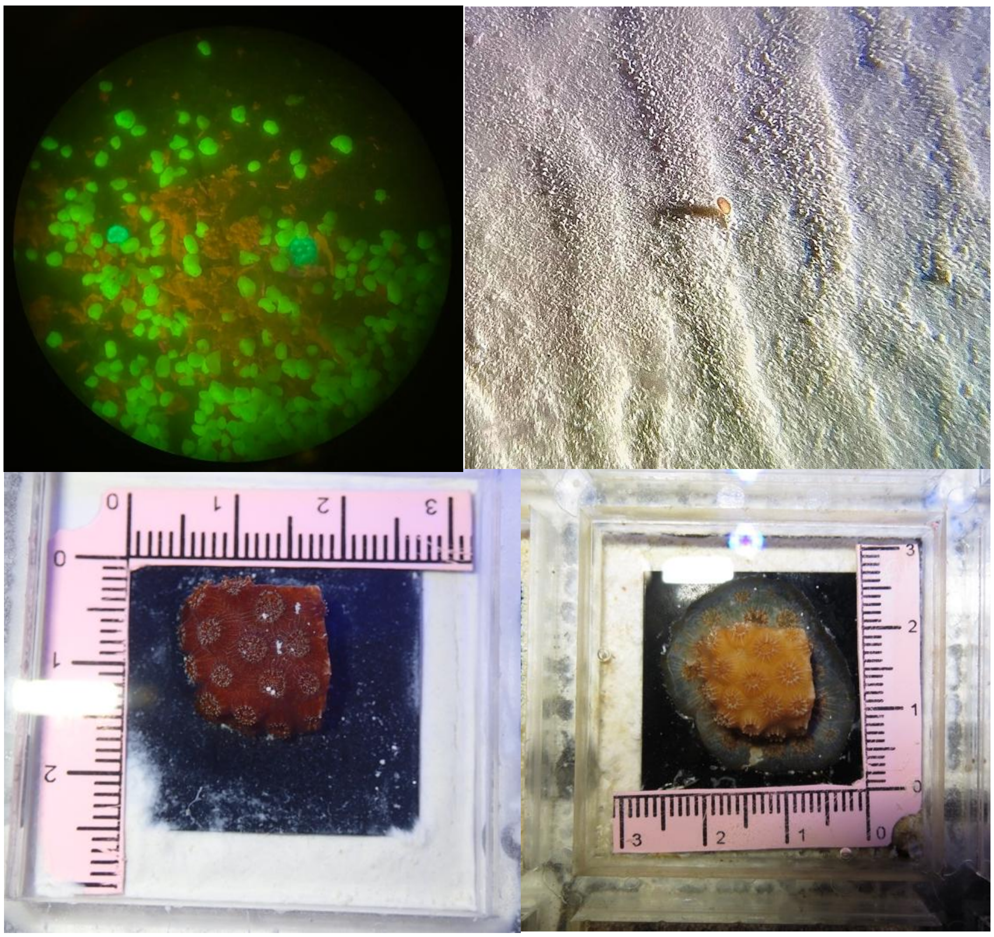
Assessing the effects of sediment grain size on coral settlement and recruit survival across multiple Caribbean species



Assessing the effects of sediment grain size on coral settlement and recruit survival across multiple Caribbean species

Final Report

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Management Summary
We conducted experimental studies to assess the impact of 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. Furthermore, we assessed the sublethal effects of sediment presence on the survival, photosynthetic efficiency, and growth rates of *O. faveolata* recruits over a two-month timespan. *O. faveolata* recruits that were 10 mm away from sediment grew 77% more than corals that had sediment touching all of their sides. Photosynthetic efficiency oscillated among treatments for 60 days and began to decline for all treatments after 70 days. Although adjacent sediments did not kill any corals, they severely limited growth, which is essential for coral recruits to mitigate their susceptibility to predation and competition. Anthropogenic impacts, such as the dredging of port channels can produce sediment layers 0.5–10 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 sediment to reduce or completely inhibit coral recruitment and post-settlement growth, 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 reef-building species, mitigate their future loss, and 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. In addition, we assessed the effects of the presence of sediment on the health of *O. faveolata* recruits over a two-month timespan. No recruits died during the two months and photosynthetic

efficiency only began to decline after 70 days, yet coral recruits with sediment touching all of their sides grew much less than corals with sediment 2–10 mm away from them. Although sediment burial is far more detrimental to coral health and survival than sediment presence (without burial), the presence of sediments can still severely undermine the ability of coral recruits to develop into large-sized adults. These trends provide tangible evidence of the extreme susceptibility corals have to sediment stress for at least the first 1.5 years of their lifespan. 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.

Main Findings

Larval settlement assays

Burial of settlement substrate severely reduced settlement rates 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.**

Sublethal effects of sediment on coral recruits

Sediment proximity to coral recruits severely limited their growth potential regardless of sediment grain size. **Within a two-month period, corals with sediment 10 mm away from them grew 77% more than corals with sediment touching all of their sides**. Variations in the concentration of dissolved oxygen (DO) within the sediment matrices indicated that a photosynthetic microbial community had developed within said matrices. **Within the first 1.5 mm layer of sediments, DO increased by 27–53% during the daytime, yet DO decreased by 20–38% during the nighttime. Fine sediments had the highest DO concentrations during the daytime but coarse sediments had the lowest DO concentrations during the nighttime.**

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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 µm) 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 (≤4 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 µm).

Coarse sediments (>125µm) are naturally abundant on coral reefs and are usually autochthonous. Fine silt-sized sediments (<62µm), 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 and sublethal 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 effect of adjacent sediments and their grain size on coral recruit survival and growth. 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 µm), 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 adjacent sediments and their grain size on recruit survivorship and growth.

Objective 2 – Assess the effect of sediment proximity on the photosynthetic efficiency, growth rate, and survivorship of 6-month-old recruits

> *Rationale:* Although coral larvae may successfully settle onto suitable substrates, the deposition of sediments on the surrounding substrate could impact habitat quality, potentially decreasing growth rates and impairing the coral-zooxanthellae symbiotic relationship due to the loss of suitable substrate and changes in the adjacent water chemistry. Therefore, it is important to address how the distance between coral recruits and sediments influence growth rates and overall survivorship.

Objective 3 – Assess variations in oxygen concentrations of the sediments adjacent to coral recruits

> *Rationale:* Other than the physical stressors sediments exert on corals, the geochemical processes occurring within sedimentary matrices could also contribute to coral stress. Therefore it is important to identify variations in

microbial activity within sediments of different grain sizes to identify the potential contribution of these processes to declines in habitat quality and subsequent coral survival.

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 proximity assays

To evaluate the effect of sediment grain size and proximity on the health and survivorship of young corals, we conducted sediment exposure experiments using fragments of *O. faveolata* that were cut to sizes that approximate 6-months-old corals (approx. 1 cm^2 live tissue area). 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.

Our species selection was based on the availability of recruits generated from summer 2023 coral spawning activities and species' relevance in terms of ecological importance and susceptibility to current stressors. For instance, *O. faveolata* is a key reef-building species on Florida's reefs listed under the Endangered Species Act (ESA), and their populations have been on a steep decline over the last few decades from bleaching events, disease outbreaks, and poor water quality among other stressors.

