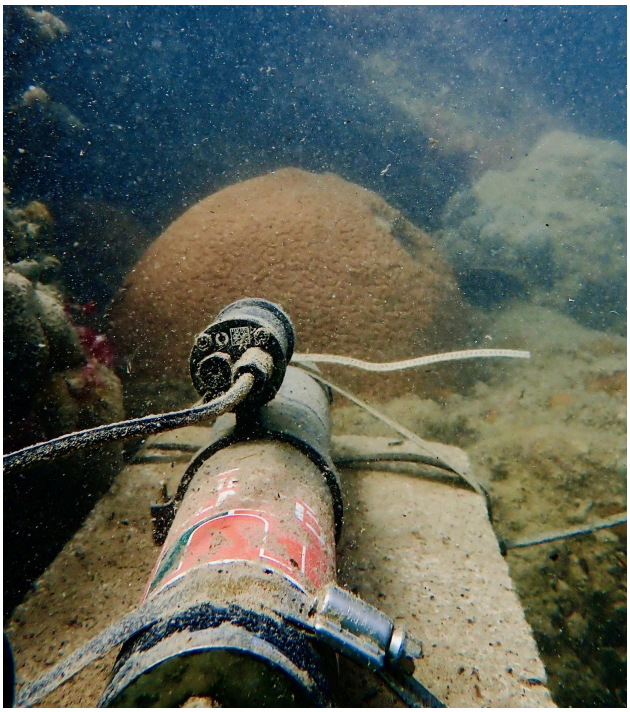
Restoration potential of corals from urbanized and marginal habitats in Florida (Phase 2)



Restoration potential of corals from urbanized and marginal habitats in Florida (Phase 2)

Final Report
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Management Summary

Given decades of population declines on Florida's Coral Reef and recent large-scale disturbance events such as the stony coral tissue loss disease (SCTLD) epidemic and the fourth global coral bleaching event, it is critical to identify priority coral habitats and populations for targeted conservation and restoration. 'Urban corals' have been discovered on artificial substrates in urbanized habitats such as the Port of Miami, and research by the Coral Program at the University of Miami's Cooperative Institute for Marine and Atmospheric Studies (CIMAS) and NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) since 2018 has shown these corals are more resilient to environmental stressors than their reef counterparts. This project evaluated the spawning activity of urban corals through field-based observations using KiloCam timelapse camera platforms and fecundity assessments via histological analysis, across two urbanized sites: the Port of Miami and Port of Palm Beach. Long-term KiloCam timelapse deployments resulted in 301,743 images in summer 2025 and 253,916 images in spring 2026, confirming spawning activity in all four studied species. Observed spawning did not occur during the anticipated timing windows of reef corals, but rather as a prolonged dribble of gamete bundles both within and outside of those windows, likely driven by artificial light at night (ALAN). Fecundity analysis confirmed that viable gametes were produced in sampled corals at the Port of Miami—with all five species (*Colpophylia natans*, *Diploria labyrinthiformis*, *Orbicella faveolata*, *Pseudodiplora clivosa*, and *P. strigosa*) producing oocytes comparable in size to Caribbean reef corals, and post-spawning samples showing empty mesenteries confirming gamete release. At the Port of Palm Beach, reproductive viability was more variable: approximately half of sampled colonies were non-reproductive, and post-spawning cores from *P. strigosa* showed signs of oocyte reabsorption. Urban corals remain a conservation priority, but given asynchronous spawning that reduces the likelihood of natural crossbreeding with reef populations, they are best suited for land-based assisted sexual reproduction to increase genetic diversity. Taken together, these outcomes add to growing knowledge on the ecological benefits of urban coral populations in the persistence and recovery of Florida's Coral Reef.

Executive Summary

Florida's Coral Reef has experienced severe declines due to disease outbreaks, thermal stress, and degraded water quality, with notable recent impacts from stony coral tissue loss disease (SCTLD) and the fourth global coral bleaching event. This project investigated the spawning biology and reproductive viability of "urban corals"—coral communities discovered on artificial substrates and persisting in highly urbanized environments such as the Port of Miami and Port of Palm Beach. Studied since 2018, these corals have demonstrated molecular and physiological resilience to thermal stress, sedimentation, and disease, making them high-priority candidates for incorporation into restoration pipelines.

The study addressed two primary objectives: 1) establishing spawning windows for wild urban coral populations, and 2) quantifying their reproductive capability and gamete viability (fecundity). Field-based monitoring consisted of 15 total field days in summer 2025 and 29 in spring 2026 in the Port of Miami and Port of Palm Beach, tenting of 48 colonies of the species *Colpophyllia natans*, *Diploria labyrinthiformis*, *Orbicella faveolata*, and *Pseudodiploria strigosa* with gamete collection tents, extended observation of 22 colonies of the same species with timelapse cameras, and sampling of 67 colonies of the same species but also including *Pseudodiploria clivosa*, before and after their respective spawning seasons (127 samples total) for fecundity analysis. Long-term camera deployment confirmed wild spawning of all four species outside of the anticipated reef window. Corals in the Port of Miami appear to release low volumes of gametes for longer periods of time than their reef counterparts, and at more sporadic time intervals. However, fecundity analysis revealed that urban corals in the Port of Miami are reproductively viable and produce gametes comparable in size and fecundity to reef corals, and post-spawning sampling shows these corals released gametes during the predicted spawning season. Corals in the Port of Palm Beach are sporadically reproductively viable, and when reproductive in pre-spawning, are likely to release their gametes, however there was evidence of some oocyte reabsorption.

These findings confirm that urban coral communities are reproductively viable and ecologically significant, but that asynchronous spawning makes natural crossbreeding with reef populations unlikely without human intervention. Urban corals therefore offer the greatest restoration value through land-based assisted sexual reproduction, where spawning can be synchronized and urban genotypes crossed with reef populations to maximize genetic diversity. Continued research and targeted conservation of these corals are essential, particularly as urban development intensifies along Florida's coastlines. Ultimately, these efforts will improve restoration success, efficiency, and cost-effectiveness in the recovery of Florida's Coral Reef.

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1. Background

Coral populations have been declining on Florida's Coral Reef over the past four decades due to disease outbreaks, thermal stress causing coral bleaching events, and coastal development leading to declining water quality. Most recently, the devastating impacts of stony coral tissue loss disease (SCTLD; Papke et al., 2024) and the fourth global coral bleaching event (Hoegh-Guldberg et al., 2023) on Florida's coral populations underscore the urgent need to identify and integrate resilient genotypes into restoration pipelines. Consequently, it is of paramount importance to identify priority habitats for conservation and to consider alternative sources of broodstock to improve restoration efforts. Despite myriad stressors, diverse coral populations have been discovered on artificial substrates (e.g., seawalls and rip-rap) in highly urbanized habitats throughout southeast Florida, including the Port of Miami and north Biscayne Bay (Miami-Dade County), Port Everglades (Broward County), and the Port of Palm Beach (Palm Beach County).

