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Detecting sedimentation impacts to coral reefs resulting from dredging the Port of Miami, Florida USA

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The federal channel at Port of Miami, Florida, USA, was dredged between late 2013 and early 2015, to widen and deepen the channel. While the precise effects of the dredging on surrounding coral reefs are not well quantified, previously published remote sensing analyses, as well as agency and anecdotal reports suggest the most severe and largest area of sedimentation occurred on a coral reef feature referred to as the Inner Reef, particularly in the sector north of the channel. A regional warm-water mass bleaching event followed by a coral disease outbreak during this same time frame confounded the assessment of dredging-related impacts to coral reefs adjacent to the federal channel. In-water field assessments conducted after the completion of dredging and a time series analysis of tagged corals photographed pre-, during, and post-dredging, are used to discern dredging-related sedimentation impacts for the Inner Reef north. Results indicate increased sediment accumulation, severe in certain times and places, and an associated biological response, including significantly greater proportion of live coral tissue loss, occurred within coral reef sites located closer to the channel. Dredging projects near valuable and sensitive habitats subject to local and global stressors require monitoring methods capable of discerning non-dredging related impacts and adaptive management to ensure predicted and unpredicted project-related impacts are quantified. Anticipated increasing frequency and intensity of warming stress also suggests that manageable- but-unavoidable local stressors such as dredging should be partitioned from the warmest times of year.

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Detecting sedimentation impacts to coral reefs resulting from dredging the Port of Miami, Florida, USA

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Abstract

The federal channel at Port of Miami, Florida, USA, was dredged between late 2013 and early 2015, to widen and deepen the channel. While the precise effects of the dredging on surrounding coral reefs are not well quantified, previously published remote sensing analyses, as well as agency and anecdotal reports suggest the most severe and largest area of sedimentation occurred on a coral reef feature referred to as the Inner Reef, particularly in the sector north of the channel. A regional warm-water mass bleaching event followed by a coral disease outbreak during this same time frame confounded the assessment of dredging-related impacts to coral reefs adjacent to the federal channel. In-water field assessments conducted after the completion of dredging and a time series analysis of tagged corals photographed pre-, during, and post-dredging, are used to discern dredging-related sedimentation impacts for the Inner Reef north. Results indicate increased sediment accumulation, severe in certain times and places, and an associated biological response, including significantly greater proportion of live coral tissue loss, occurred within coral reef sites located closer to the channel. Dredging projects near valuable and sensitive habitats subject to local and global stressors require monitoring methods capable of discerning non-dredging related impacts and adaptive management to ensure predicted and unpredicted project-related impacts are quantified. Anticipated increasing frequency and intensity of warming stress also suggests that manageable- but- unavoidable local stressors such as dredging should be partitioned from the warmest times of year.

Key words: dredging, coral, coral reef, sedimentation, impact assessment, coral disease, monitoring, adaptive management

1.0 Introduction

Numerous examples of dredging projects have resulted in widespread environmental effects on coral reef communities (Bak, 1978; Rogers, 1990; Erftemeijer et al., 2012a). Coastal dredging and port construction exacerbates sediment influx by resuspending benthic sediments (PINAC, 2010) and fine sediments tend to have greater effects on corals compared to coarse sediments (Erftemeijer et al., 2012a). The spatial extent of impacts from dredging can be variable, and in a severe case, impacts have been detected up to 20 km away from the dredging activity when oceanographic features included unidirectional flow during the project (Fisher et al., 2015). Erftemeijer et al. (2012a) note poor understanding of the biological response of corals to sedimentation can result in inappropriate management of dredging projects that may lead to preventable coral mortality or unnecessarily high costs from implementation of no-work windows and delays in dredging operations and provide several examples of dredging operations near coral reefs where inadequate management contributed to significant damage to reefs and mortality of corals. However, establishing realistic and ecologically meaningful sedimentation thresholds, as permit conditions and for use as triggers in an adaptive monitoring and management program, can be a challenge in coral reef environments (Erftemeijer et al., 2012a). To effectively minimize negative impacts on corals and coral reefs, a combination of reactive (feedback) monitoring of water quality and coral health during dredging activities and spill-budget modelling of dredging plumes could be used to guide decisions on when to modify (or even stop) dredging (Erftemeijer et al., 2012a).

The Port of Miami entrance channel traverses coral reefs within the northern portion of the Florida Reef Tract. Six coral reef or hardbottom features characterized by Walker (2009) surround the federal channel at the Port of Miami, and include the nearshore ridge complex, both north and south of the channel, Inner Reef north and south, and Outer Reef north and south (Fig. 1). The Inner Reef north[1] is composed of two reef habitat types, including a Ridge-shallow (western portion) and Linear Reef (eastern portion). The current direction in the outer sections is dominated by the Florida Current with strong north-northeasterly flows and current reversals resulting in less frequent, lower magnitude currents to the south south-west (McArthur, Stametes & Proni, 2006). Eddies associated with the Florida Current can generate currents capable of

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[1] Walker (2009) refers to this coral reef feature as Inner Reef. This portion of the Florida Reef Tract lacks a Middle Reef, and USACE reports often misidentify the Inner Reef as Middle Reef or Reef 2.

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transporting material shoreward. These eddies may be both large and of extended duration, but are infrequent (McArthur et al. 2006).

