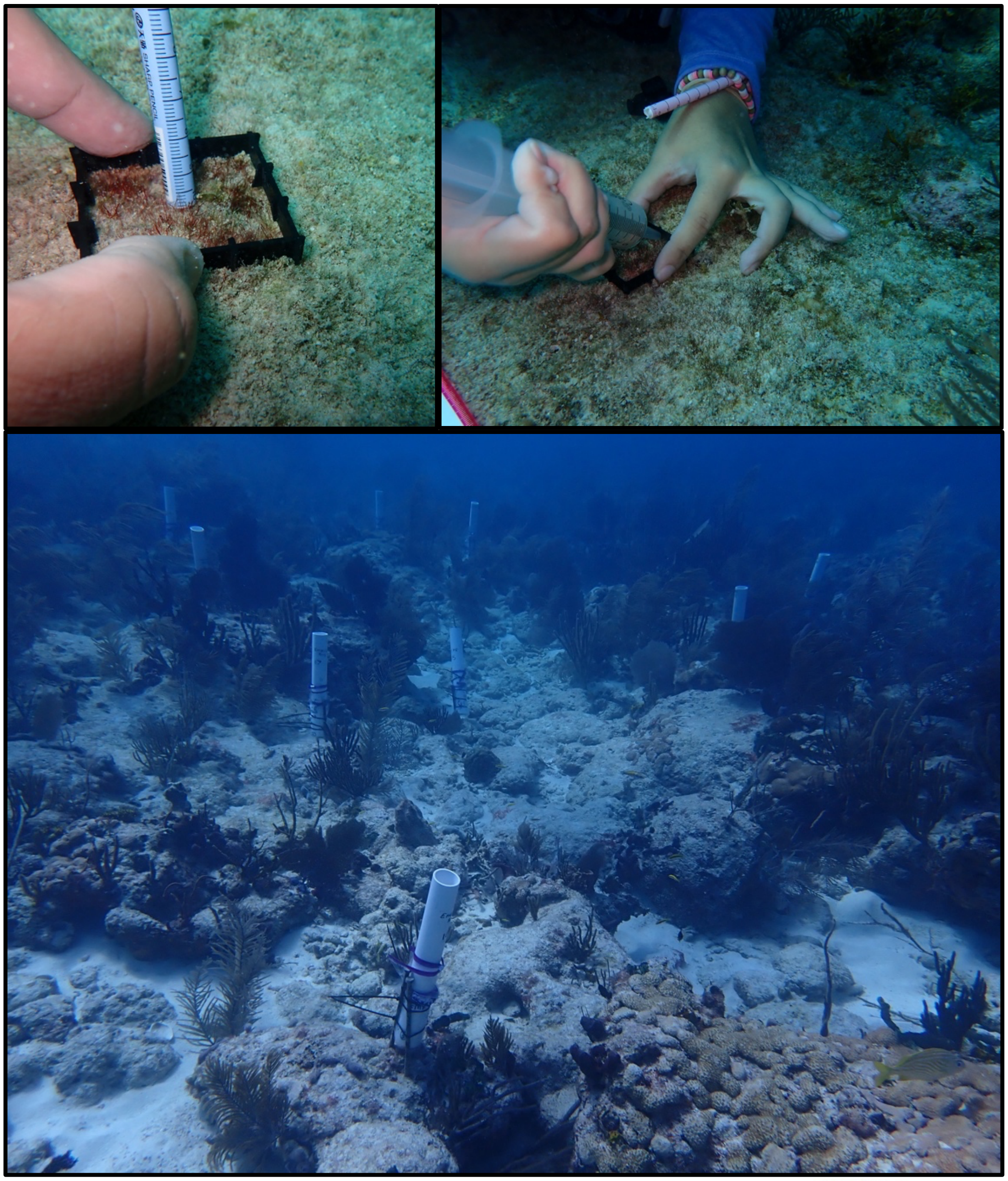
Title: Understanding spatiotemporal dynamics of sediments on Florida's Coral Reef and their impact on coral settlement and recruitment



FIU FLORIDA INTERNATIONAL UNIVERSITY
Department of Biological Sciences

FLORIDA'S CORAL REEF

FLORIDA DEPARTMENT OF ENVIRONMENTAL PROTECTION

Title: Understanding spatiotemporal dynamics of sediments on Florida's Coral Reef and their impact on coral settlement and recruitment

Final Report

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FLORIDA INTERNATIONAL UNIVERSITY
Department of Biological Sciences

