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# Natural vs. Anthropogenic Sedimentation: Does Reducing a Local Stressor Increase Coral Resilience to Climate Change?

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NOVA SOUTHEASTERN UNIVERSITY  
HALMOS COLLEGE OF NATURAL SCIENCES AND  
OCEANOGRAPHY

Natural vs. anthropogenic sedimentation:  
Does reducing a local stressor increase coral resilience to climate change?

By

FRANCESCA FOURNEY

Submitted to the Faculty of  
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## **ABSTRACT**

Corals face serious worldwide population declines due to global climate change in combination with direct anthropogenic impacts. Global climate change is difficult to manage locally, but policy makers can regulate the magnitude of local stressors affecting reefs. The objective of this experiment is to investigate if reducing sedimentation will enable reef corals to better endure global climate change. It has been shown that some coral species can handle climate change stress when provided with additional energy resources. Here I tested if the capacity of corals to cope with climate change can be improved when their ability to feed and photosynthesize was not compromised by increased sedimentation. Sedimentation can impede coral feeding and their ability to photosynthesize due to direct polyp blocking and increased turbidity, which reduces light availability. To evaluate the potential of enhancing coral ability to tolerate climate change by reducing a local stressor, I examined the survival and growth of brooding coral *Porites astreoides* juveniles when exposed to ambient and elevated water temperatures under differing sedimentation rates. I also assessed if sediment composition has significant impacts on these results. I used sediment from a reef and sediment from a boat basin within a port to mimic natural and anthropogenic sediment types and processes (e.g. dredging). Experiments were conducted to quantitatively assess the synergistic effects of sediment concentration and composition, along with increased temperature on the survival and growth of juvenile *P. astreoides*. The most detrimental effects were observed with anthropogenic sediment, when both sediment concentration and water temperatures were high. However, increased natural reef sediment was found to be beneficial to juvenile corals. More interestingly, I found that corals capacity to deal with higher temperatures is improved when anthropogenic sedimentation is maintained at minimal levels and turbidity resulting from sedimentation was low. Therefore, this information will aid managers in making decisions that regulate dredging and construction activities to minimize sedimentation, which will contribute to increase coral survival under climate change.

**Keywords:** dredging, ocean warming, juvenile corals, survival, growth

# 1. INTRODUCTION

## 1.1. Importance and Status of Coral Reefs Globally

Coral reefs are one of the most important and biologically diverse ecosystems on Earth. These habitats provide several essential ecosystem services and have significant economic value. Scleractinian corals construct the foundation of the reef by excreting calcium carbonate skeletons. These skeletons provide habitat, shelter, nursery areas, and food for over 9 million species of animals and plants (Knowlton, 2001). Coral reef ecosystems span only 0.2% of the ocean floor but support an estimated 25% of all marine life (Spalding et al., 2001). Coral reefs are also vital to the human population. An estimated \$375 billion of net benefits in goods and services are derived globally from coral reefs each year (Veron et al., 2009). For example, some of the ecological commodities supplied by coral reefs include: seafood products, raw materials for medicines, mineral oil, and petroleum gas (Carté, 1996; Moberg & Folke, 1999). Coral reefs also provide important ecosystem services such as physical shoreline stabilization, carbon dioxide-calcium budget control, tourism and recreational services, and biotic maintenance of these aesthetically pleasing habitats (Carté, 1996; Moberg & Folke, 1999). These goods and services are essential in sustaining the livelihood of many coastal communities.

Corals face natural stressors such as predation, competition, and physical disturbances. Predation occurs at all stages of their life cycle. Coral larvae can be eaten while in the water column where predation intensity is generally high (Pechenik, 1999). Parrotfish or other corallivores such as Crown-of-Thorns starfish will directly eat adult corals (De'ath & Moran, 1998). Corals are also vulnerable to competition for space and light among conspecifics, as well as between other benthic organisms. Corals obtain much of their energy through photosynthesis via a symbiotic relationship with algae of the genus *Symbiodinium*, so there exists competition for space and light. Disturbances due to weather phenomena such as severe storms also occur naturally in tropical marine areas. Even though storms cause direct physical destruction to reefs, corals normally recover through biological processes and because they have evolved in storm prone locations (Sheppard et al., 2009). Recovery is dependent on the growth of the surviving coral population through asexual reproduction and recruitment during sexual



reproduction. Successful coral recruitment requires larval availability, successful settlement, and post-settlement survival and growth (Ritson-Williams et al., 2009). A disturbed reef can be repopulated either through the retention of locally produced larvae or by settlement of larvae dispersing from a connected reef (Ritson-Williams et al., 2009). There has been no sign of recovery for these organisms and even the most pristine reefs have shown system-wide decline (Sebens, 1994; Hughes et al., 2003; Bellwood et al., 2004). In fact, coral reef ecosystems have been in a serious decline over the past few decades (Hoegh-Guldberg et al., 2007) and in the past 30 years, the percent cover of live coral has decreased globally (Gardner et al., 2003; Pandolfi et al., 2003; Bruno & Selig, 2007). It is also estimated that 30% of reefs have already been severely degraded and a 60% loss is predicted by 2030 (Hughes et al., 2003). These estimates show that the natural recovery processes of coral reefs are being compromised by other factors.

## *1.2. Anthropogenic Impacts and Climate Change*

Anthropogenic impacts such as overfishing, pollution, eutrophication, and coastal construction have accelerated the decline of coral reefs. The combination of anthropogenic impacts and natural stressors together can cause major phase shifts from coral-dominated reefs to less desirable states, such as macroalgae or sponge dominated reef ecosystems (Jackson et al., 2001; Norström et al., 2009; Bozec & Mumby, 2015). This is largely due to overfishing of large herbivorous fishes, the die off of the sea urchin *Diadema antillarum* in the 1980's, and added nutrient runoff and sedimentation from sewage and land development (Smith et al., 1981; Jackson et al., 2001; Hughes et al., 2003; Mumby et al., 2006).

Coastal construction activities are particularly stressful for corals as it increases turbidity and sedimentation. Although sedimentation does occur naturally through wind-driven waves and tidal currents (Browne et al., 2012), anthropogenic activities such as dredging and construction can increase sedimentation duration, severity, and frequency causing detrimental consequences for coral reefs (Jordan et al., 2010; Erftemeijer et al., 2012). Sediments have different compositions and sizes, but fine particles (<63  $\mu\text{m}$ ) are known to have the most harmful effects on corals (Bak & Elgershuizen, 1976; Fisk, 1981; Nugues & Roberts, 2003). Natural sediment found on the reef usually has larger grain

sizes compared to anthropogenic sediment from construction activities. When turbidity is increased due to the presence of fine particles in the water column, light availability is significantly reduced. The United States Environmental Protection Agency (U. S. EPA) declared in 1988 that standard water turbidity for Florida coastal waters not exceed 29 NTUs (Nephelometric Turbidity Units, measured based on how much light is scattered by suspended particles in the water) during construction and nourishment events (U. S. EPA, 1988). Increased turbidity reduces light availability, which negatively impacts the photosynthetic productivity of *Symbiodinium*, an endosymbiotic algae within coral tissue (Riegl & Branch, 1995). Landfills, beach re-nourishment, and coastal construction can also cause burial and physical disturbance of corals (Erftemeijer et al., 2012; Barnes et al., 2015). Sedimentation can directly smother corals and block polyps, therefore reducing active feeding mechanisms and depleting energy reserves (Stafford-Smith & Ormond, 1992). Energy typically used for growth and reproduction will be allocated towards clearing sediments that have settled on top of the coral subsequently blocking polyp-feeding structures (Erftemeijer et al., 2012). This change in energy utilization in turn lowers calcification rates, reduces productivity and reproductive output (Goreau, 1959; Erftemeijer et al., 2012). Coral reef recovery has been undermined by anthropogenic impacts overlaying natural stressors and coral reef populations have been declining (Hoegh-Guldberg et al., 2007). In absence of local anthropogenic stressors, corals should be able to recover from natural impacts (Smith et al., 1981; Gilmour et al., 2013).

