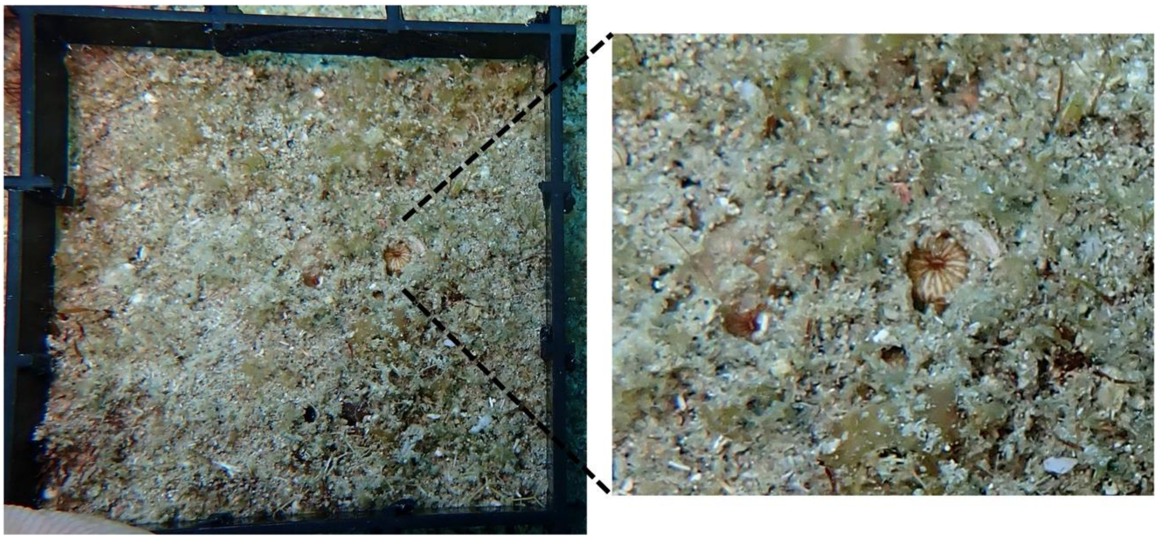
Title: How do long sediment-laden algal turfs affect coral recruitment on Florida's Coral Reef?



Title: How do long sediment-laden algal turfs affect coral recruitment on Florida's Coral Reef?

Final Report

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FLORIDA'S CORAL REEF

Management Summary
The upper section of Florida's Coral Reef, from Fort Lauderdale to Key Largo, showed density of juvenile corals (5 juv. m^{-2}) dominated primarily by *Siderastrea* and other weedy coral genera (*Porites* and *Agaricia*). Long sediment-laden algal turf LSAT covered approximately 42% of the reef's seafloor, creating challenging conditions for settlement and survival of corals. Indeed, our results indicate a significant negative relationship between juvenile coral presence and LSAT abundance and sediment thickness. The model shows a 50% decrease in juvenile presence from 0 to 2 mm of sediment and a gradual decline until 6mm, with a total absence of juveniles above this depth. These values are not considered thresholds but could offer a baseline for investigating management strategies. Lab and field experiments are highly encouraged to validate our field results. The high abundance of LSAT region-wide might be related to the levels of sedimentation (0.01 g. day^{-1} $20cm^{-2}$), which appeared to increase gradually from north to south. The experimental removal of sediment revealed that plots with turf algae gained, on average (2.75 mm in 19 days), 1 mm more sediment than turf-free plots. However, turf grew quickly (0.14 mm/day or 27% tissue gain/day) and started accumulating sediment as well. For management strategies, we propose 1) conducting a full year of assessment of LSAT, similar to this study, to understand the temporal dynamics of these patterns, 2) to continue evaluating coral recruitment throughout the year using settlement tiles to estimate larval supply, and 3) to partner with coral restoration agencies to field test how habitat quality improvement (sediment removal) can affect the survival of juvenile corals.