The purpose of the Port of Miami expansion dredging project was to provide improved navigation and safety for larger vessels, including post-Panamax class ships. An Environmental Impact Statement (EIS) prepared by the Army Corps of Engineers (USACE) concluded the dredging would result in 13,355 m^2 (3.3 acres) of direct impacts (i.e. reef that was ground up and permanently removed) to Outer Reef north and Outer Reef south. The EIS concluded impacts may also include the resuspension and deposition of sediments on nearby coral reef assemblages, but the area of anticipated sedimentation impact was not quantified (USACE, 2004). Nine years later, the Port of Miami entrance channel expansion dredging project was implemented during a 17 month period between November 20, 2013, and March 16, 2015 (Suppl Fig. 1). Additional maintenance dredging also occurred in the inner-harbor and federal channel, prior to and after the expansion dredging. A permit[2] was issued in 2014 to the USACE by the Florida Department of Environmental Protection and included conditions for biological monitoring areas adjacent to the channel along each of six coral reef or hardbottom features (Fig. 1). All monitoring stations were located within 70 m north and south of the channel (channel-side) in addition to reference areas (control sites) located between 1.2 to 9.3 km away from the channel (Fig. 1). Two baseline surveys were conducted in August 2010 (USACE, 2011) and October 23 through December 30, 2013 (USACE, 2014). While the former baseline assessment included sites up to 450 m north of the channel on the Inner Reef north, the baseline surveys from 2013, during-dredging, and post-construction monitoring included only potential impact locations within 70 m from the channel.

Barnes et al. (2015) undertook an independent remote sensing analysis which partitioned natural drivers of sediment plumes in the vicinity of the Port of Miami channel from dredging-associated sediment plumes. They determined that sediment plumes detectable from satellite imagery during the dredging period were of 5x greater extent (127-228 km^2 during dredging compared to 18-46 km^2 under normal conditions) and 23-84% greater frequency than a baseline period prior to the start of dredging. This study also documented the greatest frequency and intensity of dredging-associated sediment plumes over the Inner Reef north reef sector. For this reason, we focused limited post-hoc sediment impact assessment effort in this reef sector,

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[2] Florida Department of Environmental Protection Permit #0305721-001-BI

recognizing that additional reef area was likely impacted in the other sectors, but perhaps with lesser intensity over a smaller extent.

This paper reports results from post-hoc field sampling focused on coral condition and standing sediment on reef substrates. Sampling was conducted at five sedimentation assessment locations within the Inner Reef north reef sector and in the matched reference area, approximately 9 km north of the channel composed of similar reef habitat types, chosen and followed as part of the compliance monitoring program (Fig. 1). In addition, analyses of photographic time series of individual tagged coral colonies within channel-side and reference locations throughout the project provide a Before/After comparison for coral status over the project duration.

2.0 Methods

2.1 Post-hoc field sampling

In December 2015, field sampling was conducted to quantify coral condition and standing sediment on reef substrates at locations spanning increasing distance from the channel in the Inner Reef north reef sector, in addition to the reference location (all 8-10 m depth; Fig. 1; Suppl Fig. 1). These ‘sediment assessment’ locations were spaced at 100, 200, 300, 500 and 700 m from the channel. At each distance except 700 m, transects were evenly distributed in both Ridge-shallow (RR) and Linear Reef (LR) habitat types. At the 700 m distance, only the Linear Reef habitat was assessed due to dive time limitations. The reference location also included transects sampled within both Ridge-shallow and Linear Reef habitat. All the project reference reefs were designated as part of the permit-compliance monitoring and were at least 0.8 km away from the channel (with the Inner Reef North control sites located 9.3 km to the north). This distance was expected to be far enough away to prevent confounding effects from background channel turbidity, sedimentation, and effects from the commercial anchorage. The reference reefs were groundtruthed and verified to be representative of the intended habitat type (USACE, 2010).

Using Google Earth Pro, specific dive sites for each sediment assessment location were randomly selected to be at or near the 100-m interval mark and include a dive site in each habitat type. Exceptions were three dive sites (100-RR, 200-RR, and 300-RR) that were selected to correspond with dive sites surveyed in a pre-construction assessment that was completed in 2010 by the USACE. A temporary marker buoy was deployed from the boat at the pre-determined coordinates. At each dive site, two 50-m long transects were run in opposite directions from the buoy and sampled at 1.0-m intervals (50 point samples per transect, two transects per site). Observers recorded the occurrence of standing sediment along the line-intercept transects, where present, in two categories. 'Sediment-over-hardbottom' (SOHB) was designated if there was a visible accumulation of sediment. For example, algal turfs normally have some sediment embedded within them, but if the turfs were engulfed by sediment, this would be labelled as SOHB. If the sediment was qualitatively observed to be deeper (estimated >4.0 cm), it was labelled as "deep sediment over hardbottom" (DSOHB). In addition, at every 5.0 m along the transect, the depth of the sediment (cm) over hardbottom was measured with a ruler and the deepest of several measurements within one meter of the sample point was recorded.

Six 10 m^2 belt transects were also sampled along or parallel (within 10 m distance from) the two line-intercept transects at each dive site to quantify the condition of coral colonies within each area. Each scleractinian colony was recorded by species and condition; namely if the coral displayed recent partial mortality (i.e., minimally encrusted skeleton in which individual calyces were still discernable, Lirman et al., 2014), sediment present on live coral tissue (sediment accumulation), active disease (distinct white skeleton progressing across the colony), bleaching, "halo" mortality, or healthy if there was no noticeable signs of stress present. A "halo" refers to a pattern of partial colony mortality in which a concentric ring of dead coral skeleton occurs at the base of the coral colony as results from prior burial of the colony edges (Suppl Fig. 2A-C).

One-way ANOVAs followed by post-hoc tests between the assessment and reference locations were used to determine statistically significant differences in each survey parameter. For each of six parameters, (% cover SOHB, % cover DSOHB, sediment depth, and prevalences of recent partial mortality, 'halo' partial mortality, and sediment accumulation), preliminary one-way ANOVAs (on ranks, due to violation of parametric assumptions) showed no significant differences between the two habitat types (p-values ranging from 0.134 to 0.975 among the six parameters). Thus, transects of both habitat types were pooled at each location (i.e. distance from channel or reference) to increase replication and power to detect differences among the locations via one-way ANOVAs (on ranks when parametric assumptions were violated).