Since 2018, the Coral Program at the University of Miami's Cooperative Institute for Marine and Atmospheric Studies (CIMAS) and NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) has sought to characterize the environmental variability and benthic communities of 'urban coral' habitats in the Port of Miami (Enochs et al., 2023), as well as to examine the molecular signatures of resilience in urban versus reef corals (Rubin et al., 2021; Studivan and Enochs, 2022; Macartney et al in revision). Through these efforts, we have shown that Port of Miami corals are remarkably persistent in the face of thermal stress, sedimentation, and disease events (Enochs et al., 2023). Molecular assessments have identified that these urban corals employ resilience mechanisms, including front-loading of genes associated with immunity and increased heterotrophy (Rubin et al., 2021; Macartney et al in revision), and exhibit increased tolerance to environmental stressors compared to reef corals (Studivan and Enochs, 2022). Ongoing efforts by our group are also identifying the genetic components of urban corals' resilience relative to reef populations across southeast Florida with high-resolution DNA sequencing and population genetics approaches (https://mstudiva.github.io/Urban-coral-population-genetics/code/), as well as characterization of algal symbiont assemblages that may confer stress tolerance to urban corals (Ing, 2024). Finally, spawning observations of the species *Colpophyllia natans*, *Pseudodiploria strigosa*, and *Pseudodiploria clivosa* in the Port of Miami since 2023 revealed that these corals are reproductively viable (Rossin et al in prep), though outstanding questions remain pertaining to their spawning periodicity and settlement success in the wild. Species present and thriving in these urban habitats include *Orbicella faveolata*, *C. natans*, *Diploria labyrinthiformis*, *P. strigosa*, and *P. clivosa*, among others. These species in particular are now largely absent on nearby reefs due to the SCTLD epidemic and are therefore priority species for restoration efforts.

Given their environmental tolerances, unique molecular makeup, and reproductive potential, ***urban corals are excellent candidates for targeted restoration efforts of resilient genotypes.*** In this project, we tested this hypothesis by addressing the following goals:

1. To establish spawning windows for wild urban corals through continuous observations of gamete release, and
2. To quantify fecundity of wild urban corals through histological analysis.

2. Methods

2.1. Establish spawning windows for wild populations of urban corals

2.1.1. Development of urban coral spawning calendars

In Phase 1 of the project (C3EAC4), we used prior knowledge regarding spawning and fecundity of corals on natural reefs to determine diver and camera deployment priorities for field-based observations, since these data did not exist for urban corals in Florida. Spawning observations of wild corals throughout the Caribbean have been collected for several decades, resulting in the publication of region-specific spawning calendars that predict the most likely nights to observe peak spawning activity based on previous years' observations. For example, the most comprehensive spawning guide was developed by CARMABI for Curaçao and the southern Caribbean, which is updated every year: (https://www.researchstationcarmabi.org/wp-content/uploads/2025/08/Screenshot-2025-CSTs.png). While a similar guide does not exist for Florida's Coral Reef, researchers here often use it as a guide, modifying the predicted spawn windows based on local sunset times. For Phase 1 of this project, we adopted a modified version of the CARMABI spawning calendar that was developed by the Coral Ecology Unit at NOAA's Southeast Fisheries Science Center (SEFSC), which is tailored to Florida-specific patterns such as sunset times and previous years' observations (Bright et al., 2024). We then used the Florida spawning prediction calendar to determine which peak dates to target for field-based spawning observations in the Port of Miami. For our priority species (*C. natans*, *D. labyrinthiformis*, *O. faveolata*, *P. clivosa*, and *P. strigosa*), the peak spawning calendars can be found in Table 1.

2.1.2. Field-based spawning observations and timelapse camera deployments

To identify potential spawning windows of urban corals in the Port of Miami in Phases 1 and 2, we used a combination of timelapse camera deployments and targeted, in-water diver observations. We conducted field-based spawning observations at an urban coral site in the Port of Miami, where long-term monitoring has occurred since 2018, and spawning observations have been conducted since summer 2023 (MacArthur Causeway North: 25.77293, -80.15263; Figure 1). Field observations were done using small boats or shore-based snorkeling, and targeted extended timeframes beyond peak spawning windows established for target species *C. natans*, *D. labyrinthiformis*, *O. faveolata*, and *P. strigosa* (Table 1). *Pseudodiploria clivosa* was not actively monitored for spawning activity, however, as this species has not been reliably observed to spawn in Florida.

In addition to in-water observations by personnel, we invested in open-source, low-cost technologies to greatly expand upon our observation periods. In Phase 1 of the project, this included modified GoPro cameras with experimental firmware or infrared lenses and

emitters, but these deployments were largely unsuccessful due to poor battery life (Studivan et al. 2025). In Phase 2, we pivoted to the KiloCam platform (https://www.austingreenephotography.com/store/p/kilocam), which are modified trail cameras paired with custom circuit boards, external battery packs, and strobe lights, all inside a 3D-printed chassis and waterproof housing. This variation of the KiloCam platform was purpose-built for coral spawning, and allows variable deployments depending on photo interval and strobe intensity. In this project, we programmed the cameras to take one photo every minute with supplemental strobe light from 20:00-06:00, which allowed continuous deployments of up to 5 days. Using a rotation of 6 KiloCams, we conducted timelapse camera deployments through the entire spawning season (11 weeks in the spring, 5 weeks in the summer), compared to Phase 1 where we were only able to target the peak predicted spawning windows. Due to the increased field time required for camera deployments and lack of observed spawning in previous years, we moved away from nighttime, in-water observations during predicted peak spawning windows. Following identification of gamete release in timelapse photos collected during summer 2025 and spring 2026 deployments (see section 2.1.3), however, we returned to nighttime, in-person observations for peak spawning windows as well. Snorkelers conducted in-water observations for four nights each in May and June 2026, for six hours each night. Additionally, gamete collection tents were deployed during the anticipated window – this timing encompassed both the reef window and when spawning had been observed in April 2026 photos.

2.1.3. Timelapse camera photo analysis and urban coral spawning periodicity

Photos from each camera were uploaded into individual, consistently named folders, and the total photo count per camera was recorded in the KiloCam validation log alongside relevant camera metadata. Deployment details recorded on wrist slates during the dive were subsequently entered into the KiloCam deployment log. Photos were considered valid if the camera captured between 4,000 and 10,000 images; counts below 3,500 were flagged for review, and counts below 1,000 were attributed to battery failure and set aside. A cursory review of the first ~100 frames was conducted to screen for color anomalies (pink, orange, or green cast), which indicated a malfunctioning camera requiring further inspection. Valid photos were then analyzed one at a time, and evidence of gamete bundles (appearing as yellow/pink spheres; Figure 4) were recorded along with their associated timing in a spawning log spreadsheet.

2.2. Evaluate fecundity of urban coral species

2.2.1. Coral sampling strategy and tissue collection for histology

In corals, oocytes take ~9–12 months to develop, whereas spermatocysts take ~1–2 months (Leinbach et al., 2021; Rossin et al., in prep). Corals do not have true gonads, however, oocytes and spermatocysts develop within mesenterial filaments in bundles. During spawning, the entire bundle is released from the polyp, leaving the mesenteries empty. Tropical corals spawn in peak summer months following the full moon, when water temperatures are at their peak. This high temperature can result in bleaching or

thermal stress for the corals, which can affect reproductive capacity. Corals and other invertebrates are able to reabsorb their oocytes and redistribute the lipids to essential biological processes (Rossin et al., 2019). This process takes several months, and is evident in tissues before and after spawning events.

In Phase 1 of the project, tissue sampling was conducted before and after the predicted peak spawning windows to quantify gamete production, development, and potential release (i.e., fecundity) in urban corals. Samples were taken as close to the peak spawning window as possible to accurately quantify oocytes and determine size and stage of oocytes prior to spawning. Summer 2023 and spring 2024 samples were collected in the Port of Miami (Fig. 1): *C. natans* (*n* = 10 pre/post), *P. clivosa* (*n* = 10 pre/post), and *P. strigosa* (*n* = 11 pre/post) in summer 2023, and *D. labyrinthiformis* (*n* = 10 pre/post) in spring 2024. During summer 2024, *O. faveolata* samples (*n* = 11 pre, 10 post) were collected in the Port of Miami, and *C. natans* (*n* = 3 pre/post), *O. faveolata* (*n* = 1 pre/post), *P. clivosa* (*n* = 7 pre, 3 post), and *P. strigosa* (*n* = 4 pre, 2 post) samples were collected from Peanut Island in the Port of Palm Beach (26.771530°, -80.044210°; Figure 1). In total, 127 samples were collected for fecundity analyses (Table 3). Tissue cores were collected using a Nemo underwater drill and 2.5 cm diamond-tipped core bits by SCUBA divers, held in separate zip-top bags for the duration of the dive, and returned to the boat for processing. Pre- and post-spawning tissue cores were taken from the center of colonies to avoid non-reproductive tissue areas as the colony margins.