Management Summary

The benthic assemblages of the upper section of Florida's Coral Reef (Fort Lauderdale to Key Largo) were evaluated seasonally between summer 2023 and spring 2024. Long sediment-laden algal turf (LSAT) comprised approximately 40% of the reef's benthic cover, with site-specific fluctuations in abundance and sediment load. Summer and winter surveys displayed a 10% higher abundance of LSAT and approximately 1mm of sediment deeper than fall and spring surveys. High sediment loads likely contribute to the low number of juvenile corals throughout the year, which averaged 5 juveniles m^{-2} and were dominated primarily by *Siderastrea*. As found in previous work (Duran *et al*. 2023 FDEP report), our work suggests that LSAT on the reefs is a stable sediment matrix held by turf-forming macroalgal species, specifically *Digenea nana,* which can grow up to 15 mm tall within the sediment. On the contrary, crustose coralline algae, some of which are coral recruitment promoters, disappear once LSAT sediment depth reaches about 5mm.

The estimated sedimentation rates for Florida's Coral Reef ranged from 0.6 g day^{-1} m^{-2} (South Canyon, fall 2023) to 106 g day^{-1} m^{-2} (Dania Beach, spring 2024) and displayed wide variation. Summer, the season with the deepest LSAT sediment, had the lowest sedimentation rate across all seasons (8 g day^{-1} m^{-2}). Results from our field surveys found a 50% decline in the likelihood of juvenile coral presence as a function of sediment depth trapped within LSAT (5mm), but only during the summer despite significant increases in sediment depth in winter. This season-specific result could reinforce the negative effect of LSAT on coral recruitment, especially on broadcast species that spawn during summer. Lab and field experiments are highly encouraged to validate our field results, particularly the effect of sediment and sediment type on different stages of the coral life cycle and coral larvae.

Executive summary
This project evaluated the distribution and composition of long sediment-laden algal turfs (LSAT) in relation to recruitment and success of corals on Florida's Coral Reef. We conducted high-resolution field surveys and experimental sediment manipulations to quantify temporal variation of LSAT abundance and composition, recently recruited juvenile corals (<4 cm), and sedimentation rates in the upper section of Florida's Coral Reef. In this report, each task represents a season (fall, winter, and spring). Since this is a continuation of previous work conducted in summer 2023, we combined data from all four seasons in this report to better illustrate the temporal-spatial dynamics of LSAT, coral recruitment, and sedimentation rate in Florida's Coral Reef. All tasks were completed as proposed.

The benthic assemblages of the upper section of Florida's Coral Reef (Fort Lauderdale to Key Largo) were evaluated seasonally between summer 2023 and spring 2024. LSAT constituted approximately 40% of the reef's benthic assemblages, with site-specific fluctuations in abundance and sediment load. Summer and winter surveys displayed a 10% higher abundance of LSAT, approximately 1mm of sediment deeper than fall and spring surveys. High sediment loads likely contributed to the low abundance of juvenile corals observed throughout the year (average: 5 juveniles m^{-2}), dominated primarily by corals from the genus *Siderastrea*. As found in previous work (Duran *et al*. 2023 FDEP report), LSAT appears to be a stable sediment matrix held by turf-forming species, specifically *Digenea nana,* which can grow up to 15 mm tall within the sediment. On the contrary, crustose coralline algae, some of which are coral recruitment promoters, disappear once LSAT sediment depth reaches approximately 5mm.

The logistic regression model showed a 50% decline in the likelihood of juvenile coral presence as a function of sediment depth (5 mm) trapped within LSAT, but only during the summer despite significant increases in sediment depth in winter. This season-specific result could reinforce the negative effect of LSAT on coral recruitment, especially for broadcast species of coral that spawn during summer. Lab and field experiments are highly encouraged to validate our field results, particularly the effects of sediment and sediment type on different stages of the coral life cycle, including coral larvae. The estimated sedimentation rates for Florida's Coral Reef ranged from 0.6 g day^{-1} m^{-2} (South Canyon, fall 2023) to 106 g day^{-1} m^{-2} (Dania Beach Spring 2024) and displayed wide variation. Summer, the season with the deepest LSAT sediment depth, had the lowest sedimentation rate across all seasons (8 g day^{-1} m^{-2}).

