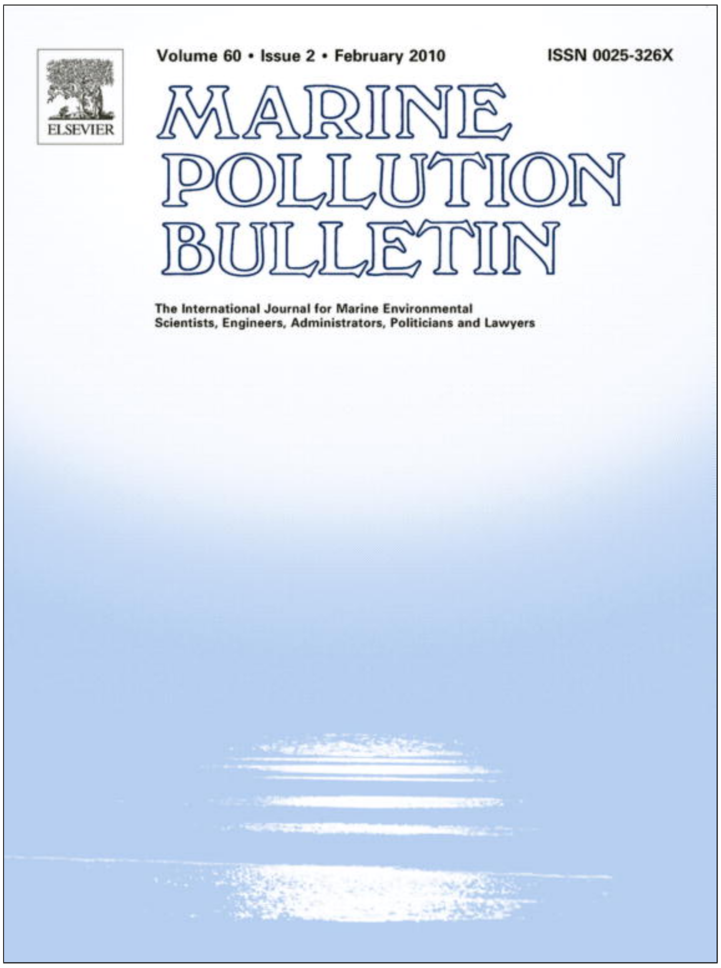

Volume 60 • Issue 2 • February 2010 ISSN 0025-326X

MARINE POLLUTION BULLETIN

The International Journal for Marine Environmental Scientists, Engineers, Administrators, Politicians and Lawyers

Marine Pollution Bulletin 60 (2010) 261–271

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Elevated sedimentation on coral reefs adjacent to a beach nourishment project

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ABSTRACT

An increasingly common method to restore eroding beaches is nourishment, a process by which lost sand is replaced with terrestrial or offshore sediments to widen beaches. The southeastern Florida coastline contains shore-parallel coral reef communities adjacent to eroding beaches. Scleractinian corals and other reef-associated organisms are known to demonstrate sensitivity to elevated sedimentation levels. Sediment traps were used to examine spatio-temporal sedimentation patterns and assess the effects of nourishment (dredge and fill) activities. Several environmental variables correlated with among-site spatial variability of sediment parameters. Intra-annual variability correlated with wind velocity and direction. Nourishment activities showed localized effects, with sites in close proximity to dredging areas exhibiting significantly higher collection rates and lower percent fines than control sites. A regional increase in sedimentation occurred while nourishment activities were ongoing. Due to concurrent impacts of hurricanes, only one during-construction sampling interval revealed substantially higher collection rates relative to corresponding pre-construction sampling intervals.

1. Introduction

Worldwide declines in coral coverage and overall reef degradation can be attributed to a variety of anthropogenic and natural causes (Pandolfi et al., 2003; Côté et al., 2005). Increased sedimentation has been identified as a stressor known to negatively influence corals at the polyp and colony level and as a factor controlling morphology and local distributional patterns of reefs (Hubbard, 1986; Rogers, 1990; McCulloch et al., 2003; Goldberg and Wilkinson, 2004). While global climate change will force resilient coral reefs to adapt (IPCC, 2007), chronic human-induced stresses (such as increased sedimentation from coastal construction and land development) may reduce larval replenishment and impede their ability to persist (Hughes et al., 2003; Fabricius, 2005).

In addition to corals, increases in sedimentation can affect other reef-associated organisms. Coverage of crustose coralline algae (which cements reefs and functions as a settlement substrate for coral planulae) is related to the sedimentary environment, with lower percent cover recorded in areas with thicker sediment deposits (Fabricius and De'ath, 2001). Declines in coral reef fish populations have been related to increased sedimentation levels (Hawkins et al., 2006.). Settlement of early-life stages of seaweeds is disrupted by high levels of sediment (Schiel et al., 2006). Even entire benthic assemblages can be altered as a result of human-induced, high-sedimentation events (Colosio et al., 2007). Due to the ecological relationships among organisms associated with coral reefs and the surrounding ecosystem, changes (natural or anthropogenic) affecting population levels of one species could perpetuate throughout the entire community.

Although the negative effects of increased sedimentation on corals have been experimentally observed (Rogers, 1990), some coral reefs can flourish in high-sediment regimes (Riegl, 1995; Anthony et al., 2004). Few studies have produced threshold values reasonably applicable to resource management (Vargas-Angel et al., 2006; Fisher et al., in press). Therefore, knowledge of the natural spatial and temporal sedimentation patterns on a coral reef becomes vital for understanding the effects of human-induced environmental impacts on that habitat.

Beach erosion in Florida is primarily caused by human coastal construction activities, as well as, natural forces (Schmidt and Woodruff, 1999). Beach erosion in Florida has been attributed to interruption of longshore sand flow caused by manmade navigational passages through barrier islands (Douglass, 2002). Erosion functionally reduces the width of sandy beach habitat, which can support a wide range of birds, reptiles, fishes, and invertebrates (Brown and McLachlan, 1990). One method to combat beach erosion is to nourish (e.g., replenish, fill, restore, etc.) beaches with local or imported sands from offshore or inland sources. Despite numerous beach nourishment projects, little is known about sedimentation effects, especially on coral reef or other hardbottom communities located in immediate proximity (Peterson and Bishop, 2005). Due to the common use of beach nourishment and the known effects of siltation, burial, and disruption of normal

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0025-326X/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2009.08.032

granulometric parameters on benthic and infaunal organisms, an understanding of potential effects has become vital to proper resource management.

Sediment traps have been shown to provide adequate measurement of relative spatial and temporal variability of sediment fallout (Woolfe and Larcombe, 1998), despite the inability to distinguish between net deposited allocthonous sediment and the resuspension of autocthonous material. Gardner et al. (1983) showed that sediment trap accumulations depict particle resuspension and settlement fluxes, but this is not necessarily representative of net sedimentation rate (Gardner, 1980). Limitations such as sediment trap design, trap tilt, and mooring height greatly influence collection efficiency and do not allow for calibration of sediment traps (Gardner, 1985; Taguchi et al., 1993; van Raaphorst et al., 1998). Nevertheless, they provide a useful tool for comparative studies (Gust et al., 1994).