Using a laser cutter, we constructed experimental trays containing a series of equal-sized compartments from transparent acrylic sheets , each sized to fit a single 3.8 x 3.8 cm x 0.5 cm (L x W) black acrylic tile. Smaller acrylic 'islands' were glued to each tile and a coral was attached to each island. The size of the 'island' varied depending its assigned treatment. The tile dimensions for each treatment varied based on the desired distance to place between the coral fragment (10 x 10 mm) and the adjacent sediments. There were a total of 10 treatments:

- A control with no sediments present (10 x 10 mm),
- Fine sediments touching all borders of the coral fragment (10 x 10 mm),
- Fine sediments 2 mm away from all borders (14 x 14 mm)
- Fine sediments 5 mm away from all borders (20 x 20 mm),
- Fine sediments 10 mm away from all borders (30 x 30 mm).
- A control with no sediments present (10 x 10 mm),
- Coarse sediments touching all borders of the coral fragment (10 x 10 mm),
- Coarse sediments 2 mm away from all borders (14 x 14 mm)
- Coarse sediments 5 mm away from all borders (20 x 20 mm),
- Coarse sediments 10 mm away from all borders (30 x 30 mm).

Each tray contained a total of 60 compartments housing 60 tiles with corals on islands in a 10 x 6 grid. Each column contained a representative sample of each treatment, and they were haphazardly organized to emulate a randomized-block design. Each column (6 per tank) represented an individual 10-day sampling period across 60 days, and five of these replicates were placed in individual tanks (n = 5 tanks). Sediments were carefully added in the space between the islands and the compartment walls using a pipette until the surface of the sediments was flush with the surface of the island the corals were settled on (**Figure 4**).

On day 0, we mapped the location of all the coral fragments and their designated treatment. Each coral received a unique ID number to keep track of each individual through time (**Figure 4**). We then photographed each fragment with a 3-cm ruler on the side as a reference for surface area measurements. All fragments were re-photographed on day 60 and the surface area was calculated from the images using the area measurement tool from Coral Point Count with Excel Extensions (CPCe version 4.1) Using a diving Pulse Amplitude Modulator (Diving PAM II WALZ Photosynthesis Instruments Effeltrich, Germany), we measured the photosynthetic efficiency (Fv/Fm) for the corals within their 10-day interval (i.e. all corals located in the columns labeled as "1" were sampled on day 10, all corals located in the columns labeled as "2" were sampled on day 20, etc. **Figure 4**). We extended the experiment beyond the initial 60 days and measured photosynthetic efficiency all of the corals on day 70 to assess any potential changes in health parameters that might be detected after the initial 60 days that this project aimed to address.

We measured daytime and nighttime dissolved oxygen (DO) concentration (μmol L^{-1}) for one replicate of each treatment on days 30 and 60 with amperometric oxygen microsensors (O_2 Microsensor, Unisense Aarhus, Denmark). For fine sediments, we used microsensors with tips that were 50 μm in diameter and for coarse sediments we used microsensors with tips that were 100 μm in diameter. The microsensors were connected to an Fx-6 Uniamp meter (Unisense Aarhus, Denmark) to read and log the data. Before measuring DO, we conducted a two-point calibration. For the high calibration point, we immersed the microsensor in air-saturated seawater of known salinity and temperature; once the signal stabilized, we recorded the upper calibration point using the SensorTrace logging software. For the zero-calibration point, we used the Unisense zero O_2 solution calibration kit (Unisense, Aarhus, Denmark), which contains a slightly alkaline ascorbate that depletes DO. We immersed the microsensor in the solution until the signal stabilized and recorded the lower calibration point in the SensorTrace software. We measured DO along six stations within each coral-sediment compartment every 2 mm between the coral fragment and the compartment wall (**Figure 5**). Along each station, DO was measured every 250 μm within the last 1–1.5 mm of the bottom of the water column and within the first 1–1.5 mm of the sediment matrix, totaling 2–3 mm within the water-sediment interface. When stations fell along the islands (no sediment), we sampled the last 2 mm of the bottom of the water column.

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 6**). 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 6e**). Burial of the settlement substrate had a much stronger effect on settlement probability (**Figure 7**). 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 7a and c**). Fine sediment significantly decreased settlement probability more than coarse sediment for three species: *C. natans*, *D. labyrinthiformis*, and *P. clivosa* (**Figure 7 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 7e**).

3.2. **Task 2 – Coral recruit sediment exposure assays**

There was a significant difference in coral growth rates among treatments but not among sediment grain sizes (sediment: $F_{1,4} = 0.013$, $p = 0.910$; treatment: $F_{4,30} = 0.998$, $p < 0.0001$; **Figure 8**). Coral fragments subjected to the 10 mm treatment grew by 53% of their original size, which was the most growth exhibited out of all treatments (0.64 ±0.09 cm^2). The 5 mm and 2 mm treatments grew by 39 and 35% of their original size, respectively (0.45 ±0.05 and 0.41 ±0.03 cm^2), and the control and touch treatments both grew by 13% their original size, respectively (0.16 ±0.02 and 0.15 ±0.02 cm^2). Corals that had sediment 10 mm away from them grew 77% more than corals that had sediments touching all of their sides, highlighting the high potential that sediments possess to inhibit recruit growth. Photosynthetic efficiency varied based on coral distance from sediment and through time but not by sediment grain size (day: $F_{7,316} = 24.553$, $p < 0.0001$, treatment: $F_{4,316} = 5.118$, $p < 0.001$; **Figure 9**). Photosynthetic efficiency spiked during days 10 (0.637 ±0.006), 20 (0.639 ±0.007), and day 40 (0.625 ±0.007) relative to day 0 ($F_v/F_m = 0.593$ ±0.005) and significantly decreased for all treatments on day 70 (0.554 ±0.003). At the treatment level, all treatment exhibited similar levels of photosynthetic efficiency and the only treatment with detectable differences, surprisingly, was the 10 mm one, which exhibited the lowest photosynthetic efficiency out of all treatments (F_v/F_m at day 0 = 0.583 ±0.012, F_v/F_m at day 70 = 0.553 ±0.006) and was significantly different from the photosynthetic efficiency of the controls, which exhibited the highest photosynthetic efficiency overall (F_v/F_m at day 0 = 0.607 ±0.013, F_v/F_m at day 70 = 0.563 ±0.006).

DO concentrations were highly dynamic under different light conditions (**Figures 10–13**). During the daytime, DO increased by 38% (320.01±12.03 µmol L^{-1}) within the first mm of coarse sediment and by 53% (355.45 ±10.04 µmol L^{-1}) within the first mm of fine sediment relative to the DO concentration in the water column (232.30 ±5.76 µmol L^{-1}). During the nighttime, DO decreased by 38% (133.29 ±6.153 µmol L^{-1}) within the first mm of coarse sediment and by 20% (171.50 ±4.27 µmol L^{-1}) within the first mm of fine sediment relative to the DO concentration in the water column (215.02 ±2.96 µmol L^{-1}). By day 60, during the daytime, DO increased by 27% (267.12 ±8.35 µmol L^{-1}) in coarse sediment and by 47% (309.76 ±8.50 µmol L^{-1}) in fine sediment relative to the DO concentration in the water column (211.10 ±2.11 µmol L^{-1}). During the nighttime, DO decreased by 23% (147.47 ±3.60 µmol L^{-1}) in coarse sediment and by 20% (152.94 ±5.55 µmol L^{-1}) in fine sediment relative to the DO concentration in the water column (191.73 ±0.41 µmol L^{-1}). Overall, DO concentrations during the daytime were significantly higher within the first mm of fine sediment than within the first mm of coarse sediment (KS test $D = 0.40$, $p = 0.01$), and DO concentrations during the nighttime were significantly lower within the first mm of coarse sediment than within the first mm of fine sediment (KS test D = 0.47, $p < 0.001$; **Figure 14**).