Our results highlight one of the potential major drivers underpinning the coral recruitment crisis on Florida's Coral Reef. We found juvenile corals in 32% of all plots we surveyed (n = 600 plots total across six sites and four seasons)) and an almost complete 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 (i.e., supply), 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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List of Acronyms

LSAT. Long sediment-laden algal turf
SPAT. Short productive 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, information on LSAT abundance or composition is extremely limited or absent. 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), suggesting that other taxa cover the majority of the reef bottom. 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 distribution and composition of LSAT in relation to recruitment and success of corals on Florida's Coral Reef. To do so, we proposed field surveys to assess the distribution and composition of LSAT on reefs spanning Broward County to the Upper Florida Keys. We conducted field surveys and experimental sediment manipulation to quantify temporal variations of LSAT abundance and composition, recently recruited juvenile corals (<4 cm), LSAT, and sedimentation rates in the upper section of Florida's Coral Reef.

2. METHODS

Assessment of benthic communities and juvenile corals

To evaluate the relationship between LSAT and juvenile corals, we conducted high taxonomic resolution surveys at six shallow coral reef sites (6 to 8 m depth) located along reefs in Broward County, Miami-Dade County, and the north section of the Upper Florida Keys (Table 1). These locations include Fort Lauderdale, Dania Beach, South Canyon (Miami Beach), Emerald Reef (Key Biscayne), Carysfort Reef (Key Largo), and Conch Reef (Key Largo). Based on our previous data, we selected these reefs because they have some of the highest density of juvenile corals. Surveys were conducted every four months from July 2023 until May 2024 to study the seasonal variation of benthic communities, particularly the composition (turf algae identity and sediment load and composition) of LSAT.

Each season, we surveyed the benthos in n = 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 the highest taxonomic resolution possible. Short productive algal turf (SPAT) was classified as a relatively sediment-free, dense, and stable multi-species (e.g., *Polysiphonia* spp., *Ceramium* spp., *Hypnea* spp., *Laurencia* spp.) algal assemblages forming a layer <1 cm in height. We binned all crustose coralline algae (CCA) species into one group. Species from the genus *Peyssonnelia,* a non-coralline crustose alga, were classified as a single group (*Peyssonnelia*). We also evaluated the abundance of coral juveniles (colonies ≤4 cm in diameter) within each plot. Each juvenile found within a plot was measured (diameter; cm) 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 Reef	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

Physical characteristics of the substrate, such as slope, can influence the benthic composition and sediment retention. Accordingly, 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.

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 per season). Within each 5 x 5 cm subplot, we first measured the depth of the sediment layer of the matrix at the center of the plot. The sediment thickness (depth; 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 all sediment trapped within a 5 x 5 cm subplot using a modified 60-ml syringe. 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. Sediment samples were dried to a constant temperature (70 Celsius) to obtain a dry weight (g). We then separated the dried sediment samples by grain sizes using a series of sieves and obtained weight by size class for each plot.

Sediment rate characterization

Sediment removal

To estimate the LSAT formation rate (mass of sediment trapped within turf), we conducted sediment removals at one reef location (South Canyon). To do so, we established 30 experimental (25 x 25 cm) plots separate from the randomly placed plots used in Task 1 and intentionally placed in areas with a high abundance of LSAT. Within each experimental plot, we measured sediment depth as described above (calibrated pencil). Sediments were then removed from 20 plots, and 10 plots had no sediment removed and served as controls. In 10 of the plots where sediment was removed ("turf only"), we assessed the turf community exposed to sediment removal via measurements of turf length (mm), percent cover, and species composition. We also removed all macroalgae and algal turf from the other ten plots where sediments were removed ("turf-free"). After 19 days, we returned and measured sediment deposited in the two different experimental sediment removal plot types ("turf-free" and "turf only") and control plots.

Sediment traps

We used sediment traps deployed at each site (n = 10) to estimate sedimentation rates (mass of sediment deposited over time). Sediment traps were constructed of PVC pipe (5 cm internal diameter; 43 cm height) and were set on the reef in a vertical orientation approximately 50 cm from each sediment removal plot at each site. Sediment traps were deployed for approximately 14 days, with total deployment time based on field conditions to return to each site. At the end of the deployment, sediments collected in each trap were collected *in situ* and transported to the lab at FIU, where they were analyzed for composition (grain size) analysis as described in "*Sediment depth and characterization*" under part B.