2.2.2. Histological analysis to quantify fecundity in urban corals

Tissue cores were preserved in buffered formalin (Anatech Z-fix) diluted with seawater immediately following collection, with unique identifier tags in each sample container. Preserved samples were returned to the lab at room temperature for further processing: 1) tissue cores were removed from buffered formalin after a minimum of at least 24 hours, 2) soaked in seawater for 24 hours, and then 3) transferred to 70% ethanol for shipment to Louisiana State University (LSU). Once there, samples were processed and analyzed per the protocol described in Leinbach et al. (2021). In summary, samples were first decalcified (i.e., the skeleton was dissolved away, leaving only the coral tissue) with a 1% HCl EDTA solution that was changed every 24 hours, and resulting tissues of three polyps or an area of approximately 1 cm^2 were processed in serial dilutions of ethanol to remove all water from the samples, and then serial changes of xylenes as a clearing agent to prepare the tissues for wax infiltration and make the tissues more transparent for visualization. Samples were then embedded in paraffin wax blocks in cross section and longitudinal orientations, which allowed tissue layers to be cut on a microtome and then mounted on slides for visualization and data collection. Tissue sections were 5 µm thick, then stained with hematoxylin and eosin stain. Hematoxylin and eosin are standard stains for viewing various tissue structure types, making oocytes and spermatocytes (cells that become eggs and sperm, respectively) easy to identify and determine developmental stages.

Fecundity was evaluated through the quantification of nucleated and non-nucleated oocyte diameter/stage per polyp averaged over three polyps per coral for *O. faveolata*,

and per cm^2 for *C. natans*, *P. strigosa*, and *P. clivosa* (Leinbach et al., 2021; Rossin et al., in prep). Oocyte density is measured from the areas of non-nucleated and nucleated oocytes compared to overall tissue area. Spermatocyst stage, and presence of oocyte reabsorption and degradation were evaluated qualitatively. Twenty-five oocyte diameters were measured for each individual where 25 oocytes were present. Only oocytes with nuclei were measured (Rossin et al., 2019; Leinbach et al., 2021).

3. Results

3.1. Establish spawning windows for wild populations of urban corals

During summer 2025 and spring 2026 spawning seasons, KiloCams were deployed every Tuesday and Friday morning for the entire season (12 snorkel deployments in summer 2025, 21 deployments in spring 2026; KiloCam Spring Deployment), allowing continuous coverage of coral colonies during the spawning seasons (Figures 2–3). Six cameras were deployed at a time in summer 2025, with five deployed at a time in spring 2026. This resulted in 301,743 images in summer 2025, and 253,916 images to date in spring 2026 (KiloCam Validation). The average number of images per camera per deployment in summer 2025 was 5,803, and in spring 2026 was 5,078.

Gamete release was observed for all four species (*D. labyrinthiformis*, *C. natans*, *O. faveolata*, and *P. strigosa*) monitored across their anticipated spawning seasons (Figure 4). Twelve of the 14 colonies watched have spawned according to image analysis. None of the colonies that released gametes appeared to spawn during their corresponding reef window timing, and instead appeared to "dribble" throughout the entire season (Spawning Evidence). These dribbling events can take anywhere from one minute to eleven hours (Table 2). The total spawning observations for *D. labyrinthiformis* recorded to date in spring 2026 range from 1 minute to 4 hours, with a mean time of 1 hour and 19 minutes; additional observations are anticipated as further analysis is completed for spring 2026 deployments. For *C. natans*, it ranged from three to eight hours, *P. strigosa* 2-11 hours, and *O. faveolata* 1-11 hours.

For in-water, snorkeler-based observations conducted in May and June 2026, no spawning activity was observed in person (spring_snorkellogs.pdf), despite extending observation times to include predicted gamete release based on April photo evidence. In reviewing the corresponding timelapse photos from May, however, *D. labyrinthiformis* colonies released gametes at 00:02, nearly an hour after snorkelers had departed the site.

3.2. Evaluate fecundity of urban coral species

For Port of Miami pre-spawning samples, all species had oocytes and spermatocysts with no signs of oosorption (i.e., sign of coral reabsorbing gametes to redistribute energy to biological processes; Rossin et al., 2019). Post-spawning samples had empty mesenteries, also with no signs of oosorption, indicating gamete bundles had been released from all species (Figure 5). To assess gamete viability, we measured oocyte diameter and fecundity, and assessed spermatocyst development for all species (*C. natans*, *D.*

labyrinthiformis, *O. faveolata*, *P. clivosa*, and *P. strigosa*). Average oocyte diameter for *C. natans* was 158.84 ± 41.83 µm, *D. labyrinthiformis* was 249.58 ± 34.75 µm, *O. faveolata* was 217.69 ± 37.32 µm, *P. clivosa* was 284.21 ± 12.83 µm, and *P. strigosa* was 226.64 ± 46.44 µm (Figure 9). Spermatocysts from all four developmental stages were seen in the pre-spawning cores. Average fecundity per cm^2 for *C. natans* was 0.28% of coral tissue, 3.45% for *D. labyrinthiformis*, 9.14% for *O. faveolata*, 0.97% for *P. clivosa*, and 0.23% for *P. strigosa* (Figure 7).

For Port of Palm Beach (Peanut Island) samples, of the three *C. natans* colonies sampled, one was competently reproductive (i.e., produced spermatocysts and oocytes that were large and late-stage, and spawned), one was non-reproductive, and one was marginally reproductive. The single *O. faveolata* colony was competently reproductive. For *P. clivosa*, three were non-reproductive, two were marginally reproductive and one was competently reproductive. For *P. strigosa*, two were non-reproductive, one was marginally reproductive, and one was competently reproductive. Following the spawning window, all but two reproductively competent samples showed completely empty mesenteries. The other two showed signs of reabsorption. All reproductive colonies had at least two stages of spermatocysts. Average oocyte diameter for *C. natans* was 294.66 µm, *O. faveolata* was 258.59 µm, *P. clivosa* was 289.09 µm, and *P. strigosa* was 251.64 µm (Figure 6). Average fecundity per cm^2 for *C. natans* was 1.32% of coral tissue, 1.33% for *O. faveolata*, and 0.8% for *P. strigosa* (Figure 7).

4. Discussion

4.1. Urban and reef corals demonstrate asynchronous spawning periodicity

The UM CIMAS/NOAA AOML Coral Program has been conducting coral spawning observations in the Port of Miami since 2023, and we are excited to report that we have identified gamete releases in four priority coral species in 2025 and 2026 spawning seasons. Based on long-term, time-lapse camera deployments over entire spawning seasons, we have identified a seemingly inconsistent pattern of gamete release in urban coral communities (Table 2). This contrasts with established spawning windows for reef corals (Table 1), both in terms of predicted peak spawning days, as well as timing of gamete release per day. For example, *O. faveolata* is predicted to spawn 6–7 days after the full moon (AFM) from 285–370 minutes after sunset in reef habitats, but has been observed to spawn 5–6 days before the full moon (BFM) from 22 minutes to 10 hours after sunset in the Port of Miami, as well as 5–9 days AFM with gamete release from 1–10 hours after sunset. These observations suggest that urban corals in the Port of Miami release small amounts of gametes over much longer periods (i.e., dribbling) both within and outside of the predicted Florida reef window, rather than as one primary "pulse" of gamete release as is common with reef conspecifics. The majority of gamete releases were also observed earlier in the season than reef corals. This mismatch in gamete release between reef and urban communities has profound implications for the likelihood of genetic exchange between populations, and therefore in developing management priorities for urban coral communities.

