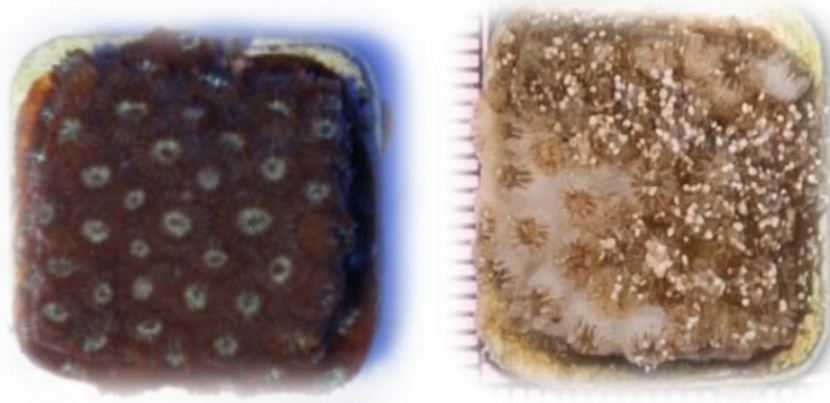
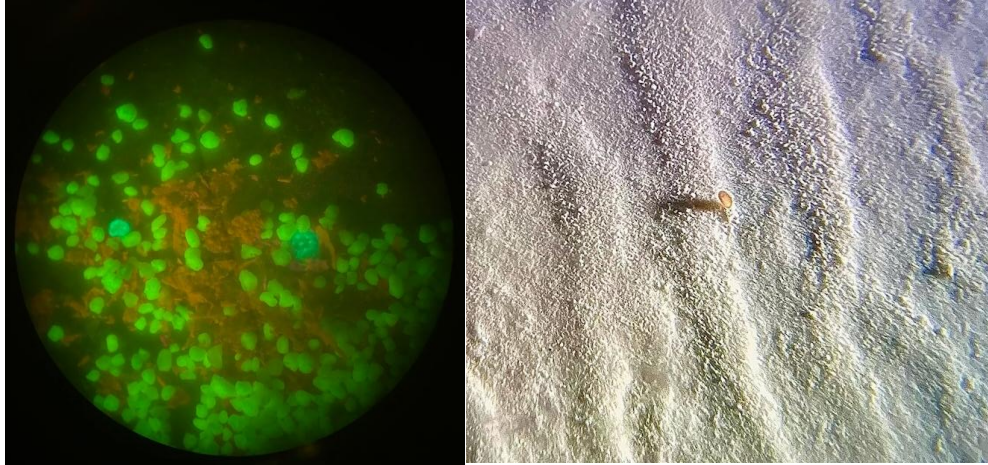


Effect of distinct sediments on Florida's reef corals



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Final Report

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Management Summary

We conducted experimental studies to assess the impact coarse-grain (125–250 μm) and fine-grain (<62 μm) sediments on the settlement success of coral larvae for multiple reef-building species (*Acropora cervicornis*, *Acropora palmata*, *Colpophyllia natans*, *Diplora labyrinthiformis*, *Orbicella faveolata*, and *Pseudodiploria clivosa*). Fine-grain sediment was more detrimental to larval settlement than coarse-grain sediment, with burial under 2 mm of sediment decreasing settlement probability to 10% or less, and 4 mm suppressing settlement entirely. Species listed under the Endangered Species Act (*A. cervicornis*, *A. palmata*, *O. faveolata*) were the most susceptible to sediment burial regardless of sediment grain size. By contrast, recruits were more susceptible to coarse sediments than to fine sediments. Coarse sediment decreased photosynthetic efficiency of coral symbionts by 77–100%, and the burial of recruits under 4 mm of coarse sediment significantly decreased survival probability to 64–32% within ten days. This response, however, varied among size classes with large recruits exhibiting higher survivorship than small recruits, highlighting the importance of size to escape mortality risk from disturbances. Coastal development projects such as the dredging of port channels and beach renourishment efforts can produce sediment layers between 0.5 and 10 cm thick, yet even the relatively shallow sediment layers we tested (≤ 0.4 cm) were enough to cause drastic decreases in larval settlement and recruit survival. These results underscore the strong potential for sediments to reduce or completely inhibit coral recruitment, reflecting the urgent need to identify the main sedimentary sources on reefs to limit future declines in reef-habitat quality. Our data provide an essential tool for managers to assess the impacts of future sedimentation events on the juvenile assemblages of key reef-building species and to assist them in mitigating their future loss to maximize future coral recovery.

Executive Summary

This project aimed to identify the impacts of coarse-grain (125–250 μm) and fine-grain (<62 μm) sediments on larval settlement and recruit survival across multiple species of coral found on Florida's Coral Reef (*A. cervicornis*, *A. palmata*, *C. natans*, *D. labyrinthiformis*, *O. faveolata*, and *P. clivosa*). Overall, fine sediment was a greater deterrent to larval settlement than coarse sediment and species listed under the Endangered Species Act (*A. cervicornis*, *A. palmata*, and *O. faveolata*) were the most susceptible to the burial of substrate regardless of sediment grain size. When coral recruits were buried under different sediment depths of different sediment grain sizes, we found a pattern opposite to larval settlement: coral recruits were more susceptible to

coarse sediment than to fine sediment. Furthermore, large recruits were more likely to survive being buried under sediments for ten days than small recruits. Nevertheless, all recruits exhibited a decline in survival probability when buried under 2 and 4 mm of fine and coarse sediment between 25 and 75%. These findings highlight the need to address sedimentary stressors across the Florida Reef Tract to promote future coral recovery via sexual reproduction. These data could be of further use for predicting how future sedimentation events could impact the stock of juvenile corals, allowing managers to address the impact of multiple proposed scenarios. Importantly, these experiments were conducted using sterilized sediment rather than live sediment with diverse microbiomes that are major drivers of sedimentary biogeochemical processes. Therefore, future research should address variation in coral settlement and survival across live sediments from different sources with distinct microbiomes, such as port-derived and reef-derived sediments. Such endeavors would provide more accurate data on the response of reef-building corals to sediments that are more representative of what is usually present in the natural environment and introduced by anthropogenic disturbances.

Main Findings

Larval settlement assays

Burial of settlement substrate severely reduced the potential for the settlement for all coral species tested and fine sediment was more impactful than coarse sediment. Burial of settlement substrate by 2mm of fine sediment **decreased the predicted probability of settlement by 10–0%. Burial of settlement substrate by 4mm of fine sediments resulted in complete settlement inhibition for all species.**

Lethal effects of sediment grain size on coral recruits

Coarse sediment was more detrimental to recruit survival than fine sediment. Burial under coarse sediment for 10 days severely reduces the survivorship of coral recruits, and **size is an important factor that can increase survival probability.** Predicted survival probability of 1 cm² and 4 cm² corals **decreased by 36–68% after 10 days of burial under 4mm of sediment.**

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Figure 6: Line plots depicting the predicted settlement probability when settlement tiles are buried under varying sediment loads of coarse (yellow curve) and fine (red curve) sediments. Vertical lines indicate the vertical depth of the sediment layer that the respective sediment load translates to. The curves were fitted using generalized linear mixed-effects models with logit link functions for each species to determine the influence of sediment presence and the interaction of grain size on the settlement success of coral larvae. L = estimated model coefficient for sediment load; G S = estimated model coefficient for grain size; significant coefficients are indicated by the boldened p value below them. Acer = *A. cervicornis*; Apal = *A. palmata*; Ofav = *O. faveolata*; Cnat = *C. natans*; Pcli = *P. clivosa*; Dlab = *D. labyrinthiformis*.

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1. BACKGROUND/INTRODUCTION

Coral recruitment and juvenile survival are critical components of resilient coral reefs. The life cycle of broadcast-spawning corals is a complex process that entails the release of sperm and eggs, fertilization, larval development and settlement, recruit survival, and the growth of corals. Settlement success often depends on numerous factors, with a major driver being the availability of suitable substrate for settlement. Coral settlement and survival also depend on factors such as larval supply, water flow, and microhabitat conditions including sediment abundance, substrate position, roughness, color, and benthic composition. Sediments can negatively affect corals through a variety of mechanisms, causing partial or full coral mortality. Although we have a general understanding of the effects of sediments on corals, we lack information on the species-specific effects of sediments on Atlantic coral species. Moreover, we lack information on the effects of sediments on the early life history stages of corals, arguably the time at which they may be most vulnerable to the impacts of sediments. Understanding how sediments affect larval settlement and recruit survival — critical life history stages when corals are most vulnerable to mortality — is essential to establishing biologically relevant benchmarks regarding sediment accumulation and identifying potential actions that can be taken to improve coral survival on Florida's reefs.