The first portion of this study aimed to quantify the spatio-temporal patterns of sedimentation (using sediment traps) on coral reefs adjacent to a highly urbanized coastline and examine potential physical and environmental attributes driving these patterns. The second portion examined sedimentation patterns during a large-scale beach nourishment project (at the same study area); comparing patterns of sedimentation during nourishment to those obtained in the first study portion (prior to nourishment). Comparison of control and experimental sites were used to gain insight into the spatial patterns associated with dredging inter-reef sand plains.

2. Methods

2.1. Regional setting

In southeast Florida, a reef system with parallel-running reef tracts and a complex of nearshore ridges comprises geologically distinct habitats which support a common biotic reef community (Banks et al., 2007; Walker et al., 2008; Gilliam et al. (2008), Walker et al., 2009). During the dry season (November-March), Florida experiences the passage of mid-latitude, synoptic-scale cold fronts (Hodanish et al., 1997) which bring strong winds from the northeast. These "northeasters" usually last for 2–3 days. From June through November, Florida is a prime landfall target for tropical cyclones. In the winter, low-pressure systems form on the Atlantic coast of the US. Short-period, wind-driven waves develop near the center of these lows. As these seas move away from the center of low pressure they can develop into long-period swells which affect southeast Florida. The wave climate of southeast Florida is greatly influenced by the shadowing effect of the Bahamas and, to a lesser extent, Cuba (Banks et al., 2008).

2.2. Beach nourishment operation

Beach nourishment construction activity began on 14 May 2005 and continued through 3 February 2006 (sampling intervals 2005–3 through 2006–1). Sand was dredged from sand plains (areas hereafter referred to as sand borrow areas [SBAs]) which separate the shore-parallel reef tracts (Fig. 1). The hopper dredge vessel that collected sand rotated among the five SBAs in an attempt to minimize potential long-term turbidity effects on surrounding corals and other benthic fauna located within a few hundred meters (<500 m) from the operation.

2.3. Sedimentation monitoring

Beginning in 1997, 22 sediment monitoring stations (control stations) were established throughout the reef system offshore of Broward County, Florida, USA (one station in southern Palm Beach County) (Fig. 1). Two additional stations, FTL 5 and FTL 6, were established in September 2003 and November 2003, respectively. These stations were positioned on three reef/hardbottom tracts (hereafter referred to as categories): nearshore ridge complex (NRC) ($n = 11$, depth range = 3.0–8.8 m), middle reef (MR) ($n = 7$, depth range = 8.7–15.7 m), and outer reef (OR) ($n = 6$, depth range = 14.5–17.1 m) (Fig. 1). The 24 stations were used to describe the sediment regime offshore Broward County prior to the beach nourishment activity.

To examine the local sedimentation rates associated with dredging activity, nine additional sediment traps were deployed in December 2004. These traps were deployed at sediment monitoring stations on reef adjacent to five SBAs: NRC, $n = 3$; MR, $n = 5$; and OR, $n = 1$ (Fig. 1). Each SBA was bracketed by two sediment monitoring stations; one on each reef edge adjacent to the SBA with the exception of SBA 6, which had only one station located to the east of the SBA (Fig. 1). Five of the 24 control stations (HB1, DB1, HB2, DB2, and HB3) were also located within immediate proximity to the SBAs. Therefore, analyses which examined the local effects of dredging included these five control stations with the SBA stations in the "experimental" SBA treatment group used for comparison with the remaining 19 control stations (see above).

At each station, sediment was collected using a sediment trap ring stand, constructed of steel reinforcing rods, which held three collection bottles approximately 0.5 m above the substrate (modified from Fisher et al., 1992). The PVC sediment trap openings had a diameter of 51 mm with a length of 152 mm (3:1 ratio as suggested by Gardener, 1980) and sat atop a 2-L, high-density, polyethylene collection bottle. Bottles were collected from the sediment monitoring stations approximately every 60 days, weather conditions permitting. To ensure minimal sediment loss during the bottle change-out process, collection bottles were sealed by replacing the PVC trap tops with standard bottle lids before underwater removal of the bottle from the ring stand. Divers also noted any anomaly that could interfere with the sediment analysis, such as the presence of large living organisms (e.g., octopuses, eels, etc.) in a particular bottle or a missing trap bottle.

Sediment sieve analysis followed methodology similar to Fisher et al. (1992). Sediment samples were preserved with 10% formalin solution. After fixing, samples remained undisturbed for 48 h for particles to settle, allowing for the preservative solution to be removed by aspiration. The remaining sample was then rinsed (using freshwater) through a no. 230 (0.063 mm) sieve. Particles passing through the sieve constituted the silt/clay (fines; <0.063 mm) fraction. All visible organisms (e.g., fish, crabs, worms, algae, etc.) were removed from the sand fraction remaining atop the sieve. Both sand and silt/clay fractions were dried in an oven (at 68° C). Once the sand fraction and fines fraction samples were dry, they were removed from the oven and quickly placed into desiccators for cooling. After cooling, whole samples (both fractions) were weighed to the nearest 0.01 g.

To determine mean grain size of the sand fraction, only the heaviest sample of the three sediment bottles from each sampling station was analyzed. If this sample weighed >80 g, it was split through a Humboldt Riffle-type sample splitter until reaching a subsample of 40–70 g. The subsample was then placed atop the 4.00 mm sieve of a stacked sieve series (US Standard Series) and shaken for 15 min. Then, each of the sieve fractions was weighed. Analysis of mean grain size in the first portion of this study (natural spatio-temporal patterns) used data from May 2001 through June 2003. Because of a change in the sieve series after June 2003, mean grain size analysis in the second portion of the study was only performed to examine the local effects of the nourishment, a comparison of the experimental SBA group (i.e., the nine SBA stations and HB1, DB1, HB2, DB2, and HB3) to the control stations.

