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EFFECTS OF SUSPENDED SEDIMENT AND BURIAL ON SCLERACTINIAN CORALS FROM WEST CENTRAL FLORIDA PATCH REEFS

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ABSTRACT

The distribution and abundance of eight species of endemic scleractinian corals were determined for patch reefs off west central Florida in the depth range of 7–18 m. *Phyllangia americana* and *Cladocora arbuscula* were the most abundant species encountered. Five of the eight species censussed were absent from the shallowest reef (7 m). Seven species of corals were exposed to increasing levels of suspended sediment in the laboratory and seven species were subjected to prolonged burial in sediment. Survival rates were not affected by 10-day exposures to suspended sediment concentrations of 49, 101, 165, or 199 mg·liter^{-1}. Combined mean growth rates for six species were significantly different between control and experimental treatments at 165 mg·liter^{-1} suspended sediment. Coral burial experiments produced survival LT_{50} values of 7 days for *Scolymia lacera*, 7.2 days for *Isophyllia sinuosa*, 10 days for *Manicina aereolata*, 13.6 days for *Siderastrea radians*, 15 days for *C. arbuscula*, 16.2 days for *Stephanocoenia michelinii*, and 15+ days for *Solenastrea hyades*. The results of these experiments indicate that the species tested are among the most resistant corals in the Caribbean region to the effects of suspended sediment and physical burial. These findings are consistent with the fact that west central Florida patch reefs are exposed to more severe environmental conditions, such as high turbidity and low light penetration (in addition to a broader range of temperatures) than more tropical reefs to the south.

Since most vigorous coral reef development occurs in transparent tropical waters, it has become axiomatic that low levels of turbidity and suspended sediments are essential for optimal hermatypic coral growth and survival. High turbidity and sedimentation rates may depress coral growth and survival due to 1) attenuation of light available to symbiotic zooxanthellae (Rogers, 1979), 2) redirection of energy expenditures for clearance of settling sediments (Dallmeyer et al., 1982; Abdel-Salam and Porter, 1988), or 3) actual smothering of coral tissue (Rogers, 1983). However, tolerance of corals to high sediment loads may vary considerably among species, with some corals being fairly resistant to low light levels and/or sedimentation effects (Edmondson, 1929; Dodge and Vaisnys, 1977; Lasker, 1980; Rogers, 1983; Hodgson, 1990). Sensitivity to these effects depends on sediment clearing ability, calyx and colony morphology, orientation of growth, and the types of sediment involved (Hubbard and Pocock, 1972; Bak and Elgershuizen, 1976; Dodge and Szmant-Froelich, 1985).

Rogers (1990), in a review of the effects of sedimentation on corals, suggested that reefs with high sediment loads may have lower diversity, percent cover, and growth rates of coral species, small colony sizes (or large colonies in areas in which recruitment is limited by siltation), an upward shift in depth zonation, and a predominance of resistant growth forms or species. In general, field observations have confirmed a relationship between suspended sediment levels and coral distributions in a variety of geographic locations including: Palau (Motoda, 1939), Australia (Mayer, 1918; Marshall and Orr, 1931); Fanning Island (Roy and Smith, 1971), Guam (Randall and Birkeland, 1978), Hawaii (Edmondson, 1928), Costa Rica (Cortes, 1990), Florida (Hubbard and Pocock, 1972), Jamaica (Dodge et al., 1974), Puerto Rico (Loya, 1976; Acevedo and Morelock, 1988), and the Virgin Islands (Rogers, 1983; Hubbard et al., 1987). In many cases, the same species or

genera are found in similar "suboptimal" turbid conditions in different geographic locations (Colin, 1978).

There have been few studies that address the effects of suspended sediments on growth and mortality of individual coral species. Field studies have demonstrated that growth rates of *Montastrea annularis* are inversely correlated with sediment loads (Dodge et al., 1974; Dodge and Vaisnys, 1977; Dodge and Lang, 1983; Tomascik and Sander, 1985; Hubbard et al., 1987). However, other workers have found that there was little or no evidence of decreased growth rate for surviving colonies of *Porites lutea,* even in areas where high coral mortality has been attributed to effects of sedimentation (Hudson et al., 1982; Brown et al., unpubl., in Rogers, 1990).

The present investigation was undertaken to test the effects of increasing sediment loads on the survival and growth rates of scleractinian corals from Gulf of Mexico patch reefs off west central Florida. Although these patch reefs are atypical of other, more luxuriant, coral reefs of the southern Florida Keys and Caribbean, they share common features with the latter in that they provide hard substratum for concomitant diverse and unique biotic assemblages relative to the surrounding soft bottom. Coral communities on the west central Florida patch reefs are characterized by low species diversity and abundance, and a predominance of species with large, solitary polyps or small colony sizes. They are subject to seasonal increases in suspended sediments due to winter storms and occasional hurricanes. These reefs are also adjacent to designated dredge spoil disposal sites. Although these patch reef corals may be surviving at or near their physiological limits relative to a number of environmental variables (particularly temperature extremes), only the effects of increasing suspended sediment loads and burial were addressed in this study.