Global climate change has lately become an environmental concern and introduces additional stressors to reefs on top of natural and local anthropogenic impacts. Human activities affect the Earth's energy budget due to increased emissions from fossil fuels resulting in the modification of atmospheric concentrations of important greenhouse gasses (IPCC, 2014). The emissions of these gases such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) have been accumulating over the past 30 years, causing global temperatures to rise (IPCC, 2014). Climate change models predict that tropical sea surface temperatures will rise up to 3°C this century (IPCC, 2014). Some of these gases, and the associated increase in trapped heat, are absorbed by the ocean, which causes surface waters to warm and acidify. It has been commonly found that increased

seawater temperatures facilitate coral bleaching (Glynn & D’Croze, 1990; Glynn, 1993; Glynn, 1996; Hoegh-Guldberg, 1999). Bleaching is an event where the coral loses its endosymbiotic algae, *Symbiodinium*, from its tissues, leaving the coral stark white in color. There are multiple cases throughout differing regions of the world that indicate unusually high seawater temperatures as the main factor causing coral bleaching (Brown, 1987; Glynn & D’Croze, 1990; Glynn, 1993; Glynn, 1996). Corals obtain significant nutritional resources from *Symbiodinium* that increase energy reserves and skeleton growth of scleractinian corals (Abrego et al., 2012). The symbionts provide >50% of the energy budget for the coral and in ideal conditions it can account for 90-95% (Davies, 1984; Cesar et al., 2003; Grottoli et al., 2004; Grottoli et al., 2006; Hoegh-Guldberg et al., 2007). When bleached, coral tissue growth, fecundity, calcification, and overall survival are severely degraded and mass bleaching events threaten entire reef ecosystems (Glynn, 1993; Glynn, 1996; Sheppard et al., 2009). Bleaching reduces energy reserves supplied by the symbionts, leaving the coral in a fragile condition, which negatively impacts coral maintenance and growth (Anthony et al., 2007). Unfortunately, recent studies have predicted that coral bleaching may become an annually occurring event within the next 25-50 years, potentially hampering reef recovery and thus causing exponential declines of coral populations worldwide (Cesar et al., 2003).

Recovery from the combination of anthropogenic impacts and climate change would need to be profound to increase or maintain current coral cover. Since climate change is a global issue, moderation and strict management of CO<sub>2</sub> emissions and other greenhouse gases would need to be implemented uniformly worldwide (Bellwood et al., 2004); however, global consensus is difficult to achieve. It is possible however that some corals may be able to tolerate climate change when their energy reserves are reinforced. Studies have shown that some coral species can buffer deleterious effects of ocean acidification and increased temperatures when coral feeding was increased (Edmunds, 2011; Towle et al., 2015). This trend was also found in fishes. Well-fed fish exposed to temperatures representative of future climate scenarios had higher body condition and increased survivorship in comparison to unfed fish (McLeod et al., 2013). By investigating the possibility of reducing sedimentation, which reduces coral energy reserves, coral survival, even when climate change is present, may be conceivable.

### 1.3. Objectives

This study investigates if reducing a local stressor will increase coral resilience to climate change. With sediment representing the local stressor because it is known to impede coral energy storage (Riegl & Branch, 1995). The objectives were to determine the synergistic effect of sediment concentration coupled with elevated temperatures on coral juvenile survival and growth as well as describe if natural and anthropogenic sediment lead to differences on coral juvenile survival and growth. I hypothesized that corals will be better able to cope with climate change if sedimentation is minimized, particularly since sedimentation reduces coral energy reserves. The study represents differing sedimentation concentrations including naturally observed levels and the increased levels observed during dredging and construction activities. In addition to the varying sediment concentrations, the composition of sediment will also be assessed, comparing natural sediment versus anthropogenic sediment. These sedimentation concentrations and compositions will be tested in combination with temperatures, both current ambient summer averages of Broward County, FL and elevated temperatures predicted by climate change models. These effects will be tested on the most critical stage for coral recovery, the juvenile stage. Examining the most vulnerable life stage of coral will provide insight on the recovery of reefs. Benthic marine invertebrate juvenile mortality is highest within the first four weeks of settlement (>90%) and may be >30% during the initial day of settlement (Gosselin & Qian, 1997). The study results may be utilized as a future management tool to aid coral populations to overcome global climate change stress. Coral reef conservation and anthropogenic impact assessments will improve the potential recovery of these valuable and exquisite ecosystems.

## 2. METHODOLOGY

### 2.1. Study Species

*Porites astreoides* (LAMARCK, 1816) colonies are commonly found encrusted in high wave energy areas on shallow reefs and as rounded domes in deeper water. This particular species normally has a porous appearance because of its bumpy surface with small corallites set closely together. They can be a variety of colors including yellow-green to yellow-brown or sometimes gray and when the polyps are extended the colonies

seem soft and fuzzy (Sheppard et al., 2009). The scleractinian coral species *Porites astreoides* was selected for this experiment because of its reproduction mode and local abundance. *P. astreoides* has a brooding sexual reproductive mode meaning that fertilization and embryonic development occur within the parent tissue, thus released larvae are fully developed planulae ready to settle (Baird et al., 2009). This species also has high abundance in the South Florida region, as well as the rest of the Caribbean. *P. astreoides* also occurs at depths around 5 – 20 m, where they are more likely to experience shallow water bleaching (Glynn, 1993).

## 2.2. Coral Collection and Planulae Acquisition

Ceramic tiles with 2.5 cm diameter and 0.5 cm height were previously conditioned in the ocean in Broward County, FL at the same depths (~ 8 m) as the adult species were collected for approximately 2 months to be colonized by bacteria and crustose coralline algae to facilitate successful planulae settlement.

Eighteen adult colonies of *Porites astreoides* < 20 cm in diameter were collected 4 days prior to the new moon in April 2015 from two different sites (24° 44.004' N, 80° 49.577' W and 24° 43.908' N, 80° 49.634 W) within the Florida Keys reef tract off of Layton, Florida. These sites called “Rubble Clusters” are artificial patch reefs constructed from old broken bridge materials. Ambient summer temperatures in this location range from 25-26°C. The colonies were collected using chisels, pry-bars, and hammers to remove them from the reef. Careful consideration was taken not to cause tissue damage to the colonies. Both sites had a depth range of 3 – 7 meters. The detached colonies were brought up from the bottom using metal dish racks. The collection tools were rinsed in bleach between sites to avoid any contamination or crossing of disease. Once on the boat, the colonies were individually wrapped in bubble wrap and put into coolers containing seawater from the site. Water changes were conducted on the boat every half hour as needed throughout the trip.

The colonies were transferred to NSU’s facilities and kept in recirculating aquaria tanks supplied with filtered seawater at an average rate of ~ 1.3 liters per minute to ensure ideal oxygen distributions. The adult colonies were placed into large plastic bowls. Planulae were collected using a manifold system with rubber tubing that directed water

into the bowl. The water pressure transported the planulae from the adult colony into PVC pipes fitted with plankton mesh (10  $\mu\text{m}$ ) (Figure 1). Every day, ~0700 hours, the PVC pipes were examined for planulae. The colonies released approximately 10,000 planulae total. The peak releasing day was two days before the new moon, with colonies releasing about 5,000 planulae total. The remaining days colonies would release 100-500 planulae in total until the lowest day, which was two days after the new moon where only 10 planulae were released. The planulae were pooled randomly by the hundreds, which ensured that planulae released on different days were allocated randomly throughout all treatments, so fitness influences due to release day would not affect the results. Planulae were transferred to large tanks with air pumps containing 50-100 pre-conditioned settlement tiles. These tiles were inspected every 8 hours for planulae settlement. Once larvae had settled and metamorphosed into a juvenile, tiles that contained settled juveniles were assessed and the entire tile was photographed to track juvenile placement and initial surface area of the juvenile. In order to track one single polyp, overlapping juveniles were separated and one was retained for the experiment. The tiles were randomly distributed by the treatments while keeping the number of juveniles similar in each treatment. Light intensity levels were selected to approximate those found during the collection at depths of the parent colonies in April. Light was measured at the sites of the coral collection using a Li250A (Li-Cor) with an Underwater Quantum Sensor LI-192 (~220  $\mu\text{mol m}^{-2} \text{s}^{-1}$  at noon). Once an adequate amount of planulae settled for the experiment, the adult colonies were brought back to their original sites in May and were reattached to the substrate using marine epoxy.



**Figure 1:** Recirculating aquaria system with adult colonies of *Porites astreoides*. Rubber tubing regulates water flow and water pressure to assure ideal oxygen distribution. The water leads to PVC pipes fitted with plankton mesh to sieve out planulae.

### 2.3. *Sediment Collection, Drying, and Quantification*

Two different types of sediment were collected: natural and anthropogenic. Natural sediment was collected via SCUBA diving from the upper 10-30 cm of sand at locations where the adult colonies were collected in the Florida Keys. Anthropogenic sediment was collected via SCUBA diving from the upper 10-30 cm of sediment in NSU's boat basin, which is located next to Port Everglades in Broward County FL. Sediment samples were put into a drying oven at 70°C for at least 24 hours to kill any interstitial organisms and to ensure accurate weighing of sediment. The dry sediment was sieved (Sieve Shaker model RX-86) to quantify the percentages of different grain sizes. The effect of sedimentation was tested with rates of 30, 60, 90, 120 mg cm<sup>-2</sup> d<sup>-1</sup> representing natural rates, double natural rates, and rates typical during dredging and other construction activities, respectively (Jordan et al., 2010). In order to reproduce these sedimentation rates before the experiment started, the quantity of sediment that needed to be added to each tank to produce the desired sedimentation rates was tested to account for the amount of sediment that would remain suspended. To do this, several known amounts of sediment were added to each tank and the final sedimentation rate produced was

measured using sediment traps. The traps were glass jars with 25.65cm<sup>2</sup> openings. Tank dimensions were approximately 45 cm X 30 cm X 30 cm to ensure viable space for the tiles.