In Fiscal Year (FY) 23–24 (PO#: C1F0F3), we conducted a series of aquaria-based experiments to assess the impact of coarse sediment on the settlement of larvae and survivorship of coral recruits of four scleractinian coral species. We found that 2 mm of coarse sediment ($>250\ \mu\text{m}$) dramatically reduced the probability of settlement of coral larvae across the four species by 65–100%. Our results also found that burial of coral recruits under 4 mm of coarse sediment reduced survival by 70–100%. These findings indicate that even a relatively small ($\leq 4\ \text{mm}$) amount of coarse sediment can have consequences for early life history stages of corals. However, using coarse sediments may underestimate the impacts of sedimentation to coral larvae/recruitment compared to fine sediments ($<62\ \mu\text{m}$).

Coarse sediments ($>125\ \mu\text{m}$) are naturally abundant on coral reefs and are usually autochthonous. Fine silt-sized sediments ($<62\ \mu\text{m}$), on the other hand, are naturally scarce on coral reefs and large loads are introduced via coastal runoff or coastal development projects such as port dredging and beach renourishment. Given that the import of allochthonous sediments via coastal runoff and dredging projects are the major drivers of

coral mortality from sedimentation, the overarching goal of this project was to build on our findings from last year to test the lethal impacts of different sediment grain sizes on larval settlement and coral recruits. To do so, we conducted a series of aquaria-based experiments to address two main goals: (1) understand the effect of sediment presence/absence, depth, and grain size on coral larval settlement rates, and (2) Understand the effects of sediment burial and grain size on coral recruit survival. This project addresses research priority 1; objective 1; *‘Reduce Water Quality Impacts and Establish Coral-Specific Water Quality Standards’*, and research priority 1; objective 3; *‘Restoration Planning and Site Selection; Action: Enhance benthic habitat conditions to optimize conditions for natural larval settlement for coral and other reef obligate species’*, which were outlined in FDEP’s Resilience Action Plan for Florida’s Coral Reef (2021–2026). Additionally, the project also addresses research priorities 4: *‘Restoration Planning; 4.2 - Restoration Site Selection’* and 5: *‘Direct Restoration Activities; 5.6 - Optimization of Restoration Sites to Promote Natural Larval Settlement’* of the state of Florida’s restoration priorities for Florida’s coral reef (2021–2026).

1.1. Goal 1: Understand the effect of sediment grain size and depth on larval settlement rates.

Objective 1 – Assess variations in settlement rates of multiple coral species when exposed to substrate surrounded by, or buried, under coarse and fine sediments.

Rationale: Sedimentation reduces suitable habitat space for larval settlement, yet using coarse sediments (125–250 μm ; naturally-occurring on reefs) may underestimate the impacts of sedimentation to coral larvae compared to fine sediments ($<62\ \mu\text{m}$), which are a byproduct of dredging activities and coastal runoff. To understand the mechanisms through which sedimentation inhibits future coral recovery, it is essential to understand the response of larvae from multiple coral species to the presence of sediment around suitable substrate and the burial of this substrate under varying sediment depths within the context of different grain sizes representative of different sedimentary stressors.

1.2. Goal 2: Understand the effect of sediment burial and grain size on recruit survivorship and growth.

Objective 2 – Assess the effect of sediment burial and grain size on the survivorship of coral recruits

Rationale: Although coral larvae may successfully settle onto suitable substrates, post-settlement burial could kill off young recruits. Furthermore, corals may respond differently to sediments with varying physical properties such as grain size. Therefore, it is important to address how different sediment depths for different sediment grain sizes decrease survivorship of coral recruits.

1.3. 1.3 Reef Management Application

Outcomes of this project have multiple potential applications for improved reef management. New knowledge, techniques, and capabilities generated by this project may aid restoration efforts, improve planning for projects that include the potential to generate sedimentation on coral reefs, and may be applied to increase coral resilience through:

- Improved understanding on the influence of sedimentary stress on juvenile corals and, therefore, insights into its contribution to the lack of coral recovery in Florida.
- The quantification of survivorship trends for multiple coral species at different life stages can be used to predict decreases in the stock of juvenile corals through time in the context of sedimentation events.
- Develop and implement practices to minimize the impact of future events that may promote an increase in sedimentary stress on reefs, such as beach renourishment projects and dredging activities.

2. METHODS

The purpose and intended use of the data generated by the described activities are to inform regional and local management, specifically active restoration activities, aimed at improving the health and resilience of Florida's Coral Reef. Activities detailed herein were conducted under the advisement of relevant groups associated with and staff of the Florida DEP Coral Protection and Restoration Program. This was done to ensure that methodologies were not duplicated, best practices were employed, and project results were effectively communicated to all stakeholders. All required state and federal permits were obtained prior to the beginning of the work.

2.1. Task 1 – Conduct coral settlement assays

We conducted settlement rate assays in August and September of 2024 using larvae from coral spawning during the August and September spawning windows. Settlement assays were conducted in individual glass chambers (118 ml capacity, 6.5 x 8 cm, diam. x H). We placed settlement chambers into water baths (35 L capacity, 62 x 43 x 17 cm; L x W x H) in a random block design. Each water bath contained 35 individual chambers, such that a single replicate (n = 70 chambers) was spread across two water baths. Water baths were maintained at 28 °C using digital temperature controllers (Finnex HC-810M, ISK Merchandising Inc. USA) and 300 W titanium heaters (Finnex TH-303005 titanium heater, ISK Merchandising Inc. USA). A powerhead (Eco Wave EW-10 Wave Pump, Sea Side Aquatics, LLC, Anaheim, CA USA) consistently circulated water throughout each bath, and temperature data loggers (HOBO Pendant MX Temperature/Light Data Logger, Onset Corporation, Bourne, MA USA) recorded water temperature every 10 minutes.

Each chamber received a single 3.8 x 3.8 x 0.5 cm ceramic tile (Boston Aquafarms, Boston, MA USA; L x W x H) and then was filled with 100 ml of filtered (20 µm mesh size) and UV-sterilized seawater originating from Bear Cut, Miami, FL USA. This water

source and level of filtration are routinely used by our team for larval settlement and recruit rearing without issue. Before adding sediments to the chambers, the top surface of each tile received a standardized amount of crushed crustose-coralline algae (CCA) to encourage settlement. CCA was harvested from a single aquarium using a razor blade and thus was of consistent origin and identity for all treatments and replicates. To create a gradient of sediment presence and depth of substrate burial, coarse sediment treatments consisted of 0.16 g of sediment, which provided a ‘sprinkle’ of sediment across the settlement substrate, 2.34 g of sediment, which covered the settlement substrate with 2 mm of sediment, or 4.68 g of sediment, which covered the substrate with 4mm of sediment. Fine sediment treatments consisted of 0.11 g of sediment for the ‘sprinkle’ treatments, 1.65 g of sediment for the 2 mm treatments, and 3.30 g of sediment for the 4 mm treatments. Dried sediments were pre-weighed to standardize the amount of sediment added to each settlement chamber. For the “Sediment Present” treatments, sediments were added to the bottom of the chamber surrounding the tile (i.e., no sediments present on top of the settlement substrate), while for the “Sediment Burial” treatments the sediments were added directly on top of the settlement substrate. The “Sediment Present” treatments were designed to explicitly test the effect of the presence of sediments in the chamber but not physically covering the settlement substrate, and the “Sediment Burial” treatments were designed to test the effect of sediments physically covering the settlement substrate (**Figure 1**). Each chamber was assigned one of eight experimental sediment treatments or a control, which received no sediment addition. Altogether, each settlement assay consisted of nine different treatments:

- Control (no sediment present)
- +0.15 g fine sediment present
- +2 mm fine sediment present
- +4 mm fine sediment present
- +0.15 g fine sediment burial
- +2 mm fine sediment burial
- +4 mm fine sediment burial
- +0.15 g coarse sediment present
- +2 mm coarse sediment present
- +4 mm coarse sediment present
- +0.15 g coarse sediment burial
- +2 mm coarse sediment burial
- +4 mm coarse sediment burial

All sediments were collected via SCUBA in August of 2024 from Elbow Reef, Key Largo. Sediments were collected using a glass scoop and were placed into 2-gallon teflon bags that were sealed underwater. Upon surfacing, bags were drained of as much seawater as possible, sealed, and placed on ice for transport to the lab, where they were frozen at -20 °C until they were dried. All sediments were dried at 60 °C until they reached a consistent weight, at which point they were sieved to separate the specific grain size classes of interest: 125–250 µm for coarse sediments and >62 µm for fine sediments.