2.2 Before/After analysis of coral status, qualitative and quantitative

Time series photographs of tagged coral colonies were obtained from the USACE. The colonies were tagged along each of six, 20 m transects at the channel-side and the reference (~ 9.3 km north; Fig. 1) locations which had been designated in the permit monitoring. The six transects in each location were evenly distributed among the Ridge-shallow and Linear Reef habitat types. The colonies tagged at each location were of mixed species composition according to what was present, but included *Porites astreoides, Solenastrea bournoni, Pseudodiploria strigosa, Stephanocoenia intersepta, Meandrina meandrites, Siderastrea siderea,* and *Dichocoenia stokesii*. Photographs were taken at irregular intervals between a four week pre-construction phase[3] (October - November 2013) and a four week post-construction phase (July 2015), with greater frequency of images during periods of time when dredging was active in close proximity (< 750 m) to the monitoring site.

The time series of each colony was examined and the temporal sequence of conditions affecting each colony was noted. Specifically, the presence of sediment accumulation on live tissue, partial sediment burial generally of colony edges, complete colony burial by sediment, the presence of active White Plague disease signs (i.e. bright white exposed skeleton along colony margins, generally with a scalloped shape, grading into gradually more encrusted, longer dead, skeleton), and 'sudden death' (the complete mortality of a colony between sequential photos in the time series, presumably attributable to disease, though no active disease signs were observable) were recorded in sequence. The potential effect of sediment stress on disease susceptibility was examined by estimating the risk of subsequent disease in a group of colonies which had previously experienced partial sediment burial compared to the remaining colonies which had not shown partial burial.

From this same set of time-series photographs, the live tissue area was quantified from the best-matched photo (angle and orientation) of each colony from the pre-construction and from the post-construction phase (generally four weekly photos in each phase) using the software

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[3] A portion of the pre-construction phase overlapped the onset of expansion dredging (Suppl Fig 1)

CPCe (Kohler & Gill, 2006). Each photograph was calibrated using a scale bar with 5-cm increments included in each image, and then the area (cm^2) was calculated by outlining the live tissue area for each colony. Proportional change in live tissue area was calculated for each colony (i.e. (post-pre) / pre)). Colonies which went missing prior to the post-construction phase were excluded from this analysis. The colonies from the two habitat types in each location were pooled and the change in colony area between locations was compared by a Mann-Whitney U-test.

3.0 Results

3.1 Post-hoc field sampling

The mean percent cover of reef substrate characterized as “sediment over hardbottom” (SOHB) and “deep sediment over hardbottom” (DSOHB) was higher along the Inner Reef north transects (incorporating both Ridge-shallow and Linear Reef habitat), than the reference location transects (within the same habitat strata; Fig. 2A). The mean percent cover of SOHB was 17.5 to 36.0x higher at Inner Reef north locations, when compared to reference location (Fig. 2A), representing significant differences between each Inner Reef north location and the reference (One- way ANOVA $p=0.002$ followed by post-hoc Holm-Sidak comparisons of each location with the reference at $p<0.05$). At the reference location, 1% of the survey points exhibited reef substrate characterized as SOHB. The mean percent cover of DSOHB showed significant variation among sampled locations (one-way ANOVA on ranks, $p=0.045$), ranging from 0.8 to 10.8% at distances 100, 200, 500, and 700 m from the channel (Fig. 2A), compared to no DSOHB recorded at the reference location nor the location 300 m north of the channel. However, statistical power was not adequate to discern significant differences among locations.

The mean depth of sediment was significantly higher, ranging from 2.7 to 10.0x higher, at Inner Reef north locations (Fig. 2B), compared to that measured at the reference location (one-way ANOVA on ranks $p=0.001$ followed by Dunn’s post-hoc comparisons with controls). Specifically along the transects located 200 m north of the channel, the mean sediment depth was 3.0 cm, compared to 0.3 cm at the reference location (Fig. 2B-D)

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There was up to a 3.1 to 5.1x increase in the prevalence of corals with recent partial mortality at sediment assessment locations when compared to reference (Fig. 3; One-way ANOVA on ranks p=0.009). Specifically, the 100, 300, and 700 m locations were significantly different than the reference (Dunns' post-hoc comparisons with control, p<0.05). The occurrence of sediment accumulation (SA) on live coral tissue ranged from 4.8 to 21.3x higher at sedimentation assessment locations when compared to the reference location with the 100 m and 200 m locations being statistically higher (SA; One-Way ANOVA on ranks p=0.002 followed by Dunn's post-hoc comparisons with control; Fig. 3). Sediment halos (mortality at the base of colonies due to elevated levels of sedimentation) on scleractinian corals ranged from 3 to 26x more frequent at sedimentation assessment locations when compared to the reference location with the 200 m and 300 m locations being significantly higher (Fig. 3; One-Way ANOVA on ranks p=0.011 followed by Dunn's post-hoc comparisons with control).