3. RESULTS

Assessment of benthic communities and juvenile corals

Long sediment-laden algal turf (LSAT) covered approximately 40% of the reef's benthic assemblages with site- and season-specific fluctuations in abundance (Figure 1) and sediment load (Figure 2). Summer and Winter displayed a 10% higher abundance of LSAT with approximately 1mm of sediment deeper than Fall and Spring. The abundance of Upright brown macroalgae (*Dictyota* spp. and *Stypopodium zonale*) peaked substantially (double the abundance) in Spring 2024 in the southern study sites (Emerald Reef, Carysfort Reef, and Conch Reef). On the contrary, SPAT (e.g., *Ceramium* spp. and *Laurencia* spp.) and crustose algae were more abundant in Fall 2023 and Winter 2024). Throughout the year, the density of juvenile corals remained very low (~5 Juv. m^2). Out of the 600 plots surveyed (25 x 25 cm each), we found juvenile corals in only 193 (~32%) (Table 2).

On average, summer and Winter displayed a ~10% higher abundance of LSAT, with the sediment depth approximately 1mm deeper during these surveys compared to the Fall and Spring surveys (Figure 2). During Winter, increased sediment depth within LSATs was especially pronounced at Conch Reef (Key Largo).

Results from our logistic regression models indicated that there was only a significant relationship between sediment depth and the likelihood of juvenile coral presence during the summer season ($p = 0.007$). Indeed, results from the summer surveys showed a 50% decline in the likelihood of juvenile coral presence in the presence of just 2 mm of sediment trapped within LSAT. Moreover, our summer model predicted a complete lack of juvenile coral presence after sediment depth within LSAT surpassed 6 mm.

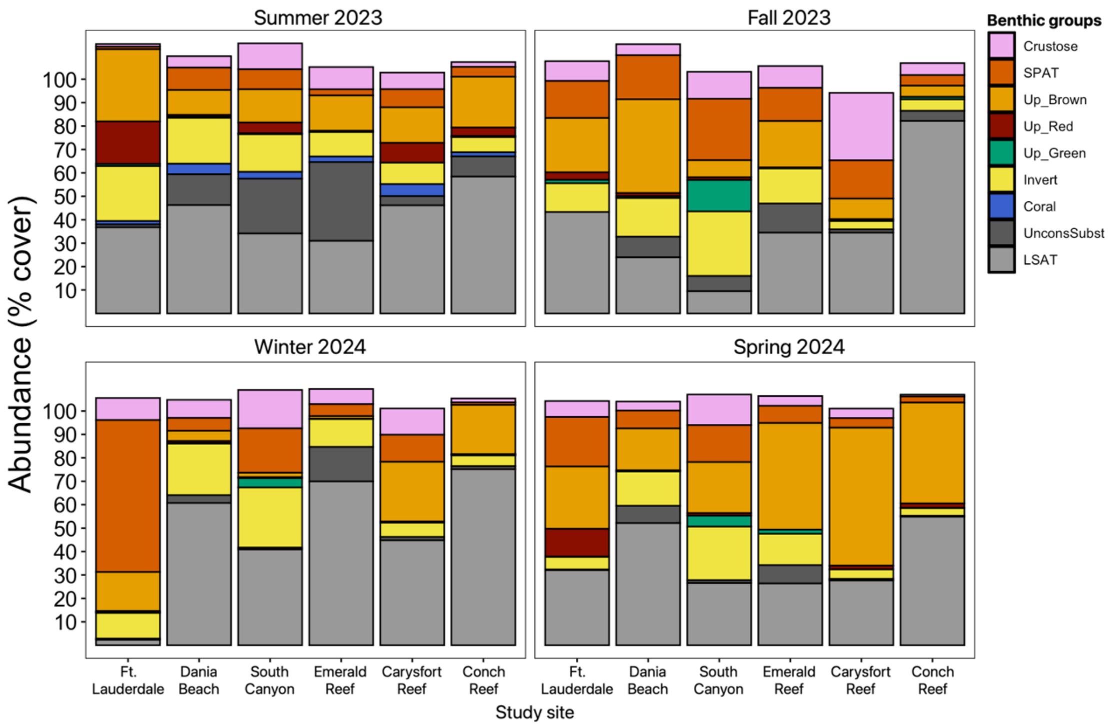

Figure 1. Mean abundance (% cover) of the nine most common benthic groups found across all sites by season within the 25 x 25 cm plots surveyed. Long sediment-laden algal turf (LSAT), crustose coralline algae and peyssonnelids (crustose), short productive algal turf (SPAT), upright brown algae (Up_Brown), upright red algae (Up_Red), upright green algae (Up-Green), sessile invertebrates (Invert), and unconsolidated substrate (Uncons_Subst). Full data set provided in the deliverables.

Table 2. Total count of juvenile corals (in 25 plots) by site and season.