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 inhibitted 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 health and survival

The presence of sediments around coral recruits did not induce any mortality within the first 60 days and the main health parameter that was affected was the growth of the coral fragments. Although these trends might suggest that the presence of sediments around coral recruits may not be as detrimental as sediment burial, corals unobstructed by sediment within the first 10 mm grew 77% more than corals obstructed by sediments on all sides. Growth is an essential process for juvenile corals to transition onto larger size classes that increase their chances of surviving other disturbances such as predation and overgrowth by other benthic competitors. Photosynthetic efficiency of the coral symbionts oscillated across the 60-day timeframe and a detectable, steady decrease was not recorded until 70 days later. Surprisingly, the only corals with detectable decreases in photosynthetic efficiency were the ones with sediment furthest away from them (10 mm), which were also the corals that grew the most out of all treatments. It is necessary to conduct more detailed studies that quantify how the presence of sediments influences various metabolic parameters of the coral holobiont over longer timescales, which could unravel the dynamic interactions among these parameters and accurately assess their contributions to coral development and overall health.

The dynamic DO patterns within the sediment suggest that photosynthetic microbial communities had established within the sediment matrices by day 30 and persisted through day 60. We detected marked decreases in DO concentration, likely due to high respiration rates, within the first mm of the sediment matrix. It is also important to keep in mind that these sediments were oven-dried at the beginning of the experiment, and these trends are likely due to the microbes that colonized the sediment throughout the course of the experiment. Contrary to our predictions, coarse sediments exhibited the steepest drops in DO concentration during the nighttime. Although fine sediment may limit O_2 exchange with the water column more than coarse sediment, the high porosity of coarse sediment may ease the trickle-in of organic matter that may promote higher respiration rates. Given that sediment loads >1 mm are prevalent on Florida's reefs, these findings underscore the need to conduct studies that assess O_2 dynamics within deeper sediment matrices across different locations with different microbial assemblages. These efforts could identify the contribution of O_2 depletion to coral stress and how it varies among sediments from different sources (port/terrigenous vs reef).

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 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 material and tiles conditioned with long, sediment-laden algal turfs.

6. TABLES AND FIGURES

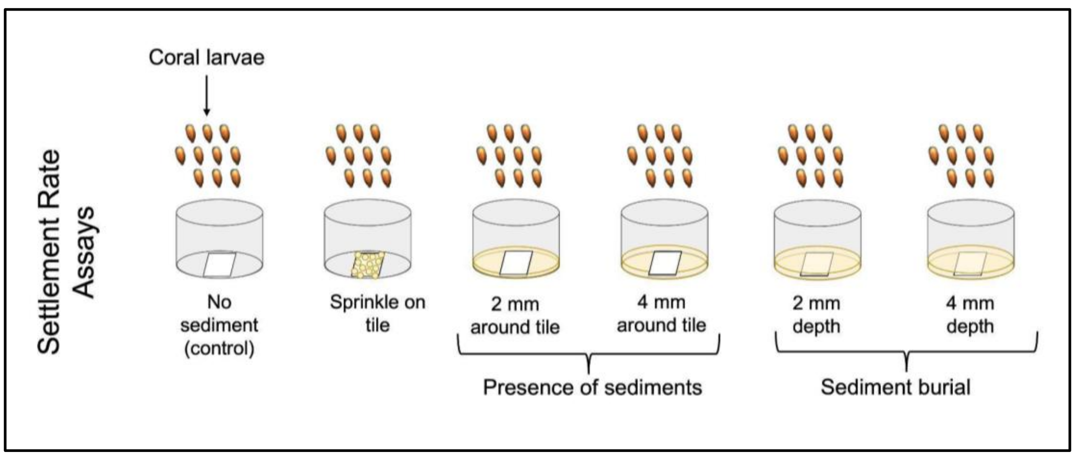

Figure 1: Schematic representation of the larval settlement assays depicting the different treatments established to test the response of larval settlement to the presence of sediments around the substrate and the burial of the substrate by sediments.

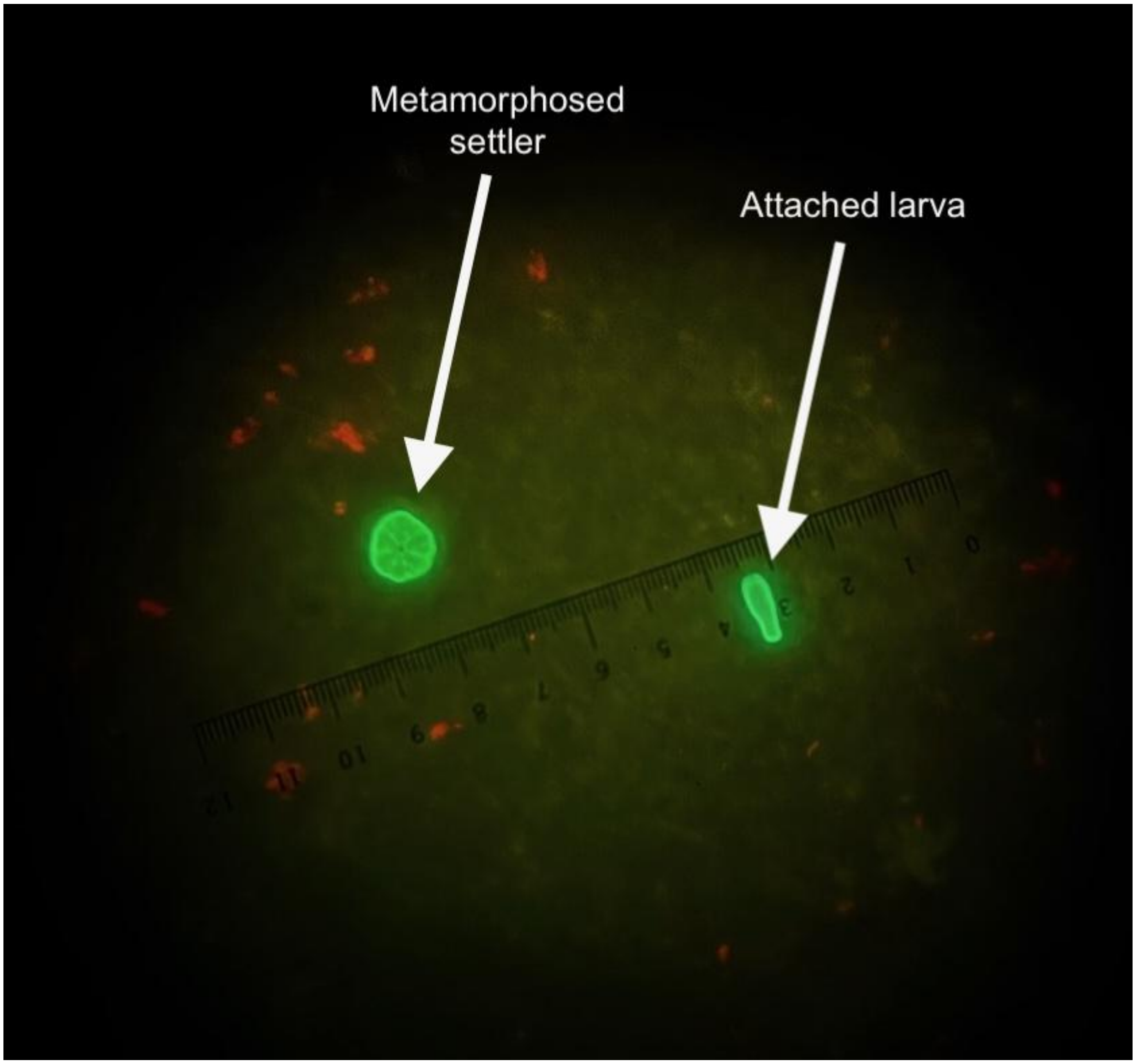

Figure 2: Photograph of a settlement tile after 72 hours depicting a fluorescent green larva that has attached but not metamorphosed and a disk-shaped, metamorphosed settler.