#### 2.4. *Experimental Set-up: Natural Sediment vs. Anthropogenic Sediment*

Two experiments were conducted to represent the differences between natural sedimentation that occurs on the reef and sedimentation that occurs during dredging and development activities. To mimic natural sedimentation I used the sediment collected from the Florida Keys. This consisted of 5% grain sizes >2000  $\mu\text{m}$ , 65% grain sizes 500-2000  $\mu\text{m}$ , and 30% grain sizes 180-500  $\mu\text{m}$ ; based on Udden-Wentworth US standard classification scale of sediment (Wentworth, 1922). No silt (<63  $\mu\text{m}$ ) was found in these sediments. Because the composition of the sediment was not representative of typical grain sizes found during dredging areas including ports, boat basins, and developed areas, a second experiment was conducted using sediment from NSU's boat basin, located in Port Everglades to mimic anthropogenic sedimentation. This sediment regime consisted of 35% grain sizes 180-500  $\mu\text{m}$ , 45% grain sizes 63-180  $\mu\text{m}$ , and 20% of grain sizes <63  $\mu\text{m}$  (Wentworth, 1922). Due to logistical constraints the two experiments could not be conducted concurrently, thus they used a different number of juvenile corals and corals of different ages. The first natural sedimentation experiment consisted of 1,503 individual corals and the experiment began immediately after settlement. The second anthropogenic sedimentation experiment consisted of 80 individual corals and the experiment began 5 months after they had settled. Nephelometric Turbidity Units were measured using a LaMotte 2020we Turbidity Meter. The NTUs for the natural sediment all fell below 1 NTU (Table 1). The NTUs for the anthropogenic sediment fell between ~5 – 43 NTUs (Table 2). The effect of temperature and sedimentation rates on coral juvenile survival and growth was examined using a fully crossed experimental design with two temperatures (26°C and 30°C) and four sedimentation rates (30, 60, 90, 120 mg cm<sup>-2</sup> d<sup>-1</sup>). The temperatures tested intended to mimic average Broward County summer levels and elevated climate change predictions respectively. Tanks were individually heated using temperature-regulated, programmable Aqueon Submersible Aquarium 300 watt digital heaters ( $\pm 0.1^\circ\text{C}$ ).



**Table 1:** Comparison of sediment level, NTUs, and irradiance for natural sediment.

<b>Sediment Level</b>	<b>Avg NTU 26°C</b>	<b>Avg NTU 30°C</b>	<b>Irradiance</b>
30 mg cm <sup>-2</sup> d <sup>-1</sup>	0.07 NTU	0.09 NTU	240 μmol m <sup>-2</sup> s <sup>-1</sup>
60 mg cm <sup>-2</sup> d <sup>-1</sup>	0.18 NTU	0.25 NTU	175 μmol m <sup>-2</sup> s <sup>-1</sup>
90 mg cm <sup>-2</sup> d <sup>-1</sup>	0.47 NTU	0.97 NTU	145 μmol m <sup>-2</sup> s <sup>-1</sup>
120 mg cm <sup>-2</sup> d <sup>-1</sup>	0.94 NTU	1.01 NTU	130 μmol m <sup>-2</sup> s <sup>-1</sup>

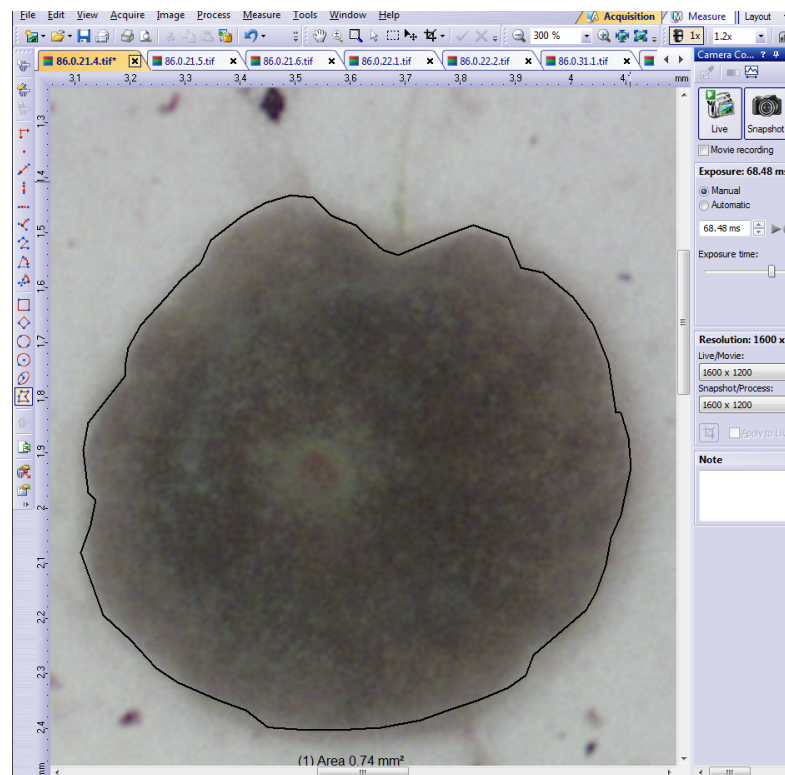
**Table 2:** Comparison of sediment level, NTUs, and irradiance for anthropogenic sediment.

<b>Sediment Level</b>	<b>Avg NTU 26°C</b>	<b>Avg NTU 30°C</b>	<b>Irradiance</b>
30 mg cm <sup>-2</sup> d <sup>-1</sup>	4.62 NTU	6.55 NTU	160 μmol m <sup>-2</sup> s <sup>-1</sup>
60 mg cm <sup>-2</sup> d <sup>-1</sup>	14.20 NTU	15.00 NTU	81 μmol m <sup>-2</sup> s <sup>-1</sup>
90 mg cm <sup>-2</sup> d <sup>-1</sup>	24.80 NTU	33.30 NTU	40 μmol m <sup>-2</sup> s <sup>-1</sup>
120 mg cm <sup>-2</sup> d <sup>-1</sup>	37.50 NTU	42.30 NTU	16 μmol m <sup>-2</sup> s <sup>-1</sup>

### 2.5. Tank Maintenance

All tanks had a 12:12 hour light:dark photoperiod (Babcock et al., 2003) with Aqua Illumination Sol LED lights. Photosynthetic active radiation (PAR) was measured for tanks that were set to mimic conditions in the field. Control tanks without any sediment sustained PAR readings of approximately 230 μmol m<sup>-2</sup> s<sup>-1</sup> for 5 hours between 0900 and 1400 hours. The initial experiment with natural sediment had 240, 175, 145, and 130 μmol m<sup>-2</sup> s<sup>-1</sup> for 30, 60, 90, and 120 mg cm<sup>-2</sup> d<sup>-1</sup>, respectively (Table 1). The second anthropogenic sediment experiment had 160, 81, 40, and 16 μmol m<sup>-2</sup> s<sup>-1</sup> for 30, 60, 90, and 120 mg cm<sup>-2</sup> d<sup>-1</sup>, respectively (Table 2) Temperature and salinity of each tank

was measured daily to ensure stabilization and R/O water was added to tanks as necessary to maintain salinity at 35 ppt. Fifty percent water changes were conducted 4 times per week and 100 percent water changes were conducted once per week. All treatment tanks had two ReSun SP-800 Submersible Aquarium pumps that were attached to a 1lb lead weight to keep them submerged and anchored to the bottom. All tanks were monitored weekly for surviving and dead specimens. Survivorship and death of each individual polyp was recorded considering its known orientation and placement on the settlement tiles. Areas of the polyps were measured weekly using photographs to assess coral growth. Photographs were taken with an Olympus LC20 digital camera attached to an Olympus SZ61 dissecting microscope. The imaging software CellSens® was used to assess the photographs and record total surface area of the individual polyps (Figure 2). Logistically it was not feasible to have replicate tanks, however tile position was tested as a factor and was controlled. The initial natural sediment experiment ran over a period of three months, from April to July 2015. The second anthropogenic sediment experiment ran over a period of one month, from September to October 2015.