Season	Fort Lauderdale	Dania Beach	South Canyon	Emerald Reef	Carysfort Reef	Conch Reef	Total
Summer 2023	4	8	11	13	12	5	**53**
Fall 2023	8	9	6	10	8	9	**50**
Winter 2024	3	7	6	13	6	5	**40**
Spring 2024	4	6	14	7	11	8	**50**

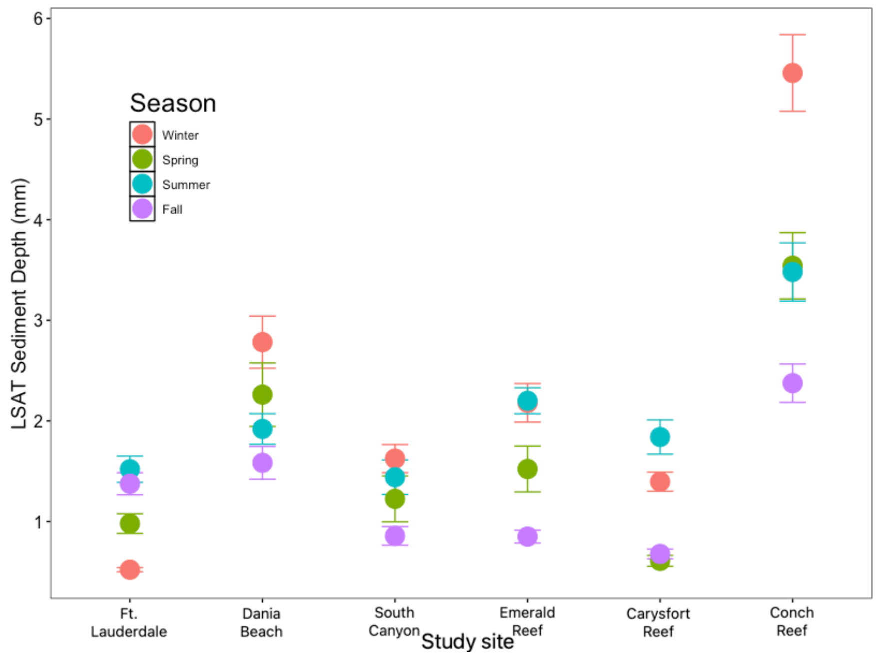

Figure 2. Mean sediment depth (mm) trapped within the long sediment-laden algal turf (LSAT) at each site by season. Bars indicate standard error.

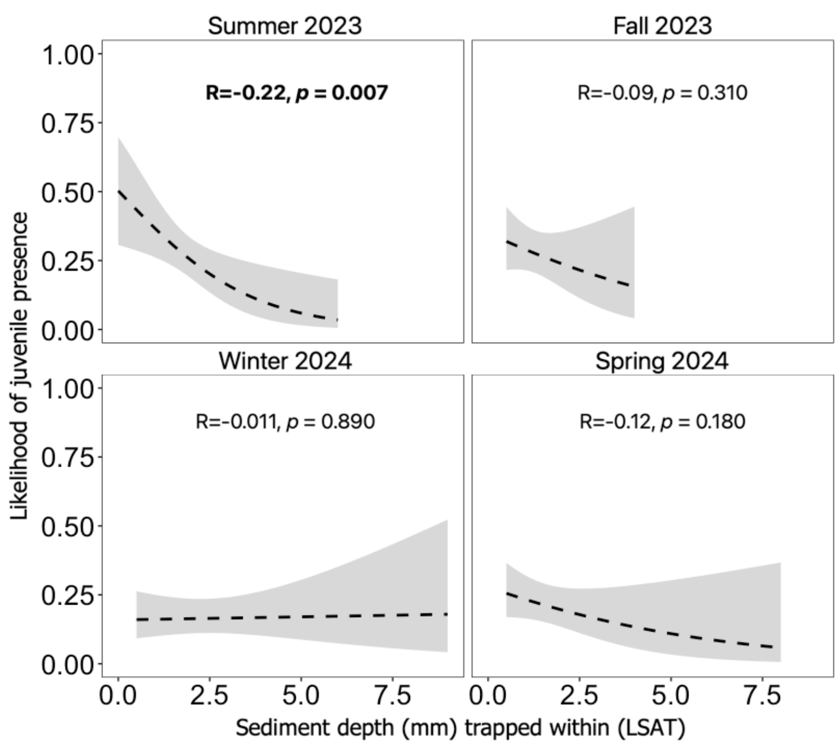

Figure 3. Presence of juvenile corals as a function of sediment depth (mm) trapped within the long sediment-laden algal turf (LSAT) across all sites by season.