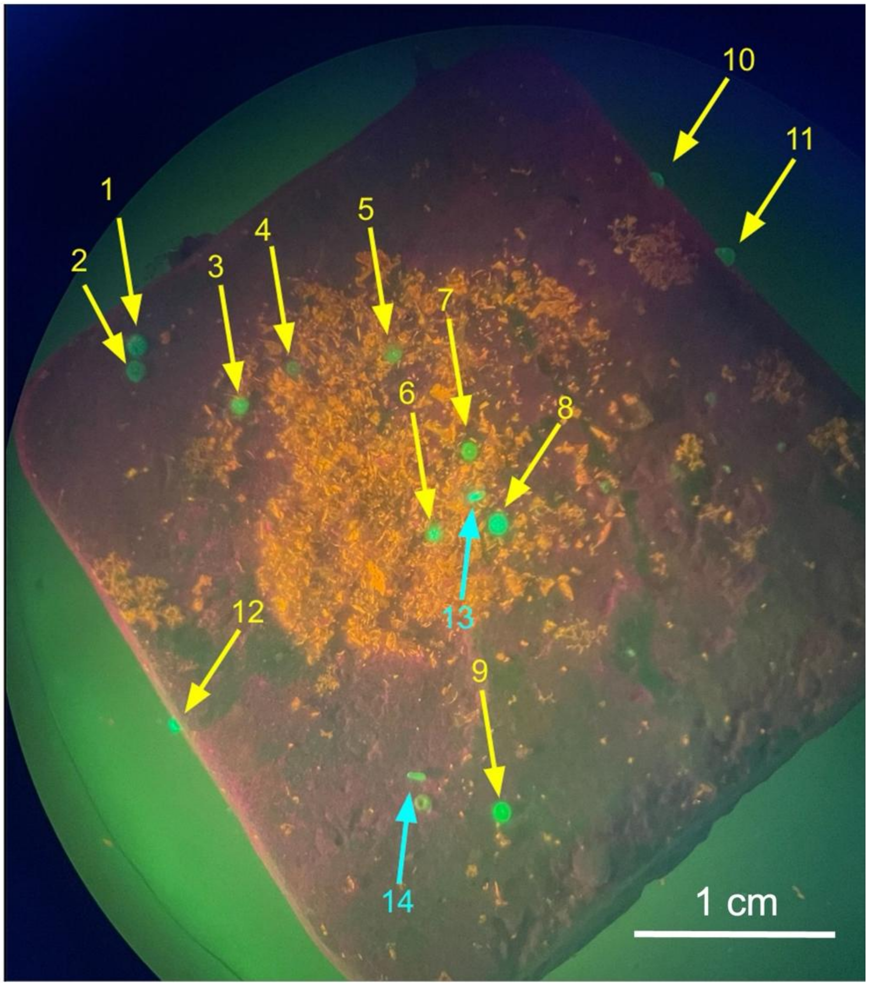

Figure 3: Photograph of a settlement tile (control treatment) after 72 hours. The fluorescent green dots are coral larvae that have settled or attached onto the tile. The yellow arrows point to larvae that have successfully settled and metamorphosed into a flat, disk-like shape to adhere to the substrate. 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.

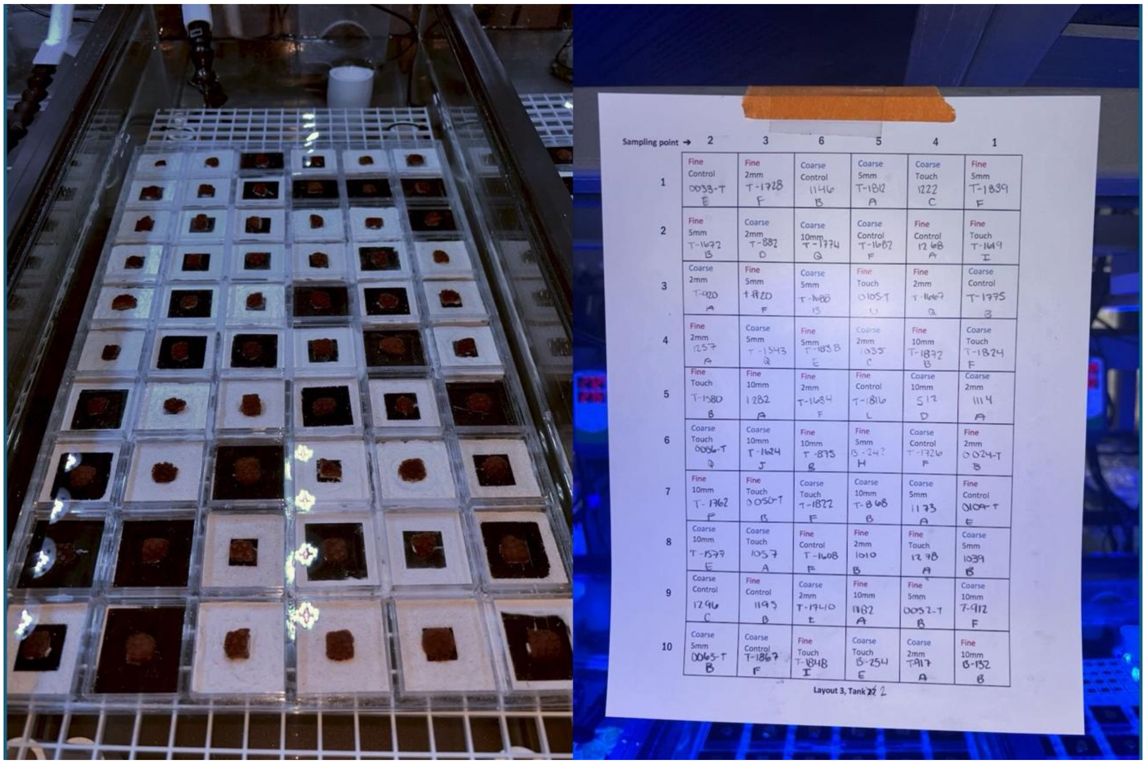

Figure 4: Photograph and schematic representation of a representative replicate of a sediment proximity assay depicting the different treatments we set up for each replicate to test the presence of sediments around the substrate on coral health parameters.