Executive summary
This project evaluated the potential impact of long sediment-laden algal turfs (LSAT) on coral recruitment in Florida's Coral Reef. We conducted field surveys (tasks 1 and 2) and experimental sediment manipulation (task 3) to 1) evaluate benthic communities and juvenile corals, 2) characterize LSAT (sediment and turf communities), and 3) describe sedimentation rates across sites and LSAT formation at an experimental site. While corals covered about 3% of the benthos, LSAT was the dominant benthic group across all sites covering approximately 42% of the reef. LSAT tends to be more abundant at sites further south. For instance, LSAT coverage at Conch Reef in the FL Keys (59%) was almost double compared to Emerald Reef (Miami), South Canyon (Miami), and Fort Lauderdale. The abundance of macroalgal taxa such as *Dictyota*, *Laurencia*, and *Galaxaura* also differed across sites indicating different habitat qualities for corals to settle and develop. We found juvenile corals (<4cm) in 38 out of 150 plots for a 25% presence across all sites, largely dominated (66% of all juveniles) by the genus *Siderastrea*. The rest of juveniles belonged to weedy coral genera *Porites* and *Agaricia*. Only four juveniles of reef-forming genera, *Montastrea* and *Diploria*, were found at the northern sites.
The logistic regression model predicted a significant decrease in the likelihood of finding juvenile corals as abundance or thickness of the LSAT sediment layer increases. The model predictability decreases substantially when looking at *Siderastrea* alone, supporting the described sediment resistance traits of the genus. The analysis of LSAT composition revealed a significant correlation ($R=0.83$, $p<0.001$) between LSAT turf length and thickness of the sediment layer, which supports the positive feedback loop between sediment and turf algal assemblages. Certain species, such as *Digenea* sp., the most abundant taxa within LSAT, have a filamentous morphology that allows them to grow within a certain amount of sediment. We found that other ecologically important species, such as some crustose coralline algae (CCA), tend to disappear once the LSAT sediment layer surpasses 5 mm thickness. Indeed, our results showed a positive correlation between turf length and sediment mass, especially grain sizes ranging from 125 to 500 microns. As sediment accumulates, it could create anoxic conditions and block light penetration, preventing crustose algal development. Sedimentation rates ranged from 0.004 to 0.020 g day^{-1} 20 $cm^{-2,}$ gradually increasing towards the south, which might explain the deep LSAT sediment layer observed on southern reefs. We also noticed that the mineral sediment composition might differ among these sites. The experimental removal of sediment revealed that plots with turf algae gained, on average (2.75 mm in 19 days), 1 mm more sediment than turf-free plots. However, turf grew quickly (0.14 mm/day or 27% tissue gain/day) and started accumulating sediment as well. All proposed tasks were completed on time, regardless of permitting and weather-related delays. The results highlight the coral recruitment crisis on Florida's Coral Reef. We found an almost absolute absence of reef-forming juvenile corals. To better understand the drivers of the lack of recruitment, we identified several major questions: (1) Is the lack of coral recruitment due to a poor larval pool, compromised settlement habitat quality, or a combination of both? (2) Does LSAT dominance act as an ecological filter by reducing the settlement of reef-forming species?

Acknowledgments
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LSAT. Long sediment-laden algal turf
CCA. Crustose coralline algae

1. DESCRIPTION

Settlement and post-settlement survival and growth of corals are fundamental drivers of coral reef resilience. Sedimentation has been recognized as a major threat to adult corals, but its potential effects at different life history stages of coral, particularly coral recruitment, are still unclear. In Florida, no long-term monitoring programs of coral reefs include long sediment-laden algal turfs (LSAT) as a category; thus, no information on LSAT abundance or composition is available. Yet the reported overall cover by major benthic groups (stony coral, octocoral, sponge, macroalgae) is usually less than 50% (except for Dry Tortugas National Park). Although the composition of the remaining substrate is quite variable (e.g., covered by *Peyssonelia* spp. and CCA), LSAT is ubiquitous across most habitats, suggesting that sediment accumulation might create unsuitable conditions for the settlement and growth of coral recruits. This project evaluated the potential impact of LSAT on coral recruitment in Florida's Coral Reef. We conducted field surveys (tasks 1 and 2) and experimental sediment manipulation (task 3) to 1) evaluate benthic communities and juvenile corals, 2) characterize LSAT (sediment and turf communities), and 3) describe sedimentation rate across sites and LSAT formation at an experimental site.

2. METHODS

2.1. Assessment of benthic communities and juvenile corals

To evaluate the relationship between LSAT and juvenile corals, we conducted high taxonomic resolution surveys along six shallow coral reefs (6 to 8 m depth) located along reefs in Broward County, Miami-Dade County, and the north section of the Upper Keys (Table 1). Those locations include Fort Lauderdale, Dania Beach, South Canyon (Miami Beach), Emerald Reef (Key Biscayne), Carysfort Reef, and Conch Reef (Key Largo). We have selected these reefs because they have the highest density of juvenile corals based on previous surveys conducted by Nicholas Jones (NSU graduate student), SECREMP, and our previous data.