**Figure 2:** Coral juvenile measurements using the imaging software CellSens.

## 2.6. *Statistical Analysis*

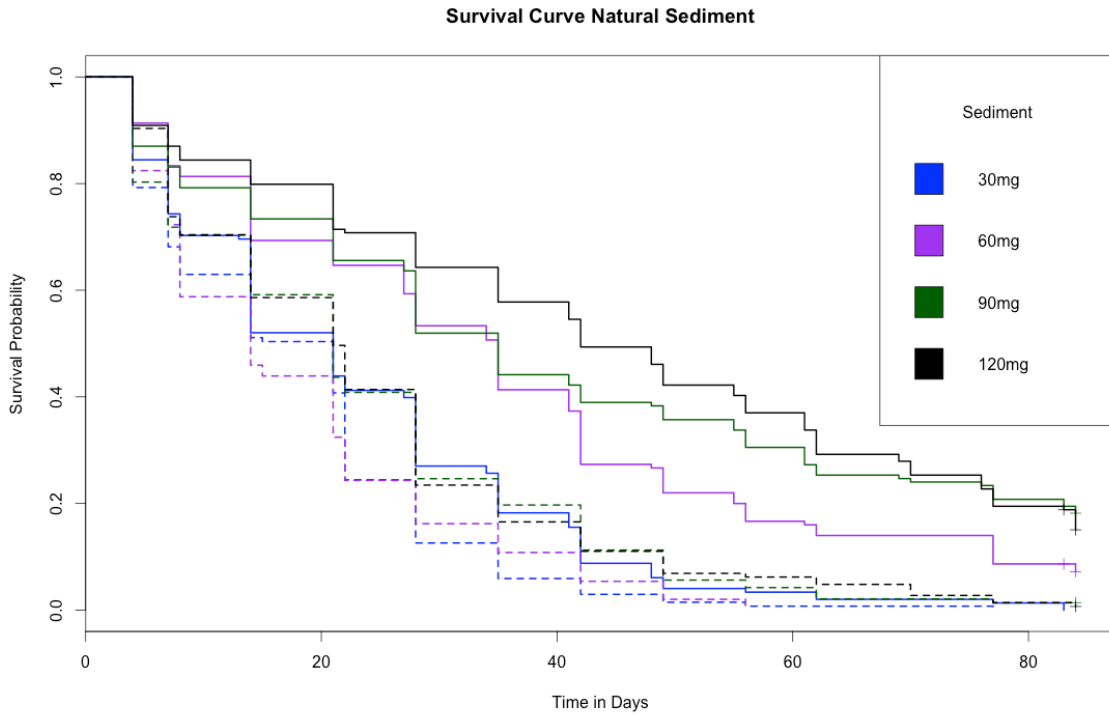
The experiment was designed to test the null hypothesis that temperature and sedimentation rates of natural and anthropogenic sediment have no singular or interactive effects on coral juvenile survival and growth. I expected to reject the null hypothesis, therefore finding that coral juveniles' survival and growth were affected by temperature and sedimentation rates, particularly between natural and anthropogenic sediment composition. Specifically, we expected that juveniles exposed to natural sedimentation will be better able to feed and photosynthesize compared to anthropogenic sediment, thus storing more energy reserves, allowing them to better cope with higher temperatures. The programming language and statistical software R® version 3.2.1 was utilized to conduct the analysis. Survival analysis was conducted using methods in the R package “survival” (Crawley, 2012). The Kaplan-Meier was used to estimate the survival curves of juvenile corals to display the effect of temperature and sediment. A Cox model was used to assess the effects of temperature, sediment, and tile position on coral juvenile survival. Mantel-Haenszel (log-rank) tests were conducted to do pairwise comparisons of survival curves between the different temperature and sediment treatments. Coral juvenile growth was conducted using several methods in the R package “lme4” (Logan, 2011). Juvenile growth was plotted and assessed in a linear mixed effects regression model. Parameter estimates were compared using the Akaike Information Criteria (AIC) in a forward step-wise model to test significant difference in coral juvenile growth (considered as the change in surface area) between treatments. Parameter estimates dependent on temperature and sediment rates were tested with models that were independent of temperature and sediment to obtain p-values. Sediment and temperature were considered fixed effects and the tile position considered was a random factor for all tests.

## 3. **RESULTS**

### 3.1. *Survival Analysis – Natural sediment*

Coral juvenile survival was significantly affected by temperature ( $p < 2.2 \times 10^{-16}$ ), where higher mortality was seen at the elevated temperature (30°C). Coral juvenile survival was significantly affected by sediment, where survival increased with increased sedimentation ( $p < 2.2 \times 10^{-16}$ ). Tile position showed a significant effect on coral juvenile

survival as well ( $p = 0.018$ ). A Kaplan-Meier survival curve was created to show survival for each sedimentation level per temperature treatment (Figure 3).



**Figure 3:** Kaplan-Meier survival curves of juveniles at all combinations of temperature and natural sediment. Color represents different sediment levels. Smooth lines represent temperature 26°C and dashed lines represent 30°C.

**Table 3:** Pairwise comparisons of survival curves for treatments in natural sediment using Mantel-Haenszel (log-rank) tests. Asterisks show significant p values, meaning the treatments are significantly different.

		26 °C			
		30 mg cm <sup>-2</sup> d <sup>-1</sup>	60 mg cm <sup>-2</sup> d <sup>-1</sup>	90 mg cm <sup>-2</sup> d <sup>-1</sup>	120 mg cm <sup>-2</sup> d <sup>-1</sup>
30 °C	30 mg cm <sup>-2</sup> d <sup>-1</sup>	0.00837*	5.06 x 10 <sup>-16</sup> *	1.11 x 10 <sup>-16</sup> *	0.0*
	60 mg cm <sup>-2</sup> d <sup>-1</sup>	0.0215*	2.87 x 10 <sup>-13</sup> *	0.0*	0.0*
	90 mg cm <sup>-2</sup> d <sup>-1</sup>	0.445	4.74 x 10 <sup>-5</sup> *	5.05 x 10 <sup>-10</sup> *	5.44 x 10 <sup>-14</sup> *
	120 mg cm <sup>-2</sup> d <sup>-1</sup>	0.404	3.18 x 10 <sup>-6</sup> *	5.9 x 10 <sup>-10</sup> *	1.28 x 10 <sup>-14</sup> *

**Table 4:** Pairwise comparisons of survival curves for treatments in natural sediment using Mantel-Haenszel (log-rank) tests. Comparing within the same temperature (26°C) but different sediment levels. Asterisks show significant p values, meaning the treatments are significantly different.

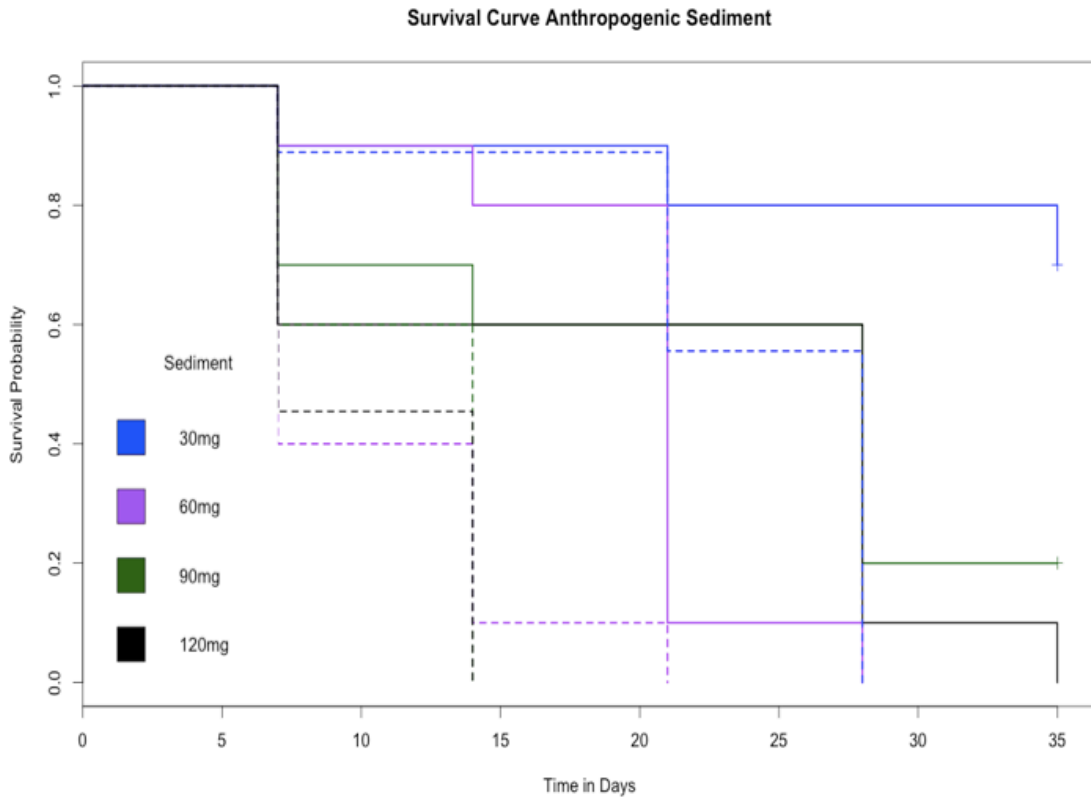
		26 °C		
		30 mg cm <sup>-2</sup> d <sup>-1</sup>	60 mg cm <sup>-2</sup> d <sup>-1</sup>	90 mg cm <sup>-2</sup> d <sup>-1</sup>
26 °C	60 mg cm <sup>2</sup> d <sup>-1</sup>	4.62 x 10 <sup>-8</sup> *		
	90 mg cm <sup>2</sup> d <sup>-1</sup>	4.59 x 10 <sup>-12</sup> *	0.022*	
	120 mg cm <sup>2</sup> d <sup>-1</sup>	0.0*	0.000792*	0.51

**Table 5:** Pairwise comparisons of survival curves for treatments in natural sediment using Mantel-Haenszel (log-rank) tests. Comparing within the same temperature (30°C) but different sediment levels. Asterisks show significant p values, meaning the treatments are significantly different.