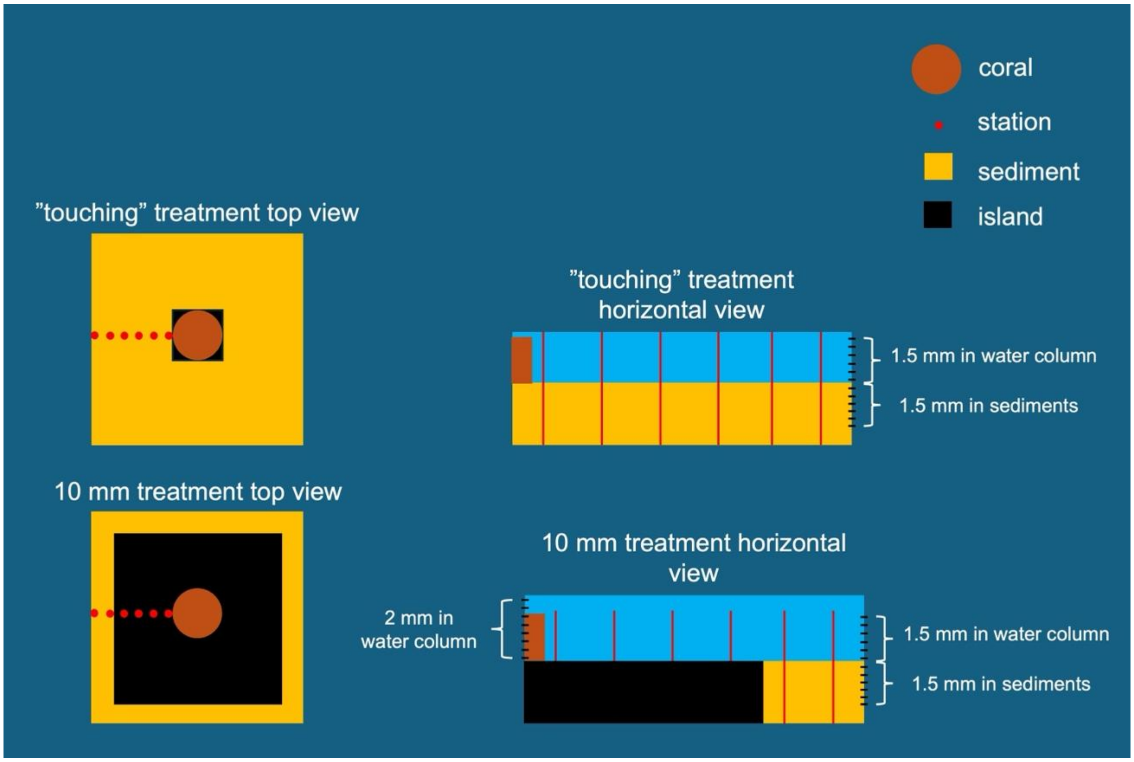

Figure 5: Diagram outlining the sampling procedure for vertical profiles of dissolved oxygen within the water-sediment matrix for the sediment proximity assays.

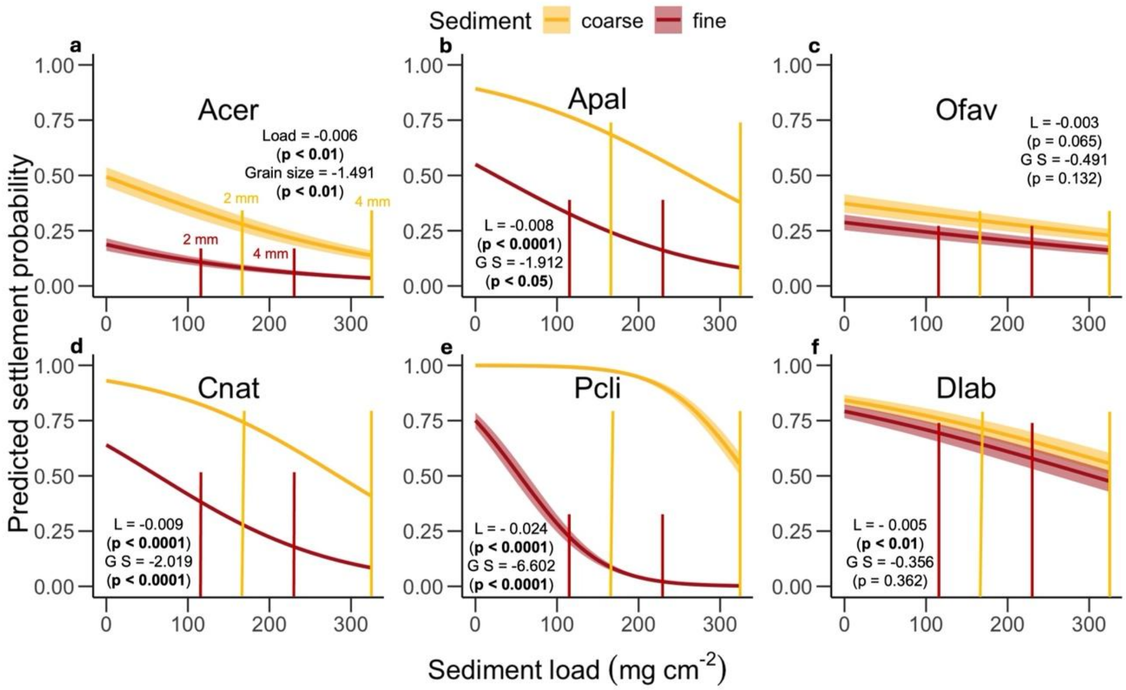

Figure 6: Line plots depicting the predicted settlement probability when settlement tiles are surrounded by varying sediment loads of coarse (yellow curve) and fine (red curve) sediments. Vertical lines indicate the vertical depth of the sediment layer that the respective sediment load translates to. 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; 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*.

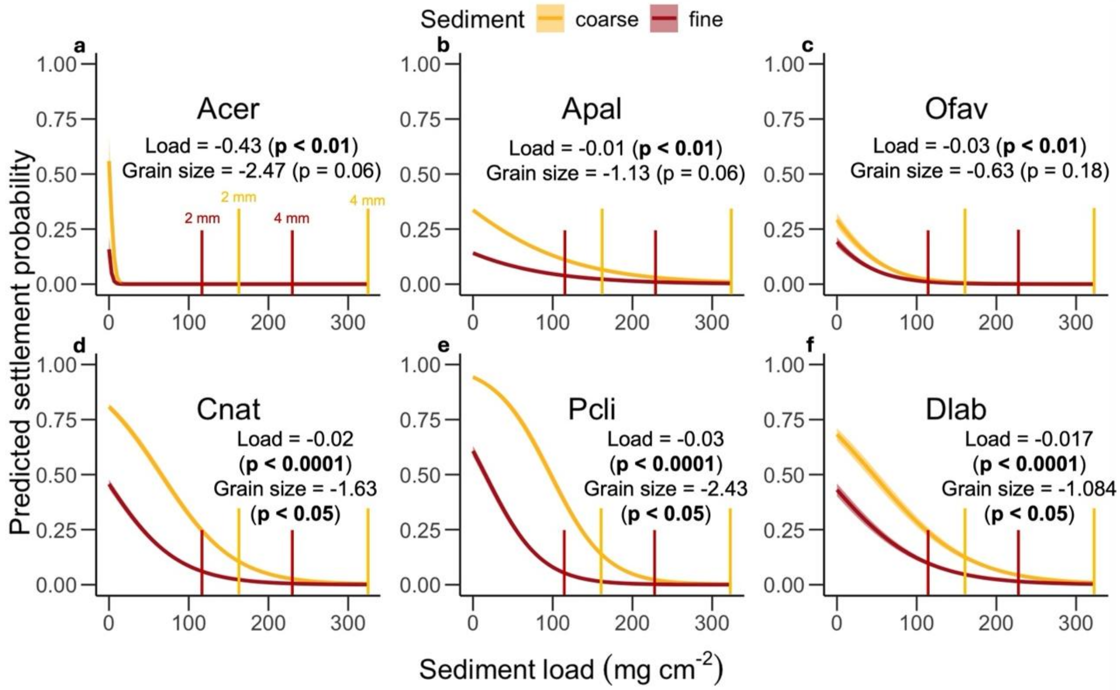

Figure 7: Line plots depicting the predicted settlement probability when settlement tiles are buried under varying sediment loads of coarse (yellow curve) and fine (red curve) sediments. Vertical lines indicate the vertical depth of the sediment layer that the respective sediment load translates to. 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*.

