements directly from the coral used in experiments or from similar growing conditions it is difficult to discern any potential relationships between polyp size and response as there are slight morphological differences within species exposed to different environmental conditions (Foster, 1979, Todd et al., 2002, Erftemeijer et al., 2012). Generalized responses for active ingestion presented in this study are important to understand active coral MP ingestion as it relates to coral polyp size. These relationships presented here can streamline future research towards improved prevention and/or targeted mitigation.

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Highlights

- Ingestion of microplastic different for coral species with different calyx sizes
- Calyx size and microplastic ingestion data were used to develop model for active ingestion
- Ingestion of microplastics (>0.462 mm) by coral is a function of calyx and microplastic sizes

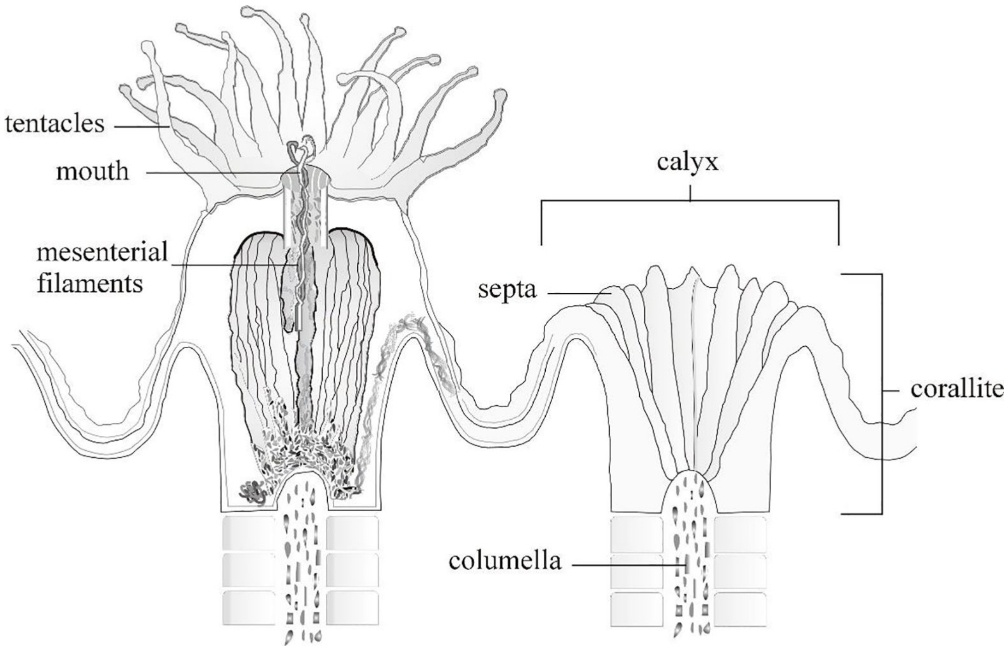

Figure 1.

Basic anatomy of a coral showing an extended coral polyp (left) and its skeletal structure (right). From: Goreau et al., 1979, modified by C. Hankins.