Since fine sediments are naturally scarce on reefs, sediments were ground down to the desired grain size class using a Cuisinart DCG-20 coffee grinder.

After establishing sediment treatments, coral larvae were placed into each settlement chamber ($n = 20$ larvae/chamber for *Orbicella faveolata*, $n = 15$ larvae/chamber for *Colpophyllia natans*, *Diploria labyrinthiformis* and *Psuedodiploria clivosa*, and $n = 10$ larvae for *A. palmata* and *A. cervicornis*). Larvae were deemed ready for use in experiments when we observed the onset of settlement within the main larvae holding tanks. Coral larvae were removed from their main holding tank via pipette and placed into individual 0.2 ml wells for transfer to experimental settlement chambers. Once larvae were introduced, the chambers were sealed shut to prevent evaporation and changes in salinity. We quantified larval settlement rates in each treatment after 72 hours by closely inspecting each tile using a dissecting microscope and fluorescent lights. For Sediment Burial treatments, we first inspected the surface of the sediments for the presence of any coral settlers. Then, while looking under the microscope, we gently pipetted the sediment off the tile to reveal the settlement substrate below to allow observation of any coral settlers. Settlers were recorded as either “settled”, meaning that they had metamorphosed into a flat, disk-like shape to adhere to the substrate, or “attached”, whereby they had firmly attached themselves to the substrate but had not yet metamorphosed (**Figure 2**). The number of larvae settled and attached was recorded for the upward-facing surface of each settlement substrate, the tile side, and the bottom of the tile (**Figure 3**). Only settlers recorded as settled or attached on the upward facing surface of settlement substrates were included as larvae that successfully settled in the analyses.

2.2. Task 2 – Conduct coral recruit sediment burial assays

We tested the influence of sediment burial on the survival of recruits for *O. faveolata* across three different size classes: 1x1 cm (1 cm^2), representative of 6-month-old recruits, 1.5x1.5 cm (2.3 cm^2), representative of 12-month-old recruits, and 2x2 cm (4 cm^2), representative of 18-month-old recruits. We fragmented established *O. faveolata* colonies into the respective size classes representative of each age group. These fragments were cut from established *O. faveolata* colonies from the 2019 spawning period (approx. 5 years old) that were reared at NOAA’s Southeast Fisheries Science Center. These colonies were reared independently from the larvae we used for the settlement assays specified in Goal 1 in aquaria consisting of 20-gallon tanks with 20-gallon sumps fed filtered (20-micron) and UV-sterilized seawater with a turnover rate of ~6x per day. Lighting was consistent for each cohort via Radion XR30 G6 Pro LED aquarium lights (EcoTech Marine, PA USA), and temperature was kept consistent at ~28 °C using 300W titanium heaters (Finnex TH-303005 titanium heater, ISK Merchandising Inc. USA) controlled by an Apex Neptune controller system. To test survival of recruits and different sized fragments through time, we exposed the corals to sediment burial for 2, 4, 6, 8, and 10 days. Our experimental design was fully orthogonal and thus exposed all possible species combinations, life stages, and burial duration. For these experiments, we exposed coral recruits to five treatments: a control (no sediment present), burial under 2

mm of coarse sediment, burial under 4 mm of coarse sediment, burial under 2 mm of fine sediment, or burial under 4 mm of coarse sediment (**Figure 4**).

We built recruit sediment burial chambers consisting of PVC chambers (5 x 5 cm each) oriented in one 4 x 5 grid and an additional 1 x 5 grid. Each individual chamber was designed to house a single tile, with each column of five chambers containing the five treatments (control, 2 mm coarse, 2 mm fine, 4 mm coarse, and 4 mm fine). Each column within the 4 x 5 grid, and the row of the additional 1 x 5 grid, corresponded to a distinct sampling timepoint (days 2, 4, 6, 8, and 10). We established nine tanks total, with coral fragments haphazardly dispersed across all tanks to minimize the influence of confounding factors. On day 0 before initiating the experiment, all recruits were counted, photographed, and the photosynthetic efficiency (Fv/Fm) of their symbionts was measured using a Junior pulse amplitude modulated fluorometer (Junior PAM; WALZ Photosynthesis Instruments Effeltrich, Germany). The tiles were then placed into their respective chambers and sediment was added to the tiles undergoing experimental treatments (2 mm and 4 mm of coarse and fine sediment, respectively) using a pipette. At each timepoint, sediment was removed from the respective tiles using a siphon. Photos were taken of each sampled coral along with measures of photosynthetic efficiency. Survivorship was assessed by measuring live tissue surface area (cm²) using Coral Point Count with Excel Extensions (CPCe version 4.1). We calculated rates of live tissue loss per day for each size class and treatment. To account for differences in live surface area, we standardized the rate of tissue loss (cm² lost per day) by the initial surface area to yield percent area lost through time. We continued to measure photosynthetic efficiency for all coral fragments that survived sediment burial to track recovery through time. Photosynthetic efficiency was measured weekly for an additional period of 30 days.

3. RESULTS

3.1. Task 1 – Coral settlement assays

Both coarse and fine sediments decreased larval settlement across all species with 4 mm of sediments on the tile causing near-complete inhibition of settlement, yet the response of larval settlement to sediment burial varied among grain sizes. The presence of sediment around the settlement tiles led to a significant decrease in settlement probability for five out of the six species we tested: *A. cervicornis*, *A. palmata*, *C. natans*, *D. labyrinthiformis*, and *P. clivosa*, and the presence of fine sediment around the settlement tiles further decreased settlement probability for four out of the six species we tested: *A. cervicornis*, *A. palmata*, *C. natans*, and *P. clivosa* (**Figure 5**). The presence of fine sediments were able to reduce the probability of larval settlement by 43–75% relative to the reduction caused by coarse sediment. *P. clivosa* was the species that was the most sensitive to the presence of fine sediment, with 4 mm of sediment around the tile inhibiting settlement entirely (**Figure 5e**). The effect of burial of the settlement substrate on settlement was far stronger (**Figure 6**). The species that were the most sensitive to sediment burial were *A. cervicornis* and *O. faveolata*. The predicted settlement probabilities for *A. cervicornis* and *O. faveolata* when no sediment was present were

~50% and 25%, respectively, yet 2 mm of sediment, regardless of grain size inhibited larval settlement entirely for both species (**Figure 6a and c**). Fine sediment significantly decreased settlement probability more than coarse sediment for three species: *C. natans*, *D. labyrinthiformis*, and *P. clivosa* (**Figure 6 d–f**). Fine sediment had the highest impact on the settlement of *P. clivosa* larvae, causing a reduction in larval settlement 86% greater than coarse sediment, with 4 mm of fine sediment suppressing settlement entirely (**Figure 6e**).

3.2. Task 2 – Coral recruit sediment burial assays

The probability of survival for all coral size classes decreased through time when buried under 2 mm and 4 mm of both sediment grain sizes; however, they were more susceptible to coarse sediment than to fine sediment. More surprisingly, their survival probability when buried under 2 mm of coarse sediment was lower than their survival probability when buried under 4 mm of coarse sediment. Overall, coral fragments that were 1 cm² exhibited the highest mortality rates. Their absolute survival probability decreased to 25% when buried under 2 mm of coarse sediment and their absolute survival probability decreased to 62% when buried under 4 mm of coarse sediment (**Figure 7a**). By contrast, absolute survival probability did not decrease when buried under 2 mm of fine sediment and their absolute survival probability decreased to 60% when buried under 4 mm of coarse sediment (**Figure 7a**). Similarly, coarse sediments had a higher impact on the photosynthetic efficiency of their symbionts than fine sediments. Photosynthetic efficiency declined close to 0 by day 4 when corals were buried under coarse sediments, compared to a decline to ~0.400 when buried under fine sediment (Fv/Fm of controls = 0.500; **Figure 7b**). Once corals were removed from the sediment, the symbionts of most fragments fully recovered to their baseline photosynthetic efficiency after 20 approximately days (**Figure 7b**).

For 2.3-cm² fragments, absolute survival probability decreased to 75% when buried under 2 mm of coarse sediment and their absolute survival probability decreased to 32% when buried under 4 mm of coarse sediment (**Figure 8a**). By contrast, absolute survival probability did not decrease when buried under 2 mm of fine sediment and their absolute survival probability decreased to 67% when buried under 4 mm of coarse sediment (**Figure 8a**). Similarly, coarse sediments had a higher impact on the photosynthetic efficiency of their symbionts than fine sediments. Photosynthetic efficiency declined to 0.200–0.100 by day 10 when corals were buried under coarse sediments, compared to a decline to 0.500–0.300 when buried under fine sediment (Fv/Fm of controls = 0.550; **Figure 8b**). Once corals were removed from the sediment, the symbionts of most fragments fully recovered to their baseline photosynthetic efficiency after approximately 10 days (**Figure 8b**).