Experiments were conducted under controlled laboratory conditions intended to simulate the levels of suspended sediment that might be expected to occur due to storms or dredge spoil disposal. Four different levels of suspended sediment were tested in 10- and 20-day coral survival and growth experiments. Additional laboratory experiments were employed to evaluate the resistance of seven coral species to total burial under natural marine sediments. Results of these bioassays were used to test the hypothesis that increasing suspended sediment load effects survival and growth rate of these corals and contributes to the species distributional patterns observed in west central Florida patch reef environments. Field observations included abundance estimates of eight species encountered on natural and artificial reefs in depths from 7–18 m.

Methods

Field Surveys.—Species abundance and composition were censussed at three sites off west central Florida in between 1986–1989 (Stations A, B, C, Fig. 1). SCUBA divers counted total numbers of coral individuals and colonies within 11, 1 m^2 quadrats on a 15 m deep reef and 9–35 1 m^2 quadrats on an 18 m deep reef (see Table 1 for sample size by coral species). On these two reef areas, quadrats were placed over random sections of natural hard bottom. An artificial reef (7 m depth) was also censussed by intentionally placing quadrats over sections of the reef where corals were present. Twelve square meters of area were examined on the 7-m reef. This reef had been deployed for 3 years at the time of sampling, and was constructed of concrete rubble, culverts, pilings, and tires (some of which had little or no growth on them) interspersed between areas of soft bottom.

Total Suspended Solids.—Nineteen seawater samples were collected from six stations located from 1 to 18 nmi offshore in the Gulf of Mexico (Fig. 1, Stations 1, 4, 7, 10, 12 and 18) during March–June, 1984 for determination of total suspended solid loads in near bottom water. Samples were collected by divers or with a Niskin bottle within 1 m of the bottom and transferred to precleaned polypropylene containers for transport to the laboratory.

Water samples were also collected periodically from the experimental and control exposure aquaria

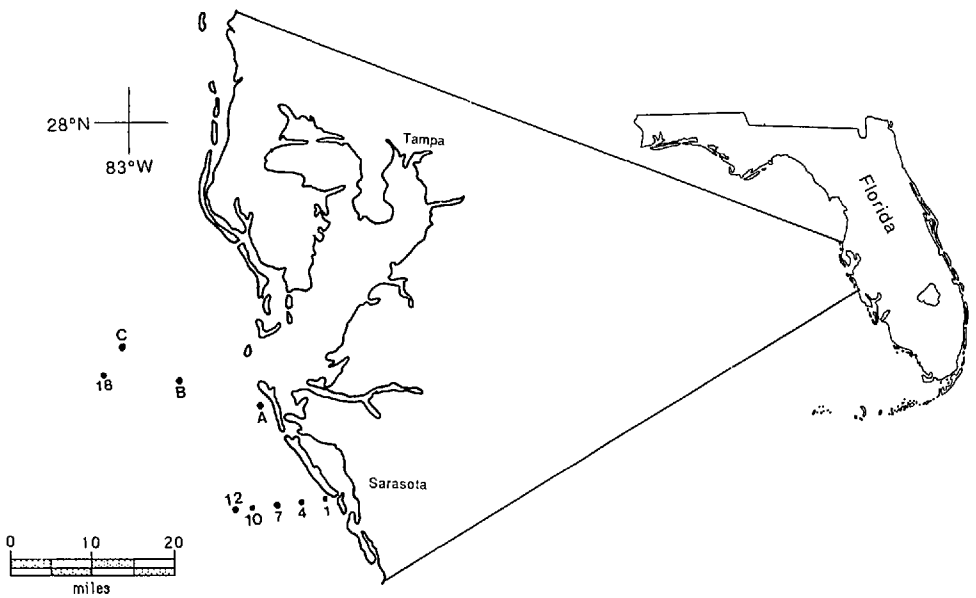

Figure 1. Location of stations visited for coral collection, suspended sediment measurements, and coral population estimates. Station 1, 27:19:10N, 82:36:11W; Station 4, 27:17:15N, 82:39:10W; Station 7, 27:16:11N, 82:42:09W; Station 10, 27:14:62N, 82:45:00W; Station 12, 27:14:34N, 82:45:55W; Station 18, 27:31:45N, 83:04:09; Station A, 27:29:30N, 82:44:05W; Station B, 27:32:21N, 82:54:30W; Station C, 27:39:15N, 83:01:15W.

during the course of each suspended sediment bioassay. All suspended solid samples were stored at 4°C until analyzed, and all samples were analyzed in duplicate.

Polycarbonate filters with a pore size of 0.45-μm were vacuum rinsed with distilled-deionized water, dried at 100°C for 2 h and weighed. A premeasured volume of well-mixed sample was then filtered, followed by a second distilled-deionized water rinse to remove any salt. Filters were dried at 100°C for 2 h and reweighed.

Sediments used in suspended sediment and burial studies were collected by SCUBA divers from Station 12 (Fig. 1). This reef is not in the vicinity of any known ocean disposal sites and the sediments collected there are believed to be representative of naturally occurring deposits in the Gulf of Mexico. Sediment samples were scooped into 4 liter, acid washed, polypropylene jars in the field and stored at 4°C in the laboratory until used.