We surveyed the benthos in 25 (25 x 25 cm) plots per site. Plots were randomly selected within our study sites. Each plot was photographed before surveying for further quantification/quality control assessment. Taxonomic identification and quantification (percent cover) of all benthic taxa within the plot took place *in situ* at a high taxonomic resolution. Short productive algal turf (SPAT) will be classified as a relatively sediment-free, dense, and stable multi-species (e.g., *Polysiphonia* spp., *Ceramium* spp., *Hypnea* spp., *Laurencia* spp.) algal assemblage forming a layer <1 cm in height. We binned all species of CCA. Species from the genus *Peyssonnelia*, a non-coralline crustose alga, were classified as a single group (*Peyssonnelia*). We evaluated coral juveniles (colonies ≤4 cm in diameter) within each plot. The diameter of each juvenile was measured and identified to the genus level. The number of coral juveniles was divided by the area of the plot (0.0625 m^2) to estimate the density of juvenile corals m^{-2}.

Table 1. Location, depth, and approximate distance from shore of the study sites

Site	Latitude	Longitude	Depth (m)	Distance from shore (m)
Fort Lauderdale	26.212200 (26º12’43.9”)	-80.086683 (80º05’12.1”)	6	439
Dania Beach	26.011577 (26º00’41.7”)	-80.112620 (80º06’45.4”)	6	277
South Canyon	25.85015 (25 º51’0.54”)	-80.10014 (80º06’0.50”)	6	1200
Emerald reef	25.66681 (25º40’00.5”)	-80.08357 (80º05’009”)	8	7000
Carysfort	24.221947 (25°13’19.01”)	-80.21145 (80°12’41.22”)	8	9000
Conch Reef	25.22273 (25°13’21.8”)	-80.20875 (80°12’31.5”)	8	9000

Since the physical characteristics of the substrate, such as slope, can determine the benthic composition, we collected information on rugosity and substrate slope around each plot (for 25 rugosity measurements). We estimated the rugosity index (RI) using a 50 cm chain (1 link = ~1 cm length) laid parallel to the quadrat. We calculated RI by dividing the chain's total length (50 cm) by the linear length covered by the chain within the plot where RI = 1 indicates the lowest complexity, with values increasing with higher complexity. We recorded the slope of the substrate (i.e., the angle from horizontal) using a protractor with a small foam float. Small angles correspond to relatively flat (horizontal) substrates, whereas higher degree angles (up to 90°) are associated with more vertical substrates.

2.2. In situ characterization of LSAT

To quantify the LSAT *in situ*, we selected a 5 x 5 cm subplot near the larger 25 x 25 cm plots established for Task 1 (n = 25 per site). Within each 5 x 5 cm subplot, we first measured the sediment layer of the matrix at the center of the plot. The sediment thickness (mm) was measured using a pencil calibrated with 1 mm increments. The pencil was inserted vertically into the sediment layer until it reached the hard substrate to measure the sediment depth (Figure 2). We collected the sediment trapped within a 5 x 5 cm subplot using a modified 60-ml syringe. Sediment samples were dried to a constant temperature (70 Celsius) to obtain a dry weight (g). We separated the dried sediment samples by grain sizes using a series of sieves and obtained weight by size class for each plot. Once the sediment was collected from each subplot and the turf algae was fully exposed, we measured turf height with the calibrated pencil and recorded species composition.

2.3. Sediment rate characterization

2.3.1. Sediment removal

To estimate the LSAT formation rate (mass of sediment trapped within turf), we established ten experimental (25 x 25 cm) plots at one reef location (South Canyon). These plots were separate from the randomly placed plots used in Task 1 and placed in areas with high abundance of LSAT. Within each experimental plot, we measured sediment depth as described above (calibrated pencil). The turf community exposed by sediment removal was assessed to measure turf length, percent cover, and species composition. From another ten experimental plots (25 x 25 cm), we collected sediment and removed any macroalgae (turf-free). A third group (10 plots) was used as a control (no sediment or turf removal). After 19 days, we returned and measured sediment deposited in the two different experimental plot types ("turf-free" and "turf only," n = 10 for each) and sediment in control (n = 10) plots.

2.3.2. Sediment traps

We used sediment traps deployed at each site to estimate sedimentation rates (mass of sediment deposited over time). Ten sediment traps constructed of PVC pipe (5 cm internal diameter; 43 cm height) were set vertically approximately 50 cm from each sediment removal plot at each site. Sediment traps were placed for about 14 days. Sediment collected in traps was later analyzed in the lab for composition (grain size) analysis.

3. RESULTS

3.1. Assessment of benthic communities and juvenile corals

LSAT was the dominant group across all sites covering approximately 42% of the reef (Figure 1). LSAT tends to be more abundant and thick at sites further south compared to sites to the north (Table 2). For instance, LSAT coverage at our most southern site, Conch Reef, was 59%, almost double compared to reefs surveyed in Miami (Emerald Reef and South Canyon) and Fort Lauderdale. The abundance of macroalgal taxa such as *Dictyota*, *Laurencia*, and *Galaxaura* also differed across sites indicating different habitat qualities for corals to settle and develop. We found juvenile corals (<4cm) in 38 out of 150 plots for a 25% presence, largely dominated (66% of all juveniles) by the genus *Siderastrea*. The rest of juveniles belonged to weedy coral genera *Porites* and *Agaricia.* Only four juveniles of reef-forming genera, *Montastrea* and *Diploria*, were found at the northern sites.