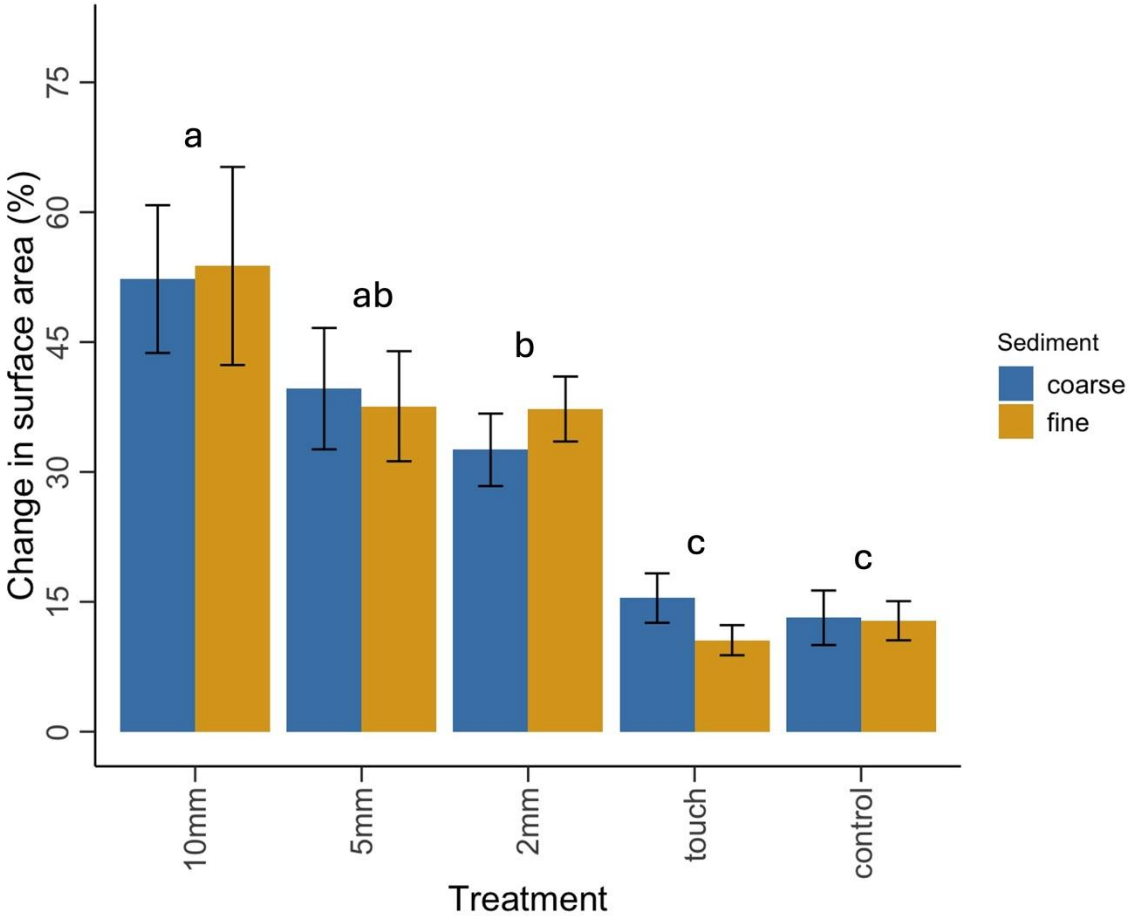

Figure 8: Bar plot depicting the mean (± standard error) percent change in surface area (cm^2) of *O. faveolata* fragments after 60 days (relative to their size at day 0) for different sediment proximity treatments: 10 mm = sediment was 10 mm away from all coral sides, 5 mm = sediment was 5 mm away from all coral sides, 2 mm = sediment was 2 mm away from all coral sides, touch = sediment touching all coral sides, control = no sediment present.

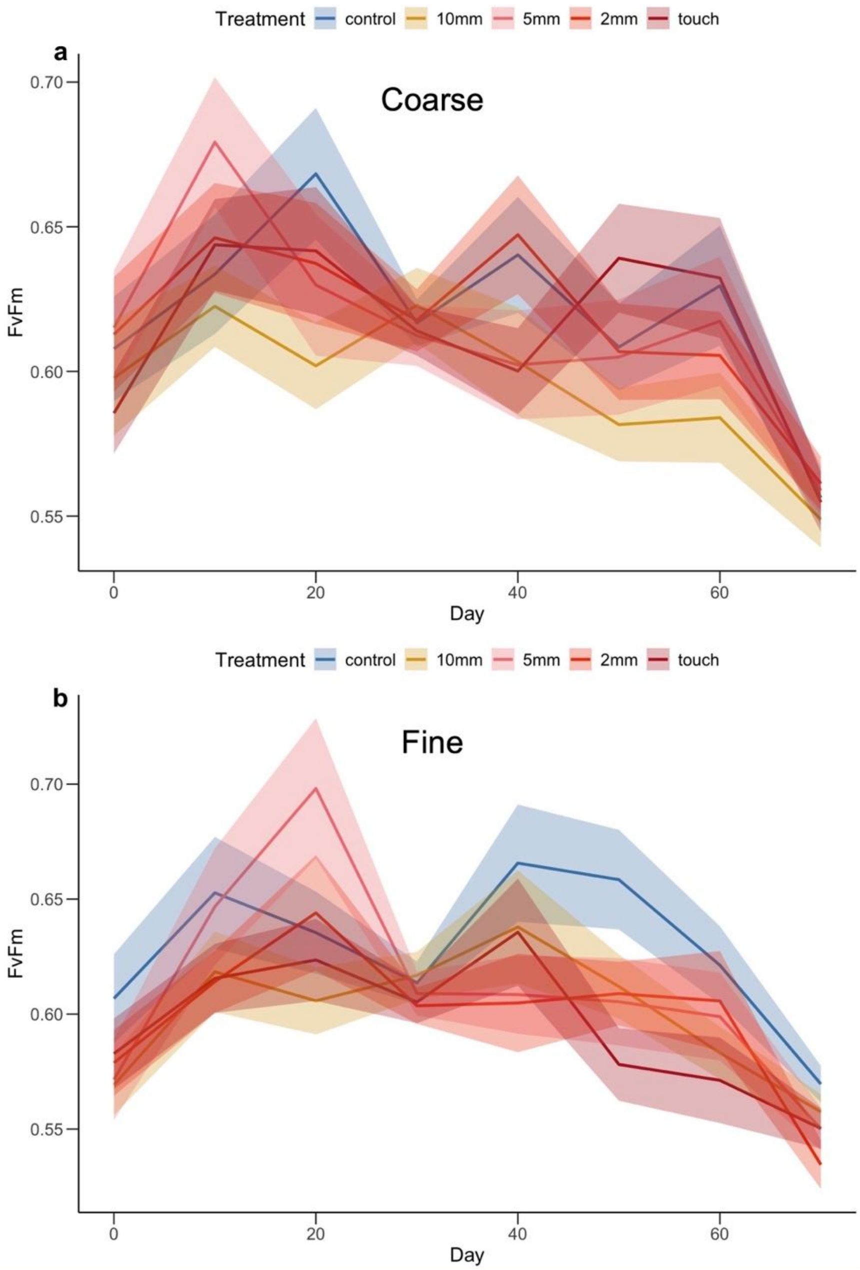

Figure 9: Line plots showing mean (± SE) photosynthetic efficiency (Fv/Fm) the *Zooxanthellae* of the corals exposed to different sediment proximity treatments: 10 mm = sediment was 10 mm away from all coral sides, 5 mm = sediment was 5 mm away from all coral sides, 2 mm = sediment was 2 mm away from all coral sides, touch = sediment touching all coral sides, control = no sediment present; **a)** corals with coarse sediment around them, **b)** corals with fine sediment around them.