While some species have relatively long gamete fertilization windows (e.g., *O. faveolata*), gametes from other species like *D. labyrinthiformis* are only viable to mix for a couple of hours post release. Observation data for urban corals of this species indicates that spawning occurs on entirely different days between urban communities and local reef populations (0–9 days AFM from 4–8 hours after sunset in the Port of Miami, versus 9–11 days AFM from 70 minutes before to 10 minutes after sunset in reef habitats), suggesting that reef and urban gametes likely do not mix to form crossbred larvae under most circumstances. Population genetics analyses are ongoing for this species, which will confirm whether the observed variation in spawning activity in urban communities has resulted in a lack of gene flow among urban and reef populations. For another priority species, *O. faveolata*, our spawning observation data indicated that urban communities released gametes over a week prior to the corresponding reef spawning window in September 2025. Complementary population genetics analyses also indicated the presence of distinct genetic lineages associated with urban habitats in this species, with additional evidence of high inbreeding or potential cryptic speciation in urban sites (https://mstudiva.github.io/Urban-coral-population-genetics/code/ofav/).

It is therefore likely that asynchronous spawning between urban and reef corals is contributing to reduced gene flow among populations, meaning that natural crossbreeding and recruitment may not be occurring outside of rare events. This does not, however, preclude the potential of migration of fertilized urban larvae to reef habitats and vice versa, though genetic evidence would suggest this is not a common occurrence. Further population genetics analyses may corroborate these findings, or provide alternative hypotheses as these data integrate migration events across multiple generations.

The breakdown of consistent spawning activity in urban corals, both in terms of day periodicity but also time duration, may be due in part to artificial light at night (ALAN) that is common in the Port of Miami and other urbanized habitats (Ayalon et al., 2021). While there are well-documented, consistent spawning windows for scleractinian corals on natural reef environments throughout Florida and the Caribbean, to our knowledge, this is the first study to examine spawning cycles for corals from urbanized habitats in Florida. Studies conducted in other urbanized environments globally, however, have identified impacts of urbanization on natural coral processes, particularly when artificial light pollution is involved. For example, in the Gulf of Aqaba, light pollution has been shown to alter coral transcriptomic patterns, symbiont and microbiome communities, seasonal physiology, and gametogenic cycles (Rosenberg et al., 2022). In a lab-based experiment with Indo-Pacific acroporids, exposure to ALAN resulted in delayed gametogenesis and a breakdown in gamete release synchronization among colonies (Ayalon et al., 2021). A meta-analysis of global spawning observations from 2000–2019 revealed significantly early release of gametes by approximately 1–3 days in corals exposed to ALAN (Davies et al., 2023). These patterns are corroborated by our observations of Miami's urban corals, with the addition of late gamete releases in some species relative to the predicted peak spawning windows as well as early releases.

Over the course of this project, we have tested several camera platforms for automated, non-diver-based observation of spawning activity, with KiloCams emerging as the clear

winner. The KiloCam platform was designed to be a low-cost, efficient timelapse camera system with relatively long deployment times (weeks to months), due to its low power-consumption components and custom-coded circuit boards (Besson et al., 2022; Boulais et al., 2023). This system was developed by Ecologis Consulting, and has been further refined as a coral spawning camera platform with a larger battery pack, supplemental strobe light optimized for nighttime photography, and waterproof housing (https://www.austingreenephotography.com/store/p/kilocam). Using a one-minute shooting interval with strobe lighting between 20:00–06:00, these cameras can be deployed for up to 5 days at a time. We have built 17 KiloCams to date, allowing biweekly deployments and continuous photo coverage of 14 colonies (6 *D. labyrinthiformis*, 3 *C. natans*, 3 *O. faveolata*, and 2 *P. strigosa*) across their entire spawning season. This increased our spawning observations from previous project phases by an order of magnitude through longer and more consistent deployments, resulting in 555,659 photos collected in Phase 2 versus 58,834 photos in Phase 1 using GoPro camera systems. The system is built from relatively inexpensive and easily procured components, as well as 3D-printed mounts and brackets to allow easy and cost-effective maintenance, resulting in a lower per-camera cost compared to GoPros. Finally, without the implementation of KiloCams in Phase 2 of this project, we would not have been able to identify spawning windows for any of our priority species.

4.2. Urban corals produce viable gametes at or above average sizes established for Caribbean reef corals

Oocyte diameter and stage are standard metrics to quantify gamete viability and to predict the time to spawning (Szmant, 1986). Prior to this study, there were no records of oocyte diameter for urban corals in Florida or the Caribbean. Gamete production is an area of research that demands more attention, particularly considering the overall failure of coral reproduction and recruitment across Florida and the Caribbean (Holstein et al., 2015). Most tropical coral reproduction studies are from Puerto Rico, the U.S. Virgin Islands, and Mexico. We found that urban corals in the Ports of Miami and Palm Beach are producing oocytes similar in size to those among Caribbean reefs (Alvarado Ch et al., 2004; Weil and Vargas, 2010; Graham and van Woesik, 2013; Holstein et al., 2015; Bloomberg and Holstein, 2021). This was surprising given that pre-spawning cores were collected from urban corals in August 2023 during the fourth global bleaching event (Hoegh-Guldberg et al., 2023). Taken together, these lines of evidence suggest that despite the harsh environmental conditions observed in urbanized habitats in southeast Florida (Enochs et al., 2023), urban corals are able to expend energy to produce gametes, possibly due to enhanced heterotrophic feeding (Rubin et al., 2021; Macartney et al., in revision).

Under sustained periods of stress, however, corals can also reabsorb their eggs to transfer the lipids, break them down, and redistribute to life-sustaining processes. Oosorption is apparent in corals as well-defined egg structures (Figure 8) to speckled oocytes where the lipids are condensing to be packaged and the outer lining breaks down (Rossin et al., 2019). No oosorption was seen in the tissue samples from the Port of Miami colonies, but evidence of oosorption was found in two *P. strigosa* colonies from the Port of Palm

Beach. This could be due to seasonal, cold-water upwelling that is common in the region during the summer months (Taylor and Stewart, 1959), reduced winter temperatures relative to nearby reefs, or perhaps stress due to sedimentation (*pers. obs.*). The oocytes from the Port of Palm Beach corals were larger than Port of Miami corals for all four species (Table 4) studied, however, fecundity was lower than expected, and almost half of individuals were non-reproductive despite being of reproductive size. This could be due to local stressors causing a delay in sexual development, although more environmental data are needed to provide additional context and to formally test this hypothesis. Combined with the smaller urban coral habitat area in the Port of Palm Beach relative to the Port of Miami, the reduced fecundity of corals at Peanut Island likely results in low success of reproductive events. It bears to be determined whether the urban population in this region is largely self-sustaining through local recruitment at Peanut Island, or whether recruits are primarily migrating from nearby reef habitats. Ongoing population genetics analyses will aim to resolve the genetic structure and patterns of gene flow among urban and reef populations in the northern extent of Florida's Coral Reef.

4.3. Management recommendations

While we will continue field-based camera deployments and diver observations to refine spawning windows and potentially collect gametes for assisted sexual reproduction in Phase 3 of this project, it has become clear that natural crossbreeding of urban corals with reef populations will likely not be broadly successful without human intervention. Our fecundity data and associated population genetic analyses suggest that urban coral communities are likely self-sustaining in the Port of Miami, however, there are genetic indicators of reduced gene flow (e.g., cryptic lineages and inbreeding) in these populations relative to nearby reef populations. Urban coral genotypes remain a high priority for incorporation into restoration initiatives due to their observed resilience to multiple environmental stressors (Enochs et al., 2023; Studivan and Enochs, 2022; Macartney et al., in revision).