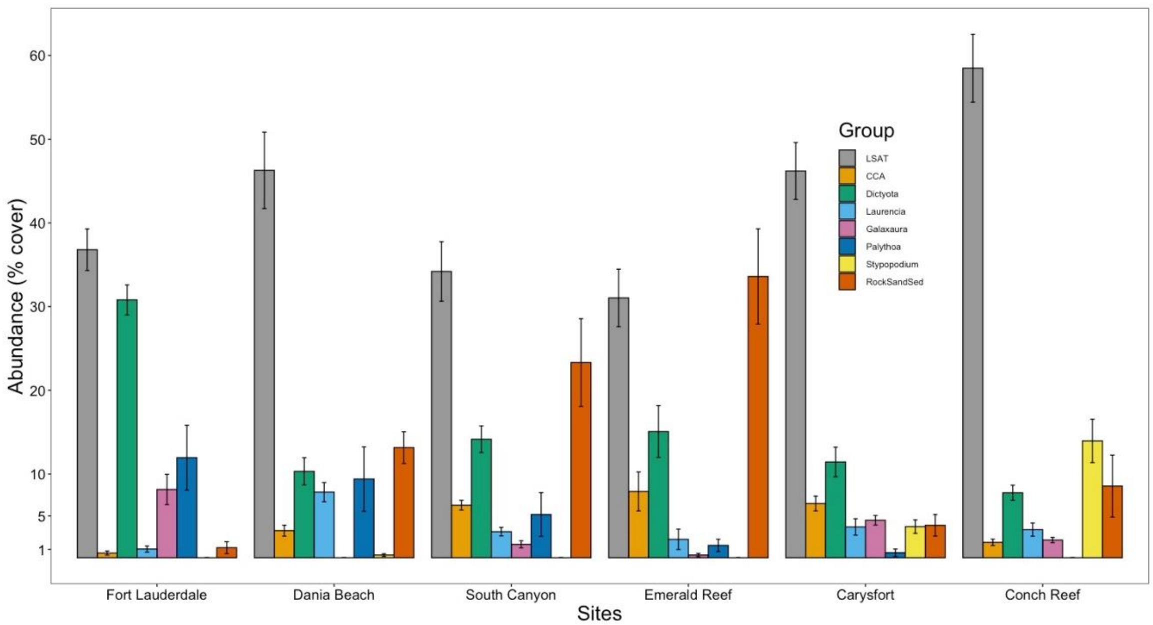

Figure 1. Mean abundance (% cover) of the eight most common benthic groups found across all sites using the 25x25 cm plots. Bars indicate standard error. Full data set provided in the deliverables.

Table 2. Benthic abiotic variables and total count of juvenile corals (in 25 plots) by site

Site	Rugosity index	Slope (degree)	LSAT sediment thickness (mm)	Juvenile corals
Fort Lauderdale	1.28 (± 0.04)	7.76 (± 1.37)	1.52 (± 0.13)	4
Dania Beach	1.33 (± 0.04)	6.92 (± 1.14)	1.92 (± 0.15)	7
South Canyon	1.40 (± 0.05)	11.88 (± 1.84)	1.44 (± 0.17)	11
Emerald reef	1.45 (± 0.07)	19.36 (± 2.80)	2.20 (± 0.13)	12
Carysfort	1.39 (± 0.05)	12.32 (± 1.83)	1.84 (± 0.17)	12
Conch Reef	1.25 (± 0.04)	6.64 (± 1.01)	3.48 (± 0.29)	5

The logistic regression model predicted a significant decrease in the likelihood of finding juvenile corals as abundance or thickness of the LSAT sediment layer increases (Figure 2). The model predictability decreases substantially when looking at *Siderastrea* alone.