		30 °C		
		30 mg cm <sup>-2</sup> d <sup>-1</sup>	60 mg cm <sup>-2</sup> d <sup>-1</sup>	90 mg cm <sup>-2</sup> d <sup>-1</sup>
30 °C	60 mg cm <sup>2</sup> d <sup>-1</sup>	0.938		
	90 mg cm <sup>2</sup> d <sup>-1</sup>	0.00284*	0.00367*	
	120 mg cm <sup>2</sup> d <sup>-1</sup>	0.00133*	0.0015*	0.847

### 3.2. Survival Analysis – Anthropogenic sediment

Coral juvenile survival was significantly affected by temperature ( $p < 1.88 \times 10^{-5}$ ), where higher mortality was seen at the elevated temperature (30°C). Coral juvenile survival was significantly affected by sediment, where survival decreased with increased sedimentation ( $p = 0.000316$ ). Tile position did not show a significant effect on coral survival ( $p = 0.25$ ). A Kaplan-Meier survival curve was created to show survival for each sedimentation level per temperature treatment (Figure 4).



**Figure 4:** Kaplan-Meier survival curves of juveniles at all combinations of temperature and sediment for anthropogenic sedimentation. Color represents different sediment level. Smooth lines represent temperature 26°C and dashed lines represent 30°C.

**Table 6:** Pairwise comparisons of survival curves for treatments in anthropogenic sediment using Mantel-Haenszel (log-rank) tests. Asterisks show significant p values, meaning the treatments are significantly different.

		26 °C			
		30 mg cm <sup>-2</sup> d <sup>-1</sup>	60 mg cm <sup>-2</sup> d <sup>-1</sup>	90 mg cm <sup>-2</sup> d <sup>-1</sup>	120 mg cm <sup>-2</sup> d <sup>-1</sup>
30 °C	30 mg cm <sup>-2</sup> d <sup>-1</sup>	0.00315*	0.0652	0.601	0.784
	60 mg cm <sup>-2</sup> d <sup>-1</sup>	9.18 x 10 <sup>-5</sup> *	0.00164*	0.00672*	0.00986*
	90 mg cm <sup>-2</sup> d <sup>-1</sup>	0.000226*	0.000756*	0.023*	0.0376*
	120 mg cm <sup>-2</sup> d <sup>-1</sup>	9.37 x 10 <sup>-5</sup> *	0.000309*	0.0097*	0.0164*

**Table 7:** Pairwise comparisons of survival curves for treatments in anthropogenic sediment using Mantel-Haenszel (log-rank) tests. Comparing within the same temperature (26°C) but different sediment levels.

Asterisks show significant p values, meaning the treatments are significantly different.

		26 °C		
		30 mg cm <sup>-2</sup> d <sup>-1</sup>	60 mg cm <sup>-2</sup> d <sup>-1</sup>	90 mg cm <sup>-2</sup> d <sup>-1</sup>
26 °C	60 mg cm <sup>2</sup> d <sup>-1</sup>	0.00091 *		
	90 mg cm <sup>2</sup> d <sup>-1</sup>	0.03 *	0.166	
	120 mg cm <sup>2</sup> d <sup>-1</sup>	0.00159*	0.175	0.425

**Table 8:** Pairwise comparisons of survival curves for treatments in anthropogenic sediment using Mantel-Haenszel (log-rank) tests. Comparing within the same temperature (30°C) but different sediment levels.

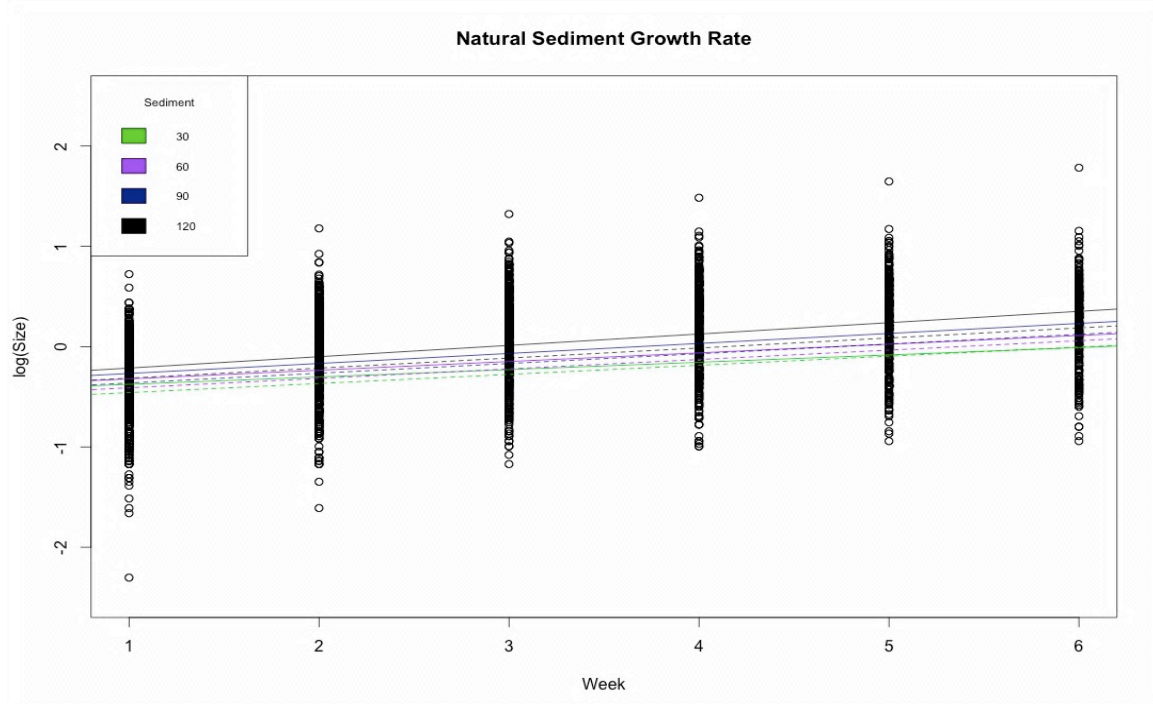
Asterisks show significant p values, meaning the treatments are significantly different.

		30 °C		
		30 mg cm <sup>-2</sup> d <sup>-1</sup>	60 mg cm <sup>-2</sup> d <sup>-1</sup>	90 mg cm <sup>-2</sup> d <sup>-1</sup>
30 °C	60 mg cm <sup>2</sup> d <sup>-1</sup>	0.000495 *		
	90 mg cm <sup>2</sup> d <sup>-1</sup>	0.0000458*	0.748	
	120 mg cm <sup>2</sup> d <sup>-1</sup>	0.000199*	0.831	0.515

### 3.3. Coral Juvenile Growth – Natural sediment

Coral juvenile growth was significantly affected by temperature ( $p < 2.2 \times 10^{-16}$ ). Coral juvenile growth was significantly affected by sediment ( $p < 2.2 \times 10^{-16}$ ). However this data originally did not fit the assumptions and was not parametric so the data was log transformed. The model shows that the fit is significantly better when there is a temperature and sediment dependency, however the confidence intervals for the growth rate for temperature 26°C would likely overlap with the confidence intervals for the growth rate of temperature 30°C and the same could be said for each sedimentation level

(Figure 5). Since these lines are so close, I am being critical in interpreting them and even though the model shows to have a better fit with temperature and sediment dependency, there does not seem to be a large effect of temperature and sediment on the growth rate. In conclusion, the coral juveniles were not growing, which is why the growth rate lines are horizontal.