Collection and Handling of Experimental Corals.—Corals for suspended sediment and burial experiments were collected from Station 12 (Fig. 1). Care was taken in collection and transport of test organisms to minimize stress and damage to tissues. When a suitable specimen was encountered, SCUBA divers gently maneuvered a knife blade or pry bar between the base of the coral and the substratum and dislodged the colony using steady pressure. Any specimens damaged during collection were not returned to the laboratory. Once dislodged from the bottom, specimens were placed into nylon mesh bags and taken to the surface where they were rapidly transferred to tubs of clean seawater. Corals were then sorted and placed into insulated containers for transport. Seawater in the containers was replaced at least once per hour and lids were kept in place to avoid stress from direct sunlight.

In the laboratory, specimens were placed into aquaria with continuously flowing seawater and allowed to acclimate for at least 7 days. Temperature (24–26°C), salinity (34.5–35.0‰), dissolved oxygen (4.3–6.2 mg·liter^{-1}), and pH (7.86–8.06) were monitored and maintained during the acclimation and experimental periods. Photoperiod was set at 14:10 (light : dark) with a 1-h transition period on each end of approximately 75% full illumination. Incident light in the photosynthetically active range (400–700 nm) was measured with a LiCor integrating photometer and found to be 2.0 and 2.5 μEs·m^{-2}·sec^{-1} for the control and experimental aquaria, respectively. This converts to approximately 0.3–0.4% of full noon solar irradiance. Brine shrimp nauplii were added to each aquarium daily in the late afternoon, since most corals feed during darkness.

Experimental Exposure System.—All suspended sediment and burial experiments were carried out in a climate-controlled laboratory. Two parallel recirculating seawater systems were used in suspended

Table 1. Coral densities on patch reefs in the vicinity of Tampa Bay, Florida. Values are mean density in colonies or individuals per square meter ± one standard deviation. The 15 m and 18 m reefs are natural patch reefs, the 7 m reef is artificial, composed of concrete pilings and culverts that had been submerged for 3+ years at the time of sampling. All species are hermatypic except for *Phyllangia americana*. N = number of 1 m^2 quadrats sampled

Species	Reef depth			Mean for all reefs*
	7 m	15 m	18 m	
Cladocora arbuscula	3.5 ± 2.0 (N = 12)	22.0 ± 14.3 (N = 11)	18.6 ± 13.9 (N = 23)	15.5 ± 13.9 (N = 46)
Stephanocoenia mitchelinii	0 (N = 12)	1.5 ± 1.9 (N = 11)	0.3 ± 0.5 (N = 23)	0.7 ± 1.3 (N = 34)
Isophyllia sinuosa	0 N = 12)	1.6 ± 2.0 (N = 11)	1.6 ± 0.7 (N = 15)	1.6 ± 1.4 (N = 26)
Siderastrea spp.	0 (N = 12)	13.5 ± 11.3 (N = 11)	0.9 ± 1.5 (N = 23)	4.9 ± 8.7 (N = 34)
Solenastrea hyades	0.5 ± 1.0 (N = 12)	1.1 ± 2.1 (N = 11)	0.7 ± 0.8 (N = 23)	0.7 ± 1.2 (N = 46)
Scolymia lacera	0 (N = 12)	0.6 ± 0.9 (N = 11)	0.7 ± 1.2 (N = 15)	0.7 ± 1.1 (N = 26)
Phyllangia americana	44.8 ± 29.6 (N = 12)	10.3 ± 6.5 (N = 11)	18.8 ± 14.8 (N = 9)	25.6 ± 24.9 (N = 32)
Manicina aereolata	0 (N = 12)	2.1 ± 1.9 (N = 11)	3.2 ± 2.8 (N = 35)	2.9 ± 2.6 (N = 46)
Total coral density	48.8	52.7	44.8	52.6

* Includes only those reefs where specimens were observed to occur.

sediment tests. These systems each consisted of a 200-liter polyethylene reservoir from which seawater was pumped to a 55-liter head tank provided with two magnetic stirrers. Sediment from the field collection site was screened through a 0.5-mm sieve and added to the experimental system reservoir. The sediment was kept in suspension by vigorous aeration and the sediment-water slurry was pumped to the head tank with a Flotec immersible centrifugal pump. Sediment in the head tank was kept in suspension with two magnetic stirrers. Water flowed by siphon from the head tanks to 60-liter exposure tanks where the experimental and control animals were housed. Constant aeration in the experimental tank helped to keep the sediment in suspension. Some sediment accumulated on the bottom of the experimental tank during experiments but the corals were not affected by this as they were placed on a plastic grating 2 cm above the bottom. Flow rates from the head tanks into the exposure tanks provided approximately 44 volume changes per 24 h. Overflow water from the exposure tanks flowed back to the reservoirs. Total water volume in each system was 115 liter. Seawater used in all experiments was obtained from the 114,000-liter laboratory-wide system pumped from New Pass, Sarasota.

During initial acclimation periods, exposure tanks were connected to the laboratory-wide flow-through seawater system. At least 2 days prior to beginning experiments, water flow through the exposure tanks was switched to the 115-liter recirculating system. Seawater in the two parallel recirculating systems was replaced with seawater from the laboratory-wide system after each 10-day experiment.

