Examination of Sedimentation Impacts to Coral Reef along the Port Miami Entrance Channel, December 2015 and April 2016

NOAA's National Marine Fisheries Service
August 29, 2023

Executive Summary

In December 2015 and April 2016, NOAA's National Marine Fisheries Service (NMFS) assessed potential damage from dredged sediments to coral reefs adjacent to the Port Miami Entrance Channel. This was an unprecedented evaluation based on concerns brought to us by various partner, regulatory, and action agencies and after reviewing satellite images depicting large sediment plumes over areas of coral reef. Based on our own observations of sediment damage to coral reefs, we were then afforded through NOAA's Coral Reef Conservation Program, the ability to take a closer look at the coral reef. The reefs examined are fishery habitats protected under the Endangered Species Act and the Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act). The surveys focused on locations more distant from the channel than those specified by the State of Florida for assessing permit compliance during dredging. The work conducted during December 2015 examined the Inner Reef North of the channel (findings described in Miller et al. 2016 and NMFS 2016a), and the work completed during April 2016 included the Inner Reef south of the channel. The purpose of the surveys was to further our understanding of the spatial extent and severity of sediment-related impacts resulting from the dredging. The majority of locations examined were not included in previous quantitative assessments by the U.S. Army Corps of Engineers (USACE), its contractors, the Florida Department of Environmental Protection (FDEP), or other groups. Our surveys were limited to areas mapped as reef or hardbottom before the dredging began and focused on determining bottom cover, measuring sediment depth, and recording coral condition related to sediment stress after dredging ceased.

We found bottom cover at sediment assessment locations differed significantly from reference locations. The bottom cover class "sediment over hardbottom" was the primary driver of the variation along the Inner Reef, representing an average of 42% of bottom cover observations at sediment assessment locations, compared to only 7% at reference locations. The mean sediment depth also differed significantly between Inner Reef sediment assessment locations, 1.4 ± 0.1 centimeter (cm), and reference locations, 0.6 ± 0.1 cm. On the Inner Reef, severe impacts to coral reef habitat from sediments occurred over an estimated 278 acres of reef, and lesser impacts likely extended to an even larger area. We view this acreage estimate as conservative for many reasons, including, but not limited to, exclusion from the acreage calculation of the nearby patch reefs, artificial reefs, Outer Reef, and Nearshore Ridge Complex. Combining our results with those from Barnes et al. (2015), Cunning et al. (2019), and data collected from the FDEP-permit required monitoring, in addition to measurements

and observations made by several groups (FDEP 2014; Miami WaterKeeper 2015; DERM 2015) of the same dredging event, it is possible that a much larger acreage of coral reef habitat was damaged by dredge-related sedimentation.

NMFS will use this information to help Port Miami, state and federal agencies, and other stakeholders with planning the Port Miami Phase IV dredging. For Port Miami Phase IV, the Endangered Species Act and Magnuson-Stevens Act require NMFS to forecast impacts relative to an environmental baseline. The environmental baseline must include the past and present impacts of all federal, state, or private actions and other human activities in the action area; the anticipated impacts of all proposed Federal projects in the action area; and the impact of state or private actions that are contemporaneous with the consultation in process. This report helps establish the environmental baseline by enumerating the acres of coral reef affected by the unplanned sedimentation impacts. The report also will guide subsequent surveys needed by the USACE and Port Miami to determine the mitigation needed for Port Miami Phase III and Phase IV.

Contents

1.0 Introduction

Dredging and related activities, such as transportation of dredged materials or pre-treatment of rock, can result in widespread damage to coral colonies and coral reef communities (Bak 1978; Dodge and Vaisnys 1977; Erftemeijer et al. 2012; PIANC 2010; Rogers 1990). Sediment released into the water column during dredging can settle onto the hardbottom, displacing space available for settlement, recruitment, and survival of coral larvae (Erftemeijer et al. 2012). Nelson et al. (2016) found sediment layers greater than 0.5 cm in depth can cause moderate stress in corals, potentially leading to death of some corals and recovery in others, and that sediment layers greater than 1 cm in depth can cause severe stress leading to coral mortality.