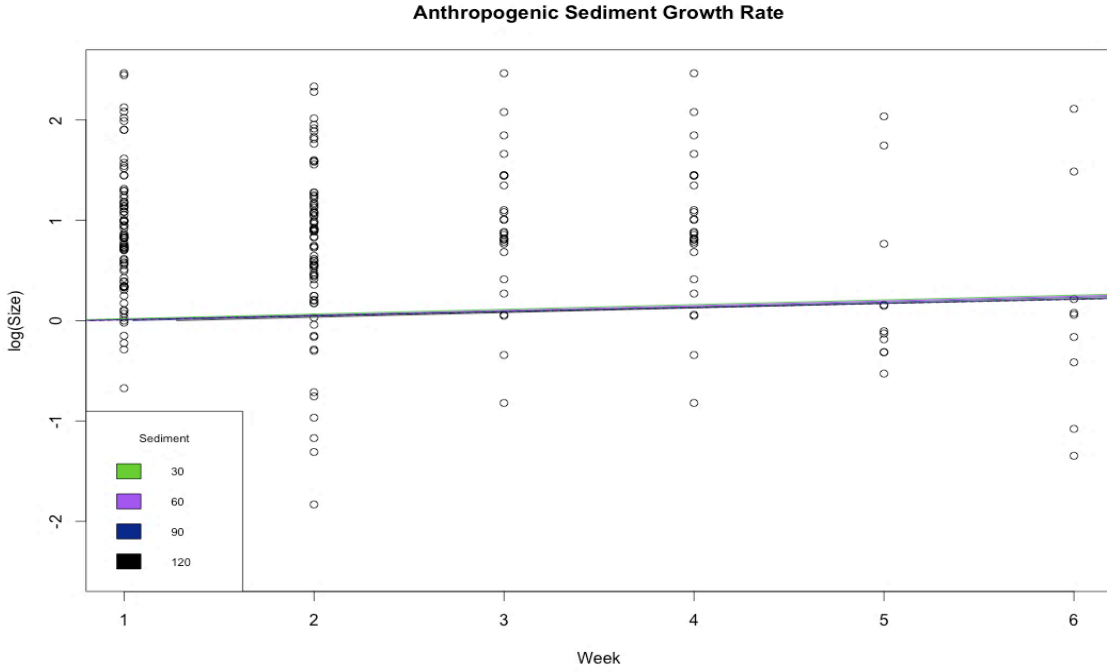
**Figure 5:** Growth rate for natural sediment. Smooth lines represent temperature 26°C and dashed lines represent 30°C.

#### 3.4. Coral Juvenile Growth – Anthropogenic sediment

Coral juvenile growth was significantly affected by temperature ( $p = 2.684 \times 10^{-5}$ ) and sediment ( $p = 5.02 \times 10^{-5}$ ) in the anthropogenic sedimentation experiments. Tile position was not significant ( $p = 0.3529$ ). However this data originally did not fit the assumptions and was not parametric so the data was log transformed. Once again the model shows that the fit is significantly better when there is a temperature and sediment dependency, however the confidence intervals for the growth rate for temperature 26°C would likely overlap with the confidence intervals for the growth rate of temperature 30°C and the same could be said for each sedimentation level (Figure 6). This is more obvious for the anthropogenic sediment and in some cases there was shrinking of the



coral juveniles. Once again there was no growth of the coral juveniles due to lack of heterotrophic feeding. The corals were relying on energy derived from the *Symbiodinium*, which was allocated towards surviving rather than growing.



**Figure 6:** Growth rate for anthropogenic sediment. Smooth lines represent temperature 26°C and dashed lines represent 30°C.

#### 4. DISCUSSION

When anthropogenic sedimentation was reduced juvenile corals could cope better with higher temperatures. The effect of ambient temperature combined with low sedimentation was equal to the effect of high temperatures combined with low sedimentation rates (Table 6). Increasing temperatures from ambient (26°C) to elevated (30°C) had similar effects to increasing anthropogenic sedimentation levels from 30 to 60 or more  $\text{mg cm}^{-2} \text{d}^{-1}$ . This indicates that a potential opportunity towards coral resilience to climate change is to reduce local stressors, such as sedimentation. The effect of climate change could be reduced if sedimentation was limited to  $30 \text{ mg cm}^{-2} \text{d}^{-1}$  (Table 6), which represents natural sedimentation concentrations (Jordan et al., 2010). In other words, the limits of sedimentation would need to reflect typical conditions, where there is no

additional anthropogenic effect at all. Temperature increased coral mortality as expected. Unexpectedly, the natural sediment did not have this negative effect and actually benefitted the corals. At ambient temperatures coral survival increased at higher natural sedimentation rates, while at elevated temperatures the high sedimentation rate did not affect survival.

Increasing sedimentation rates was expected to negatively affect coral survival but this was dependent on the composition of sediment. It is well known that increased temperatures cause coral mortality (Brown, 1987; Glynn & D’Croze, 1990; Glynn, 1993; Glynn, 1996) and when this is coupled with excessive sedimentation the effects can be intensified. Not only does the sediment concentration matter, but the composition of the sediment also has an effect on growth and survival of coral juveniles. Natural sediment typically found on the reef is characteristically coarse grained (180-2000  $\mu\text{m}$ ), normally light in color, and less likely to have presence of contaminants (hydrocarbons, heavy metals etc.). This sediment is not as detrimental compared to sedimentation arising from human construction and development, which is small grained (<63-180  $\mu\text{m}$ ), typically dark in color, and has potential presence of contaminants. The combination of high temperatures, high sediment concentration, and anthropogenic sediment has the most detrimental effects on coral survival and growth (Figure 4). Small-grained particles have been shown to be more deleterious to corals and other invertebrates (Bak & Elgershuizen, 1976; Fisk, 1981; Nugues & Roberts, 2003) particularly due to the relationship of grain size and sediment suspension in the water column. It has been shown that suspended sediment is worse for coral survival and growth compared to settled sediment (Dodge & Vaisny 1977; Bak 1976; Tomasick & Sander 1985; Erftemeijer et al., 2012). Silt, classified as grain sizes smaller than 64  $\mu\text{m}$ , is continuously suspended within the water column therefore increasing turbidity and decreasing light availability for the corals. During dredging, construction, and development activities the sediment typically contains silt and contaminants (Jordan et al., 2010; Erftemeijer et al., 2012). Therefore, anthropogenic sediment contributes to immense light reduction (160, 81, 40, and 16  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and leads to more detrimental effects on the juvenile coral growth and survival (Table 2). The EPA has regulated a standard for Nephelometric Turbidity Units for Florida coastal waters that should not exceed 29 NTUs (U. S. EPA). In this study, the

natural sedimentation experiment was equal or less than  $\sim 1$  NTU so turbidity was not likely a damaging factor. In contrast, the anthropogenic sedimentation experiment showed a range of  $\sim 5 - 43$  NTUs. It is important to note that detrimental effects were observed above 14 NTUs. Therefore, EPA regulations for allowable turbidity on corals reefs would need to be less than half of the current 29 NTUs, since this limit jeopardizes the resilience of corals.

Increased natural sediment did not hinder juvenile coral survival and growth. The grain size was larger; therefore this sediment did not smother corals and deplete light and oxygen levels as extensively in comparison to anthropogenic sediment (Table 1). Large grained sediment that is found naturally settling on top of corals is not as detrimental as suspended, small silt grained sized sediment found where development projects typically take place (Erfteimeijer et al., 2012). Light is an important factor. Since the natural sediment was not suspended within the water column in this study, the light availability was not compromised ( $240, 175, 145,$  and  $130 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) as much compared to the anthropogenic sediment ( $160, 81, 40,$  and  $16 \mu\text{mol m}^{-2} \text{s}^{-1}$ ). The settled sediment can help protect from excess light and could be beneficial for juveniles as cryptic covering. Orientation of settled larvae in corals reefs has been studied well and newly settled coral larvae have been found to settle on downward facing settlement tiles where there is cryptic covering, some coral species prefer to settle in shadier areas (Babcock & Mundy, 1996; Gleason & Hofmann, 2011) so it may not be surprising that this sedimentation covering was beneficial. Also, many studies have found a positive dynamic between sediment and corals where corals can ingest nutrients present on the sediment (Anthony, 1999b; Anthony, 2000; Anthony & Fabricus, 2000; Mills & Sebens, 2004). As stated above, settled sediment is not as detrimental to corals in comparison to suspended sediments, since settled sediment could be more readily “shed” off where smaller particles would constantly be in the water column. Corals can withstand a degree of settled sediment as it can occur naturally in the field (Erfteimeijer et al., 2012) until complete burial, which would induce death. Larger grain sizes typically allow more water flow and therefore more oxygen availability to corals, whereas silt sized sediments can create anoxic environment due to lack of water flow and a more active bacterial community is more likely to develop, further harming corals (Erfteimeijer et al., 2012).