3.2 Before/After analysis of coral status

When the sequence of sediment and disease-related conditions are examined across all colonies, only minor sediment presence (e.g., Fig. 4-B) was observed on coral tissues (12 of 52 channel-side and 4 of 58 reference colonies) prior to June 2014. Major sediment accumulation including complete burial and several centimeter sediment berm (seemingly from colony expulsion of sediments, Fig. 4-D) and the subsequent burial of colony edges was observed starting in early June 2014 (half of channel-side colonies compared to 1 of 58 reference colonies; Suppl Fig. 1). Bleaching was observed primarily in August - November 2014 (Fig. 4-G; Suppl Fig. 1) with most of the colonies recovering (Fig. 4-H). Most colonies of *Porites astreoides,* which occurred only at the reference reef, also were bleached in July 2015 at the end of the time series. The predominance of active disease signs and of presumed disease mortality ('sudden death' or complete colony mortality occurring between two time points, Fig. 4-H to I) among channel-side colonies occurred between late November 2014 and late February 2015. However, most disease (including 'sudden death') among reference reef colonies occurred later (February-July 2015; Suppl Fig. 1).

Six channel-side colonies (11.5%) displayed complete or almost complete colony mortality directly associated with sediment burial (i.e. directly following in time and tissue regression over similar footprint as previously buried, Suppl Fig. 4). Although one reference colony appeared to experience some degree of partial sediment burial of its edges, it manifested only modest partial mortality (Suppl Fig. 4C). The occurrence of disease (including 'sudden death') for reference colonies was less than half that observed for channel-side colonies (Table 1), although disease occurence was similar between channel-side colonies that were observed with substantive partial burial (38%) versus those that were not (34%).

The tagged colonies at the channel-side location (n=55), without regard to particular conditions or attributions of coral loss, showed over 4x greater tissue loss on average than the reference colonies (n=58, Fig. 5). This includes 17/55 (31%) channel-side colonies versus 6/58 (10%) reference colonies which suffered complete colony mortality. Meanwhile, 48% of reference colonies displayed positive growth over the course of the project, compared with only 18% of channel-side colonies.

4.0 Discussion

A severe warm thermal stress (Eakin et al., 2016; Manzello, 2015) and coral bleaching event affected south Florida coral reefs beginning in autumn 2014 (Margaret W. Miller, pers. comm. 2014, also documented in regional bleaching surveys as 30-55% prevalence of bleaching in the sub-regions spanning Miami-Dade and Broward county; data available from Florida Reef Resilience Program at http://frrp.org/temp/JCDM3VBD/CoralDiseaseBySubregion.html; Suppl Fig. 1). As often occurs (Muller et al., 2008; Miller et al., 2009), the coral bleaching event was followed by severe but patchy coral disease and mortality outbreaks which were reported anecdotally throughout the region starting in winter 2014-2015 (Suppl Fig. 1). Both bleaching and disease are documented in the time series observations of corals in both the channel-side and reference populations (Fig 4 and Suppl Fig. 4C). Despite these confounding disturbances throughout the south Florida region, analysis of tagged coral colony condition during the course of the dredging project shows significant and large effects in terms of more severe coral tissue loss (almost 5x) and increased risk of disease (> double) in the immediate vicinity of the dredged channel, in comparison with project-chosen reference reefs. The permit-mandated monitoring plan did not, however, incorporate spatial coverage of potentially impacted reef areas further than 70 m from the channel that would aid in determining the spatial extent of impact. We implemented the post-hoc sampling (i.e. ~ 8 mos after dredging was completed) to partially address this gap. Although the determination of causes of coral mortality or partial mortality is always problematic, we compared the prevalence of several coral conditions and the persistent levels of standing sediment on reef substrates at a gradient of potential impact locations with the reference location to aid in delineation of the extent of sedimentation impact.

This post-hoc survey showed substantial differences between the gradient of assessment locations with the reference location in terms of standing sediment and coral condition. Using the most objective measures such as sediment depth (almost 10x at the 200 m location) and prevalence of recent partial mortality (~ double across all assessment locations), significant contrast is evident with the reference location. This pattern is consistent with our survey results on potentially less-objective or ephemeral parameters such as the attribution of partial mortality patterns as ‘halos’ or the presence of sediment on live coral tissue. Unfortunately, there are no directly comparable baseline data for these parameters. Baseline sampling at a gradient of sites out to 450 m in the Inner Reef north sector, conducted by USACE in 2010, indicated that the overall prevalence of partial mortality (not specified whether recent or not) was 3.1% and showed no significant relationship with distance from the channel (USACE, 2011). Our survey results record evidence of the severe impacts of regional coral stressors such as thermal stress and disease (i.e. prevalence of recent partial mortality for reference area corals was 7x higher at 21±3.5 %, mean ± 1 SE than the 2010 baseline assessment); however the locations in the vicinity of the channel (up to 700 m distant) had values double those at the reference location (44± 3.4%, mean ±1SE). This is consistent with the results of Pollock et al., (2014) showing that extended exposure to dredging project-related sediment plumes was a significant driver of increased disease and other compromised conditions of reef corals.

While sediment movement and deposition is a normal process in a coral reef ecosystem, offshore coral reefs are not capable of developing or sustaining ecological functions when covered by sediment over prolonged periods or when the depth of sediment is centimeters or greater. The presence of deep sediment pockets within patchy reef habitats may also be a normal reef habitat feature. However, the presence of emergent sessile invertebrates (particularly soft corals, but also hard corals and sponges, Fig. 2C-D, Suppl Fig. 2) in much of the area of observed deep sediment in our post-hoc surveys clearly indicated recent, extreme levels of deposition and implies that additional, uncountable scleractinian corals have been buried in these areas. The measured sediment depths at four of the five sediment assessment locations exceeded what would result from threshold deposition rates identified by Nelson et al., (2016) as 'severe stress resulting in coral mortality' (i.e., 25 mg cm^{-2} d^{-1} over any 30 day window; Suppl Fig. 3). This is confirmed by sedimentation data from USACE (2015b) during the major sediment accumulation event and associated burial of colony edges observed in early June 2014 in the before/after photo analysis at the channel-side location. The measured sedimentation rate during this 30-day sediment trap deployment was 78.9 mg cm^{-2} d^{-1}, which is 3x the minimum threshold for Nelson et al.'s (2016) red stop light indicator, compared to 6.6 mg cm^{-2} d^{-1} at the reference location (within the range for the green stop light indicator or 'negligible or minimal impacts').