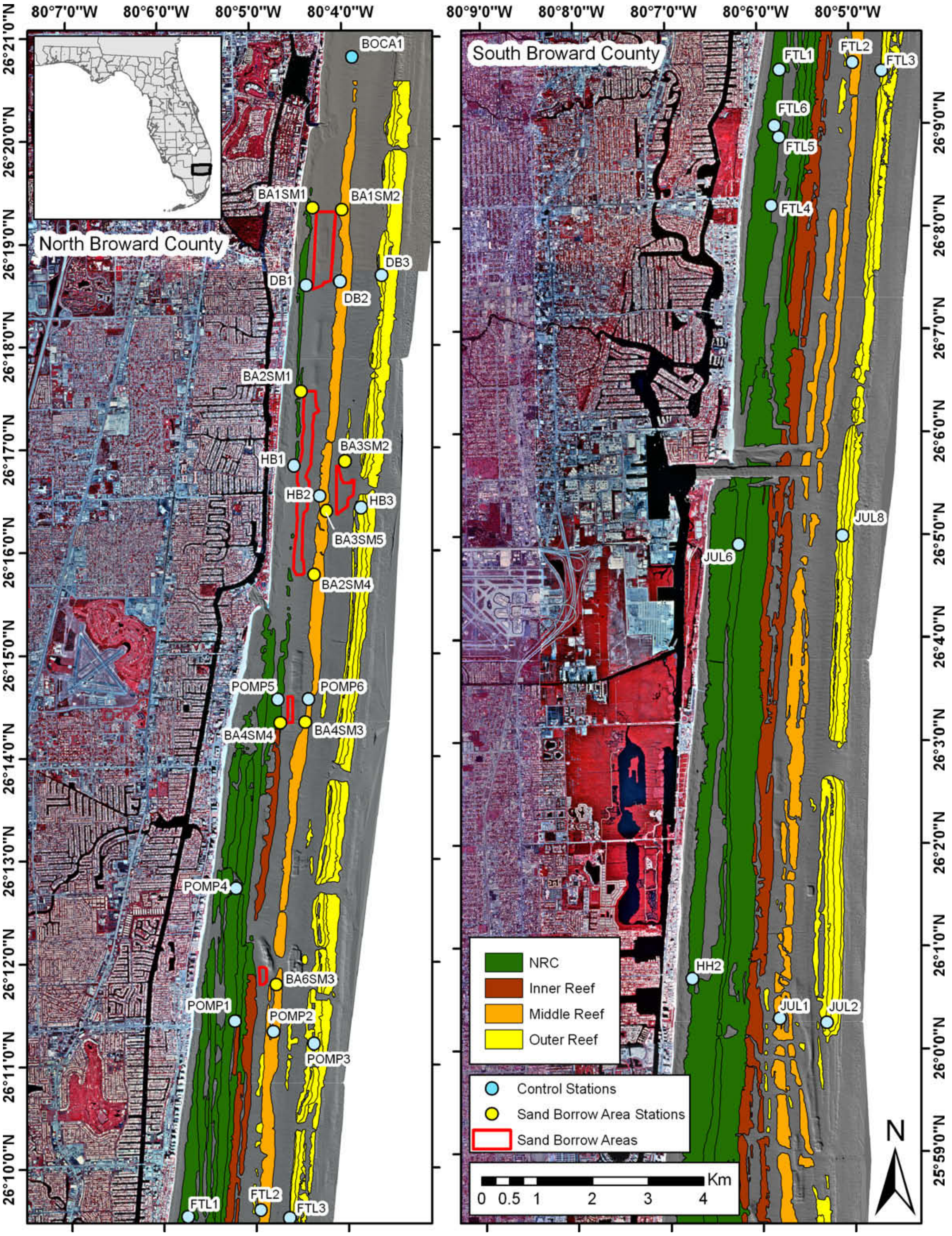

Fig. 1. Study region depicting sampling stations, sand borrow areas, and respective reef categories (nearshore ridge complex [NRC], inner reef, middle reef, and outer reef).

2.4. Geospatial characteristics

Using sediment trap position (differential GPS), distance from shore (m), distance from inlets (m), distance from nearest sand habitat (m), distance from nearest SBA (m), depth (m), and elevation above the nearest sand habitat (m) were obtained using mapping data in GIS (ArcGIS 9.2) (Walker et al., 2008). Distance from shore was calculated as the shortest linear distance from each sediment trap to the 0-m shore contour in the LIDAR bathymetry. Distance from nearest inlet represented the shortest linear distance to the center of each inlet mouth. Distance to the nearest sand habitat (and distance from nearest SBA) was calculated as the shortest linear distance to the nearest sand polygon edge. Depth represented the LIDAR bathymetric depth at the GPS location of the sediment trap. Elevation above the nearest sand habitat was the absolute value of the difference between the sediment trap LIDAR depth and the LIDAR depth at the nearest sand habitat polygon edge.

2.5. Wind data

Linear regression was used to investigate correlation of wind speed with collection rate and percent fines (see below). A global (including all sampling stations) mean collection rate and mean percent fines were calculated for each sampling interval. Mean wind speed for each sampling interval was calculated using hourly wind speed data from the Fowey Rocks C-MAN buoy (station FWYF1 25.59 N, 80.10 W), approximately 55 km south of the study area. Wind rose plots (WRPLOT View v5.3, Lakes Environmental Software) were created to illustrate the cumulative direction wind speeds (m/s) and the resultant vector for the time periods under examination.

2.6. Data analyses

Data obtained from January 2001 through December 2004 (i.e., sampling interval 2001–1 through 2004–6) were used to examine natural spatio-temporal patterns of the sediment regime. Since nourishment construction activities occurred from 14 May 2005 through 3 February 2006, the second portion of the study used data from January 2001 through December 2007 (i.e. sampling interval 2001–1 through 2007–6) to investigate the effects of the nourishment activity (dredging and beach fill) during beach construction. Table 1 lists the months associated with each of the six sampling intervals.

Factorial analyses of variance (ANOVAs) were performed on collection rate (mg/cm^2/day), percent fines (proportion of grains <0.063 mm), and mean grain size (calculated using the Wentworth phi scale [Wentworth, 1926]) for several groups of categorical predictors. Comparison of above metrics were conducted for reef categories, sampling intervals, station types (i.e. the experimental SBA group [see above] and control stations), and construction periods (pre-, during-, and post-construction). For construction period comparisons, all interval 2 data were omitted because no construction activities occurred during the time period associated with this interval. Sediment collection rate exhibited heteroscedasticity and was transformed ($\log_{10}[x + 1]$) prior to ANOVA. Percent fine values were arcsine square-root transformed while mean grain size was square-root transformed prior to ANOVA. *Post hoc* analyses among means were performed using Tukey HSD tests. To compare the mean collection rate of a particular during-construction sampling interval to the composite mean for the corresponding pre-construction sampling intervals, a difference between two means test was performed (Statsoft 6.1, Tulsa OK).

Stepwise multiple regression analysis was used to determine how six environmental parameters (see above) explained variability in collection rate, percent fines, and mean grain size seen among sampling stations. Adjusted R^2 values were reported for the multiple regression analyses. Linear regression and correlation analysis were also performed on the six individual parameters. Only a coefficient of determination (r^2) of environmental parameters that significantly correlated ($p < 0.05$) was reported. To examine the spatial influence of the nourishment activities, collection rate, percent fines, and mean grain size data from during-nourishment sampling intervals were used to perform a correlation analysis of distance from nearest construction activity (dredging [SBA] or beach fill).

Table 1
List of sampling intervals and the months to which they normally corresponded.

Sampling interval	Corresponding months
1	January–February
2	March–April
3	May–June
4	July–August
5	September–October
6	November–December

3. Results

3.1. Spatial sedimentation patterns

Prior to beach nourishment activities (January 2001–December 2004), mean sediment collection rate was 38.4 ± 3.0 mg/cm^2/day (mean ± SE). A three-way ANOVA of sediment collection rate (using reef category, year, and interval as factors) exhibited significant differences among the three reef categories ($F_2 = 684.97$, $p < 0.0001$), with collection rate decreasing from nearshore to offshore. A Tukey HSD *post hoc* test revealed that the nearshore ridge complex (NRC) stations had a higher collection rate than both middle reef (MR) and outer reef (OR) stations, with latter exhibiting the lowest collection rates (Table 2). Percent fines exhibited the opposite pattern; with collected sediments fining seaward. All three reef categories significantly differed ($F_2 = 130.85$, $p < 0.0001$, Tukey HSD test) (Table 2). Collection rate and percent fines showed a strong inverse linear relationship ($p < 0.0001$, $r^2 = 0.7471$, $r = -0.8643$). Mean grain size (mm) (May 2001–May 2003) decreased seaward, with all reef categories significantly deferring ($F_2 = 33.11$, $p < 0.0001$, Tukey HSD test), consistent with the increase in percent fines (Table 2).