Coral burial experiments were carried out in 20-liter glass aquaria supplied with flowing seawater from the laboratory system. A subgravel filter was placed in each aquarium and covered with 3.5 cm of crushed coral gravel. Experimental animals were arranged on top of the gravel and their locations within the aquaria were mapped. Sediment from the Gulf of Mexico was sieved through a 0.5-mm screen and added to the aquarium until all specimens were covered. Subgravel filters provided sufficient flow through the sediment to prevent anoxic conditions from occurring. At the end of each experiment, specimens were removed from the sediment and placed into recovery aquaria provided with flowing seawater. The health and general condition of each experimental animal was recorded immediately following removal from burial. Some organisms survived burial, but appeared to be heavily stressed. For this reason, each organism was checked again at 24 h and 7 days with final survival rates recorded after 7 days. Seven species of corals were tested in burial experiments with sample sizes ranging from 9–28 specimens per species. A summary of the specific experiments performed, species tested, and parameters measured is presented in Table 2.

Four suspended sediment experiments were completed using scleractinian corals exposed to natural

Table 2. Summary of coral bioassay experiments and species tested in each trial. Results of these experiments and statistical comparisons can be found in Tables 4–9

Experiment	Suspended sediment load	Duration	Parameters measured	Species tested	Number tested per treatment
Suspended Sediment I (SSE I)	49 mg·liter^{-1}	10 days	survival and growth	1, 2, 3, 4	20
Suspended Sediment II (SSE II)	101 mg·liter^{-1}	10 days	survival and growth	1, 2, 3, 4	20
Suspended Sediment III-1 (SSE III-1)	165 mg·liter^{-1}	10 days	survival and growth	1, 2, 3, 6, 7, 8	30
Suspended Sediment III-2 (SSE III-2)	199 mg·liter^{-1}	10 days*	survival and growth	1, 2, 3, 6, 7, 8	30
Burial I	—	1 day	survival	1, 2, 3, 5	22
Burial II	—	4 days	survival	1, 2, 3, 5	22
Burial III	—	6 days	survival	2, 3, 6, 7	22
Burial IV	—	8 days	survival	6, 7	13
Burial V	—	10 days	survival	1, 2, 5, 8	24
Burial VI	—	15 days	survival	1, 3, 5, 8	27

Species codes: 1 = *Cladocora arbuscula*; 2 = *Manicina aereolata*; 3 = *Solenastrea hyades*; 4 = *Phyllangia americana*; 5 = *Siderastrea radians*; 6 = *Isophyllia sinuosa*; 7 = *Scolymia lacera*; 8 = *Stephanocoenia mitchelinii*.
* This experiment was a continuation on SSE III-1 (see Methods).

sediments from the Gulf of Mexico. Each experiment lasted 10 days with survival and growth rates measured for each coral specimen. A different suite of experimental animals was used in each experiment except for the final two suspended sediment tests in which the same animals were exposed for 20 days and checked for survival and growth at 10-day intervals [Suspended Sediment Experiment III (SSE III-1 and 2)].

Coral Growth Rates.—During each of the four suspended sediment bioassays, the beginning and final weight of each coral colony or individual was measured using a modification of the buoyant weight technique described by Dodge et al. (1984). A basket was suspended beneath an American Scientific Products DTL 2500 toploading electronic balance and was positioned over a 38-liter aquarium so that the basket and coral were completely submerged during weighing. Each coral was weighed to the nearest 0.01 g and the temperature and salinity of the water in the weighing aquarium measured after every fifth weighing. Buoyant weights were converted to equivalent weights in air using the formula:

$$W_a = [W_w/(1-(D_w/D_m))]$$

where W_a = weight in air, W_w = buoyant weight, D_w = density of water, and D_m = density of coral. D_m was assumed to be 2.94 (the density of pure aragonite) and D_w was calculated from the temperature and salinity of the seawater in the weighing aquarium using Table 2.1 in Riley and Chester (1971). The resulting weights in air (W_a) were then used to compute growth rates. The change in weight of a specimen over the course of the experiment was divided by the initial weight of the same coral to obtain a normalized value expressed as mg growth·g^{-1} body weight·10 days^{-1}. Normalizing the growth data reduced the coefficient of variation (Sokal and Rohlf, 1969) in each analysis.

Determination of Survival.—Survival rates were determined for each species in both suspended sediment and burial experiments. Some corals, such as *Scolymia* and *Phyllangia*, represented single individuals and could be easily classified as alive or dead. Most species tested were colonies consisting of numerous corallites and for these species individual corallites were considered alive if soft tissues appeared normal, or if tentacles were extended in feeding posture during the recovery period.

Sublethal responses were recorded for corals exposed to suspended sediment or used in burial experiments. Loss of color associated with expulsion of zooxanthellae was a common response in *Manicina*, *Scolymia*, *Isophyllia*, and *Solenastrea*. Shrinkage of soft tissue and exposure of underlying skeletal features was observed in *Manicina*, *Scolymia*, and *Isophyllia*. Most corals produced mucus from their soft tissues, and this feature was used to assess relative health. In cases where it was difficult to determine if a coral was alive, mucus production was used to infer the presence of living tissues. Surface mucus was absent on all corals considered to be dead.