Coupled with climate change, the effects of sedimentation can be damaging for coral reefs. Climate change occurs on a global scale, which makes it difficult to manage. However, local stressors can be more easily managed and regulated. Sedimentation is one of the most widely recognized threats to coral reefs (Jones et al., 2015). In today's society there is an ever-increasing urge for incessant construction, which can be damaging for sensitive ecosystems such as coral reef communities. If local action can be taken to reduce the sedimentation levels that arise from these construction activities, the status of coral reef health could more likely be sustained, rather than a continuous trend of depreciation. Coral reefs can occur in close proximity to major cities around the world. This is also where most dredging takes place due to the high demand to expand ports. Coastal construction around coral reefs occurs in areas such as the Great Barrier Reef in Australia, Saudi Arabia, Thailand, and the U.S. Virgin Islands (Brown et al., 1990; Price 1993; Rogers, 1993). Recently the dredging of the Miami Port in Florida, U.S.A. and beach re-nourishment projects in the South Florida region, have likely killed millions of corals (Walker et al., 2012). The sediment from this experiment is an accurate representation of sediment more likely to be present during dredging since it was sampled from an active boat basin near a busy port, where human development usually takes place (Barnes et al., 2015). So not only are adult corals being affected, it is likely that juvenile corals have also not been able to recruit and survive these dredging activities. Note that there has been no sign of recovery for these populations (Gardner et al., 2003) and juveniles are key to regenerate populations (Ritson-Williams et al., 2009). Coral reefs can be protected and further damage may be prevented if mitigation and assessment of dredging and construction are implemented. Timing of dredging operations may be an important factor. For example, many coral species reproduce sexually through spring and summer months (Baird et al., 2009) so timing dredging and construction operations for the winter may minimize harmful effects during spawning, or for juvenile recruitment. Also, sea surface temperatures in the winter are lower compared to potential bleaching temperatures in the summer months, thus synergistic effects of sedimentation and temperature could potentially be avoided.

This study shows that reducing a local stressor can increase coral resilience to climate change. More specifically, when anthropogenic sedimentation is limited and kept

at natural levels coral juveniles survive better with elevated water temperatures. With climate change becoming an ever-increasing worldwide issue, local action must be taken to tackle the consequences. Human development and construction must be more strictly monitored and controlled. However, it is important to note that the source and composition of the sedimentation is pertinent in the capacity of destruction to coral reefs. Active management of anthropogenic activities that result in increased severity, quantity, and frequency of sediment deposition on coral reefs must be implemented in order to improve current coral cover and sustain reefs under future climate change.

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## LITERATURE CITED

- Abrego, D., Willis, B. L., & van Oppen, M. J. H. (2012). Impact of light and temperature on the uptake of algal symbionts by coral juveniles. *PLoS ONE*, 7(11), e50311.
- Anthony, K. R. N. (1999a). Coral suspension feeding on fine particulate matter. *Journal of Experimental Marine Biology and Ecology* 232:85-106.
- Anthony, K. R. N. (1999b). A tank system for studying benthic aquatic organisms at predictable levels of turbidity and sedimentation: Case study examining coral growth. *Limnology and Oceanography*, 44(6), 1415–1422.
- Anthony, K. R. N. (2000). Enhanced particle-feeding capacity of nearshore reef corals on the Great Barrier Reef, Australia. *Coral Reefs* 19:59-67.
- Anthony, K. R. N., Connolly, S. R., & Hoegh-Guldberg, O. (2007). Bleaching, energetics, and coral mortality risk: Effects of temperature, light, and sediment regime. *Limnology and Oceanography*, 52(2), 716-726.
- Anthony, K. R. N., & Fabricius, K. E. (2000). Shifting roles of heterotrophy and autotrophy in coral energetics under varying turbidity. *Journal of Experimental Marine Biology and Ecology* 252:221-253.
- Babcock, R. C., Baird, A. H., Piyomvaragorn, S., Thomson, D. P., & Willis, B. L. (2003). Identification of scleractinian coral recruits from Indo-Pacific reefs. *Zoological Studies*, 42(1), 211–226.
- Babcock, R. C., & Mundy, C. (1996). Coral recruitment: consequences of settlement choice for early growth and survivorship in two scleractinians. *Journal of Experimental Marine Biology and Ecology*, 206(12), 179-201.

- Baird, A. H., Guest, J. R., & Willis, B. L. (2009). Systematic and biogeographical patterns in the reproductive biology of scleractinian corals. *Annual Review of Ecology, Evolution, and Systematics*, 40(1), 551–571.
- Bak, R. P. M., & Elgershuizen, J. H. B. W. (1976). Patterns of oil-sediment rejection in corals. *Marine Biology* 37: 105-113.
- Barnes, B.B., Hu, C., Kovach, C., Silverstein, R. (2015). Sediment plumes induced by the Port of Miami dredging: Analysis and interpretation using Landsat and MODIS data, *Remote Sensing of Environment*.
- Bellwood, D. R., Hughes, T. P., Folke, C., & Nyström, M. (2004). Confronting the coral reef crisis. *Nature*, 429(6994), 827–833.
- Bozec Y-M., Mumby, P. J. (2015). Synergistic impacts of global warming on the resilience of coral reefs. *Philosophical Transactions of the Royal Society B*, 370:20130267.
- Brown, B. E. (1987). Worldwide death of corals—Natural cyclical events or man made pollution? *Marine Pollution Bulletin*, 18(1), 9–13.
- Brown, B. E., LeTissier, M. D.A, Scoffin, T. P., Tudhope, A. W. (1990). Evaluation if the environmental impact of dredging on intertidal coral reefs at Ko Phuket, Thailand, using ecological and physiological parameters. *Marine Ecology Progress Series*. Oldendorf, 65(3), 273-281.
- Browne, N. K., Smithers, S. G., Perry, C. T. (2012). Coral reefs of the turbid inner Great Barrier Reef: an environmental and geological perspective on occurrence, composition and growth. *Earth-Sci. Rev.* 115, 1-20.



- Bruno, J. F., & Selig, E. R. (2007). Regional Decline of Coral Cover in the Indo-Pacific: Timing, Extent, and Subregional Comparisons. *PLoS ONE*, 2(8), e711.
- Carté, B. K. (1996). Biomedical potential of marine natural products. *Bio Science*, 46(4):271-286.
- Cesar, H., Burke, L., & Pet-Soede, L. (2003). The Economics of Worldwide Coral Reef Degradation. Technical Reports.
- Crawley, M. J. (2012). The R book. John Wiley & Sons.
- Cumbo, V. R., Edmunds, P. J., Wall, C. B., & Fan, T. Y. (2013a). Brooded coral larvae differ in their response to high temperature and elevated  $p\text{CO}_2$  depending on the day of release. *Marine Biology*, 160(11), 2903–2917.
- Cumbo, V. R., Fan, T. Y., & Edmunds, P. J. (2013b). Effects of exposure duration on the response of *Pocillopora damicornis* larvae to elevated temperature and high  $p\text{CO}_2$ . *Journal of Experimental Marine Biology and Ecology*, 439, 100–107.
- Davies, P. S. (1984). The role of zooxanthellae in the nutritional energy requirements of *Pocillopora eydouxi*. *Coral Reefs*, 2(4), 181–186.
- De'ath, G., & Moran, P. J. (1998). Factors affecting the behaviour of crown-of-thorns starfish (*Acanthaster planci* L.) on the Great Barrier Reef: 2: Feeding preferences. *Journal of Experimental Marine Biology and Ecology*, 220(1), 107–126.
- Edmunds, P. J. (2011). Zooplanktivory ameliorates the effects of ocean acidification on the reef coral *Porites* spp. *Limnology and oceanography*, 56, 2402-2410.

- Erftemeijer, P. L. A., Riegl, B., Hoeksema, B. W., & Todd, P. A. (2012). Environmental impacts of dredging and other sediment disturbances on corals: A review. *Marine Pollution Bulletin*, 64(9), 1737-1765.
- Figueiredo, J., Baird, A. H., Saki, H., & Connolly, S. R. (2014). Increased local retention of reef coral larvae as a result of ocean warming. *Nature Climate Change*, 4, 498-502.
- Fisk, D. A. (1981) Sediment shedding and particulate feeding in two free-living, sediment-dwelling corals (*Heteropsammia cochlea* and *Heterocyathus aequicostatus*) at Wistari Reef Great Barrier Reef. In: Proceedings of the 4<sup>th</sup> International Coral Reef Symposium 2, 21-25.
- Ganachaud, A., Sen Gupta, A., Orr, J. C., Wijffels, S. E., Ridgway, K. R., Hemer, M. A., Kruger, J. C. (2011). Observed and expected changes to the tropical Pacific Ocean. In J. D. Bell, J. E. Johnson, & A. J. Hobday (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change* (pp. 101–187).
- Gardner, T. A., Côté, I. M., Gill, J. A., Grant, A., & Watkinson, A. R. (2003). Long-term region-wide declines in Caribbean corals. *Science*, 301(5635), 958–960.
- Gilmour, J. P., Smith, L. D., Heyward, A. J., Baird, A. H., & Pratchett, M. S. (2013). Recovery of an isolated coral reef system following severe disturbance. *Science*, 340(6128), 69–71.
- Gleason, D. F., & Hofmann, D. K. (2011). Coral larvae: From gametes to recruits. *Journal of Experimental Marine Biology and Ecology*, 408(1-2), 42-57.
- Glynn, P. W. (1993). Coral reef bleaching: ecological perspectives. *Coral Reefs* 12: 1-17.