Linear regression of global station collection rate (i.e., mean station collection rate using all sampling intervals) revealed that station depth (m) explained 70.3% of the variability seen throughout the study area ($p < 0.0001$, $r = -0.8387$). Distance from shore (m) explained 67.3% of the variability ($p < 0.0001$, $r = -0.8206$). Elevation of sediment trap above the nearest sand habitat (m) explained 22.3% of the variability ($p = 0.0199$, $r = -0.4718$), while distance from nearest sand habitat (m) was not found to explain the collection rate variability among the stations ($p = 0.1118$). No linear relationship existed for collection rate and distance from nearest inlet ($p = 0.3589$).

Stepwise multiple regression indicated three tested factors exhibited a significant influence on the collection rate. Sixty-eight percent (adjusted R^2) of the collection rate variance was explained by station depth, with an additional 5% explained by elevation of trap above nearest sand habitat ($F_{2,21} = 33.63$, $p = 0.0009$). Distance from shore, distance from nearest inlet, and distance from nearest sand habitat did not exhibit a significant effect on collection rate among the different stations. The apparent lack of influence on collection rate from distance from shore in the multiple regression analysis contradicted the results from the simple linear regression. However, this discrepancy may be attributed to the strong,

Table 2
Pre-construction comparison of reef categories and sampling intervals for mean collection rate (mg/cm^2/day), mean percent fines, and mean grain size (mm). Different letters indicate significant difference ($p < 0.05$; Tukey HSD).

	Collection rate (mg/cm^2/day) ± 1SE	Percent fines ± 1SE	Grain size (mm) ± 1SE
NRC	71.76 ± 6.83^a	34.32 ± 0.94^c	0.156 ± 0.005^a
Middle reef	24.29 ± 3.01^b	44.13 ± 1.16^b	0.134 ± 0.006^b
Outer reef	5.55 ± 0.61^c	53.00 ± 0.75^a	0.111 ± 0.005^c
Interval 1	59.18 ± 8.46^a	34.84 ± 1.48^c	0.133 ± 0.008^{ab}
Interval 2	34.53 ± 8.52^{bc}	42.04 ± 1.48^b	0.129 ± 0.007^b
Interval 3	30.98 ± 3.74^b	39.76 ± 1.49^{bc}	0.132 ± 0.008^{ab}
Interval 4	8.29 ± 2.39^d	52.22 ± 1.14^a	0.130 ± 0.007^b
Interval 5	28.53 ± 5.22^c	48.21 ± 1.45^a	0.151 ± 0.009^{ab}
Interval 6	75.94 ± 12.35^a	37.33 ± 1.53^{bc}	0.155 ± 0.009^a

positive, linear relationship between station depth and distance from shore ($p < 0.0001$, $r^2 = 0.7517$, $r = 0.8670$).

Linear regression of global percent fines (i.e., mean percent fines using all sampling intervals) for each station revealed that distance from shore explained 51.3% of the variability seen throughout the study area ($p < 0.0001$, $r = 0.7167$). Depth explained 42.18% of the variability ($p < 0.0001$, $r = 0.6495$). Elevation above the nearest sand habitat explained 24.9% of the variability ($p = 0.0131$, $r = 0.4988$), while distance from nearest sand habitat lacked a significant relationship ($p = 0.2367$). The linear regression results appeared to mirror those seen for collection rate. However, unlike collection rate, distance from nearest inlet explained 20.6% of the among-station variance exhibited by percent fines ($p = 0.0260$, $r = 0.5437$). Nevertheless, the general trends shared by collection rate and percent fines were likely due to the strong inverse linear relationship found between global station collection rate and global station percent fines (see above). Stepwise multiple regression of percent fines revealed distance from shore as the only factor significantly influencing the variance seen among all stations (adjusted $R^2 = 0.5233$; $F_{1,22} = 23.78$, $p < 0.0001$).

Linear regression using global mean grain size (i.e., mean grain size using all sampling intervals) for each station showed that depth explained 31.0% of the variability among stations ($p = 0.0047$, $r = -0.5565$). Distance from shore (although strongly correlated with depth, see above) explained 29.3% of the variability ($p = 0.0063$, $r = -0.5414$). Neither distance from nearest sand habitat ($p = 0.5504$) nor distance from nearest inlet ($p = 0.0570$) exhibited a significant linear relationship with mean grain size. Results of stepwise multiple regression analysis for mean grain size showed that only one habitat factor significantly influenced the variance among stations. Thirty-five percent of the variability in mean grain size was attributed to distance from shore ($F_{1,22} = 11.73$, $p = 0.0024$).

3.2. Temporal sedimentation patterns

Significant temporal differences were detected for sediment collection rate, percent fines, and mean grain size among sampling intervals (when pooling all station data). A three-way ANOVA (using reef category, year, and interval as factors) revealed that the highest collection rates generally occurred during the winter sampling intervals (intervals 1 and 6; which did not differ significantly) ($F_5 = 112.53$, $p < 0.0001$, Tukey HSD test) (Table 2). The summer sampling interval (interval 4) exhibited a lower collection rate than all other intervals. In contrast, percent fines were highest during the summer sampling intervals (intervals 4 and 5; $F_5 = 27.14$, $p < 0.0001$, Tukey HSD test) (Table 2). Despite the strong linear relationship of mean grain size with collection rate ($p = 0.001$, $r^2 = 0.4912$, $r = 0.7009$) and percent fines ($p < 0.0001$, $r^2 = 0.6344$, $r = -0.7965$), mean grain size did not appear to follow the collection rate or percent fines trend. Rather, generally larger mean grain sizes were apparent for autumn/winter sampling intervals (intervals 5 and 6) ($F_5 = 3.32$, $p = 0.006$, Tukey HSD test) (Table 2).

Linear regression revealed that wind speed accounted for 68.4% of the variance seen among global sampling interval collection rates (pooling all stations; $p < 0.0001$, $r = 0.8269$). Wind speed also accounted for 60.8% of the variance seen among global sampling interval mean percent fines (pooling all stations, $p < 0.0001$, $r = -0.7795$). Wind rose plots constructed to illustrate the wind patterns for the six sampling intervals (pooling dates for each of the six sampling intervals from 2001–2005) revealed southeasterly trade winds predominated the region during sampling intervals 4 and 5 (summer months), with resultant vectors of 125° (58%) and 117° (61%), respectively. Sampling interval 4 (June–August) exhibited the lowest contribution of strong (>11.1 m/s) winds and contained the highest contribution of calm winds (i.e., <0.5 m/s). Sampling intervals 1, 2, and 6 (November–December, January–February, and March–April) contained winds with a more northerly component, likely related to low-pressure systems associated with cold fronts (Banks et al., 2008).

3.3. Sedimentation adjacent to sand borrow areas

Beach nourishment construction activities (dredging and beach fill) occurred from 5 May 2005–7 February 2006 (sampling intervals 2005–3 through 2006–1). When using during-construction data, a three-way ANOVA (using treatment [SBA or control], reef category, and sampling interval as factors) revealed that the SBA treatment group (including SBA stations and 5 stations in close proximity to dredging activity) had a significantly greater mean collection rate than the control stations ($F_1 = 14.81$, $p = 0.0001$). Comparison of the SBA treatment group with control stations among reef categories also reveled a significant difference ($F_2 = 6.202$, $p = 0.0023$). A Tukey HSD test showed that the only difference between control and SBA treatment stations occurred on the NRC (Table 3). No significant linear relationship was found between collection rate of SBA treatment stations and distance from nearest SBA (m) ($p = 0.5281$). This was not surprising given that dredging activities were rotated among the SBAs.