Data Analysis.—All treatment means, standard deviations, and probabilities were calculated using StatView SE + Graphics software on a Macintosh computer. This software package performs a standard ANOVA using the Scheffé F-test (Scheffé, 1959) to test for significant differences. Treatment means

Table 3. Total suspended solids in seawater samples collected from the Gulf of Mexico. These stations represent a transect WSW from New Pass, Sarasota, Florida, to the coral collection site. Samples were collected between March and June 1984

Station number	Number of times sampled	Distance from shore (nmi)	Water depth (m)	Mean total suspended solids ± SD (mg·liter $^{-1}$)
Station 1	4	1	7	25.9 ± 12.1
Station 4	4	4	11	18.1 ± 11.3
Station 7	4	7	12	19.9 ± 14.8
Station 10	4	10	13	16.3 ± 12.0
Station 12*	1	12	15	26.2
Station 18†	2	18	26	15.1 ± 10.9

* This station was the site of coral collection for bioassays.
† This site represents a dredged material disposal site before the beginning of disposal operations.

were considered to be significantly different when the F-test probability was less that 0.05 (95% confidence).

RESULTS

Coral Distributions and Abundance.—Distributions and densities of eight coral species were determined on reefs at three different depths (Table 1). Data for *Siderastrea* includes both *S. radians* and *S. sideria* since it was difficult to distinguish between these similar species in the field. The most abundant species encountered, particularly on the shallowest reef (7 m), was the ahermatype, *Phyllangia americana.* Five of the eight species surveyed were absent from the 7 m reef and two species, *Cladocora arbuscula* and *Siderastrea* spp., displayed highest densities on the intermediate depth reef (15 m). All eight species were present on the two deeper reefs (15 m and 18 m). Overall, *Scolymia lacera, Solenastrea hyades,* and *Stephanocoenia mitchelinii* were the least abundant corals in the depth ranges sampled. The distributions of all species were patchy as indicated by the large standard deviations that equal or exceed the mean densities in many cases (Table 1).

Suspended Solids Measurements.—The highest suspended solids loads measured among the six sites sampled occurred at Stations 1 and 12 (Fig. 1) at a distance of 1 and 12 nmi offshore respectively (Table 3). Two samples taken on different days in the vicinity of a proposed ocean disposal site for dredged material contained 22.8 mg·liter^{-1} and 7.4 mg·liter^{-1} total suspended solids. All of the values reported in Table 3 represent sediment loads during relatively calm conditions and are considered to be low relative to higher loads following storms and ocean disposal activities.

Suspended Sediment Experiments—Survival.—Specimens of *Siderastrea* spp. exhibited stress reactions and bleaching under laboratory conditions. Four out of five control colonies and two out of five experimental colonies died after 17–27 days. Therefore, growth and survival data for these species were eliminated from the analyses. No deaths of control or experimental colonies of other species were recorded in the 10-day exposures to 49, 101, 165, or 199 mg·liter^{-1} of suspended sediments. Overall survival of these species was not affected by exposure to the levels of suspended solids tested during the time course of these experiments.

A few colonies became partially buried at their base as a result of sediment accumulation during the course of the experiments. At the end of SSE III-1, the following species in the experimental treatment displayed partial polyp mortality or bleaching in some individuals: *Scolymia lacera* (1 specimen), *Stephanocoenia mitchelinii* (1 specimen), and *Solenastrea hyades* (2 specimens). One control spec-

Table 4. Mean growth rates and initial mean specimen size (weight in air) for corals exposed to a suspended solid load of 49 mg·liter^{-1} for 10 days (SSE I). Values are mg increase (or decrease) per gram of initial weight ± standard deviation

Species	Treatment		Probability (F-test)
	Control	Experimental	
A. Mean growth rates in mg·g^{-1} initial weight ± one SD. N = 5 per treatment per species.			
Cladocora arbuscula	9.25 ± 2.35	10.99 ± 8.40	0.667
Manicina aereolata	7.17 ± 6.25	8.85 ± 7.72	0.716
Solenastrea hyades	5.30 ± 2.09	6.12 ± 7.78	0.825
Phyllangia americana	7.09 ± 5.66	3.14 ± 12.53	0.538
All species combined (N = 20)	7.20 ± 4.37	7.27 ± 9.07	0.975
B. Mean initial weight (g) in air by species and treatment. N = 5 per treatment per species.			
Cladocora arbuscula	15.42 ± 6.90	14.09 ± 4.70	0.731
Manicina aereolata	29.83 ± 21.40	28.48 ± 22.00	0.924
Solenastrea hyades	22.44 ± 4.93	11.98 ± 5.79	0.022
Phyllangia americana	5.07 ± 3.28	4.65 ± 3.36	0.848

imen of *S. hyades* also exhibited partial bleaching. At the end of SSE III-2 (second 10 days), color loss was noted in the following specimens of the experimental treatment: *S. lacera* (1 specimen), *Manicina areolata* (2 specimens), *S. hyades* (4 specimens), *Isophyllia sinuosa* (2 specimens), *Cladocora arbuscula* (1 specimen). Similar color loss was observed in control individuals of *M. areolata* (2 specimens), and *S. hyades* (4 specimens). No attempt was made to quantify the amount of bleaching on coral specimens since bleaching patterns and coral shapes were irregular and difficult to measure. On the basis of number of individual specimens affected, regardless of the extent of bleaching, 14% of experimental and 10% of control colonies experienced some color loss over the 10–20 days of exposure.

Suspended Sediment Experiments—Growth Rates.—Growth rates for control and experimental treatments for each of the four suspended sediment experiments are presented in Tables 4–6. Data are summarized as the average growth rates for each treatment by species and as the combined average growth rates for all species tested in that experiment. The mean initial weight of specimens was not significantly different between control and experimental treatments for all species tested except for *Solenastrea* in SSE-1 where the control treatment mean initial weight was significantly larger than the experimental mean initial weight.