Overall, coral fragments that were 4 cm² exhibited the lowest mortality rates. Their absolute survival probability decreased to 72% when buried under 2 mm of coarse sediment and their absolute survival probability decreased to 64% when buried under 4

mm of coarse sediment (**Figure 9a**). By contrast, absolute survival probability did not decrease when buried under 2 mm of fine sediment and their absolute survival probability decreased to 79% when buried under 4 mm of coarse sediment (**Figure 9a**). Similarly, coarse sediments had a higher impact on the photosynthetic efficiency of their symbionts than fine sediments. Photosynthetic efficiency declined to 0.100 by day 8 when corals were buried under coarse sediments, compared to a decline to 0.450 when buried under fine sediment (F_v/F_m of controls = 0.525; **Figure 9b**). Once corals were removed from the sediment, the symbionts of most fragments fully recovered to their baseline photosynthetic efficiency after approximately 15 days (**Figure 9b**).

Overall, all size classes exhibited similar trends of tissue loss for all treatments and sediment grain sizes (**Figure 10**). The major driver of variation in rates of loss of surface area was sediment grain size. Coarse sediment depths of 2 and 4 mm caused similar declines in live tissue surface area, decreasing it by 18–23% per day. Fine sediment depths of 2 and 4 mm decreased live tissue surface area by 8–15% per day. Fine sediment depths of 4 mm caused a higher rate of live tissue loss (15% per day) than fine sediment depths of 2 mm (8% per day) for the largest coral fragments (4 cm²).

4. DISCUSSION

4.1. Coral settlement

These experiments were designed to identify relevant biological benchmarks regarding the impacts of sedimentation across different sediment grain sizes on coral settlement to test the impact of sedimentation events from different sources (fine sediments = anthropogenic stressors; coarse sediments = natural stressors) and specifically targeted levels well below what is currently considered relevant for sedimentation (i.e., on the scale of mm instead of cm). Surprisingly, even the minimal amounts of sediment we tested were sufficient to cause severe decreases in larval settlement, and fine sediments significantly amplified the negative impacts of sedimentation on settlement.

The burial of substrate by sediments drastically affected all species and settlement was inhibited by 4 mm of substrate burial for all species. More importantly, all of the ESA-listed, primary reef-building coral species we tested (*A. cervicornis*, *A. palmata*, and *O. faveolata*) were the most susceptible to sedimentation regardless of grain size. The burial of settlement substrate under 2 mm of sediment was enough to completely suppress larval settlement for all of those species. The mere presence of fine sediment decreased the probability of settlement for five out of the six species we tested and completely inhibited settlement for one of the (*P. clivosa*) indicating that sediments may not only be a physical deterrent to settlement but also impact settlement via different mechanisms. Fine sediments easily resuspend into the water column, likely decreasing the surrounding water quality, and their compact, muddy matrix create a layer that the larvae cannot easily penetrate. Further experiments like these that assess changes in water quality through time and use sediments from various origins with different microbial processes (e.g. reef vs port-derived sediments) without any prior sterilization methods (oven-drying) could help shed light on the potential deterring effect of declining water quality,

exacerbated by sediments, on larval settlement. These results, however, are the product of experiments within a small, controlled environment, and coral reef habitats are much larger in scale and highly dynamic. Therefore, conclusions on the relationship between how sediment impacts water quality parameters and how these changes in water quality in turn affect coral settlement require additional research on larger scales.

These experiments reveal that coral larvae of numerous species in Florida are extremely sensitive to even minimal amounts of sediment deposition, and that anthropogenic inputs of sediments (from dredging, beach renourishment, and coastal runoff) can significantly amplify the effects of such deposition. The trends presented here have important management implications and indicate that disturbances that induce sediment stress have the potential to significantly impact or even inhibit the settlement of coral larvae. Therefore, minimizing sedimentation stress on coral-reef habitats during peak settlement periods is prudent to maximize the chances of successful coral recruitment and promote the recovery of coral populations via sexual reproduction.

4.2. Recruit burial, growth rates, and survival

There were significant variations in the survivorship of coral fragments across sediment depths, grain sizes, and coral size classes. Contrary to our predictions based on the trends in larval settlement, coarse sediment was more detrimental to recruit survival than fine sediment. Coarse sediment was able to decrease survival probability 25–75% more than fine sediments, indicating that once coral larvae grow into established recruits, coarse sediment grains, which are naturally abundant on coral reefs, can be a much greater disturbance than fine sediment grains. The dichotomy in these trends across life stages indicate that sediments with different physical properties, and from different sources (reef vs port-derived), can exert differential impacts depending on the predominant coral life stages present, and that one sediment grain size is not necessarily less impactful than another. Coral fragment size was also a key factor to survivorship. Corals that were 4 cm² exhibited survival rates that were 19–67% higher than the survival rates if 1 cm² corals, indicating that achieving a large-enough size is essential for coral recruits to escape increased mortality risks from disturbances.

Although some corals survived the burial assays, the trends in photosynthetic efficiency and rates of tissue loss indicate that sediments can still severely impact the metabolic parameters of surviving fragments that are essential for future growth and overall health. Sediment burial, especially under coarse sediment, can steeply decrease and, sometimes suppress, photosynthetic activity. Similarly, burial under coarse sediment severely reduces live tissue area, which could be highly detrimental for large coral fragments. Sedimentation stress could revert coral recruits to smaller size classes or fragment large coral colonies into smaller individuals, which are less likely to survive future disturbance events, regardless if said future disturbances are driven by sedimentation.

The assessment of the impacts of the lethal and subtle, sublethal impact of sediments across multiple life stages, and how these effects change with the physical properties of

sediment, provides much needed data to inform managers in the risks associated with disturbances that lead to increased sediment stress on coral-reef habitats. These data can also benefit future research that would be highly impactful for managers, such as using the risk factors we estimated for each species and size class to predict future decreases in the stock of juvenile corals in the face of future sedimentation events. Our experiments were conducted using oven-dried sediment, which depletes the microbiota present within the sediment matrix, yet microbial processes are major drivers of the variations in sediment biochemistry. Therefore, future research should focus on assessing biogeochemical variations in unsterilized sediments from different sources to accurately identify the impact of these processes on coral metabolism and overall survival across early life stages. These efforts could further disentangle the impact of anthropogenic disturbances to subtle, small-scale processes in the sediment-water interface and their contribution to large-scale repercussions on Florida's Coral Reef.

5. MANAGEMENT RECOMMENDATIONS

- Develop strategies for coastal development projects, in particular large-scale dredging projects, to avoid sediment deposits and habitat burial in areas that support reefs.
- Include sediment depth and grain-size distribution monitoring as part of dredge projects and broader coral reef monitoring programs to help assess changes in the ability of the habitat to support recruits and juvenile corals.
- Consider time of year restrictions for dredging that would allow for coral spawning, larval competency period, and recruitment to occur without additional stress from sediment.
- Adaptively manage dredging projects to allow for timely course corrections if sediment deposits or habitat burial occurs in hardbottom areas.
- Conduct complementary studies using fine-grained and coarse-grained material on tiles conditioned with long, sediment-laden algal turfs.

6. TABLES AND FIGURES

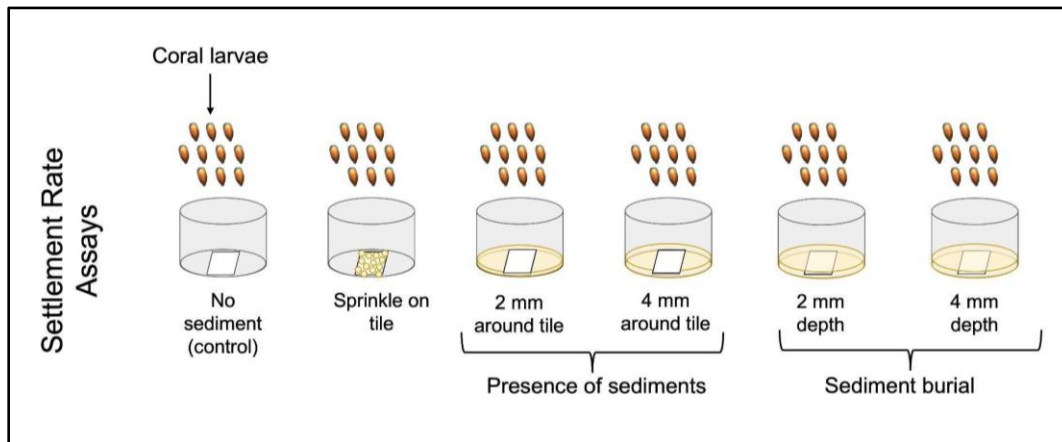


Figure 1: Schematic representation of the larval settlement assays depicting the different treatments established to test the response of larval settlement to the presence of sediments around the substrate and the burial of the substrate by sediments.