We therefore recommend that restoration efforts involving urban coral genotypes be primarily dedicated towards land-based propagation and assisted sexual reproduction. This will allow the preservation of unique urban genotypes in light of ongoing environmental stressors and coastal construction projects, but will also support the modulation of spawning periodicity via standardized lunar cues so that urban and reef gametes can be crossbred. This is one of the primary goals of Phase 3 of this project, which will be done in collaboration with Nova Southeastern University and the University of Miami's Experimental Hatchery. We anticipate collecting urban coral gametes in land-based spawning aquaria at both facilities, which will then be crossed with reef gametes. The majority of the offspring will be incorporated into propagation pipelines for bio-banking and future outplanting, but a subset of unique genetic crosses will be retained for experimental research. The Experimental Reef Laboratory at the UM CIMAS/NOAA AOML Coral Program is a state-of-the-art aquarium facility that can evaluate resilience of corals to multiple environmental stressors including bleaching, ocean acidification, hypoxia, nutrification, and disease. Genetic crosses from this project will be evaluated for heritability of stress resilience in future project phases.

Further, we have archived unique urban genotypes at other land-based nurseries including Mote Marine Laboratory, the Reef Institute, and FWC. We recommend that assisted sexual reproduction efforts at these facilities also incorporate urban genotypes, in order to increase the scale of crossbreeding success and potential for selection of resilient traits in offspring. For example, this is already underway at the Reef Institute, using corals collected from Peanut Island in March 2026 as part of this collaborative project.

Finally, the number of urban coral colonies collected as corals of opportunity in advance of coastal construction activities is generally higher than land-based facilities can intake at a time. In situ nurseries, such as common gardens, may be feasible as relocation sites. Additional benefits may be gained by taking a spawning hub approach, relocating urban colonies of reproductive maturity in relative proximity to one another at natural reef sites. Further research is warranted to identify the cost-benefit analysis of this approach versus land-based propagation and spawning efforts, such as personnel and infrastructure costs, potential for disease transmission, and influences of parrotfish predation on urban coral outplant survival.

Beyond their reproductive capabilities and potential for supplementing land-based asexual and sexual reproduction efforts, urban corals represent a critical resource for the future of Florida's Coral Reef. Their observed resilience despite constant exposure to adverse conditions is not yet fully understood. Continued research into their mechanisms of resilience, particularly at a genetic level, will help us better understand what processes enhance (or conversely, impede) stress tolerance in corals. Additionally, mixing urban gametes with reef gametes from multiple locations would provide opportunities to increase resilience by maximizing genetic diversity and adaptive potential. Combined, these strategies will improve the success and efficiency of coral propagation and restoration efforts, while simultaneously reducing cost and time investment, and ultimately promoting the recovery of Florida's Coral Reef.

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6. Tables

Table 1. Predicted spawning windows for priority species, modified from CARMABI's coral spawning calendar by NOAA-SEFSC. AFM = days after full moon, BS = minutes before sunset, AS = minutes after sunset.

Species	Month 1	Month 2	Month 3
Colpophyllia natans	August 6-8 days AFM 35-110 min AS	September 6-8 days AFM 35-110 min AS	October (possible) 6-8 days AFM 35-110 min AS
Diploria labyrinthiformis	April 9-11 days AFM 70 BS-10 min AS	May 9-11 days AFM 70 BS-10 min AS	June (possible) 9-11 days AFM 70 BS-10 min AS
Orbicella faveolata	July 6-7 days AFM 285-370 min AS	August 6-7 days AFM 285-370 min AS	September 6-7 days AFM 285-370 min AS
Pseudodiploria clivosa	August 7-8 days AFM 210-255 and 280-350 min AS	September 7-8 days AFM 210-255 and 280-350 min AS	October (possible) 7-8 days AFM 210-255 and 280-350 min AS
Pseudodiploria strigosa	August 6-8 days AFM 30-70 and 220-270 min AS	September 6-8 days AFM 30-70 and 220-270 min AS	October (possible) 6-8 days AFM 30-70 and 220-270 min AS

Alt text: Table showing predicted peak spawning windows for five coral species based on lunar timing and local sunset times, adapted from NOAA-SEFSC and CARMABI. Columns include species name and spawning windows across up to three months. Timing is given as days after the full moon (AFM) and minutes before or after sunset (BS or AS). For example, *Colpophyllia natans* is predicted to spawn 6–8 days after the full moon and 35–110 minutes after sunset from August through October. *Diploria labyrinthiformis* spawns 9–11 days AFM, between 70 minutes before and 10 minutes after sunset, from April to June. *Orbicella faveolata* spawns July through September, 6–7 days AFM, 285–370 minutes AS. *Pseudodiploria clivosa* and *P. strigosa* have dual spawning windows in August through October, with overlapping ranges of minutes AS.

Table 2. Urban spawning windows identified in July 2025-May 2026. Date ranges indicate spawning observed. Brackets indicate the time range of spawning within those dates. Cells with N/A indicate species where the primary season is two months long. Parentheses indicate days before full moon (BFM) or after full moon (AFM).

Species	**Month 1**	**Month 2**	**Month 3**
Colpophyllia natans	N/A	No spawning observed in August 2025	5 day BFM ~0.4–8.5 hr after sunset 12-14 days AFM ~0.8–10.3 hr after sunset
Diploria labyrinthiformis	0 days AFM ~4.8–10.4 hr after sunset 1–2 days AFM ~4.8–10.4 hr after sunset	9 days AFM ~4.5 hr after sunset	Photo analysis ongoing for May 2026
Orbicella faveolata	No spawning observed in July 2025	No spawning observed in August 2025	5-6 days BFM ~0.3–11.3 hr after sunset 6-9 days AFM ~1.2–11.4 hr after sunset
Pseudodiploria strigosa	N/A	5–9 days AFM ~0.1–10.9 hr after sunset 12–17 days AFM ~0.3–10.0 hr after sunset	1–9 days AFM ~1.8–11.3 hr after sunset 12–15 days AFM ~1.2–4.6 hr after sunset

Alt text: Table summarizing photographic spawning evidence observed through Kilocam photo collection for four species from July 2025-May 2026. Columns indicate spawning observed across three lunar months for each species. For *Colpophyllia natans,* spawning was observed on September 2 from 20:02-04:11 and September 19-21 from 20:07-05:35; no spawning observed in August. For *Diploria labyrinthiformis,* spawning was observed on March 31 from 22:27-22:29, April 1-2 from 00:27-05:59; and May 10 from 00:28-00:29. Photo analysis not yet completed for the rest of May, as the lunar month ends June 16. *Orbicella faveolata* was observed spawning from September 2-3 from 20:00-06:59 and September 12-16 from 20:43-06:47. No spawning observed in July or

August 2025. *Pseudodiploria strigosa* was observed spawning August 14-18 from 20:02-06:48, August 22-27 from 20:06-05:46, September 9-16 from 21:18-06:43, and September 19-22 from 20:30-23:55.

Table 3. Coral sample metadata of tissue cores collected for fecundity analysis from 2024.