Table 5. Mean growth rates for corals exposed to a suspended solid load of 101 mg·liter^{-1} for 10 days (SSE II). Values are mg increase (or decrease) per gram of initial weight ± standard deviation. N = 5 per treatment per species, except where noted

Species	Treatment		Probability (F-test)
	Control	Experimental	
Cladocora arbuscula	−0.99 ± 2.52	1.31 ± 5.52	0.422
Manicina aereolata	2.39 ± 2.35	0.38 ± 2.05	0.187
Solenastrea hyades	4.41 ± 17.47	2.51 ± 3.69	0.817
Phyllangia americana (N = 5, 4)	−9.75 ± 33.90	12.37 ± 48.98	0.448
All species combined (N = 20, 19)	−1.39 ± 16.65	4.14 ± 22.22	0.384
All species combined excluding *Phyllangia* (N = 15)	1.40 ± 3.82	1.94 ± 9.79	0.844

Table 6. Mean growth rates for corals exposed to a suspended solid load of 165 mg·liter $^{-1}$ for 10 days (SSE III-1). B. Mean growth rates for corals exposed to a suspended solid load of 199 mg·liter $^{-1}$ for 10 days (SSE III-2). Values are mg increase (or decrease) per gram of initial weight ± standard deviation. N = 5 per treatment per species

	Species	Treatment		Probability (F-test)
		Control	Experimental	
A.	*Cladocora arbuscula*	1.88 ± 6.01	−6.46 ± 10.89	0.172
	Manicina aereolata	0.55 ± 1.38	0.64 ± 1.34	0.915
	Solenastrea hyades	4.06 ± 3.13	−2.84 ± 3.67	0.013
	Scolymia lacera	2.37 ± 7.55	0.40 ± 4.64	0.631
	Isophyllia sinuosa	0.59 ± 3.89	−0.12 ± 1.41	0.712
	Stephanocoenia michellini	3.80 ± 7.76	−0.69 ± 2.32	0.251
	All species combined (N = 30)	2.21 ± 5.18	−1.51 ± 5.37	0.008
B.	*Cladocora arbuscula*	16.27 ± 7.52	20.27 ± 7.97	0.172
	Manicina aereolata	0.55 ± 1.07	3.28 ± 3.10	0.100
	Solenastrea hyades	7.85 ± 6.51	13.61 ± 4.20	0.135
	Scolymia lacera	0.71 ± 2.53	0.48 ± 2.46	0.888
	Isophyllia sinuosa	0.05 ± 1.90	−0.95 ± 1.37	0.369
	Stephanocoenia michellini	2.84 ± 3.43	3.61 ± 2.23	0.685
	All species combined (N = 30)	4.71 ± 7.19	6.72 ± 8.64	0.334

In SSE I (Table 4), where the experimental treatment was exposed to 49 mg·liter^{-1} of suspended sediment, the experimental group displayed a slightly higher, although not significantly different, growth rate than controls. *Cladocora arbuscula* had the highest growth rate in both the control and experimental treatments in this test. In SSE II (Table 5), with twice the suspended sediment load as the previous experiment, the difference between control and experimental treatments was not significant. *Solenastrea hyades* had the highest mean growth rate in the control while *Phyllangia americana* had the highest mean growth rate in the experimental treatment. Data for one specimen of *P. americana* from the experimental treatment was excluded from analysis due to an apparent weighing error, hence the smaller sample size compared to the control. The variation between individuals in both treatments for *P. americana* was high (coefficients of variation: control = 80%; experiment = 399%) and the size of the specimens tested was

Table 7. Combined growth rates of corals from all experiments comparing control and experimental treatments. Values are mg increase (or decrease) per gram of initial weight over the 10-day exposure period

Species	Treatment		Probability (F-test)
	Control	Experimental	
Cladocora arbuscula (N = 20)	6.61 ± 8.34	6.53 ± 12.87	0.982
Manicina aereolata (N = 20)	2.67 ± 4.21	3.29 ± 5.30	0.683
Solenastrea hyades (N = 20)	5.40 ± 8.86	4.85 ± 7.73	0.834
Scolymia lacera (N = 10)	1.54 ± 5.38	0.44 ± 3.50	0.593
Isophyllia sinuosa (N = 10)	0.32 ± 2.90	−0.53 ± 1.38	0.413
Stephanocoenia michellini (N = 10)	3.32 ± 5.68	1.46 ± 3.12	0.377
Phyllangia americana (N = 10, 9)	−1.33 ± 24.57	7.24 ± 31.65	0.516
All species combined (N = 100, 99)	3.24 ± 9.40	3.84 ± 12.29	0.699
All species combined excluding *Phyllangia* (N = 90)	3.75 ± 5.88	3.50 ± 8.65	0.823

Table 8. Results of coral burial experiments expressed as LT_{50} (burial time in days necessary to kill half of the experimental animals)

Species	LT_{50} in days
Scolymia lacera (N = 15)	7.0
Isophyllia sinuosa (N = 9)	7.2
Manicina aereolata (N = 23)	10.0
Siderastrea radians (N = 21)	13.6
Cladocora arbuscula (N = 24)	15.0
Stephanocoenia michelinii (N = 12)	16.2
Solenastrea hyades (N = 28)	>15

small (all were less than 5 g weight in air). For these reasons, the data are presented with and without inclusion of this species in Tables 4, 5 and 7.