Although our replication was not adequate to analyze habitat effects, the post-hoc survey results are suggestive of differences in the severity of sedimentation impact between the habitat types. Most survey locations in the vicinity of the channel showed a trend for higher sediment cover and depth in the Linear Reef than the Ridge-shallow habitat (Suppl Table 1). The Linear Reef habitat 200 m north of the channel appears to have been the most severely impacted as this location had the highest cover (43%) characterized as DSOHB (4.0 centimeters or greater sediment over reef ; Suppl Table 1), the highest measured maximum sediment depth (10.0 cm), and the highest prevalence of sediment halo (Suppl Table 1). It is possible the prevalences of recent mortality and sediment accumulation at this site are underrepresented, when compared to other sites, because many low-lying scleractinian colonies have been completely buried.

Sedimentation on reefs can reduce coral recruitment, survival, and settlement of coral larvae (Erftemeijer et al., 2012b) and suppress colony growth (Bak, 1978). Our study focused on the reef sector which experienced the greatest duration of sediment plumes during the dredging project and relies heavily on the representativeness of the reference reef. This reference area was chosen to provide a representative comparison, comprising similar reef habitats, prior to initiation of dredging. Coral disease impacts can be very site specific (e.g., Miller et al., 2014), so a more spatially comprehensive analysis of coral disease effects both in potential impact areas and regionally would be beneficial. However, the increased prevalence of indicators of sedimentation stress and partial mortality, as well as persistent standing sediment on reef substrates at the Port of Miami sedimentation assessment areas (Fig. 2,3), all suggest the cumulative sedimentation was much greater across the impact assessment sites, when compared to the reference area, and mortality and loss of function of reef organisms resulted. When considering the findings of this study coupled with the findings of Barnes et al., (2015), sediment plumes and deposition from dredging activities at Port of Miami are the most plausible drivers for this pattern.

The implementation of seasonal shutdowns for dredging projects near coral reefs has largely been based on protecting corals during major spawning events. Unfavorable conditions during a coral spawning period could negate the entire reproductive output for the year (Harrison et al., 1984). Conducting dredging activities at appropriate times to avoid spawning periods would constitute a best management practice (Jones et al., 2015). Recommendations for reduced or halted dredging range from one week based on the known coral spawning period in Singapore (Ertemeijer et al., 2012b) to as many as five months per year based on known spawning periods in northern Western Australia (Baird et al., 2011). This best management practice could provide enhanced protection if shutdowns were also to coincide with increasingly predictable seasonal thermal stress events (van Hooidonk et al., 2014; Manzello, 2015), in addition to feedback monitoring. In Florida (USA) this practice has not been well-socialized in the regulatory context with the exception of the Key West Harbor Dredging Project, where the contract provided for limited relocation of the dredge when coral health and sediment accumulation levels exceeded allowable thresholds (U.S. Navy, 2003).

Another port expansion at Port Everglades, located approximately 37 km north of Port of Miami, is on the horizon for southeast Florida. The construction plans at Port Everglades are similar in scale with USACE proposing to remove 5.5 million cubic yards of material. However, recent thermal stress and disease impacts have rendered the baseline reef condition as further impaired and less able to tolerate increments of ‘standard’ sedimentation stress associated with dredging activities in the past (e.g. Marzalek, 1982). The proposed Port Everglades monitoring plan is similar to that used for Port of Miami (USACE, 2015a), though expected to be modified to capture lessons learned in Miami. Notable improvements to the monitoring plan would include monitoring standing sediment depth, sediment-associated stressors (e.g., coral halo), near-realtime information feedback on monitoring outcomes, observations from other parties, regional warm-water and coral disease events, and status/extent of sediment plumes via remote sensing (e.g., Barnes et al., 2015) to have a better understanding of normal/historic plume conditions. Time series analysis of permanently marked corals could be used in concert with the sediment depth measurements, such as sediment deposition threshold criteria to classify sediment impacts to reef habitats based on threshold values in peer-reviewed studies and new modelling approaches as described in Nelson et al. (2016), to provide an early predictor of when and where sedimentation impacts are occurring to adaptively manage the dredging. Inclusion of this type of monitoring could help in the development of no-work windows, including when regional thermal events are ongoing. Even if no-work windows or seasonal shutdowns are not implemented, monitoring thresholds could still be identified to serve as a warning that coral impacts will exceed what was predicted under normal conditions.

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Table 1: Partitioning of tagged colonies that experienced substantial sediment burial (complete or partial) and subsequent disease (including 'sudden death' which occurred between observations as in Fig. 4I, but presumably attributable to disease). Disease risk is calculated as the percent of colonies in each category which manifest disease.

GROUP	SEDIMENT INTERACTION	SUBSEQUENT DISEASE	DISEASE RISK
Channel-side 52	Yes 26	Yes 10	38%
		No 16	
	No 26	Yes 9	34%
		No 17	
Control 59	Yes 1	Yes 0	0%
		No 1	
	No 58	Yes 9	15%
		No 49	

Figure 1. Left, Port of Miami channel-side, sedimentation assessment, and reference sites for all reef habitat types. Right upper inset, Inner Reef north (red) and Outer Reef north (yellow) reference sites. Right lower inset, Port of Miami channel-side and sedimentation assessment sites for the Inner Reef north. Red boxes are location of channel-side and reference areas for Inner Reef north. Yellow boxes are location of channel-side and reference sites for the Nearshore Ridge Complex, Outer Reef, and Inner Reef south. Dots represent sedimentation assessment dive sites at 100, 200, 300, 500 m north of the channel in the Inner Reef, Ridge-shallow and 100, 200, 300, 500, and 700 m north of the channel in the Inner Reef, Linear Reef. The base layer is from December 2014 (Google Earth Pro) during active dredging close to the Inner Reef north.