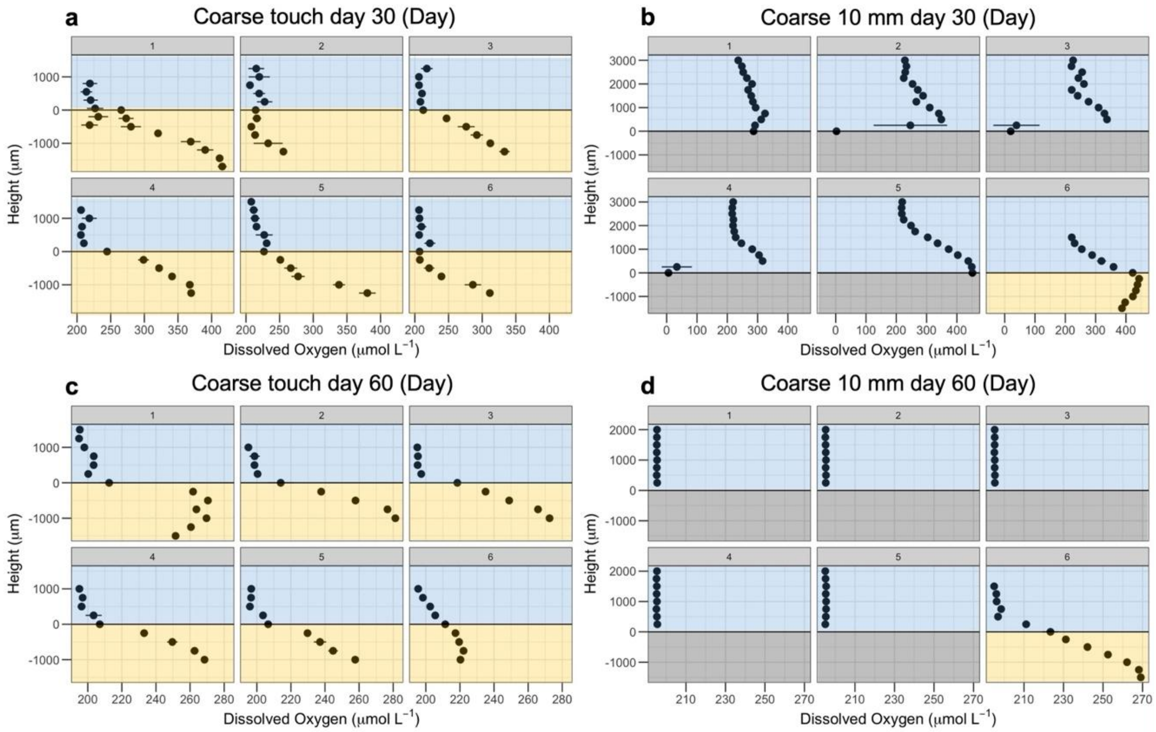

Figure 10: Daytime vertical profiles of dissolved [O_2] (µmol L^{-1}) within the first 3 mm of the sediment-water interface for **a)** coarse sediment touching the sides of a coral fragment on day 30, **b)** coarse sediment adjacent to a 10 mm treatment on day 30, **c)** coarse sediment touching the sides of a coral fragment on day 30, **c)** coarse sediment adjacent to a 10 mm treatment on day 60, **d)** coarse sediment adjacent to a 10 mm treatment on day 60. The blue background depicts samples that were taken in the water column, the tan background depicts samples that were taken in the sediment matrix and the black background depicts the 10 mm island.

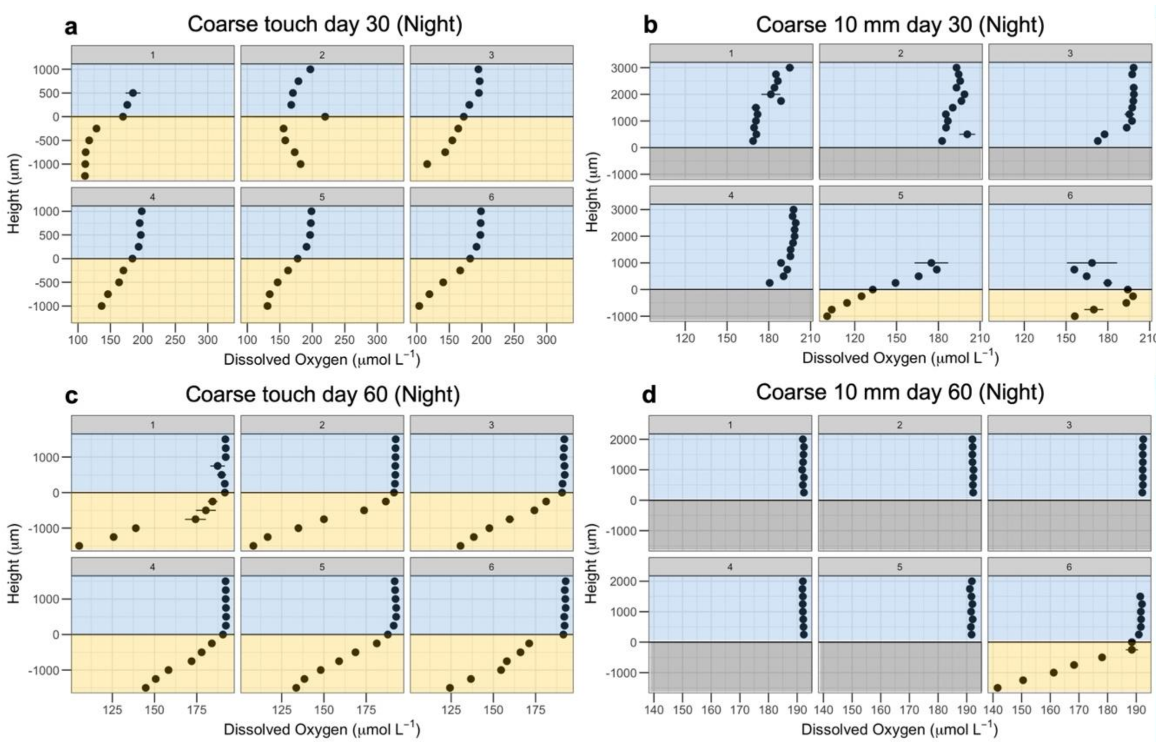

Figure 11: Nighttime vertical profiles of dissolved [O_2] (μmol L^{-1}) within the first 3 mm of the sediment-water interface for **a)** coarse sediment touching the sides of a coral fragment on day 30, **b)** coarse sediment adjacent to a 10 mm treatment on day 30, **c)** coarse sediment touching the sides of a coral fragment on day 30, **c)** coarse sediment adjacent to a 10 mm treatment on day 60, **d)** coarse sediment adjacent to a 10 mm treatment on day 60. The blue background depicts samples that were taken in the water column, the tan background depicts samples that were taken in the sediment matrix and the black background depicts the 10 mm island.