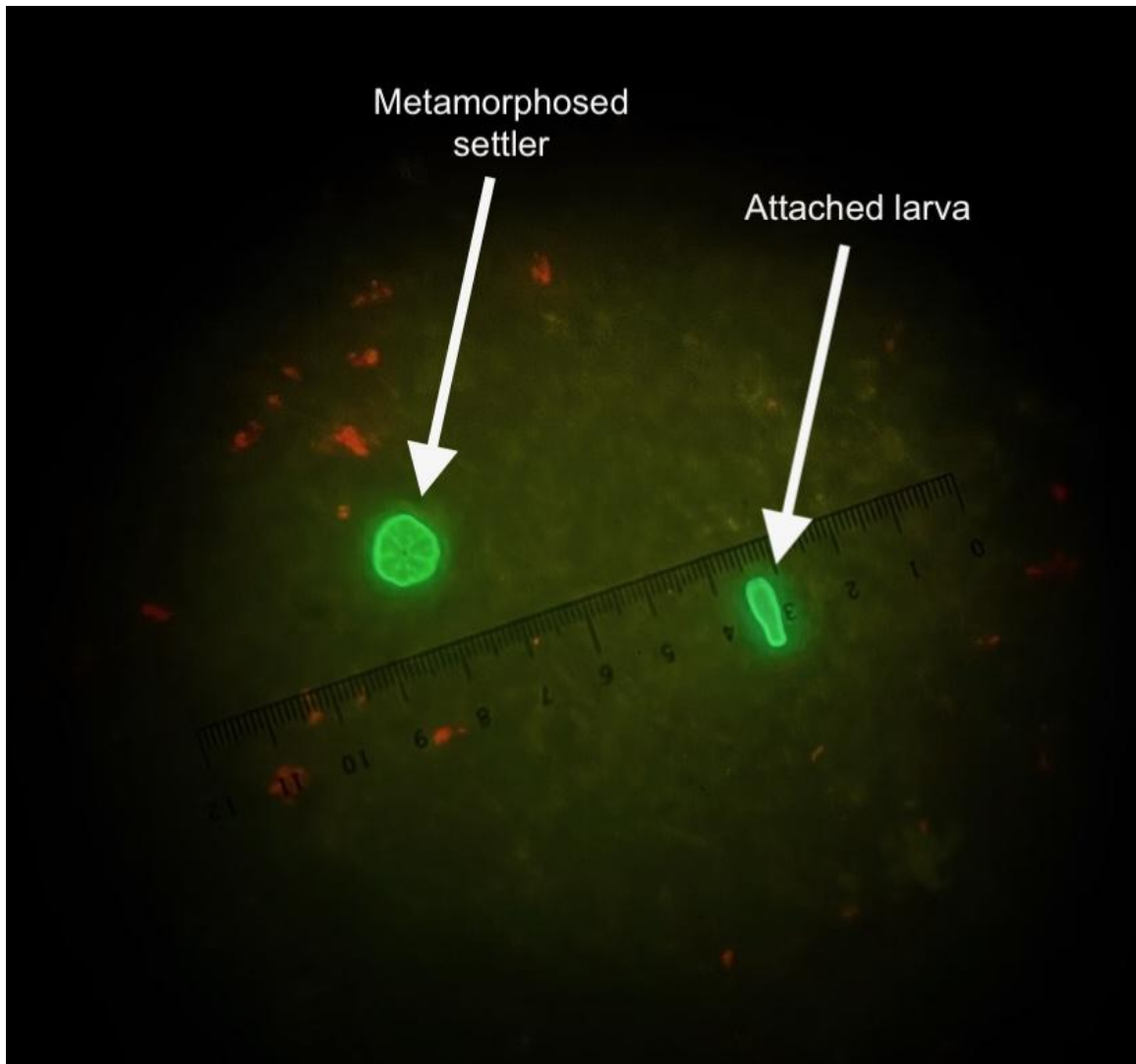


Figure 2: Photograph of a settlement tile after 72 hours depicting a fluorescent green larva that has attached but not metamorphosed and a disk-shaped, metamorphosed settler.

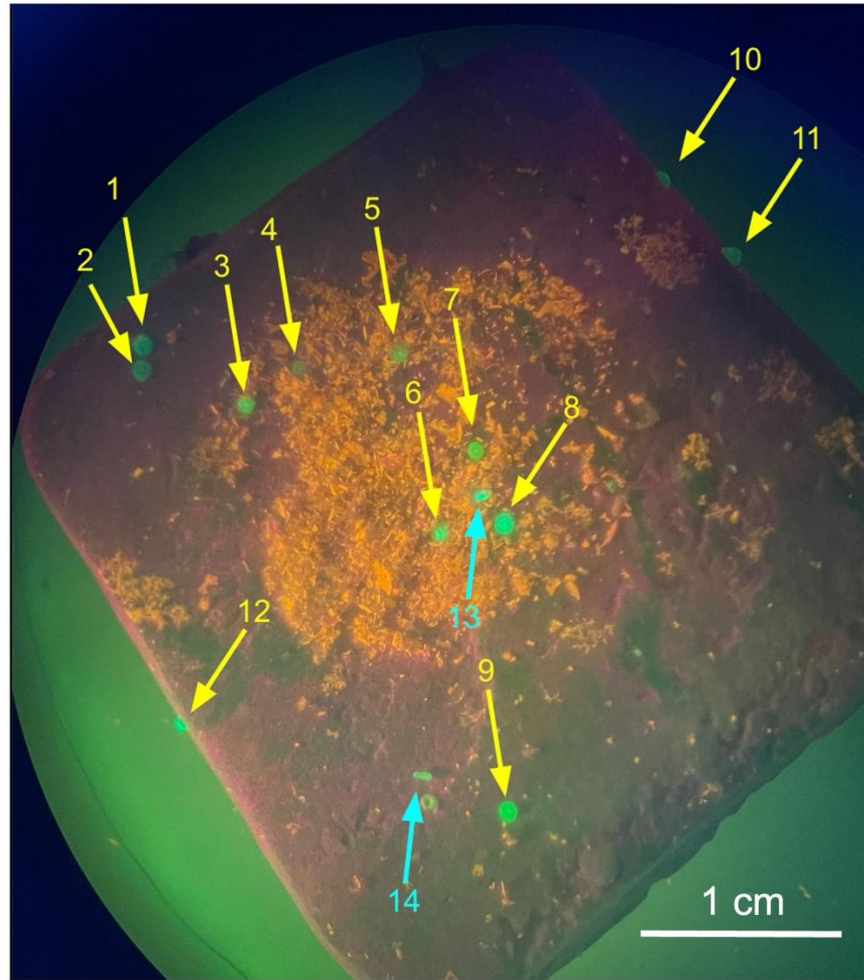


Figure 3: Photograph of a settlement tile (control treatment) after 72 hours. The fluorescent green dots are coral larvae that have settled or attached onto the tile. The yellow arrows point to larvae that have successfully settled and metamorphosed into a flat, disk-like shape to adhere to the substrate. The cyan arrows point to larvae that have firmly attached themselves to the substrate but have not yet metamorphosed. The orange areas are crushed CCA allocated to each tile to encourage coral settlement.