Characterization of LSAT

As found in our previous work (Duran *et al*. 2023 FDEP report), we found a strong positive relationship ($R = 0.82$; $p < 0.001$) between turf algae length and the depth of sediment trapped within these algal turfs. These results suggest that LSAT seems to be a stable sediment matrix held intact by turf-forming species, specifically *Digenea nana,* which can grow up to 15 mm tall within the sediment. On the contrary, we found a negative relationship between sediment depth and the abundance of crustose coralline algae (CCA) ($R = -0.11$; $p = 0.009$; Figure 4). Crustose coralline algae can provide numerous important ecological functions, including promoting coral recruitment and cementing together reef substrate. Our results suggest that CCA may disappear or decline to such low levels as sediment depth increases that they likely cease to provide key ecological functions.

Sediment rate characterization

The experimental removal of sediment revealed that in plots where sediments were removed but macroalgae and algal turfs were not ("turf only), turf algae grew on average 2.75 mm (± 0.48) in height over the course of 19 days. These turf-only plots also gained 1mm more sediment during the 19 day experiment compared to turf-free plots. However, within turf-free plots, turf proliferated (0.14 mm day^{-1} or 27% tissue gain day^{-1}) and already began accumulating sediment by the end of the 19 day experimental period. Sedimentation rates at our sites ranged from 0.66 to 106.4 g day^{-1} m^{-2} (Figure 6), displaying wide variation across sites and seasons. Surprisingly, Summer, the season with the deepest LSAT sediment, had the lowest sedimentation rate across all seasons (8 g day^{-1} m^{-2}).

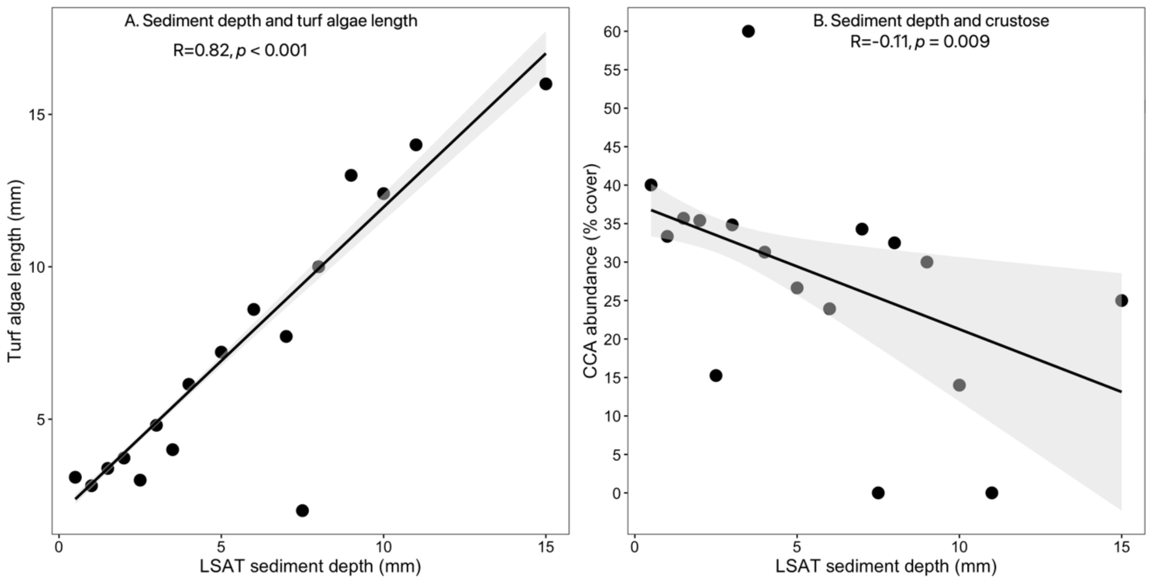

Figure 4. Relationship between sediment depth (mm) trapped within the long sediment-laden algal turf (LSAT) and length of the turf algae trapping the sediment (left) and CCA abundance (% cover) found under the sediment layer (right).