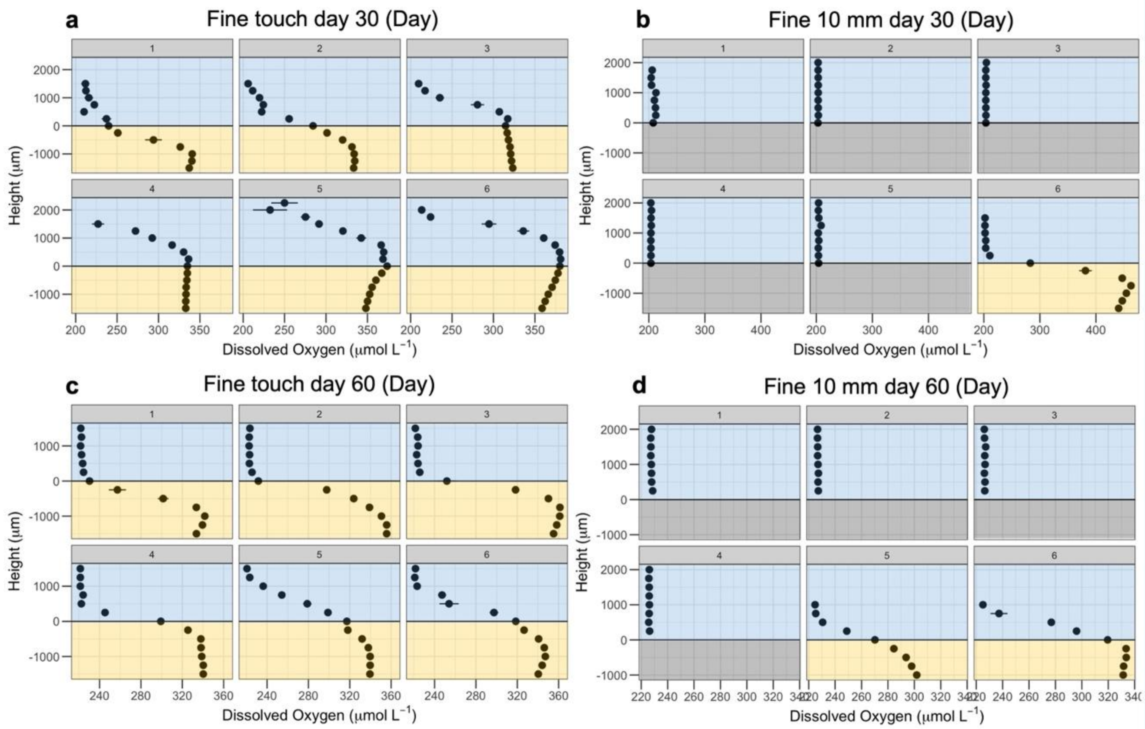

Figure 12: Daytime vertical profiles of dissolved [O_2] (µmol L^{-1}) within the first 3 mm of the sediment-water interface for **a)** fine sediment touching the sides of a coral fragment on day 30, **b)** fine sediment adjacent to a 10 mm treatment on day 30, **c)** coarse sediment touching the sides of a coral fragment on day 30, **c)** fine sediment adjacent to a 10 mm treatment on day 60, **d)** fine sediment adjacent to a 10 mm treatment on day 60. The blue background depicts samples that were taken in the water column, the tan background depicts samples that were taken in the sediment matrix and the black background depicts the 10 mm island.

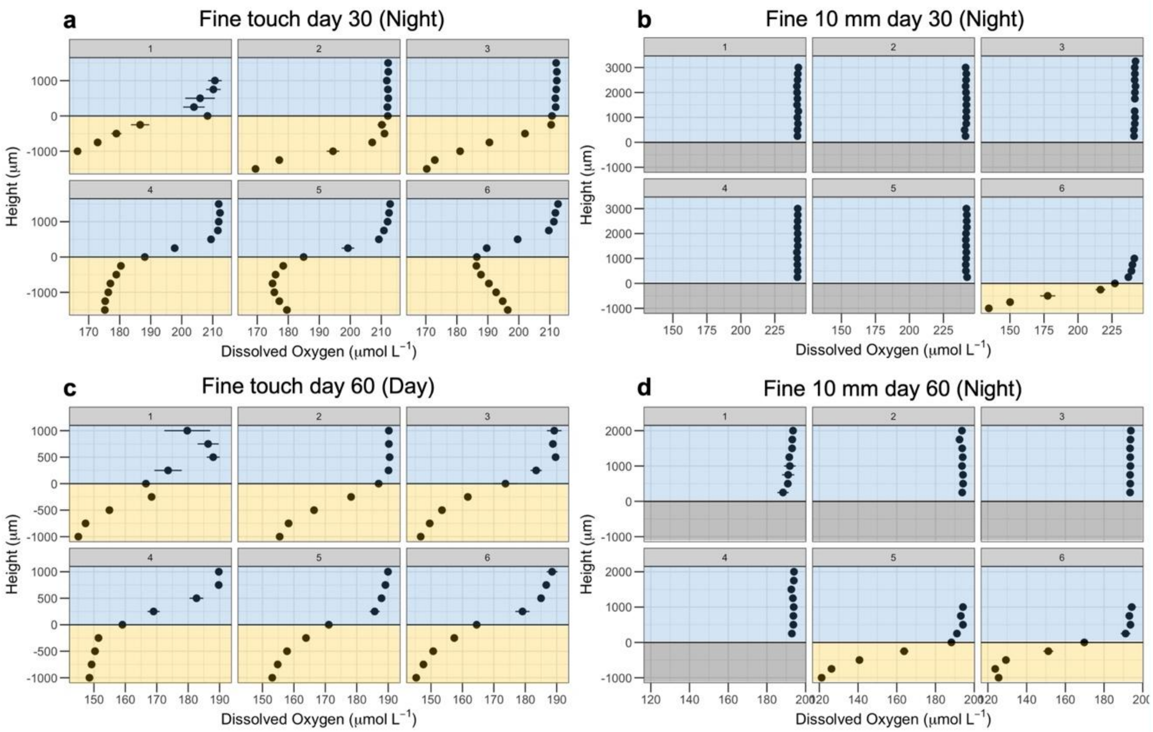

Figure 13: Nighttime vertical profiles of dissolved [O_2] (µmol L^{-1}) within the first 3 mm of the sediment-water interface for **a)** fine sediment touching the sides of a coral fragment on day 30, **b)** fine sediment adjacent to a 10 mm treatment on day 30, **c)** coarse sediment touching the sides of a coral fragment on day 30, **c)** fine sediment adjacent to a 10 mm treatment on day 60, **d)** fine sediment adjacent to a 10 mm treatment on day 60. The blue background depicts samples that were taken in the water column, the tan background depicts samples that were taken in the sediment matrix and the black background depicts the 10 mm island.

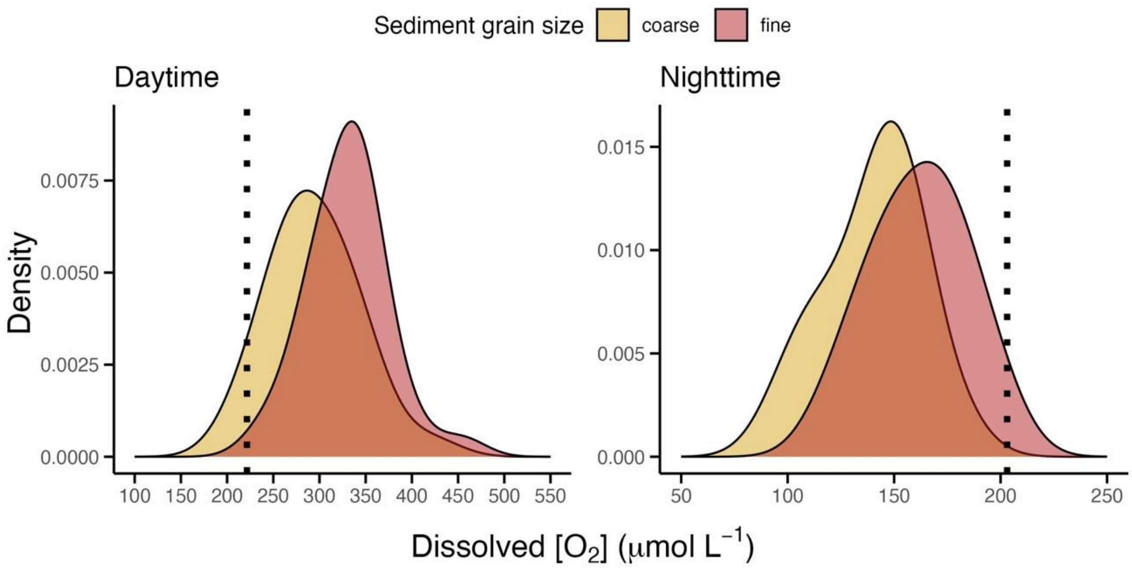

Figure 14: Density plots depicting the frequency distribution of dissolved [O_2] (μmol L^{-1}) at a depth of 1 mm into the sediment matrix across all samples. Dashed vertical lines represent the average dissolved [O_2] in the water column (daytime = 221.52, nighttime = 203.07) Kolmogorov-Smirnov (KS) tests determined that fine sediment exhibited significantly higher dissolved [O_2] than coarse sediment during the daytime ($D = 0.402$, $p = 0.01$) and coarse sediment exhibited significantly lower dissolved [O_2] than fine sediment during the nighttime ($D = 0.474$, $p < 0.001$).