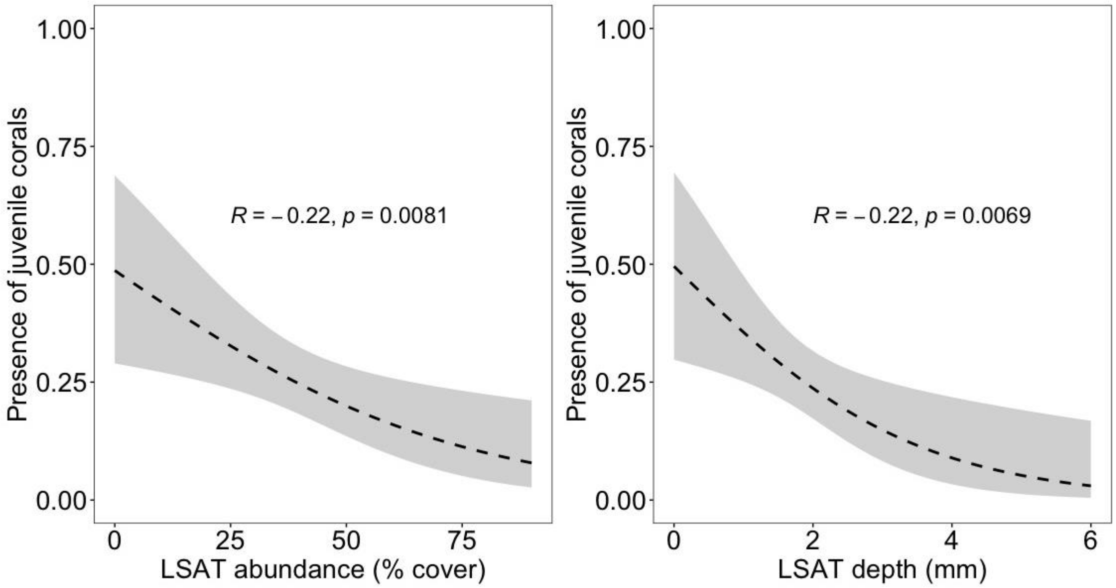

Figure 2. Presence of juvenile corals as a function of LSAT abundance (% cover, left) and thickness of the LSAT sediment layer (right).

3.2 *In situ* characterization of LSAT

The analysis of LSAT composition revealed a significant correlation (R=0.83, p<0.001) between LSAT turf length and the thickness of the sediment layer (Figure 3). Red filamentous algae were the most abundant within LSAT, whereas crustose coralline algae (CCA) tend to disappear once the LSAT sediment layer surpasses 5 mm thickness (Figure 4). Our results showed a positive correlation between turf length and sediment mass, especially grain sizes ranging from 125 to 500 microns (Figure 5).

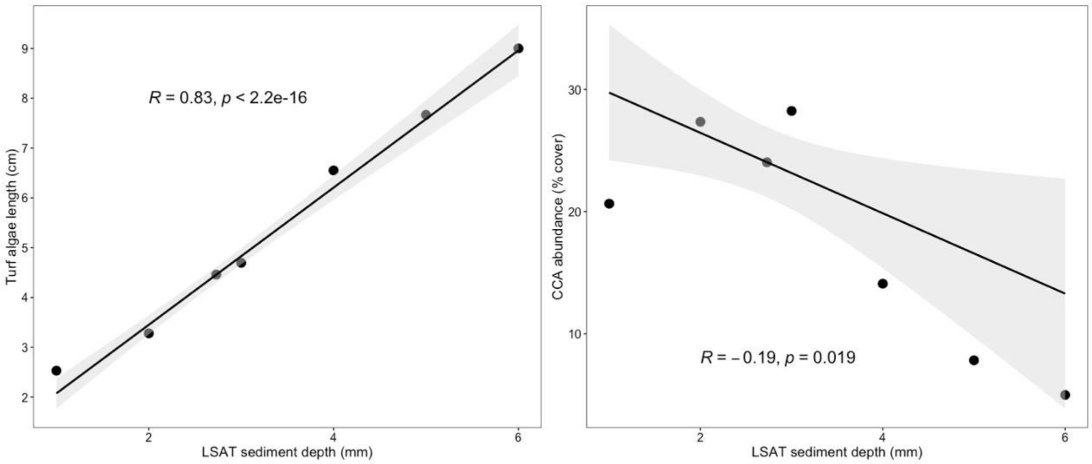

Figure 3. Relationship between depth of the LSAT sediment layer and length of the turf algae trapping the sediment (left) and CCA abundance (% cover) found under the sediment layer (right).