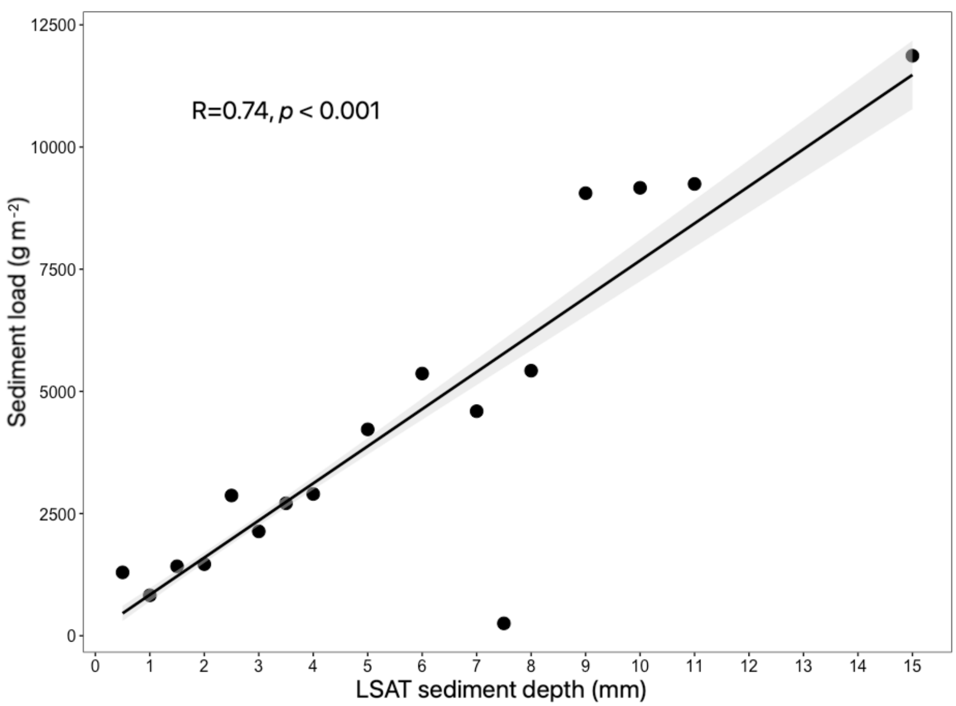

Figure 5. Sediment load (g m^{-2}) as a function of sediment depth (mm) trapped within the long sediment-laden algal turf (LSAT).