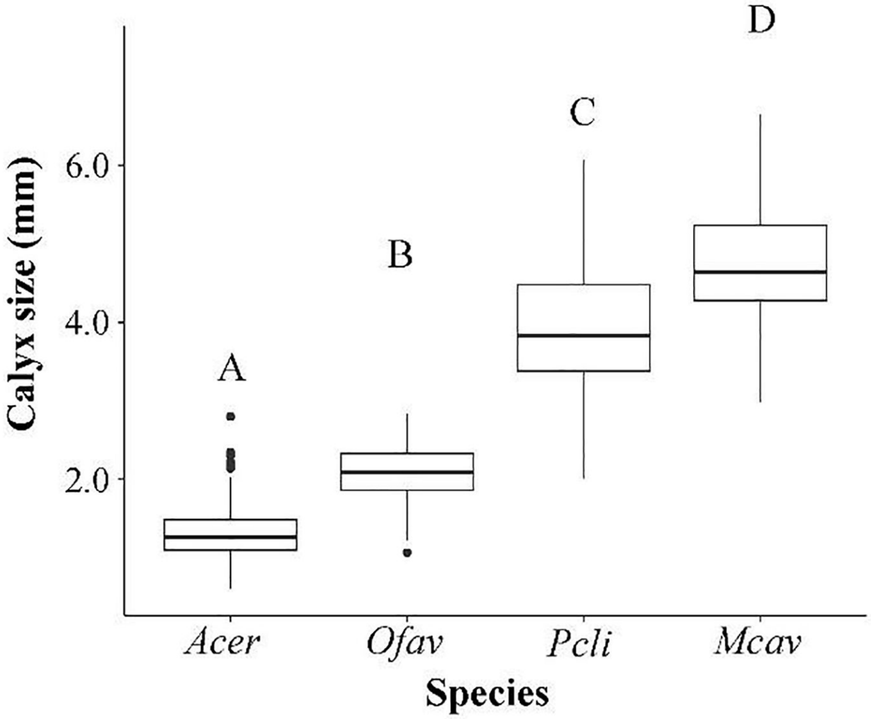

Figure 2.

Mean calyx size for *Acropora cervicornis*, *Orbicella faveolata*, *Pseudodiploria clivosa*, and *Montastraea cavernosa*. Letters indicate significant difference between species (Tukey's post hoc).

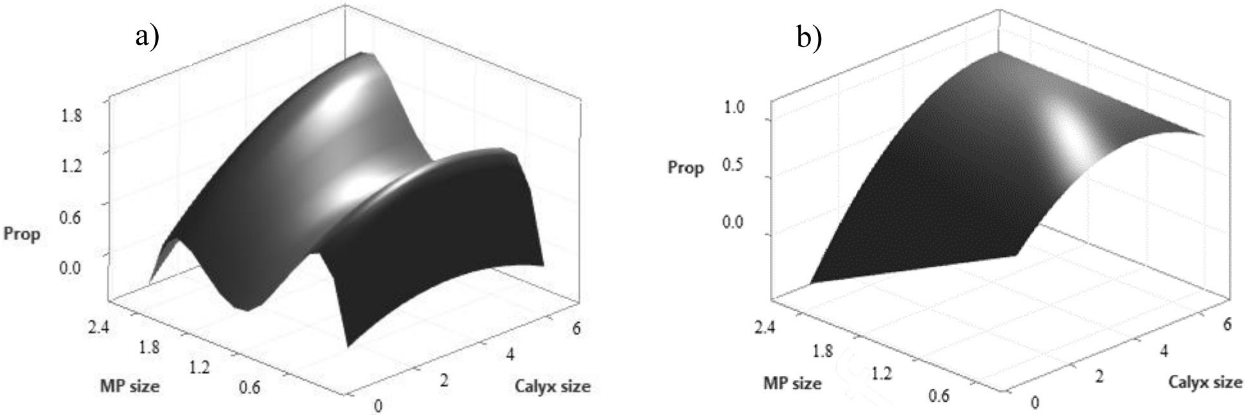

Figure 3.

Approximated relationship between calyx size and microplastic (MP) size for proportion of MP (Prop) ingested for (a) all MP size classes 0.231–2.60 mm and (b) MP sizes classes 0.462–2.60 mm.