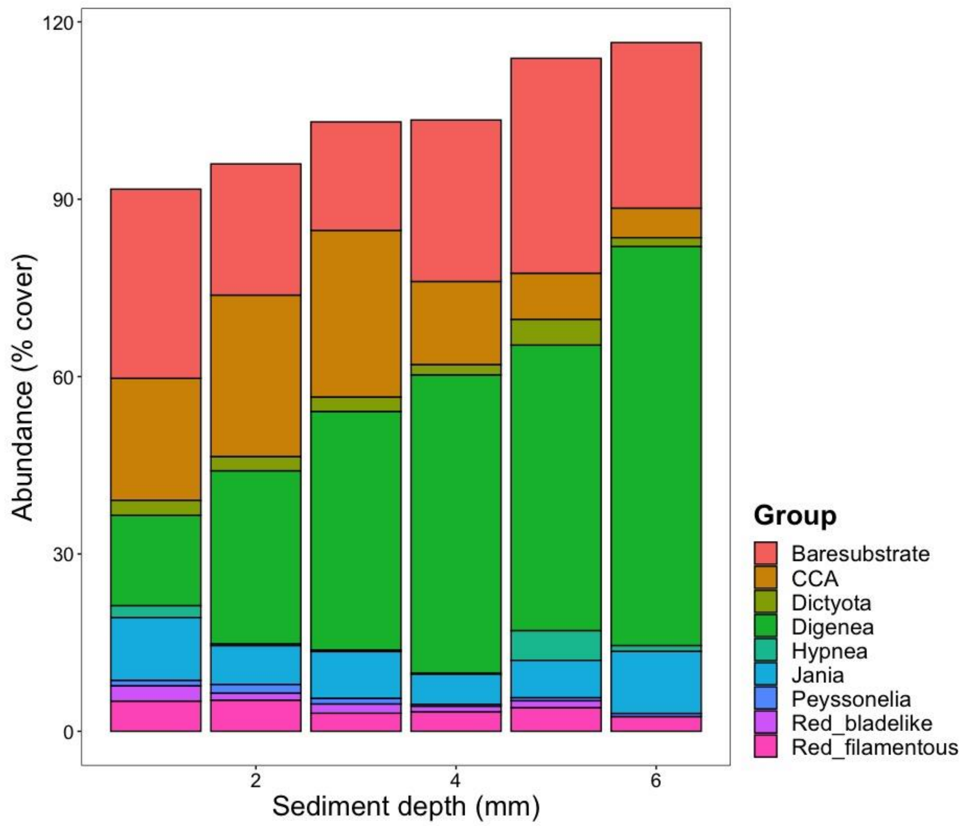

Figure 4. LSAT taxa composition as a function of the thickness of the sediment layer. Notice that percent cover is higher than 100% as a result of species overlap (e.g., Digenea and CCA)

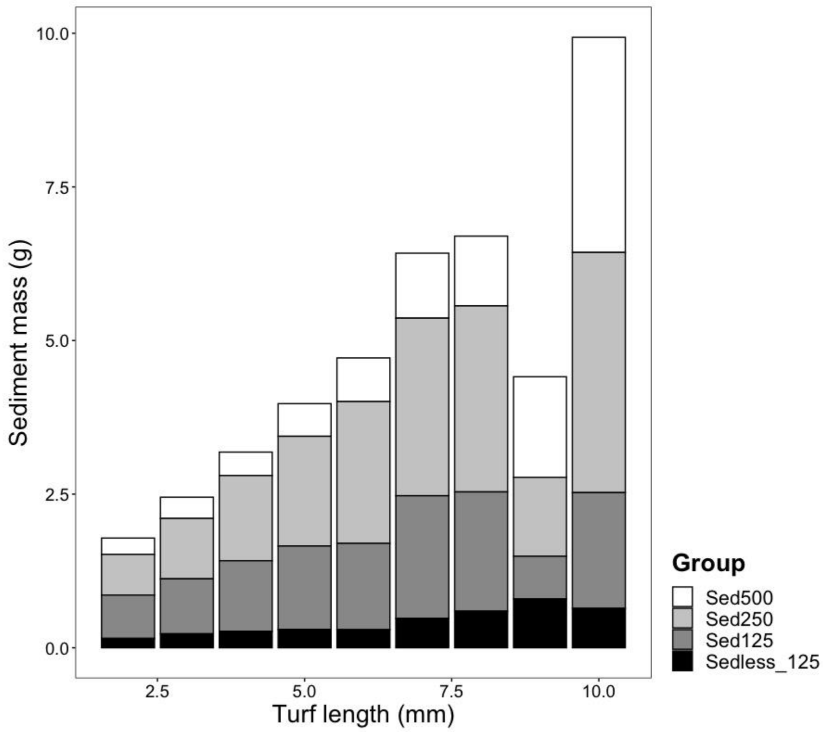

Figure 5. Sediment mass trapped within LSAT, by grain size, as a function of LSAT turf length

3.3 Sediment rate characterization

3.3.1. Sediment removal

The experimental removal of sediment revealed that plots with turf algae gained, on average (2.75 mm in 19 days), 1 mm more sediment than turf-free plots. However, turf grew quickly (0.14 mm/day or 27% tissue gain/day) and started accumulating sediment as well (Figure 6).

3.3.2. Sediment traps

Sedimentation rates ranged from 0.004 to 0.020 g day^{-1} 20 $cm^{-2,}$ gradually increasing from north to south (Figure 7).