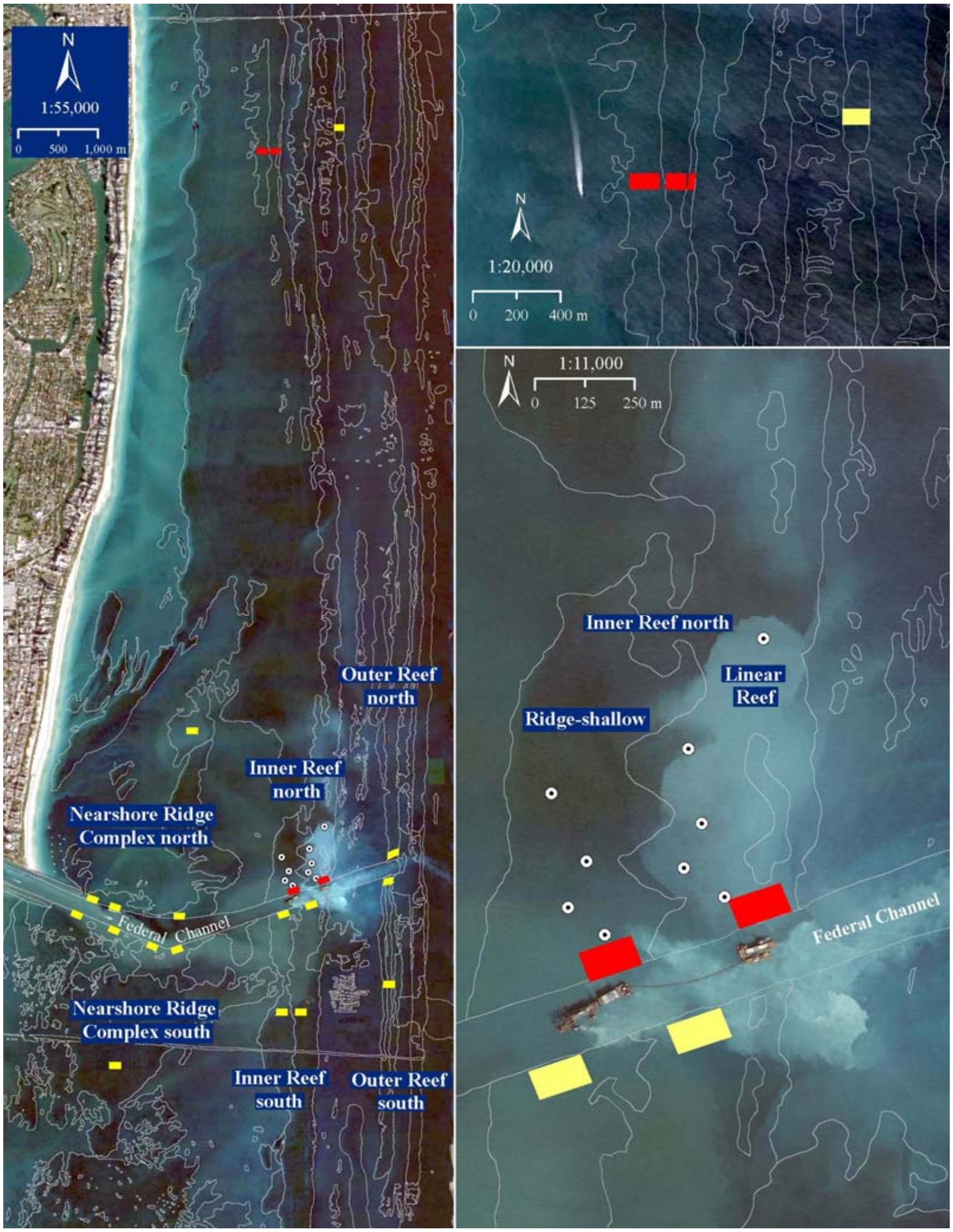


Figure 2: (A) Mean (+1 SE) percent cover of sediment over hardbottom (SOHB) and deep sediment over hardbottom (DSOHB; > 4 cm depth) along line point-intercept transects at sites of increasing distance from the channel and control site. N = 4 transects for each, except 700 m where only two transects were sampled (hence no error bars are given). (B) Mean (+1 SE) depth of sediment at 0.5 m intervals along the same transects. Both RR and LR habitats were sampled at all sites except 700m (HR only). Each of the sediment assessment locations had significantly higher SOHB cover and sediment depth than the reference area in post-hoc comparisons following one-way ANOVAs. (C-D) Illustration of expanse of deep sediment at the 200 m location showing soft corals with several cm burial.