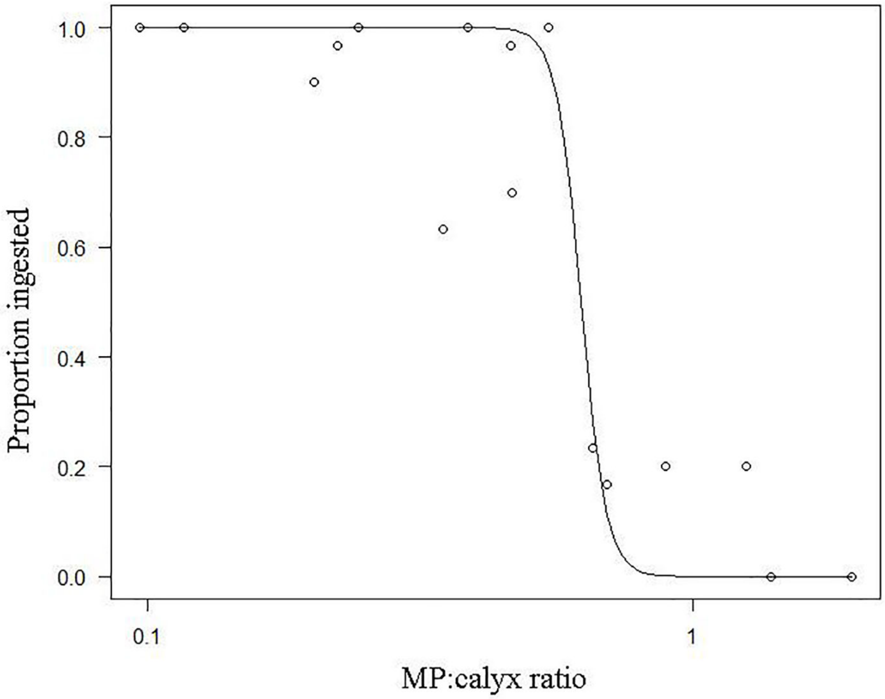

Figure 4.

Relationship of the proportion of microbeads ingested and MP:calyx size ratios.

Table 1.

Mean percent of microplastics (MPs) ingested for each species at five microplastic size classes and total mean percent ingested across all size classes. 10 fragments/species/MP size class, *n* = 3 MPs/size MP class/fragment

Species	**0.231 mm**	**0.462 mm**	**0.925 mm**	**1.85 mm**	**2.60 mm**	**Total MPs**
A. cervicornis	0% (SD=0.0)	63.30% (SD=39.9)	16.70% (SD=28.3)	0% (SD=0.0)	0% (SD=0.0)	16.0% (SD=32.5)
O. faveolata	0% (SD=0.0)	96.7% (SD=10.5)	96.7% (SD=10.5)	20.0% (SD=32.2)	20.0% (SD=23.3)	46.7% (SD=45.7)
P. clivosa	0% (SD=0.0)	100% (SD=0.0)	100% (SD=0.0)	70.00% (SD=39.9)	23.30% (SD=35.3)	58.7% (SD=46.9)
M. cavernosa	0% (SD=0.0)	100% (SD=0.0)	90.0% (SD=31.6)	00% (SD=0.0)	100% (SD=0.0)	78.0% (SD=41.9)

Table 2.

MP:calyx size ratios and 95% confidence intervals associated with various rates ofingestión, represented by the proportion of MP ingested.

Proportion MP Ingestion	Likelihood of Ingestion	MP:calyx Ratio	95% Confidence Interval
0.10	low	0.70	(0.61 – 0.81)
0.25	low	0.66	(0.61 – 0.72)
0.50	moderate	0.62	(0.57 – 0.68)
0.75	high	0.59	(0.50 – 0.69)
0.90	high	0.56	(0.43 – 0.71)

Table 3.

Upper limit of MP sizes ingested at various rates by four coral species, as represented by the proportion ingested. Likelihood of ingestion is associated with proportion of MP ingested.

		Maximum MP size by proportion ingested (mm)				
Species	**Mean calyx size (mm)**	**0.10**	**0.25**	**0.50**	**0.75**	**0.90**
		low likelihood		**moderate**	**high likelihood**	
A. cervicornis	1.33	0.93	0.88	0.83	0.78	0.74
O. faveolata	2.08	1.46	1.38	1.30	1.23	1.16
P. clivosa	3.96	2.78	2.62	2.47	2.33	2.20
M. cavernosa	4.77	3.35	3.16	2.98	2.81	2.65