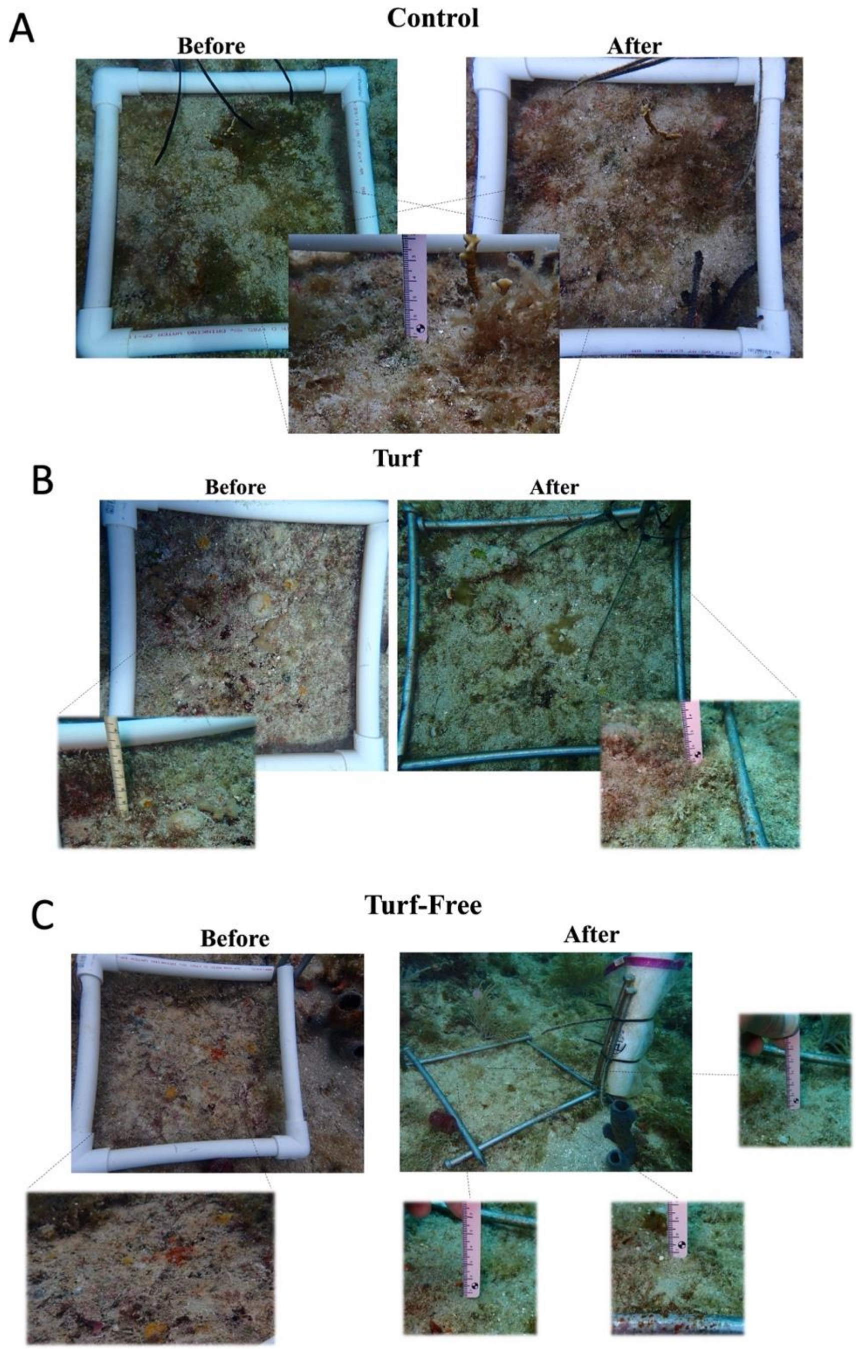

Figure 6. Sediment removal experimental plots. A (Control plots), B (Turf plots), and C (Turf-Free plots).