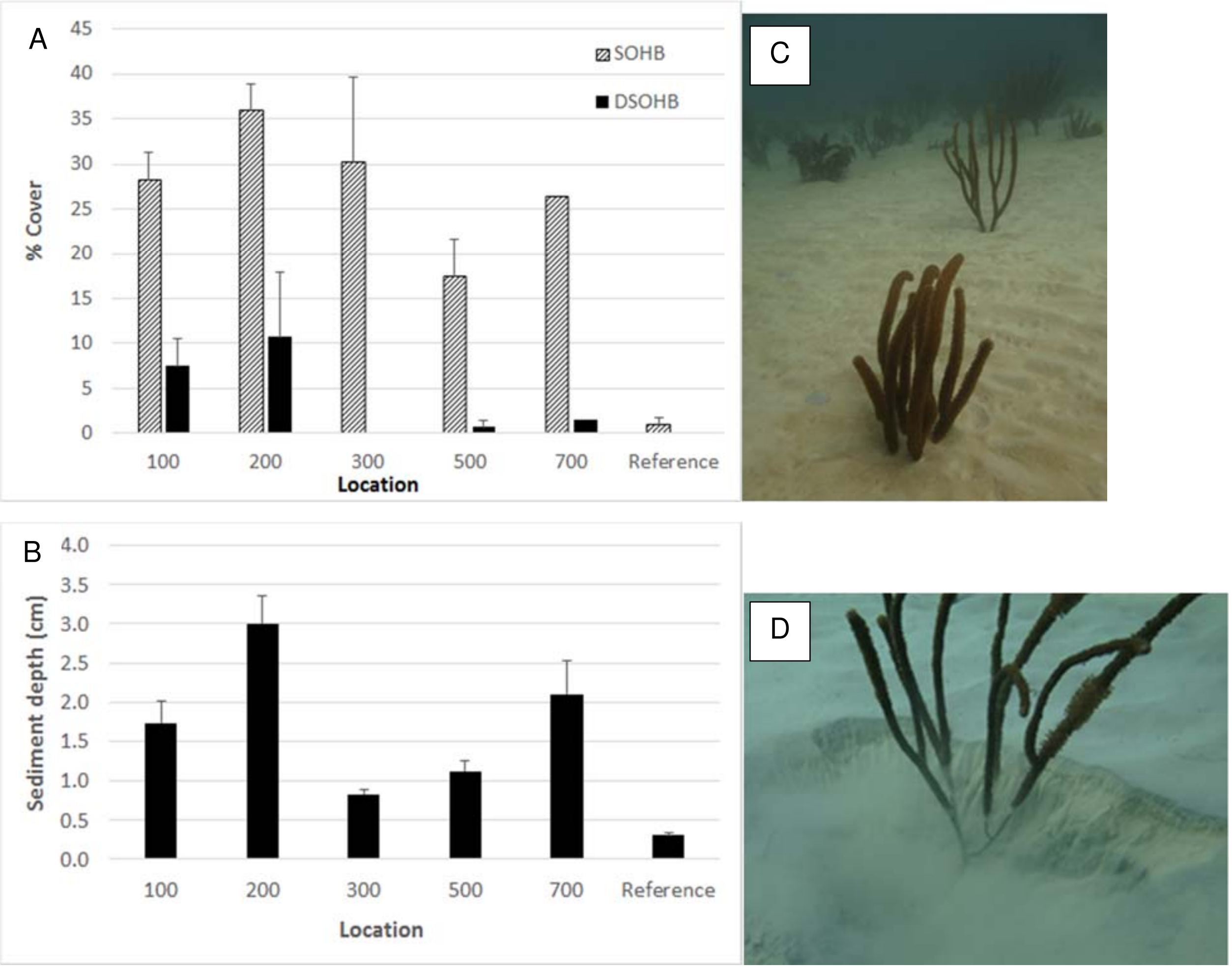


Figure 3: The overall prevalence (mean + 1 SE) of colony conditions at sites spanning a gradient of distance from the dredged channel (100-700 m) and a reference site. Habitat types are pooled (n=12 transects per location) with exception of 700 m site (only Linear Reef habitat sampled, n=6 transects) and 500 m and 300 m (n=13 transects per location, with the one additional transect being in the Linear Reef habitat). Sed Accum = sediment presence on living coral tissue; PmortRecent = recent partial mortality among colonies (Lirman et al. 2014); Halos = distinct pattern of partial mortality (not necessarily recent) in which tissue loss manifests as an outer concentric ring or partial ring which is consistent with that resulting from previous partial burial of the colony (see Suppl Fig 2 for illustration). Ref = Reference location.