Site	Season	Species	Pre-spawning	Post-spawning	Status
MacArthur Causeway North	Summer 2023	*Colpophyllia natans*	10	10	Processed; analyzed in FY25
MacArthur Causeway North	Spring 2024	*Diploria labyrinthiformis*	10	10	Processed; analyzed in FY25
MacArthur Causeway North	Summer 2024	*Orbicella faveolata*	11	10	Processed; analyzed FY26
MacArthur Causeway North	Summer 2023	*Pseudodiploria clivosa*	10	10	Processed; analyzed in FY25
MacArthur Causeway North	Summer 2023	*Pseudodiploria strigosa*	11	11	Processed; analyzed in FY25
Peanut Island	Summer 2024	*Colpophyllia natans*	3	3	Processed; analyzed FY26
Peanut Island	Summer 2024	*Orbicella faveolata*	1	1	Processed; analyzed in FY26
Peanut Island	Summer 2024	*Pseudodiploria clivosa*	7	3	Processed; analyzed in FY26
Peanut Island	Summer 2024	*Pseudodiploria strigosa*	4	2	Processed; analyzed in FY26

Alt text: Table showing coral tissue core sample metadata used for fecundity analysis across two sites and multiple spawning seasons. Columns list site, season, species, number of pre- and post-spawning samples, and processing status. At MacArthur Causeway North, samples were collected across Summer 2023, Spring 2024, and Summer 2024 for five species, with 10–11 pre- and post-spawning samples per species, all processed and analyzed in FY25 or scheduled for analysis in FY26. At Peanut Island, Summer 2024 collections were made for four species, with smaller sample sizes (1–7 pre-spawning and 1–3 post-spawning), also processed with analysis completed in FY26.

Table 4. Mean reproductive capacity metrics for Port of Palm Beach. Fecundity was assessed per area versus per polyp since there are inherent anatomical differences among star and brain corals.

Species	Port of Miami Diameter (µm)	Port of Palm Beach (µm)	Fecundity (Percent of tissue)	Qualitative observations
Colpophyllia natans	158.84	294.66	1.32%	Mesenteries were full pre-spawning but empty post-spawning
Orbicella faveolata	217.69	258.59	1.33%	Mesenteries were full pre-spawning but empty post-spawning
Pseudodiploria clivosa	284.21	289.09	Fecundity to be completed in FY27	Mesenteries were full pre-spawning but showed signs of reabsorption post-spawning
Pseudodiploria strigosa	226.64	251.64	0.80%	Mesenteries were full pre-spawning but empty post-spawning, with no signs of reabsorption

Alt text: Table summarizing reproductive metrics and qualitative spawning observations for four coral species collected from the Port of Miami and Port of Palm Beach. Columns include species name, average oocyte diameter at each site in micrometers, fecundity in oocytes per square centimeter, and qualitative post-spawning observations. *C. natans* had average oocyte diameters of 158.84 µm in the Port of Miami and 294.66 µm in the Port of Palm Beach, with fecundity of 1.32%; mesenteries were full pre-spawning but empty post-spawning. *O. faveolata* had diameters of 217.69 µm and 258.59 µm, respectively, with fecundity of 1.33% of tissue; mesenteries were full pre-spawning but empty post-spawning. *P. clivosa* had diameters of 284.21 µm and 289.09 µm; fecundity analysis was noted as to be completed in FY27. Mesenteries were full pre-spawning but showed signs of reabsorption post-spawning. *Pseudodiploria strigosa* had diameters of 226.64 µm and 251.64 µm, with fecundity of 0.80%; mesenteries were full pre-spawning but empty post-spawning with no signs of reabsorption.

7. FIGURES

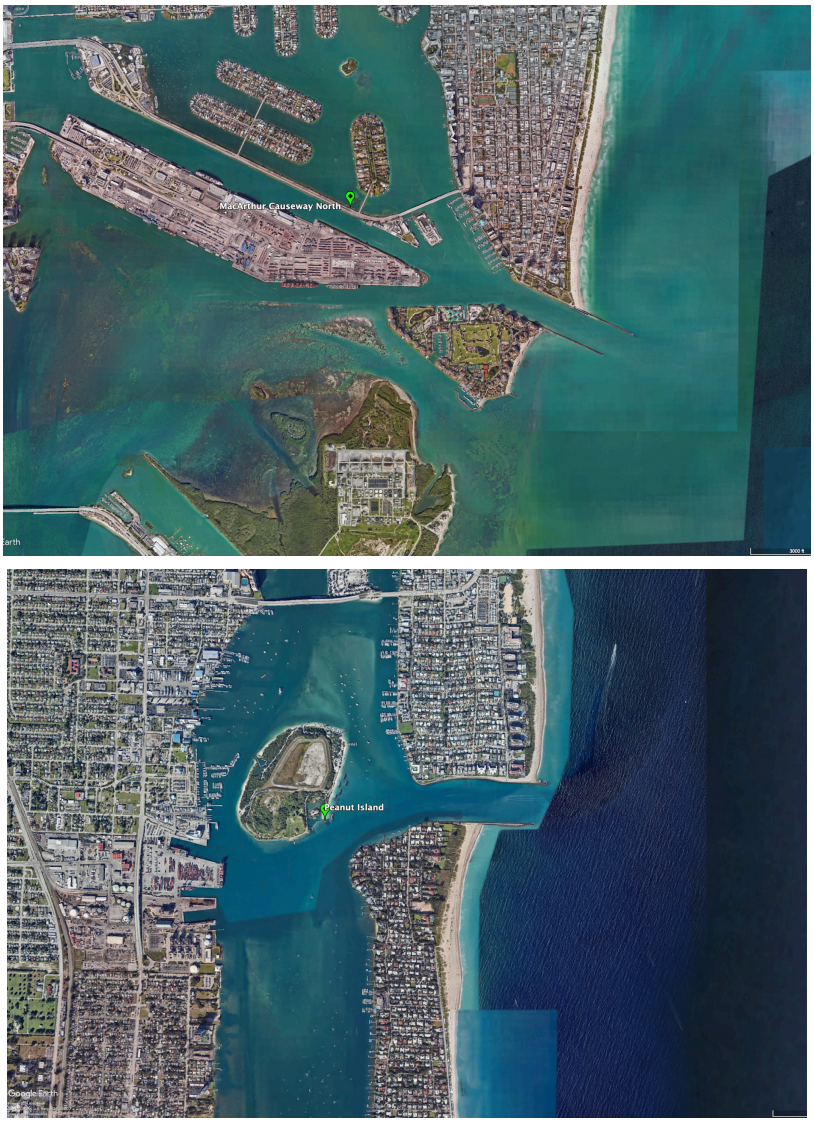

Figure 1. Top: The MacArthur Causeway North urban coral site in the Port of Miami (Miami-Dade County), where environmental monitoring and benthic community characterization has been ongoing since 2018, and spawning observations and fecundity sampling have been conducted since 2023. Bottom: The Peanut Island urban coral site in the Port of Palm Beach (Palm Beach County), where benthic community characterization and spawning observations have been underway by the Reef Institute since 2022.

Figure 2. Left: Reef gamete collection tents designed by Dana Williams of the University of Miami CIMAS/NOAA-SEFSC. Right: Modified urban coral gamete collection tents constructed by Ashley Rossin, with an akita mix (Oskar) for scale.

Figure 3. Spawning KiloCam deployment. Representative images showing deployment of KiloCam systems on urban reef habitat for coral spawning observations. Top panels show close-up views of the mounted camera apparatus positioned adjacent to coral colonies on the benthos. Bottom panels show broader environmental views of the deployment site during daytime and nighttime conditions, illustrating surrounding reef structure, algal cover, and illumination used for nocturnal spawning monitoring.