A three-way ANOVA (using same factors as above) revealed a significant difference in percent fines between the SBA treatment group and control stations, with control stations having a higher percentage than the SBA treatment group ($F_1 = 15.48$, $p = 0.0001$). A comparison of percent fines between SBA stations with control stations among reef categories also detected a significant difference ($F_2 = 5.466$, $p = 0.0046$). A *post hoc* Tukey HSD test revealed the only significant difference in percent fines between SBA treatment group and control stations occurred for the NRC reef category, with the SBA treatment group exhibiting substantially lower mean percent fines values (Table 3). Nevertheless, for all reef categories, control stations always exhibited higher values of percent fines than corresponding SBA treatment group stations. Using during-construction data from all stations, a weak positive rela-

Table 3
During-construction comparison between SBA and control sampling stations for mean collection rate (mg/cm^2/day), mean percent fines, and mean grain size (mm). Different letters indicate significant difference ($p < 0.05$; Tukey HSD).

		Collection rate (mg/cm^2/day) ± 1SE	Percent fines ± 1SE	Grain size (mm) ± 1SE
SBA (All Sites)		122.93 ± 13.63^{a}	23.02 ± 1.26^{b}	0.122 ± 0.006
Control (All Sites)		91.71 ± 8.65^{b}	30.77 ± 1.13^{a}	0.124 ± 0.009
NRC	SBA	239.01 ± 40.23^{a}	18.79 ± 2.27^{c}	0.146 ± 0.011
	Control	118.61 ± 12.77^{b}	31.72 ± 1.83^{a}	0.135 ± 0.006
Middle Reef	SBA	88.97 ± 10.53^{c}	23.28 ± 1.69^{bc}	0.116 ± 0.010
	Control	105.70 ± 18.95^{bcd}	27.66 ± 2.12^{ab}	0.136 ± 0.019
Outer Reef	SBA	49.62 ± 12.62^{de}	29.35 ± 2.94^{a}	0.094 ± 0.012
	Control	28.95 ± 4.99^{e}	32.44 ± 1.83^{ab}	0.094 ± 0.006

tionship was found for percent fines and distance from nearest SBA ($p = 0.0212$, $r = 0.4059$, $r^2 = 0.1647$). This suggests that dredging affected sediment composition. A three-way ANOVA (identical to above) of mean grain size revealed no significant difference between the SBA treatment group and control stations during the time of construction ($F_1 = 0.003$, $p = 0.9540$, Table 3). Comparison of mean grain size, using SBA treatment group and control stations among reef categories as factors, also showed no difference ($F_2 = 0.517$, $p = 0.5977$). No linear relationship was found for mean grain size and distance from nearest SBA ($p = 0.7283$).

3.4. Regional sedimentation

During-construction sampling intervals (2005–3 through 2006–1) were compared to corresponding pre-construction sampling intervals to analyze the effects of construction activities on the sediment regime. A three-way ANOVA (with reef category, construction period [pre-, during-, and post-construction], and sampling interval as factors) indicated significantly higher collection rates occurred for the during-construction period ($F_2 = 243.01$, $p < 0.0001$, Tukey HSD test). Mean during-construction collection rates were significantly higher when compared to pre-construction and post-construction intervals (the during-construction period did not include sampling interval 2; this interval was excluded from this analysis) (Fig. 2). Examination sampling intervals showed that the trend of low collection rates in summer and high collection rates in winter exhibited prior to nourishment activities persisted for during-construction intervals (Fig. 3). The opposite was true for percent fines. Mean during-construction percent fines values were significantly lower than those seen for pre- and post-construction sampling intervals ($F_2 = 61.29$, $p < 0.0001$, Tukey HSD test) (Fig. 4). The trend of lowest percent fines in winter and highest percent fines in summer persisted for during-construction intervals (Fig. 5),

To examine if construction activities significantly disrupted normal patterns of collection rate and percent fines, we compared each of the individual sampling intervals among years. Since construction occurred during sampling intervals 2005–3 through 2006–1, no during-construction sampling interval 2 (March–April) was available for comparison. The during-construction collection rates fell within pre-construction ranges in four of the five sampling intervals (intervals 1, 3, 5, and 6). The during-construction sampling interval 5 (2005–5; September–October 2005) represented the time period in which the highest collection rates were recorded. However, this sampling interval did not significantly differ from the 2004–5 (September–October 2004), pre-construction sampling interval. Both of these sampling intervals (2005–5 and 2004–5) corresponded with the timing of tropical storm activity in the vicinity of the study area. As stated above, throughout the study duration sampling interval 4 (July–August) collection rates were significantly lower than the other sampling intervals. The during-construction sampling interval 4 (2005–4; July–August 2005) exhibited a 9-fold greater collection rate than the composite mean pre-construction collection rate for that sampling interval (2005–4 rate = 82.2 ± 23.0 versus composite mean pre-construction [2001–2004] rate = 8.3 ± 2.4; $p < 0.0001$ test between two means).

Even though construction activities (dredging and beach filling) were ongoing, the timing of during-construction sampling interval 2005–4 corresponded with an episode of strong (14.1 ± 0.4 m/s), sustained (~64 h), easterly winds. The corresponding pre-construction sampling interval 2002–4, which exhibited the next-highest collection rate behind the 2005–4 during-construction sampling interval, exhibited a mean rate 2.5 times lower (Fig. 2). While no hurricanes or tropical storms were present in the Atlantic during the 2002–4 sampling interval, a period of strong (9.9 ± 0.1 m/s), sustained (~141 h), east-north-easterly winds occurred. Given the similar strength and direction of the sustained winds during the 2002–4 and 2005–4 sampling intervals, it appears that their difference in collection rate was the results of construction activities.