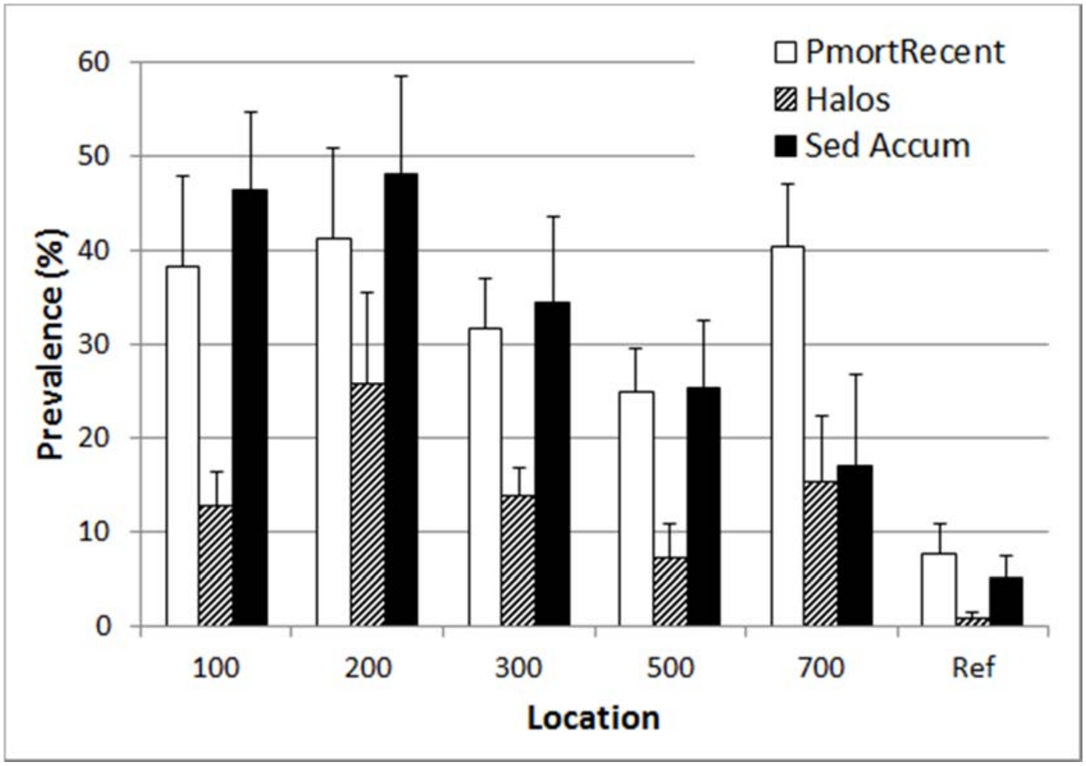
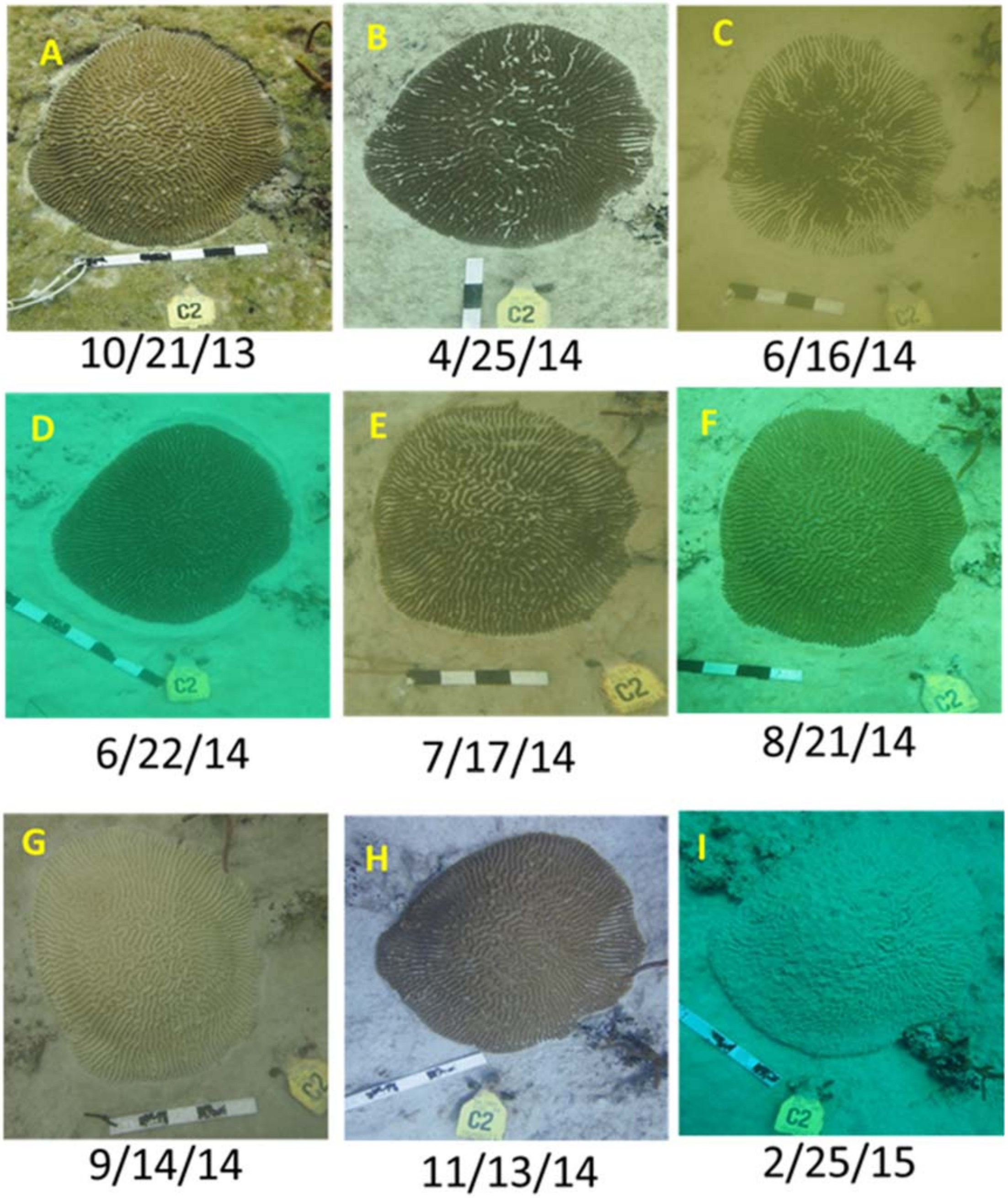


Figure 4 : Intermittent time series photos for a *Pseudodiploria strigosa* colony (designated R2N1 T1 C2) illustrating different conditions including sediment accumulation (B, E), partial burial (C), sediment 'berm' around coral margin (D), bleaching (G), recovery (H), and 'sudden death' (I) presumed due to disease, although no disease signs are evident in the photo record. Also note the degree of standing sediment on the surrounding reef substrate. Dates given as Month/Day/Year. Additional illustrations given in Suppl. Fig. 4.



10/21/13 4/25/14 6/16/14

6/22/14 7/17/14 8/21/14

9/14/14 11/13/14 2/25/15

Figure 5: Proportional change in coral tissue area (mean ± 1 SE) for tagged colonies between the Baseline and Post-Construction period (~18 months). N= 55 or 60 colonies (Channel-side, Reference, respectively). Channel-side colonies lost significantly more tissue.