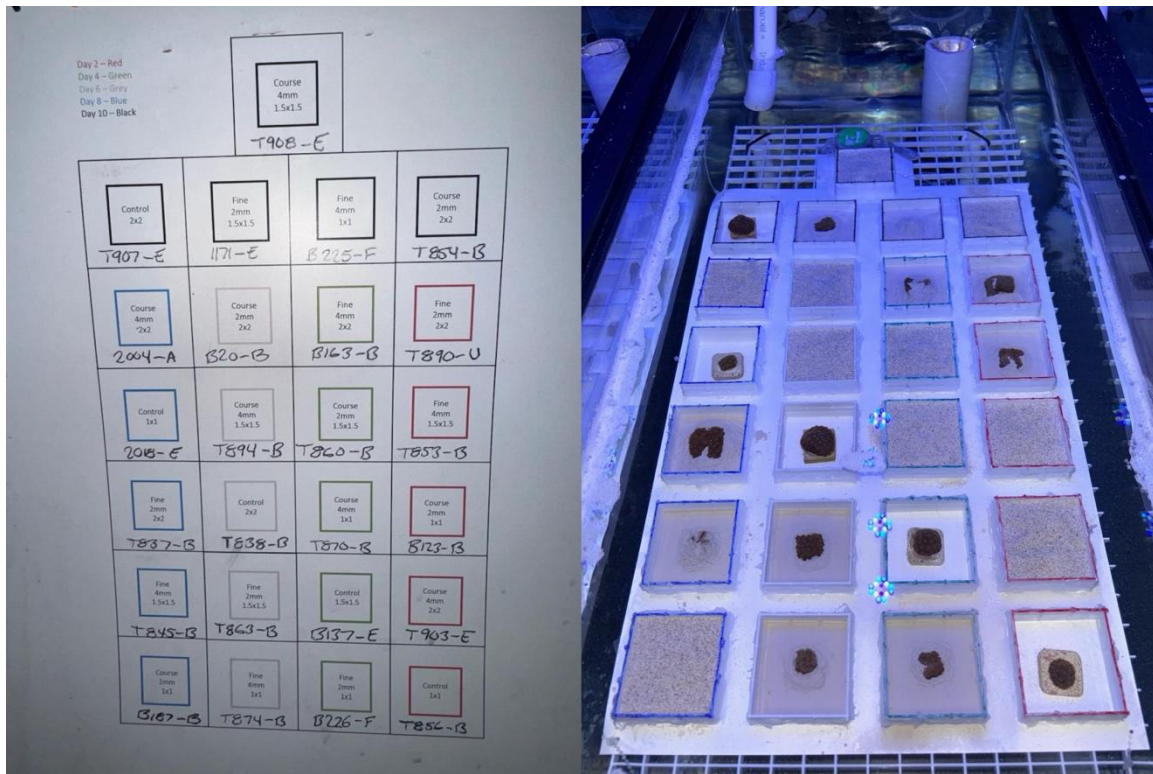


Figure 4: Photograph and schematic representation of a representative replicate of a sediment burial assay depicting the different treatments we set up for each replicate to test the effects of sediment burial and grain size coral survival.

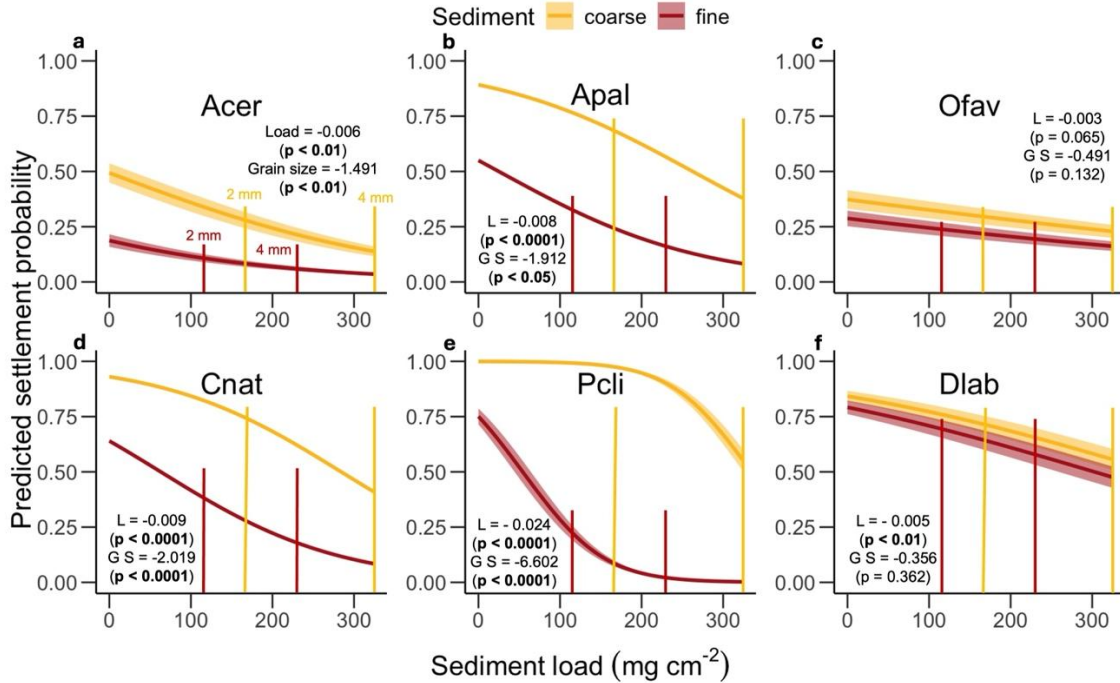


Figure 5: Line plots depicting the predicted settlement probability when settlement tiles are surrounded by varying sediment loads of coarse (yellow curve) and fine (red curve) sediments. Vertical lines indicate the vertical depth of the sediment layer that the respective sediment load translates to. The curves were fitted using generalized linear mixed-effects models with logit link functions for each species to determine the influence of sediment presence and the interaction of grain size on the settlement success of coral larvae. L = estimated model coefficient for sediment load; GS = estimated model coefficient for grain size; significant coefficients are indicated by the boldened p value below them. Acer = *A. cervicornis*; Apal = *A. palmata*; Ofav = *O. faveolata*; Cnat = *C. natans*; Pcli = *P. clivosa*; Dlab = *D. labyrinthiformis*.

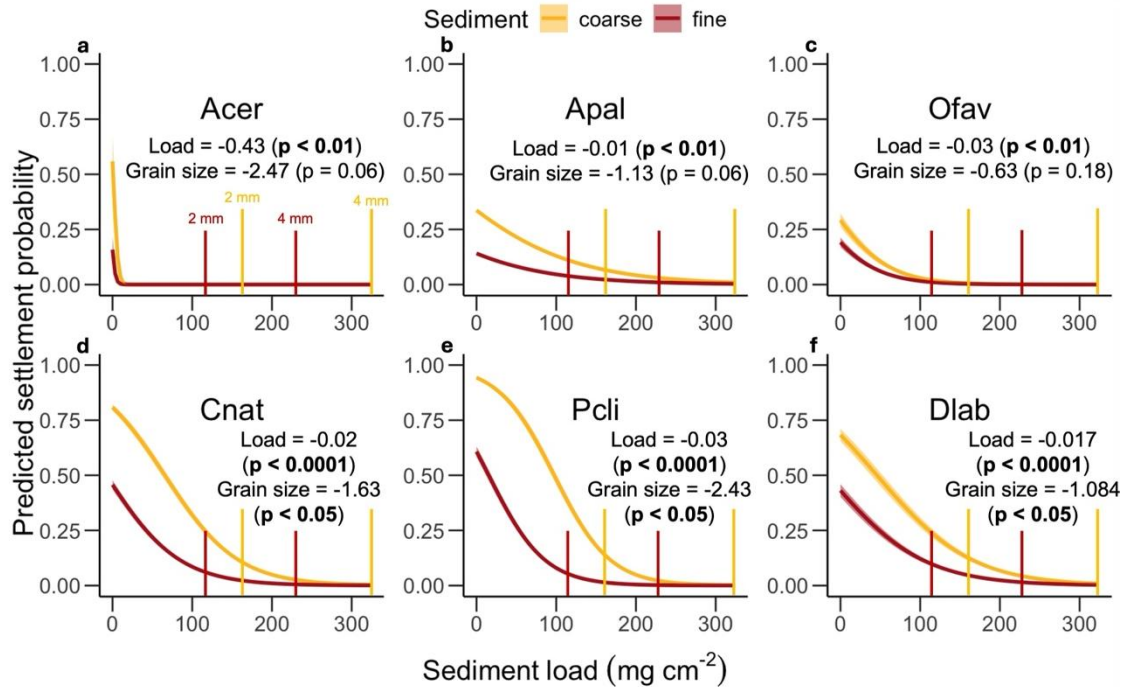


Figure 6: Line plots depicting the predicted settlement probability when settlement tiles are buried under varying sediment loads of coarse (yellow curve) and fine (red curve) sediments. Vertical lines indicate the vertical depth of the sediment layer that the respective sediment load translates to. The curves were fitted using generalized linear mixed-effects models with logit link functions for each species to determine the influence of sediment presence and the interaction of grain size on the settlement success of coral larvae. L = estimated model coefficient for sediment load; G S = estimated model coefficient for grain size; significant coefficients are indicated by the boldened p value below them. Acer = *A. cervicornis*; Apal = *A. palmata*; Ofav = *O. faveolata*; Cnat = *C. natans*; Pcli = *P. clivosa*; Dlab = *D. labyrinthiformis*.