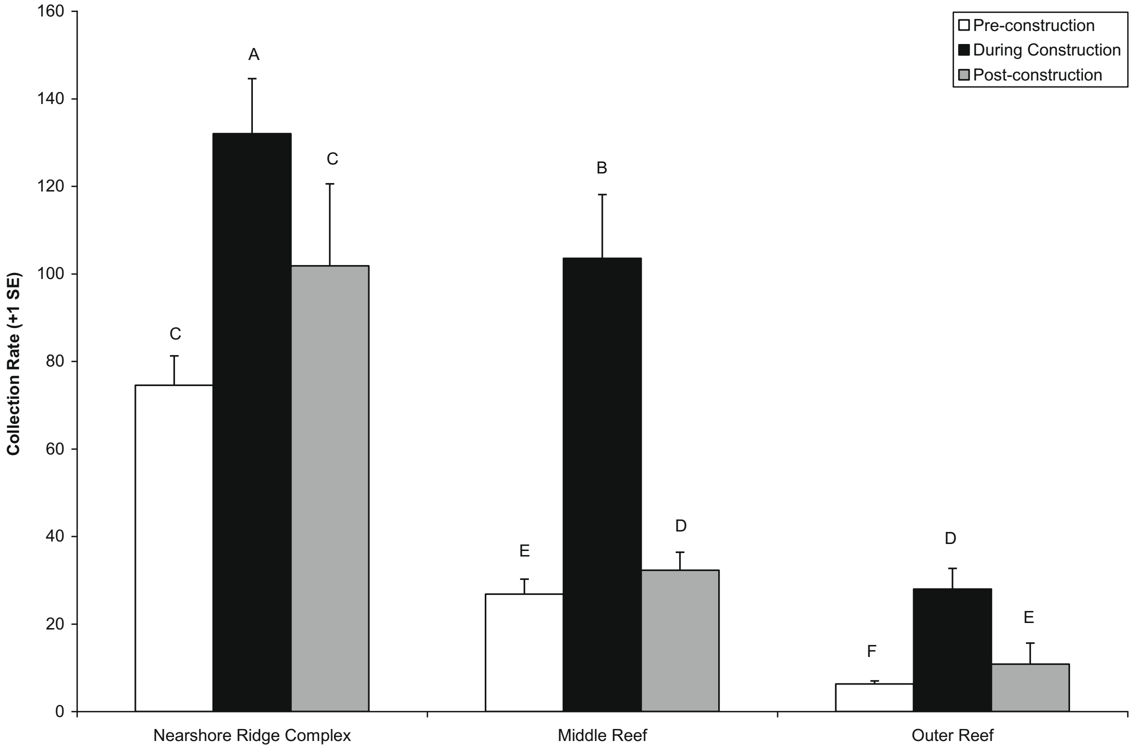

Fig. 2. Comparison of collection rate (mg/cm^2/day) for pre-, during-, and post-construction times. All sampling interval 2 data was excluded due to the lack of representation for the during-construction period. Different letters indicate significant difference ($p < 0.05$; Tukey HSD).

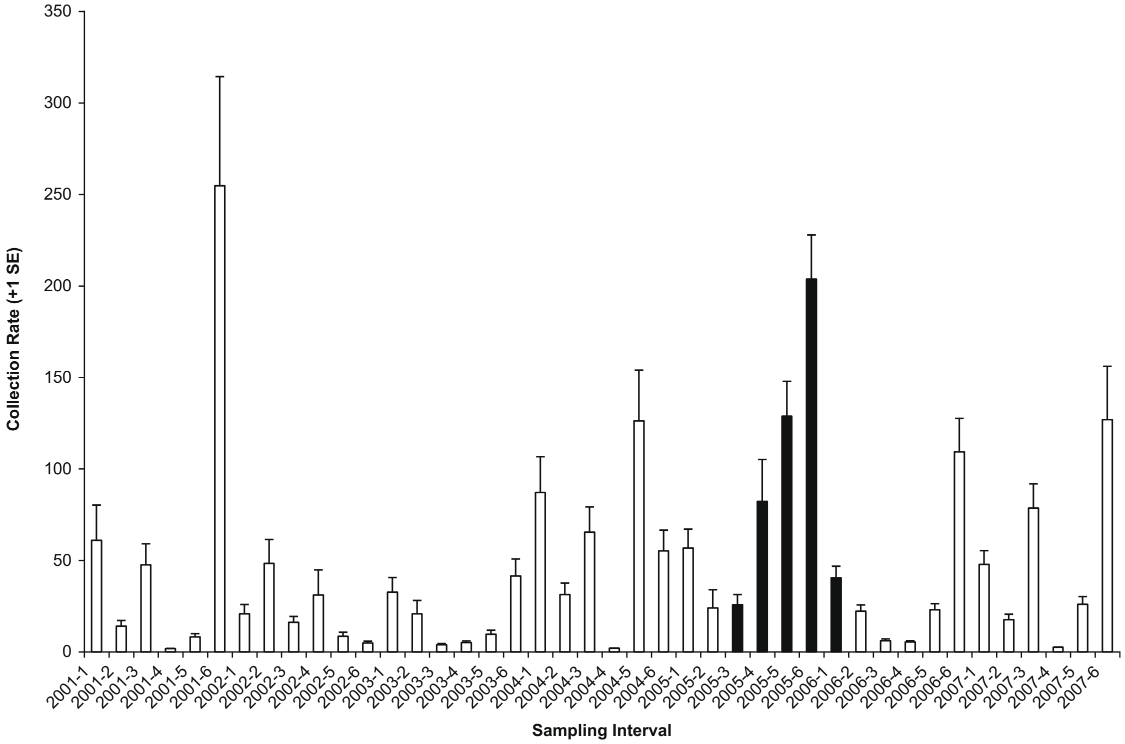

Fig. 3. Mean collection rate (mg/cm^2/day) for each sampling interval (pooling all sites). Black bars indicate during-construction intervals.

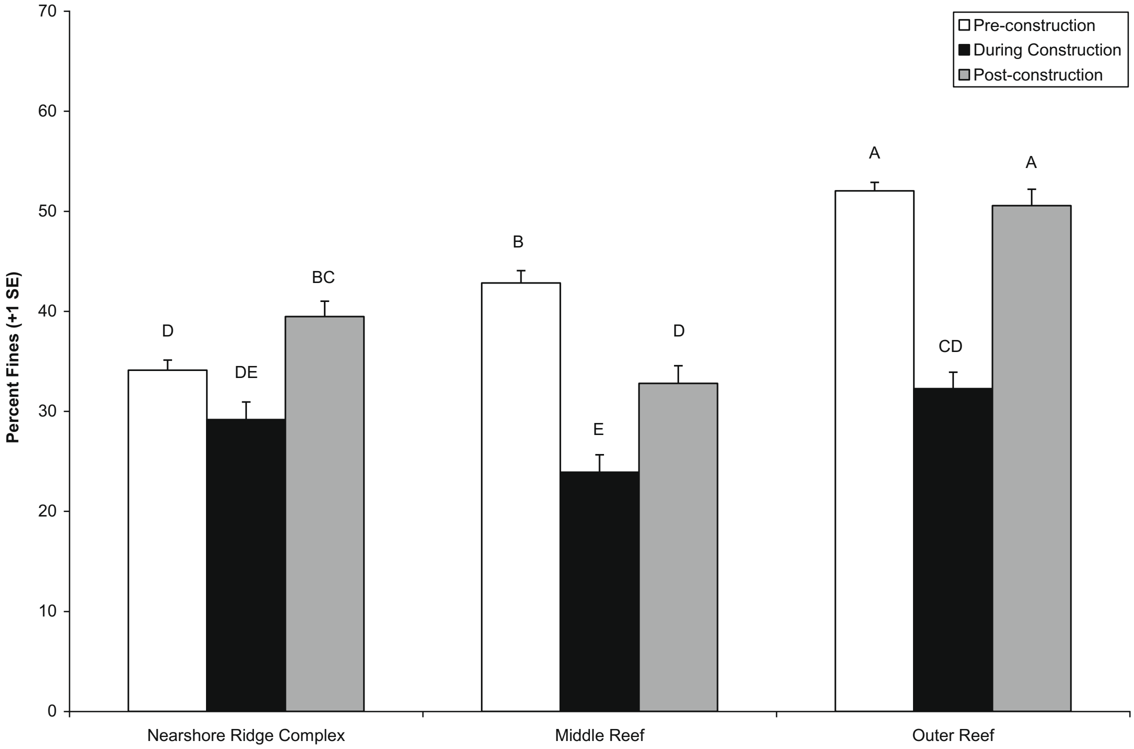

Fig. 4. Comparison of percent fines (< 0.063 mm) for pre-, during-, and post-construction times. All sampling interval 2 data was excluded due to the lack of representation for the during-construction period. Different letters indicate significant difference ($p < 0.05$; Tukey HSD).