In SSE III-1, mean growth rates were significantly higher in control colonies ($F_{1,58} = 7.45$; $P = 0.008$) than in the experimental group. The same group of specimens exposed to 199 mg·liter^{-1} (SSE III-2) of suspended sediments for a second 10-day period displayed no significant difference in growth rates compared with controls (Table 6B). Growth rates for the entire 20-day period (SSE III-1 + 2) were not significantly different between control and experimental treatments when analyzed collectively. Average growth rates of corals were higher in the second phase of SSE III than the first phase for both treatments (Table 6). This may indicate that the corals were still adapting to laboratory conditions during the first phase. The specimens used in this experiment were acclimated to laboratory conditions for 17 days prior to the beginning of Phase I, and both phases of SSE III were conducted under virtually identical physical and chemical conditions. *Solenastrea hyades* displayed the highest mean control growth rate in SSE III-1 while *Cladocora arbuscula* had the highest mean control and experimental growth rate in SSE III-2. The combined mean growth rates for seven species of corals exposed to suspended sediment loads (SSE I, II, and III) are presented in Table 7.

Experimental Error for Growth Rate Determinations.—The experimental error associated with the buoyant weighing method was estimated by weighing the same specimens 3 days apart, and subtracting the expected amount of growth (determined from means for each species in control treatments) from the observed 3-day mean change in weight. The remainder represents an estimate of experimental error. Thirty-five specimens from SSE III-2 were weighed and then reweighed 3 days later with an average weight change of 0.337 mg·g^{-1}·day^{-1}. The expected growth was determined to be 0.374 mg·g^{-1}·day^{-1}. The difference between these two, ±0.037 mg·g^{-1}·day^{-1}, represents the estimated experimental error.

Burial Experiments.—Six burial experiments were undertaken in which coral specimens were completely covered with natural marine sediment (from the same batch of sediment used in SSEs) for periods of 1–15 days (Table 2). Not all species of corals were used in each experiment. Survival rates for individual species of corals (expressed as LT_{50}) are presented in Table 8. The LT_{50} represents the burial time necessary to kill half of the experimental organisms. *Scolymia lacera* and *Isophyllia sinuosa* had the lowest tolerances to burial, with 50% mortality at about 7 days. *Solenastrea hyades* was most resistant to burial with 100% survival after 15 days burial (the longest burial period).

Many coral specimens tested in burial experiments suffered sublethal damage that was expressed as color loss, soft tissue damage, invasion by algae, or reduced

feeding activity in recovery aquaria. Each specimen was examined 7 days after being disinterred and if still alive, considered to have survived the experiment. Holding these specimens in recovery aquaria for longer periods of time would likely have resulted in additional mortality; therefore, the LT_{50} values reported in Table 8 should be considered minimum estimates.

Discussion

Seven out of eight scleractinian corals from west central Florida patch reefs showed no significant decrease in growth rate or survival when exposed to a range of suspended sediment loads in the laboratory that equal or greatly exceed those to which they are exposed in the field. LT_{50} values for complete burial of corals ranged from 7 to more than 15 days for the six species tested, suggesting a very high tolerance of these patch reef corals to the most severe effects of sedimentation.

While the remote location of west central Florida patch reefs makes them difficult to access for controlled experiments in the field, corals also can be notoriously challenging animals with which to work in the laboratory. Growth rates may often vary among individuals of the same species (Rogers, 1979; Brown and Howard, 1985) or among clones of the same individuals (Hunter, 1988). Coral growth rates have been shown to vary between day and night and in some cases, growth may be greatly reduced during periods of "mucus tunic" production as in *Porites porites* (Davies, 1989). In the present study, variability within treatments may have obscured our ability to observe statistically significant differences in growth rates between control and experimental groups. Davies (1989) has refined the buoyant weight technique and incorporated corrections for coral tissue density and for the density of skeletal material which may vary between coral species.

A number of corals in our study experienced a weight loss in both control and experimental treatments, although more commonly in the latter. Special care was taken to avoid damage to coral tissues or skeleton during weighing and handling, so this was probably not a factor in the observed weight losses. Skeletal loss may have occurred in some specimens through the activity of boring organisms such as polychaetes, bivalves, and sponges. Dodge et al. (1984) recommended collecting the residue produced by borers and weighing it along with the corals, although this was not possible in the present study due to the accumulation of sediment around corals in the experimental treatment. Cryptic non-boring invertebrates (such as shrimp, echinoderms, and amphipods) were discovered on some corals (especially *Cladocora arbuscula*), and may have left the host or switched hosts during experiments. Attempts were made to limit these associated animals as much as possible and the mass of the animals that escaped detection was unlikely to be large enough to account for observed weight losses. There was no reason to suspect that boring organisms or associated fauna were more abundant on experimental corals than on control corals, since test animals were selected at random and assigned to treatments.

Another possible mechanism of weight loss may have been related to excessive mucus production in the corals exposed to heavy suspended sediment loads. Several authors have reported copious mucus production by sediment stressed corals (Marshall and Orr, 1931; Rogers, 1983). In light of Davies (1989) findings that coral tissue is not necessarily of the same density as seawater, heavy mucus secretion may result in general shrinkage of tissue mass and result in apparent weight loss of the colony.