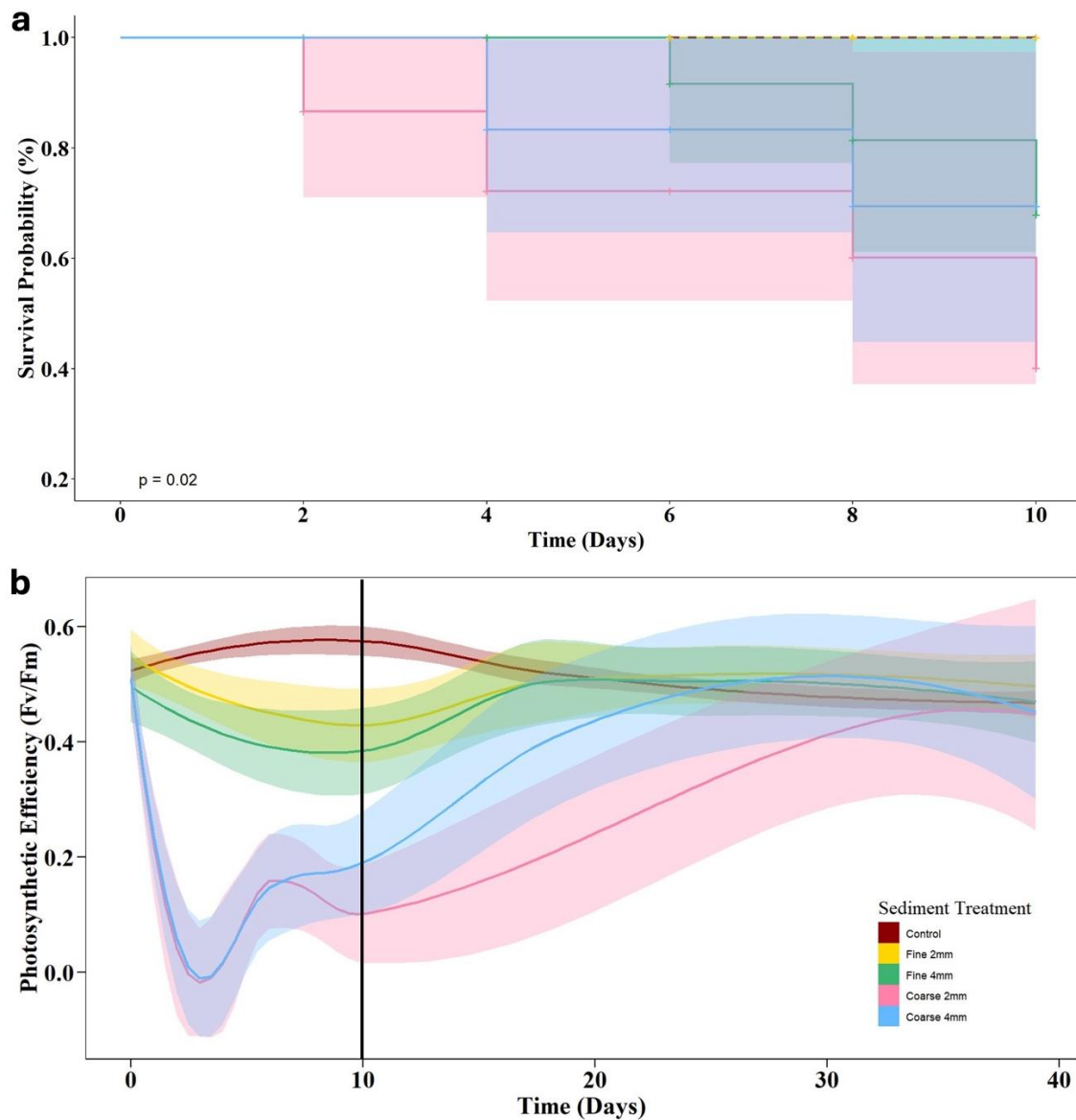


Figure 7: a) Kaplan-Meier curve depicting decreases in survival probability for 1 cm² *O. faveolata* fragments that were buried either under 2 mm of coarse sediment, 4 mm of coarse sediment, 2 mm of fine sediment, or 4 mm of fine sediment; **b)** plot depicting trends in the photosynthetic efficiency (Fv/Fm) of 1 cm² *O. faveolata* fragments for each treatment. Trend lines were fitted using locally estimated scatterplot smoothing (LOESS) and the black vertical line at x = 10 represents the end of the timeframe when fragments were subjected to sediment burial.

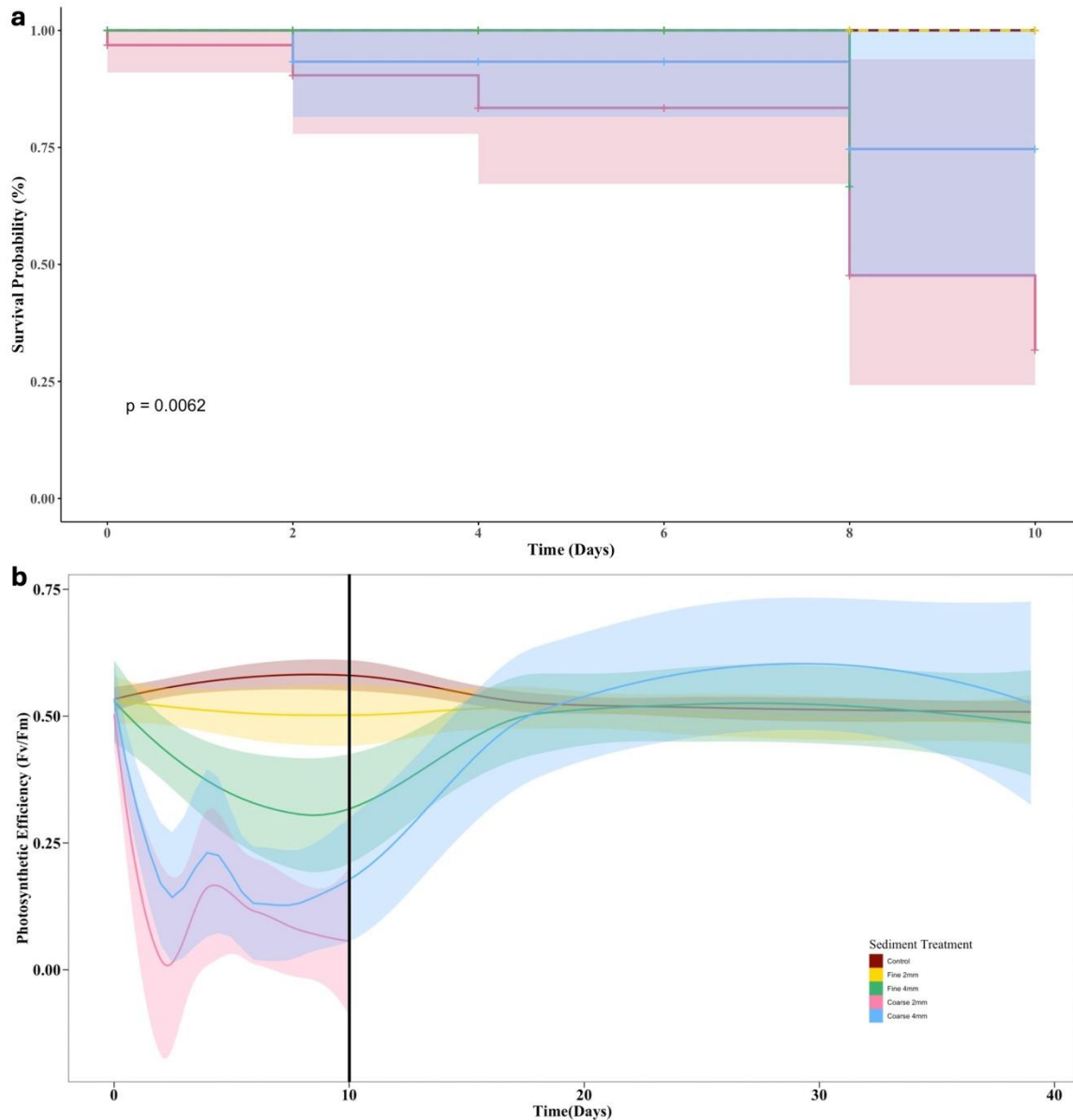


Figure 8: a) Kaplan-Meier curve depicting decreases in survival probability for 2.3 cm² *O. faveolata* fragments that were buried either under 2 mm of coarse sediment, 4 mm of coarse sediment, 2 mm of fine sediment, or 4 mm of fine sediment; **b)** plot depicting trends in the photosynthetic efficiency (Fv/Fm) of 2.3 cm² *O. faveolata* fragments for each treatment. Trend lines were fitted using locally estimated scatterplot smoothing (LOESS) and the black vertical line at x = 10 represents the end of the timeframe when fragments were subjected to sediment burial. Note: the coarse 2 mm treatment ends at day 10 because all individuals of that cohort were dead by than time step, therefore, no more measurements of photosynthetic efficiency were conducted in subsequent assessments.