4. Discussion

4.1. Spatial and temporal sedimentation patterns

Studies examining sedimentation using near-bottom sediment traps have shown collection rates primarily reflect bedload resuspension (Kozerski, 1994). Spatio-temporal patterns in collection rates, percent fines, and mean grain size on coral reefs in this study correlated well with several physical and geomorphological factors. Depth explained most of the collection rate variability among sampling stations throughout the study area. The deeper OR stations exhibited the lowest collection rates, with NRC stations

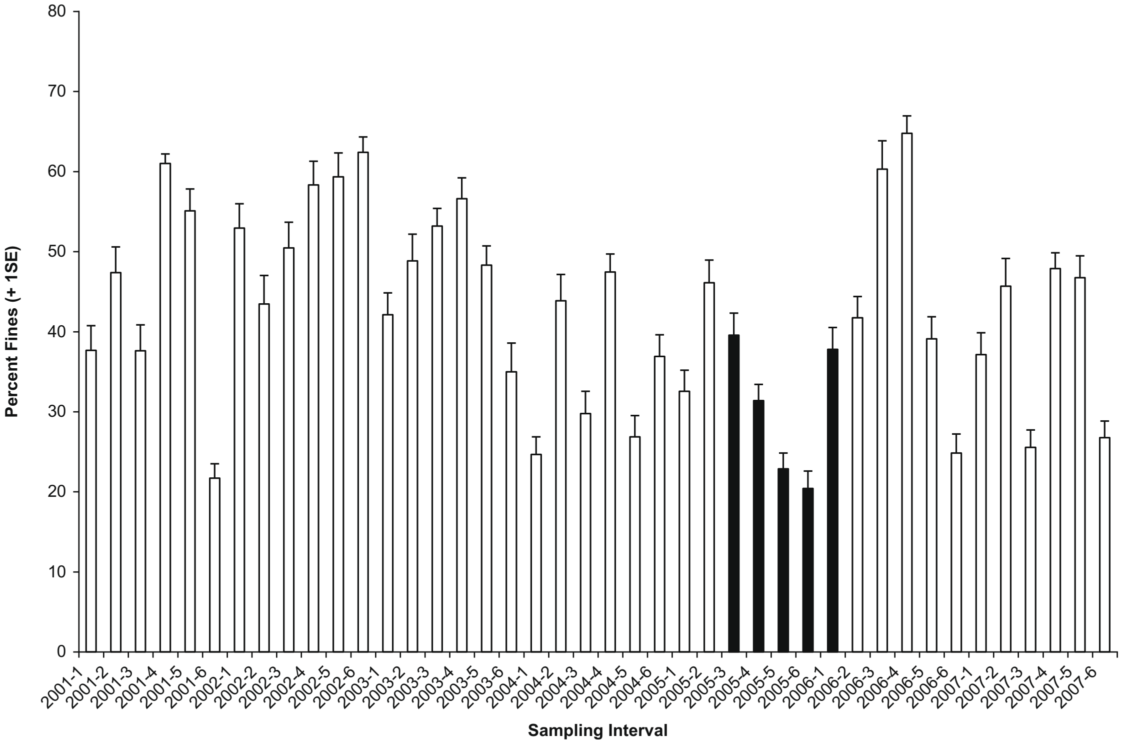

Fig. 5. Mean percent fines (< 0.063 mm) for each sampling interval (pooling all sites). Black bars indicate during-construction intervals.

averaging 14-times higher collection rates. The results for percent fines were the inverse, with increasing values as station depth increased. Due to the seaward-deepening reef profile of the southeast Florida reef tract (Banks et al., 2007; Walker et al., 2008), depth and distance from shore showed a strong linear relationship. As a result, the collection rate and percent fines patterns observed for depth mirrored those for distance from shore.

Wave orbital velocities have been shown as the primary cause for resuspension of bottom sediments (You, 2005). As depth increases, wave orbital velocities decrease, and thus, collection rate would be expected to decrease. Distance from shore is interrelated to this in southeast Florida since the shelf slopes seaward. Another factor related to distance from shore was the discharge of terrigenous sediments at tidal inlets. The lack of correlation between sedimentation parameters and distance from inlets in this study suggested that inlet discharge was not an influential factor. The seaward fining of sediments collected in this study reflected decreasing wave energy with depth.

Distance from shore has been shown to correlate strongly with sedimentation parameters. Turbidity levels (measured by light attenuation) in the central Great Barrier Reef lagoon ranged between 6 and 20 times higher at coastal sites compared to midshelf sites (Anthony, 2006). In contrast, Cooper et al. (2007) showed that percentage of fine sediments decreased with increasing distance from the coast, explaining 34% of the variance among sites. These results contradict those from our study, in which the highest percent fines values were present at the offshore stations. However, the findings of Cooper et al. (2007) reflected a difference in scale between the studies. Their inshore sites ranged from 10–20 km from shore; with offshore sites >20 km from the coast. Since our monitoring stations were located within 3 km of the coastline, our results better depicted local spatial sedimentation patterns, as opposed to the regional patterns observed in the previous study. Additionally, the discrepancy in results may also be explained by the close proximity of their study sites to rivers (and the influence of the terrestrial runoff). Nugues and Roberts (2003) found significant differences in sedimentation rate and percent fines (particles < 125 μm in their study) among sites at varying distances from river mouths. In southeast Florida, man-made inlets discharge freshwater much like natural riverine systems. Distance from the nearest inlet showed no effect on any sediment parameter measured. The shoreward decrease of the percent fines fraction found in our study suggests less resuspension occurs on OR stations, with offshore sedimentation being more indicative of downward sediment flux.

The relationships between both depth and distance from shore with collection rate remained strong when analyzing NRC and MR stations individually. This fact, in addition to the lack of a significant correlation for the OR stations, implied that the differences in sedimentation parameters seen throughout the study area (among stations) mainly reflected nearshore sediment resuspension. Resuspension of sediments correlates with wind and wave-induced bottom stress. Turbulent processes in near-surface water can cause benthic resuspension as wind velocity reaches ≈4–5 m/s (Kullenberg, 1976; Therriault et al., 1978; Gabrielson and Lukatelich, 1985). Temporal fluctuations in sediment collection rates strongly correlated with wind speed. Higher collection rates occurred during relatively windy sampling intervals and during times of meteorological events (hurricanes, tropical storms, cold fronts, etc.). Wind speed (due to its ability to generate bottom shear stress) may provide a reliable metric in which to predict short-term turbidity spikes. Orpin et al. (2004) found that 67% of the turbidity variance was explained by regional wind speed (which best reflected the long-fetch, southeasterly, Austral Trade winds causing the swell waves that resuspended sediments). During-storm, wave-induced, bottom stress also showed a high correlation with collection rate in a fringing reef environment in Hawaii (Bothner et al., 2006).