Anomalous estimates of growth rates, such as those recorded for *Phyllangia americana,* may have been due to the small size of specimens used. This species

was difficult to collect in large monospecific colonies and as a result small individuals (less than 2 g) were used in the first two experiments, exaggerating the experimental error incurred in weighing.

A possible solution to the problem of variable growth rates within species would be to chart individual growth of corals for longer periods of time (several weeks or more) in the laboratory prior to beginning experiments. This would provide a baseline for comparison with subsequent experimental treatments and would help to establish adequate acclimation times for growth studies.

With the exception of the ahermatype, *Phyllangia americana, Cladocora arbuscula* had the highest mean growth rate among control corals tested and *Isophyllia sinuosa* had the lowest. *P. americana* appeared to be a weedy, fast-growing species, occurring in high numbers on the young artificial reef. It was also dominant, although in lower densities, on the 18 m reef where growth of hermatypic species may be limited by decreasing light penetration. *C. arbuscula* densities were highest on the deeper, natural reefs suggesting that, with its relatively fast growth rates, it is a competitively dominant species.

Results of other field studies on coral distributions have indicated a negative correlation between suspended sediment loads and hard coral abundance. Mayer (1918) concluded that only corals that were tolerant to higher temperatures and turbid water were found near shore. He found *Siderastrea radians* to be among the most resistant corals that he tested, able to survive total burial for more than 73 h. Edmondson (1928) tested the resistance of Hawaiian corals to siltation and burial in the laboratory, and found that tolerance ranged from 12 h to 10 days. Marshall and Orr (1931) determined that corals with branching colonies or those with large polyps were best able to clean themselves of sediment. Studies by Hubbard and Pocock (1972) on coral morphology and behavior revealed clues to environmental distribution patterns relative to sediment removal abilities in 26 coral species. Their observations indicated that coral species vary considerably in their efficiency of sediment removal, and that many species are size-specific sediment rejectors. Several species tested in the present studies were also tested by Hubbard and Pocock (1972, p. 604). These authors found *Solenastrea hyades* to be a poor sediment rejector, while the following species are listed in order of increasing sediment rejection efficiency: *Cladocora arbuscula, Siderastrea siderea, Manicina areolata,* and *Isophyllia sinuosa.* The efficiency of sediment rejection (rate of sediment removal) measured by Hubbard and Pocock (1972) should not be equated with tolerance of a species to sediment loads, since the present studies indicate that *Cladocora arbuscula* was among the most tolerant species, based upon burial and suspended sediment studies, while *Isophyllia sinuosa* was the least tolerant to these conditions.

Trends from these and other field and laboratory studies indicate that many coral species can tolerate natural sediment suspended loads and burial for relatively short periods of time (i.e., the duration of most laboratory tests) but that long-term exposure to suspended sediment can cause reduced coral growth and reduced reef development.

Sedimentation may be the major cause of reef degradation on a global scale (Johannes, 1975; Kuhlman, 1988; Rogers, 1990). The effects of sediment resuspension on coral reefs as a result of anthropogenic activities have been documented in reviews of dredging, filling, dredged material disposal and mining effects (Levin, 1970; Courtenay et al., 1974; Endean, 1976; Bak, 1978; Rogers, 1990). The addition of complicating factors such as freshwater flooding or toxic pollutants adhered to sediments may significantly aggravate effects on corals.

In the present study, only natural uncontaminated sediments were employed

in laboratory tests. The species of hard corals inhabiting reefs off the west central portion of Florida appear to be among the most tolerant species tested with regard to suspended sediment and burial effects. These species have been found to withstand continuous exposure to 150–200 mg·liter^{-1} of suspended sediment for 20 days with no mortality and no significant reduction in growth rate. No literature reports were found that suggested that any coral specimen could survive total burial for more than 10 days, and most species previously tested could not tolerate more than 2 days of burial. For the corals in the present study, the shortest burial LT_{50} was 7 days, with that of three species greater than or equal to 15 days.

The natural distribution of corals may provide an indication of general tolerance of a species to environmental factors. Many of the corals inhabiting patch reef communities off west central Florida have been found to occupy the least favorable habitats in more tropical settings such as lagoons and near-shore reefs (Griffin, 1974; Colin, 1978). Some species (e.g., *Manicina areolata* and *Isophyllia sinuosa*) have been recorded to occur as unattached colonies in lagoon habitats and have the ability to right themselves if turned upside down in the sediment (Hubbard and Pocock, 1972).

Compared to more tropical habitats, the patch reefs off west central Florida are exposed to more severe environmental conditions, such as low winter water temperatures, high turbidity, and decreased light penetration. It is not surprising that species that inhabit these areas demonstrate high tolerances to environmental stress, but it also may be that these species are living near their physiological tolerance limits of environmental conditions and may be more sensitive to additional prolonged adverse conditions (i.e., chronic siltation stress) than their tropical congeners. Laboratory tests conducted during the present study were intended to simulate environmentally advantageous conditions for coral survival and growth with regard to temperature, salinity, food availability, and light levels. Further experiments under a range of different physical regimes, or with contaminated sediments may be useful in elucidating synergistic effects of a number of stressful parameters on reef corals.

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