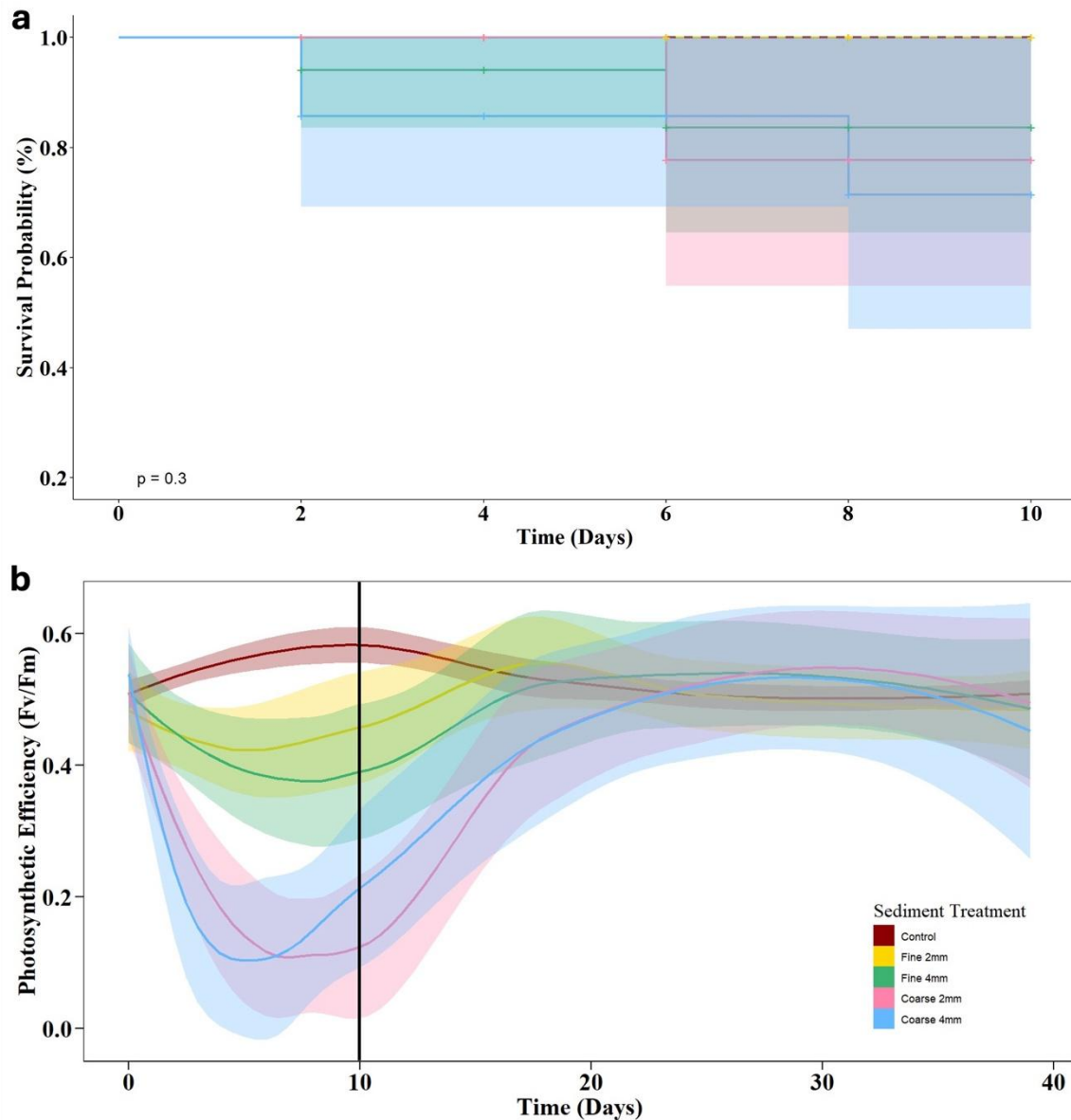


Figure 9: a) Kaplan-Meier curve depicting decreases in survival probability for 4 cm² *O. faveolata* fragments that were buried either under 2 mm of coarse sediment, 4 mm of coarse sediment, 2 mm of fine sediment, or 4 mm of fine sediment; **b)** plot depicting trends in the photosynthetic efficiency (Fv/Fm) of 4 cm² *O. faveolata* fragments for each treatment. Trend lines were fitted using locally estimated scatterplot smoothing (LOESS) and the black vertical line at x = 10 represents the end of the timeframe when fragments were subjected to sediment burial.

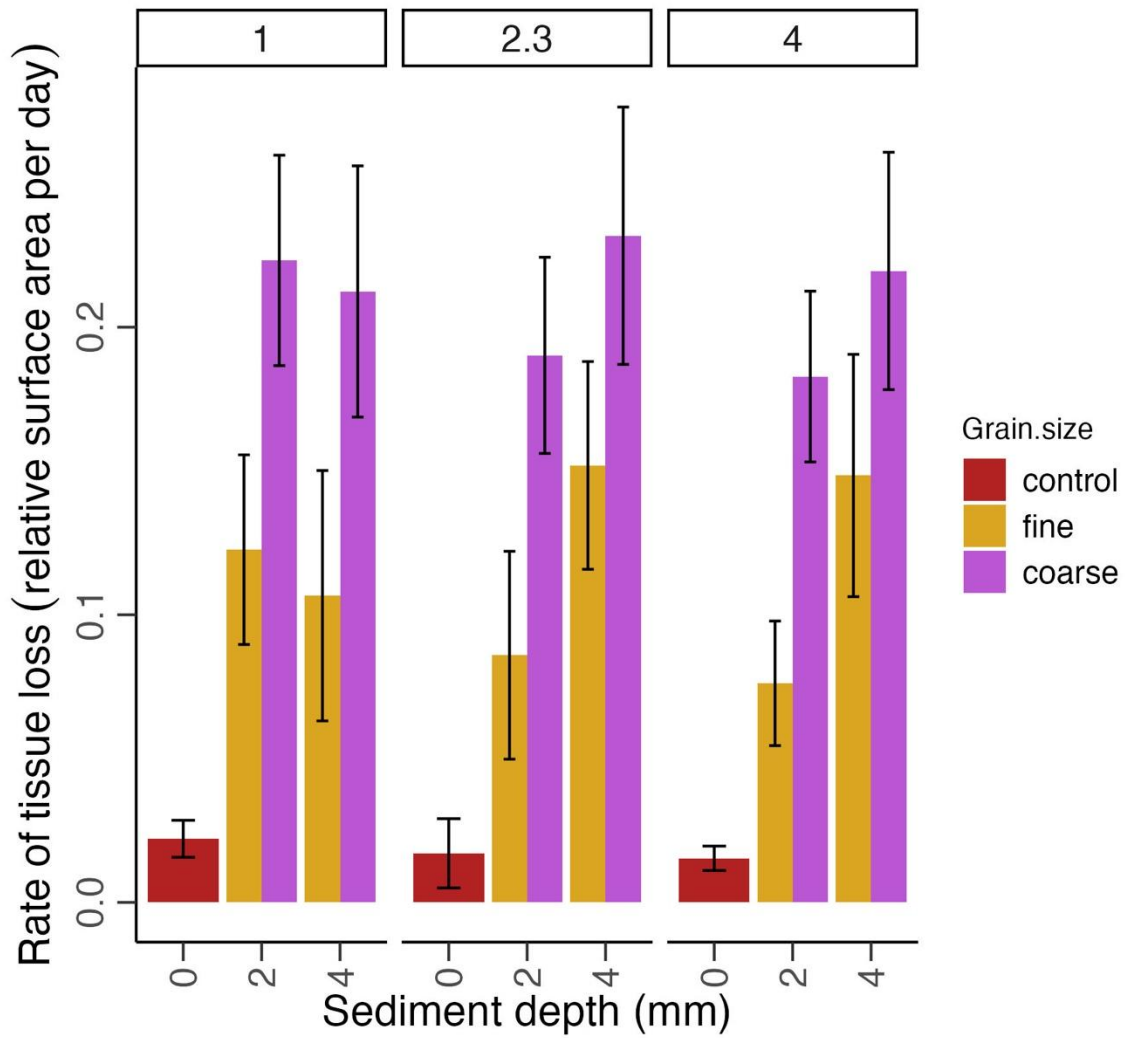


Figure 10: Bar plot depicting mean ($\pm$ standard error) rate of tissue loss (relative surface area per day), standardized by the initial surface area of each fragment, across sediment depths, sediment grain sizes, and coral size classes.