The highest collection rate recorded for a sampling interval in our study occurred during a time period that included several episodes of strong, sustained, northeasterly winds. However, high collection rates were also recorded for sampling intervals when hurricanes were in the vicinity. Although wind speed strongly correlated with collection rate ($r^2 = 0.6838$), wind direction appeared to play a pivotal role in the relationship between wind (and wave propagation) and sediment resuspension. In southeast Florida, the continental land mass buffers nearshore waters from westerly winds by dampening the fetch required to generate onshore waves. Therefore, easterly winds would have the greatest effect on wave building. As waves break on beaches they can churn nearshore benthic sediments and erode beaches, causing resuspension (Wanless and Maier, 2007). Additionally, if northerly winds met the north-flowing Florida Current, swell could be produced which could propagate shoreward. Such swell can cause larger waves to crash on beaches and may also induce near-bottom oscillatory currents at greater depths, further contributing to sediment resuspension (Larcombe et al., 2001).

4.2. Effects of beach nourishment on sedimentation

Assessment of the effects of large-scale beach nourishment (dredge and fill) projects has proven to be a problematic task (Peterson and Bishop, 2005). With such projects becoming more frequent and due to the known effects of siltation, burial, and disruption of normal granulometric parameters on benthic and infaunal organisms, an understanding of potential effects has become vital to proper resource management. Differences in collection rate and percent fines were found when control stations were compared to sampling stations near SBAs during the time of construction activity. The difference occurred only between station types (SBA and control stations) associated with NRC. The 2-fold difference between control and SBA stations seen on the OR sites was not significant but low sample replication may have masked detection of any potential difference, as only one SBA station was present on the OR for analysis. The reason for the difference between control and SBA stations on the NRC was possibly due to a localized increase in siltation as a result of the dredging. During the construction period, dredging occurred nearly every day. Hopper dredging activity created large turbidity plumes in surface waters over the SBAs (authors' per. obs.). In addition, overflowing of dredge hoppers can result in discharge of larger grain size material into the water column. The larger particles settle quickly and would likely be detectable in sediment traps near SBAs. Suspended fine grain-sized sediment requires more time to settle and could be advected away from dredging areas and dispersed by coastal currents. These two factors could explain the generally higher collection rate (lower percent fines) and larger grain size in the sediment traps adjacent to SBA for all three reef categories. However, since sediment traps mostly represented near-bottom resuspension, data may only explain changes in resuspension after the particles suspended by the dredge settled to the seafloor. The lower percent fines values at SBA stations relative to control stations implied a change to the granulometry as a result of dredging. Smaller particles can be resuspended using less energy than that needed to resuspend larger particles. However, due to the effects of porosity and shape, particle size may not represent a reliable indicator of effective size and the energy required for resuspension (Wanless and Maier, 2007).

Data from control stations revealed higher collection rates for certain during-construction sampling intervals. Construction spanned over 8 months (5 sampling intervals). Several major hurricanes directly influenced the study site during that time period. Four of five during-construction sampling intervals exhibited mean collection rates and percent fines that appeared to fall within the normal range of values seen for corresponding sampling intervals from previous years. However, the elevated collection rates and low percent fines values were sustained for a longer period of time than observed in the four years prior to nourishment. Exposure to high-sedimentation levels (through resuspension) during storms events is likely to be short-term in duration (days vs. weeks or months). Stresses caused by the short-term (days), elevated sedimentation levels as a result of storms and other wind events may continue beyond normal time durations if superimposed human-induced sedimentation levels persist. Several studies have shown the importance of prolonged sediment disturbance on corals (Vargas-Angel et al., 2006; Anthony and Fabricius, 2000; Marszalek, 1981). Thus, time duration of high-sedimentation events will likely determine the severity of the physiological and ecological stress placed upon coral reefs. The stresses on reefs exposed to high levels of sedimentation due to natural causes may be exacerbated by anthropogenic sedimentation increases (Orpin et al., 2004). The collection rate for the during-construction sampling interval that normally exhibited the lowest values (Interval 4; Jul-Aug) was 2.6 times greater than the next-highest corresponding interval (pre-construction). This implied that the construction effect was not limited to dredging. We suspect that resuspension of beach sand during a period of elevated, easterly wind speeds likely caused a widespread effect.

Wanless and Maier (2007) found that grain size and composition of sediments from SBAs substantially differed from beach sands sampled in Broward County, Florida prior to the most recent nourishment project. Sediment collected from SBAs used for the beach fill exhibited a different grain size range, composition, and lower durability (the latter based on rock tumbler tests). Thus, they suggested that the nourished beaches' sand grains may break down faster than sand with a higher quartz composition, as found in sand collected from beaches prior to nourishment. As the offshore sediments break down they may become easier to resuspend. This may, in part, explain the overall during-construction increase seen in our study.

The timing of construction coincided with a period of above-normal wind conditions (due to storm activity). Sediment traps measured resuspension over a given time period (60 days) but, because rates were calculated to reflect per-day collection, they could not accurately account for the short-term elevations caused by strong wind events. Construction activity occurred nearly every day, usually as an around-the-clock operation. While SBAs usage was rotated throughout the duration of the project, sampling stations located in close proximity to dredging (experimental SBA treatment group) generally showed elevated collection rates relative to controls stations. Because of the continuous nature of the construction activity we suggest that the higher collection rates at stations in close proximity to SBAs were likely caused by a relatively sustained disturbance compared to the short-term, yet severe, natural disturbances which caused elevated collection rates seen throughout the study duration. In addition, any effect on collection rate caused by the beach fill portion of the project (i.e., placement of sands on beaches) would have likely exhibited a sustained effect. Connell (1997) suggested that coral recovery from acute short-term disturbances (such as storms) might occur at a faster rate and more completely than from a chronic, lower-level, disturbance. Miller et al. (2002) suggested that an attempt should be made to align the timing of known anthropogenic stress with times when natural increases occur. Had it not been for an exception to the State of Florida's mandate prohibiting coastal construction during sea turtle nesting, the impact of the nourishment may have occurred during a different time of year. Thus, the timing of the naturally elevated collection rates and the construction-related elevation could have occurred successively, rather than concurrently (the latter representing a shorter time frame). Such a long period of increased collection rates resulting from successive periods of elevated sedimentation may not have allowed for a recuperative time period, thereby compromising the resilience of the ecosystem.

5. Conclusions

The results of this study indicated several environmental variables (depth, distance from shore, elevation above nearest sand habitat) correlate with the among-station spatial variability in sediment collected in benthic sediment traps. Temporal variability correlated with wind velocity and direction. Nourishment activities showed a localized effect on the sediment regime. Sampling stations within close proximity to dredging in sand borrow areas exhibited higher collection rates and lower percent fines when compared to control stations. Due to the high degree of seasonal and inter-annual variability in the sedimentation parameters measured in this study, detecting a change in the overall sediment regime as a result of beach nourishment activities (offshore dredging and beach fill) proved difficult. Nonetheless, the sampling interval typically associated with the lowest collection rates exhibited substantially greater rates (2.5 times) during construction than corresponding pre-construction intervals.

Acknowledgements

The authors would like to thank: Vanessa Brinkhuis, Allison Brownlee, Brian Buskirk, Liz Goergen, Lindsey Klink, Jenna Lueg, Melissa Sathe, Nicole Stevens and the staff from the Broward County, Florida Natural Resources Planning and Management Division for their assistance with sediment sample analysis. This study was funded through a contract agreement between Broward County, Florida and Nova Southeastern University. This publication is a result of funding from the National Oceanic and Atmospheric Administration, Center for Sponsored Coastal Ocean Science, under awards NA07NOS4000200 to Nova Southeastern University for the National Coral Reef Institute. This is NCRI contribution #114.

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