- Glynn, P. W. (1996). Coral reef bleaching: facts, hypotheses, and implications. *Global Change Biology* 2:495-509.
- Glynn, P. W., & D'Croz, L. (1990). Experimental evidence for high temperature stress as the cause of El Niño coincident coral mortality. *Coral Reefs* 8:181-191.
- Goreau, T. F. (1959). The physiology of skeleton formation in corals. I. A method for measuring the rate of calcium deposition by corals under different conditions. *Biology Bulletin*, 116, 59–75.
- Gosselin, L. A., & Qian, P.Y. (1997). Juvenile mortality in benthic marine invertebrates. *Oceanographic Literature Review*, 44(7), 730–731.
- Grottoli, A. G., Rodrigues, L. J., Juarez, C. (2004). Lipids and stable carbon isotopes in two species of Hawaiian corals, *Porites compressa* and *Montipora verrucosa*, following a bleaching event. *Marine Biology* 145:621-631.
- Grottoli, A. G., Rodrigues, L. J., Palardy, J. E. (2006). Heterotrophic plasticity and resilience in bleached corals. *Nature* 440: 1186-1189.
- Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, 50(8), 839–866.
- Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Hatziolos, M. E. (2007). Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science*, 318(5857), 1737–1742.
- Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., Roughgarden, J. (2003). Climate change, human impacts, and the resilience of coral reefs. *Science*, 301(5635), 929–933.

- Humann, P., & DeLoach, N. (2002). Reef coral identification: Florida, Caribbean, Bahamas, including marine plants (2nd ed.). New World Publications Inc.
- Intergovernmental panel on climate change (IPCC) (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds)]. IPCC, Geneva, Switzerland, 151 pp.
- Jackson, J. B. C., Kirby, M. X., Berger, W. H., Bjorndal, K.A., Botsford, L. W., Bourque, B. J., Warner, R. R. (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science*, 293(5530), 629–637.
- Jones, R., Ricardo, G.F., Negri, A.P., (2015). Effects of sediments on the reproductive cycle of corals. *Marine Pollution Bulletin*.
- Jordan, L. K. B., Banks, K. W., Fisher, L. E., Walker, B. K., & Gilliam, D. S. (2010). Elevated sedimentation on coral reefs adjacent to a beach nourishment project. *Marine Pollution Bulletin*, 60(2), 261–271.
- Knowlton, N. (2001). The future of coral reefs. *Proceedings of the National Academy of Sciences*, 98(10), 5419–5425.
- Lavens, P., & Sorgeloos, P. (1996). Manual on the production and use of live food for aquaculture. *FAO Fisheries Technical Paper*, (361), ix + 295 pp.
- Logan, M. (2011). *Biostatistical design and analysis using R: a practical guide*. John Wiley & Sons.

- McGuire, M. (1997). The biology of the coral *Porites astreoides*: Reproduction, larval settlement behavior and responses to ammonium enrichment. Dissertations from ProQuest.
- McGuire, M. P. (1998). Timing of larval release by *Porites astreoides* in the northern Florida Keys. *Coral Reefs*, 17(4), 369–375.
- McLeod, I. M., Rummer, J. L., Clark, T. D., Jones, G. P., McCormick, M. I., Wenger, A. S., & Munday, P. L. (2013). Climate change and the performance of larval coral reef fishes: the interaction between temperature and food availability. *Conservation Physiology*, 1(1), cot024.
- Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, T., Gregory, J. M., Zhao, Z. (2007). Global Climate Projections. In IPCC, 2007: Climate Change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (pp.747–846). Cambridge University Press.
- Moberg, F., & Folke, C. (1999). Ecological goods and services of coral reef ecosystems. *Ecological Economics*, 29(2), 215–233.
- Mills, M. M. & Sebens, K.P. (2004). Ingestion and assimilation of nitrogen from benthic sediments by three species of coral. *Marine Biology*, 145:109–116.
- Mumby, P. J., Dahlgren, C. P., Harborne, A. R., Kappel, C. V., Micheli, F., Brumbaugh, D.R., Gill, A. B. (2006). Fishing, trophic cascades, and the process of grazing on coral reefs. *Science*, 311(5757), 98–101.
- Norström, A. V., Nyström, M., Lokrantz, J., Folke, C. (2009). Alternative states on coral reefs: beyond coral-macroalgal phase shifts. *Marine Ecology Progress Series* 376: 295-306.

- Nugues, M. M., & Roberts, C. M. (2003). Partial mortality in massive reef corals as an indicator of sediment stress on coral reefs. *Marine Pollution Bulletin*, 46:314-323.
- Pandolfi, J. M., Bradbury, R. H., Enric, S., Hughes, T. P., Bjorndal, K. A., Cooke, R. G., McArdle, D., McClenachan, L., Newman, M. J. H., Paredes, G., Warner, R. R., Jackson, J. B. C. (2003). Global trajectories of the long-term decline of coral reef ecosystems. *Science*, 301: 955-958.
- Pechenik, J. A. (1999). On the advantages and disadvantages of larval stages in benthic marine invertebrate life cycles. *Marine Ecology Progress Series*, 177, 269–297.
- Price, A. R. G. (1993). The Gulf: Human impacts and management initiatives. *Marine Pollution Bulletin*, 27, 17-27.
- Richmond, R. H., & Hunter, C. L. (1990). Reproduction and recruitment of corals: Comparisons among the Caribbean, the Tropical Pacific, and the Red Sea. *Marine Ecology Progress Series*. Oldendorf, 60(12), 185–203.
- Riegl, B., & Branch, G. M. (1995). Effects of sediment on the energy budgets of four scleractinian (Bourne 1900) and five alcyonacean (Lamouroux 1816) corals. *Journal of Experimental Marine Biology and Ecology*, 186(2), 259–275.
- Ritson-Williams, R., Arnold, S. N., Fogarty, N. D., Steneck, R. S., Vermeij, M. J. A., & Paul, V. J. (2009). New perspectives on ecological mechanisms affecting coral recruitment on reefs, 437–457.
- Rogers, C. S. (1990). Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress Series*, 62:185-202.

- Sebens, K. P. (1994). Biodiversity of coral reefs: What are we losing and why? *American Zoologist*, 34(1): 115-133.
- Sheppard, C., Davy, S., & Pilling, G. (2009). *The Biology of Coral Reefs*. Oxford University Press.
- Smith, S. V., Kimmerer, W. J., Laws, E. A., Brock, R. E., & Walsh, T. W. (1981). Kaneohe Bay sewage diversion experiment: perspectives on ecosystem responses to nutritional perturbation.
- Spalding, M., Ravilious, C., & Green, E. P. (2001). *World Atlas of Coral Reefs*. University of California Press.
- Stafford-Smith, M., & Ormond, R. (1992). Sediment rejection mechanisms of 42 species of Australian scleractinian corals. *Marine and Freshwater Research*, 43(4), 683-705.
- Towle, E. K., Enochs, I. C., Langdon, C. (2015). Threatened Caribbean coral is able to mitigate the adverse effects of ocean acidification on calcification by increasing feeding rate. *PLoS ONE*. 10(4):e0123394.
- United States Environmental Protection Agency. (1988). *Water quality standards criteria summarizes: A compilation of state/federal criteria*. Office of Water Regulations and Standard. Washington, D.C. EPA 440/5-88013. National Technical Information Service documents #PB 89-141451.
- Veron, J. E. N., Hoegh-Guldberg, O., Lenton, T.M., Lough, J. M., Obura, D. O., Pearce-Kelly, P., Sheppard, C. R. C., Spalding, M., Stafford-Smith, M. G., Rogers, A.D. (2009). The coral reef crisis: The critical importance of <350 ppm CO<sub>2</sub>. *Marine Pollution Bulletin*, 58, 1428-1436.

- Walker, B. K., Gilliam, D. S., Dodge, R. E., & Walczak, J. (2012). Dredging and shipping impacts on southeast Florida coral reefs. Paper presented at the Proceedings of the 12<sup>th</sup> International Coral Reef Symposium, 19A Human impacts on coral reefs: general session, Cairns, Australia, 9-13 July 2012.
- Weber, M., Lott, C., & Fabricius, K. E. (2006). Sedimentation stress in a scleractinian coral exposed to terrestrial and marine sediments with contrasting physical, organic and geochemical properties. *Journal of Experimental Marine Biology and Ecology*, 336(1), 18–32.
- Wentworth, C. K., (1922). A Scale of grade and class terms for clastic sediments. *Journal of Geology*. 30,377392.
- Wild, C., Hoegh-Guldberg, O., Naumann, M. S., Colombo Pallotta, M. F., Ateweberhan, M., Fitt, W. K., Iglesias-Prieto, R., Palmer, C., Bythell, J. C., Ortiz, J. C., Loya, Y., & van Woesik, R. (2011). Climate change impedes scleractinian corals as primary reef ecosystem engineers. *Marine and Freshwater Research*. 62, 205-215.