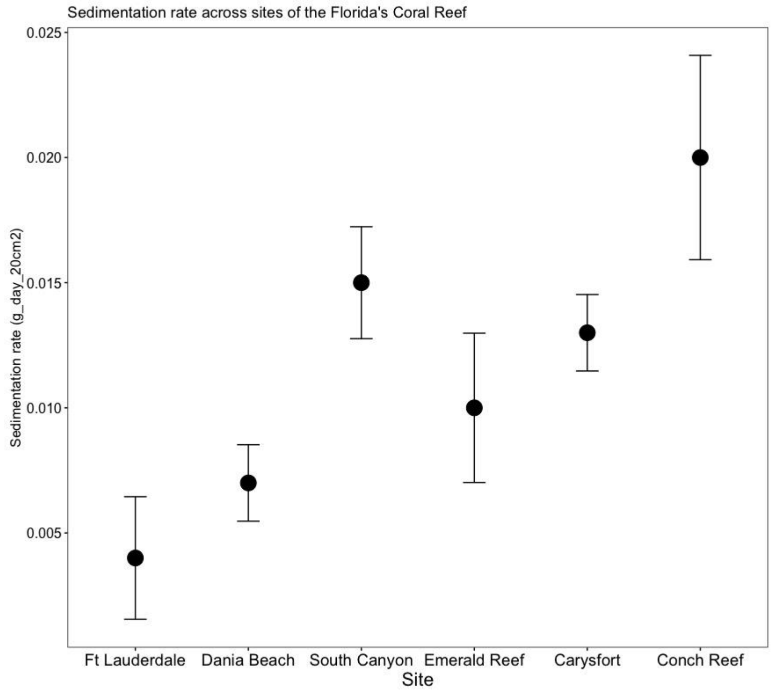

Figure 7. Sedimentation rate across the studied sites (Mean ± SE).

4. DISCUSSION

The upper section of Florida's Coral Reef, from Fort Lauderdale to Key Largo, showed poor density of juvenile corals (5 juv. m^{-2}) dominated primarily by *Siderastrea* and other weedy coral genera (*Porites* and *Agaricia*). LSAT covered approximately 42% of the reef's seafloor with a gradually increased abundance from north to south. LSAT abundance and the thickness of the sediment layer likely create challenging conditions for the settlement and survival of corals, especially for reef-building species.

Coral recruitment and survival drivers in Florida's Coral Reef remain poorly understood, but impoverished habitat quality likely compromises the process. Has the larval pool changed over time, or is the habitat quality driving settlement and survival of corals? Studies in the '70s and '80s by Phillip Dustan (Dustan 1977) and Peter Edmunds (Edmunds *et al*. 1998) reported densities of juvenile corals (at Conch and Carysfort reefs between 5 and 12 juv. m^{-2}, largely dominated by *Agaricia*. Moulding (2005) conducted field surveys in 2002 across Florida Keys patches and reported average juvenile densities between 6 and 39 juv. m^{-2} dominated by *Porites* and *Siderastrea*. Van Woesik et al. (2014) found 40% recruitment success on settlement tiles across eight sites of the Florida Keys, including Carysfort reef, between May 2011 and September 2011 (n=240 settlement tiles). The success rate Van Woesik and collaborators reported was similarly distributed among *Siderastrea, Acropora, Porites,* and Astrocoeniidae, yet our results showed *Siderastrea* as the dominant juvenile taxa. Van Woesik and collaborators pointed out the mismatch between coral larval pool and adult coral assemblages, which could be explained, at least in part, by the poor habitat quality related to LSAT formation.

Our results show that LSAT abundance and thickness of its sediment layer depth are major detractors of juvenile coral presences, particularly for species other than *Siderastrea*. Indeed, *Siderastrea* is considered a temperature and sediment-tolerant coral genus (Lirman and Manzello 2009). But several questions remain unanswered. For instance, besides mechanically impeding larval access to hard substrates, what other effects could sediment accumulation have on settlement and survival of corals? For example, we observed that certain species, such as *Digenea* sp., the most abundant taxa within LSAT, have a filamentous morphology that allows them to grow taller within a certain amount of sediment. Contrarily, crustose coralline algae (CCA) tend to disappear once the LSAT sediment layer surpasses 5 mm thickness. Seemingly, as sediment accumulates, it creates anoxic conditions and block light penetration, preventing limiting settler's survival and growth. Further, why does *Siderastrea* better cope with sediment than other coral taxa?

Sedimentation rates ranged from 0.004 to 0.020 g day^{-1} 20 $cm^{-2,}$ gradually increasing from north to south, which might explain the deep LSAT sediment layer found at south reefs (Carysfort and Conch). At this rate, the formation of LSAT (with a 2 mm sediment layer) could occur relatively quickly (less than a month), especially if there is an existing layer of turf algae. However, we also noticed that the mineral composition of sediment might differ among these sites. Further analysis of mineral composition would bring light to the origin of sediment in these reefs, which is an essential piece of the puzzle to propose management strategies.

Our results revealed that abundant long sediment-laden turf algae might compromise coral recruitment in Florida's Coral Reef. However, much more work must be done in this regard. We propose 1) conducting a full year of assessment of LSAT, similar to this study, to understand the temporal dynamics of these patterns, 2) evaluating coral recruitment throughout the year using settlement tiles to estimate larval supply, and 3) partnering with coral restoration agencies to field test how habitat quality improvement (sediment removal) can affect the survival of juvenile corals.

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