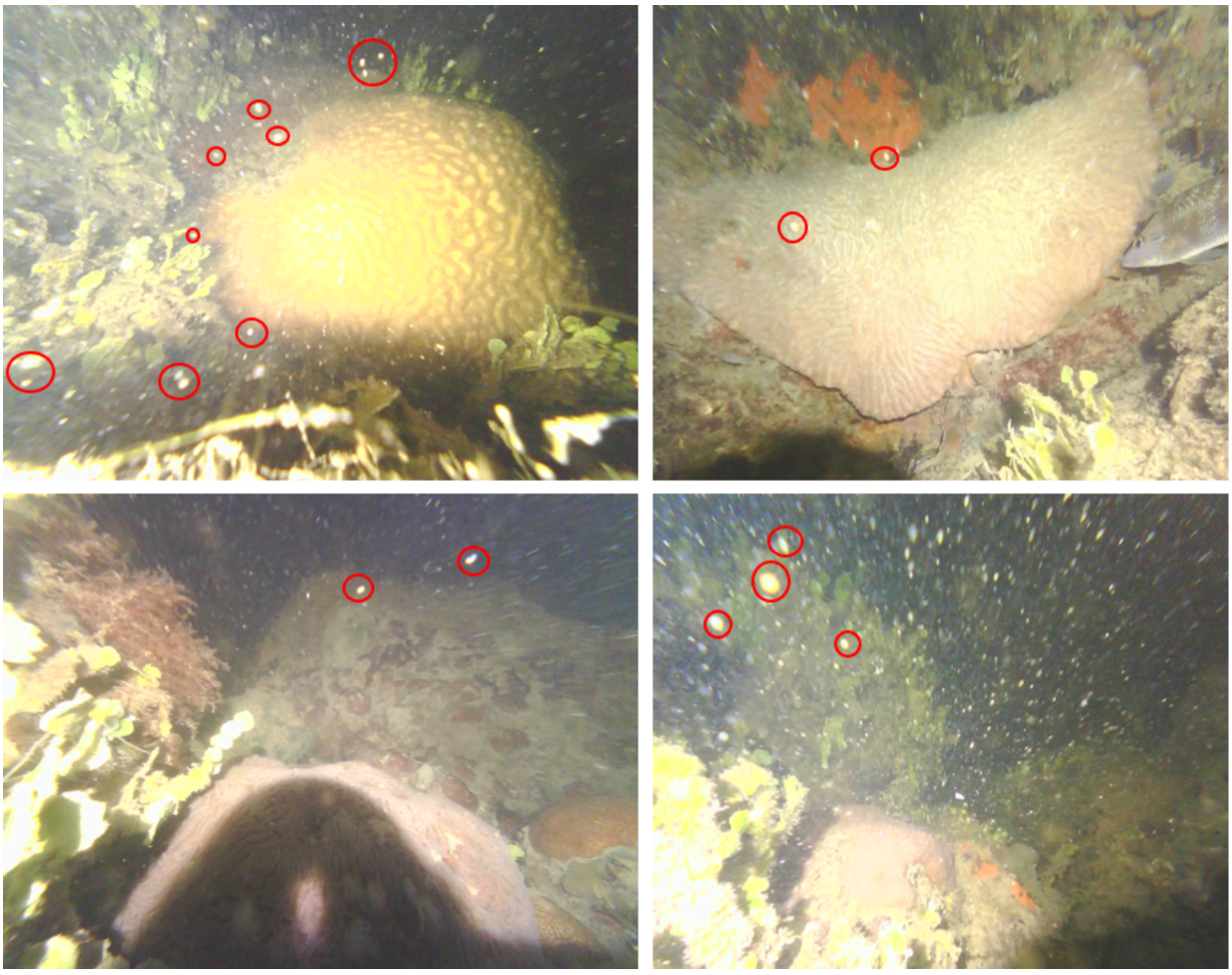

Figure 4. Spawning evidence. Still images captured from KiloCam deployments showing gamete bundle release from coral colonies during nocturnal spawning observations at urban reef sites. Red circles indicate visible gamete bundles suspended in the water column adjacent to spawning colonies. Top right is *C. natans*, top left is *P. strigosa*, bottom left is *D. labyrinthiformis*, and bottom right is *O. faveolata*.

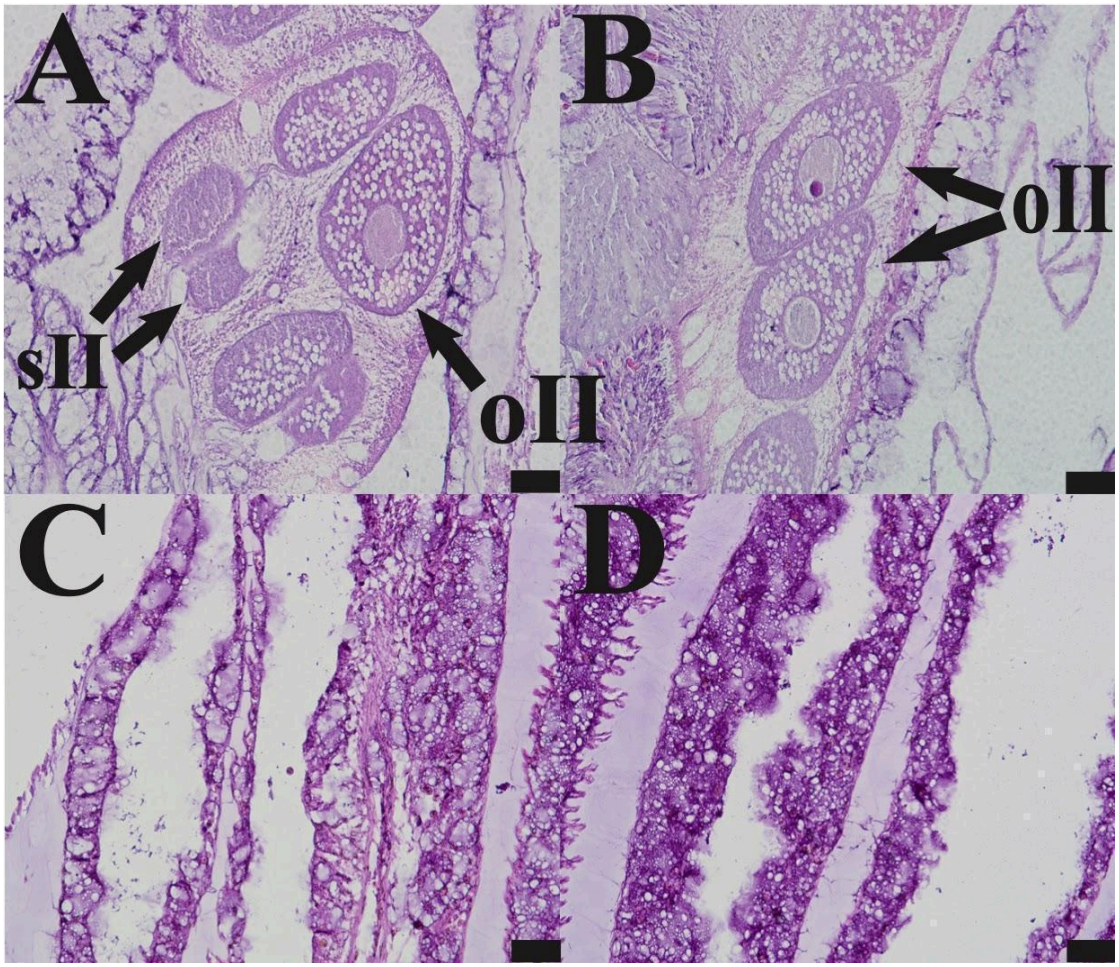

Figure 5. A & B: Histological slides of PSTR from before spawning in summer 2023; sII indicates second-stage sperm and oII indicates second-stage oocytes. C & D: PSTR post-spawning, where mesenteries no longer have gametes.