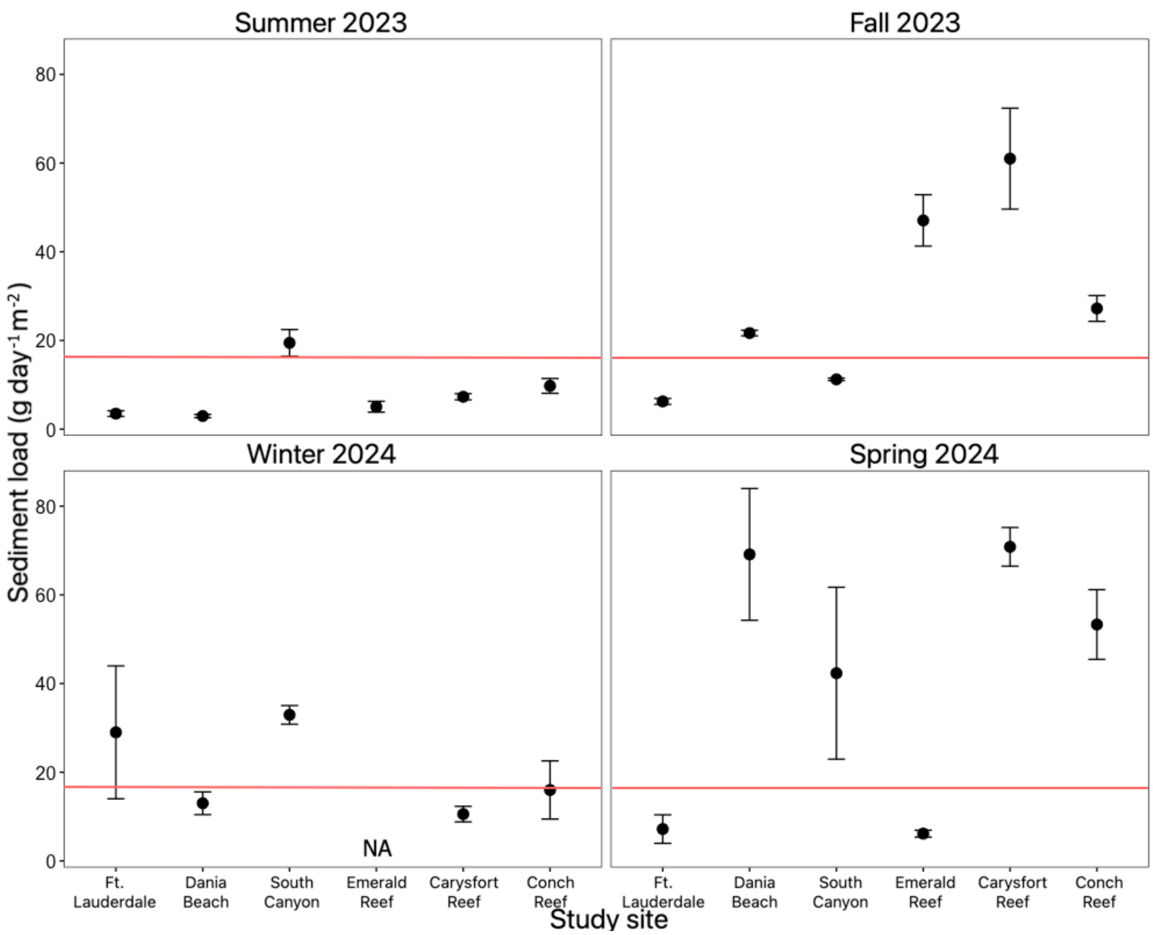

Figure **6.** Sedimentation rate across all studied sites and seasons (Mean ± SE). Red lines show values Tebbett *et al*. 2023 reported for the Great Barrier Reef using sediment traps.

4. DISCUSSION

The upper section of Florida's Coral Reef, from Fort Lauderdale to Key Largo, had a relatively low density of juvenile corals (average of 5 juv. m^{-2}) that were dominated primarily by *Siderastrea* spp. and other weedy coral genera (*Porites* and *Agaricia*). LSAT covered approximately 42% of the reef's seafloor and generally increased in 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.

The drivers of coral recruitment failure on Florida's Coral Reef remain unresolved, but impoverished habitat quality likely compromises the process. Studies conducted in the 1970s and 1980s at some of the sites included in our study reported densities of juvenile corals at Conch Reef and Carysfort Reef between 5 and 12 juv. m^{-2}, and were largely dominated by *Agaricia* spp. (Dustan 1977, Edmunds et al. 1998).

Moulding (2005) conducted field surveys in 2002 across Florida Keys patch reefs and reported average juvenile densities between 6 and 39 juv. m^{-2}, dominated by *Porites* spp. and *Siderastrea* spp. 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 the taxa *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 the sediment layer depth are negatively related to the presence of juvenile corals, particularly for species other than *Siderastrea*. Indeed, *Siderastrea* is considered a temperature and sediment-tolerant coral genus (Lirman and Manzello 2009). However, numerous questions remain unanswered regarding the impacts of sediments on the early life history stages of corals. For instance, besides physically 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. On the contrary, crustose coralline algae (CCA) tend to disappear once the LSAT sediment layer surpasses 5 mm in thickness. Seemingly, as sediment accumulates, it creates anoxic conditions and blocks light penetration, preventing the settler's survival and growth. Additional questions include understanding how coral taxa like *Siderastrea* better cope with sediment than other coral taxa.

Sedimentation rates ranged from 0.66 to 106.4 g day^{-1} m^{-2}, gradually increasing from north to south, which might help 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 observed that the mineral composition of sediment (e.g., silicate-based vs. carbonate-based) appears to differ among these sites. Further analysis of mineral composition would highlight sediment origin in these reefs, an essential piece of the puzzle to develop effective management strategies regarding sedimentation on Florida's Coral Reef.

Our results revealed a high abundance of 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.

5. MAIN FINDINGS AND MANAGEMENT RECOMMENDATIONS

Main findings:

- Long sediment-laden algal turf (LSAT) covered approximately 40% of the reef's benthic assemblages with site- and season-specific fluctuations in abundance
- Juvenile coral density remains extremely low in the upper section of the Florida Coral's Reef, likely influenced by the sediment load trapped within LSAT
- During summer, the coral spawning season, we found that sediment load trapped within LSAT had a negative relationship with presence of juvenile corals.

Management recommendations:

- For dredging activities, implement measures to avoid sediment deposits on reefs as a means to maintain habitat functions needed for coral recruitment and survival of juvenile corals.
- For dredging projects, incorporate monitoring of sedimentation, algal turf communities, and juvenile coral abundances to understand changes resulting from projects.
- Conduct complementary studies to characterize further the spatio-temporal patterns of LSAT distribution on Florida's coral reef.

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