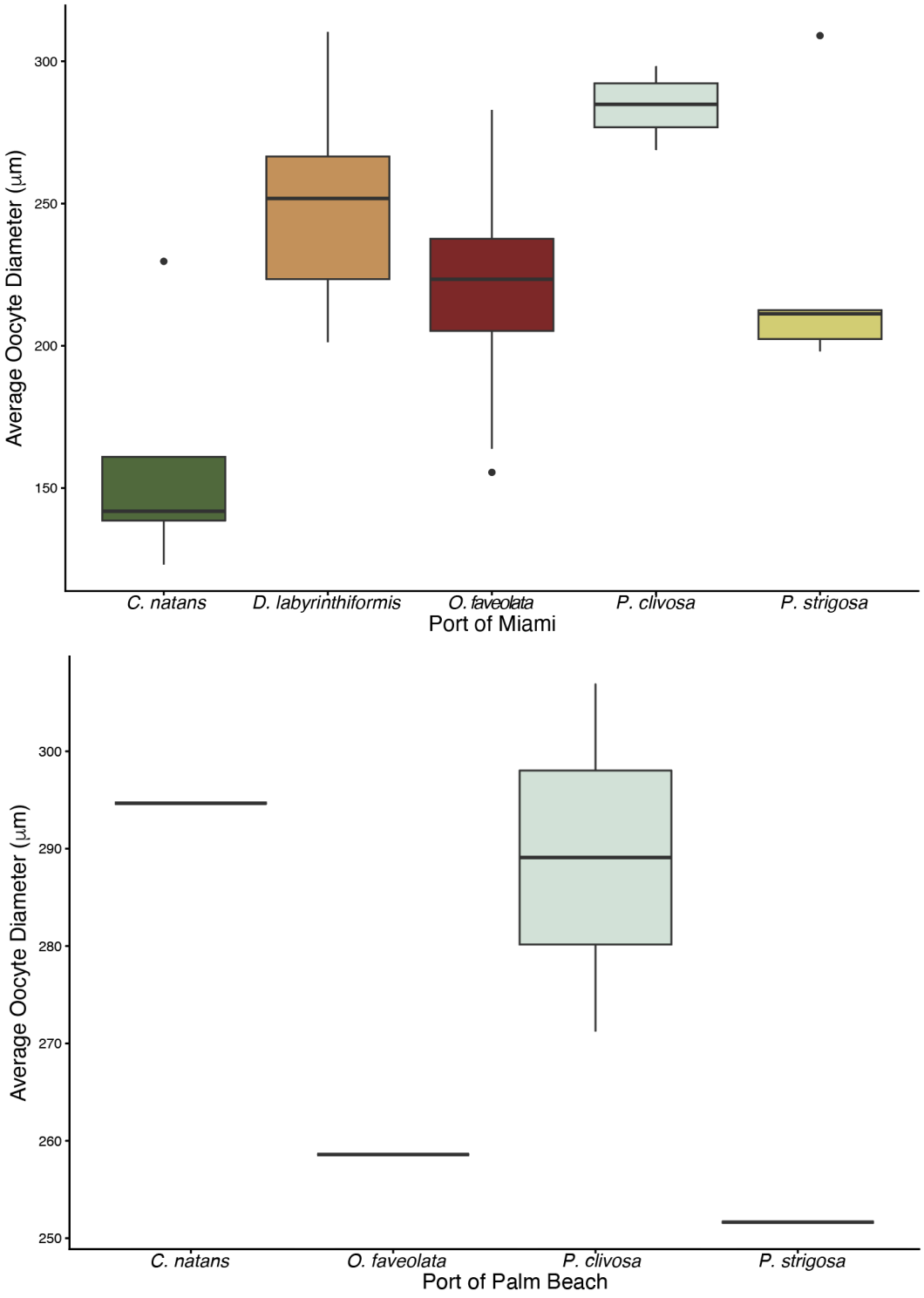

Figure 6. Oocyte diameter for *C. natans*, *D. labyrinthiformis*, *O. faveolata*, *P. clivosa*, and *P. strigosa* from 2023 and 2024 before the spawning window from both Ports of Miami and Palm Beach. Diameter reflects Feret diameter and is measured in microns.

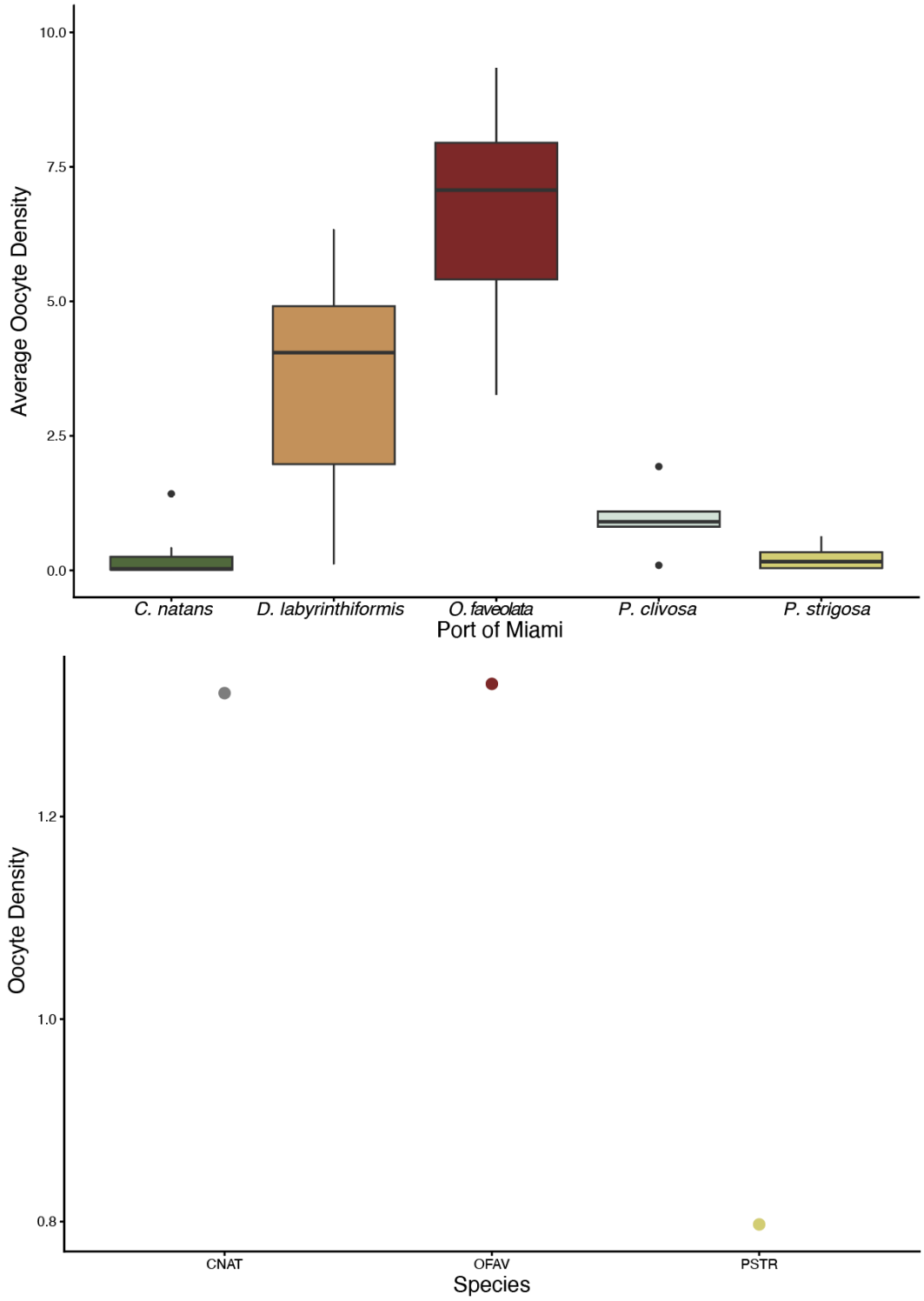

Figure 7. Fecundity per mesentery per cm^2 of coral tissue for cores from Port of Miami and Port of Palm Beach. Port of Palm Beach is not an average measurement due to the low values of reproductive colonies in the Port of Palm Beach.