Sediment deposition onto the surfaces of stony corals can cause live tissue to suffocate or starve, leading to loss of entire or portions of colonies (Rogers 1990). Stony corals can remove small amounts of sediments accumulating upon their living tissues, most commonly by producing mucus or ciliary action. However, chronic exposure to moderate amounts of sediment or acute exposure to large amounts of sediment can exhaust a coral's ability to clear the sediment, leading to tissue thinning, loss of cilia and mucosecretory cells, and ultimately death (Erftemeijer et al. 2012). Corals that bleach due to thermal stress are less capable of removing sediments from their surface compared to normally pigmented corals (Bessell-Browne et al. 2017). Halo mortality, as described in Miller et al. (2016), is a distinct pattern of partial colony mortality where a ring of dead tissue or exposed skeleton beneath sediment is present around the base of a colony resulting from prior burial of the colony edges. Reliable identifications of partial colony mortality (lesion formation) caused by a recent environmental condition, like sediment accumulation, must be done within days to months after an incident occurs (Lirman et al. 2014). Once the live tissue is lost, the coral skeleton is exposed and subject to erosion, covered by sediment, or overgrown by algae or sponges prohibiting recovery (Kramer 2003).

Dredging occurring over 17 months at Port Miami exposed sections of reef to sedimentation. We examined bottom cover and sediment depth at various distances north and south of the Entrance Channel on the Inner Reef to determine impacts and inform compensatory mitigation to offset impacts.

The Port Miami Entrance Channel traverses coral reef habitat within the northern portion of the Florida Reef Tract[1]. The main coral reef features characterized by Walker and Klug (2014) from east to west include the Outer Reef[2], Inner Reef[3], and Nearshore Ridge Complex[4]. While the Florida Current, with its strong north-northeasterly flows, dominates flows in the outer sections of the tract, the flow environment is complex with current reversals

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[1] Also referred to as the Kristen Jacobs Coral Reef Ecosystem Conservation Area and the entire reef tract is also referred to as Florida's Coral Reef; https://floridascoralreef.org/

[2] Also referred to as Third Reef or Reef 3 in reports prepared by USACE and USACE contractors

[3] Referred to as Middle Reef or Reef 2 in reports prepared by USACE and its contractors

[4] Referred to as Hardbottom in reports prepared by USACE and its contractors

and vortices at various spatial scales capable of transporting suspended material, such as sediment derived from dredging, in complex patterns (Martinez-Pedraja et al. 2004; McArthur et al. 2006).

The purpose of the dredging that occurred between 2013 and 2015 at the Port Miami (referred to as Phase III in federal plans) was to improve navigation and safety for larger vessels, including post-Panamax class ships. An Environmental Impact Statement (EIS) prepared by the USACE concluded the dredging would result in 13,355 square meters (m^2) (3.3 acres) of direct impacts (i.e., reef that would be permanently removed by dredging) to the Outer Reef (USACE 2004). The EIS noted impacts may also result from resuspension and deposition of sediments on nearby coral reef communities, but the EIS did not quantify the area of this sedimentation impact.

Approximately nine years after the EIS was completed, the dredging of the Port Miami Entrance Channel began on November 20, 2013 and continued for 17-months. The dredge operations were deemed complete by USACE on April 8, 2015 (Water & Air 2017). Additional spot dredging occurred until September 17, 2015 (see Appendix: Timeline). A reported 4.4 million cubic meters of material was dredged (Water & Air 2017) using cutterhead-suction, backhoe, and clamshell dredges. The majority of the material was disposed of in a permitted, offshore site 2.4 kilometers (km) east-southeast of the project site in water depths of 120 to 240 meters (m).

Rather than conducting confined underwater blasting prior to dredging to pre-treat hard rock as described in the EIS (e.g., three blasts per day for up to 1,333 days), an alternative method, not considered in the EIS, referred to as “rock chopping” (or “roller chopping”), was implemented to pre-treat the rock. Rock chopping is the practice of using the draghead of the Cutterhead Suction Dredge (CSD) to grind, pulverize, or pound the rock without the suction function engaged. Rock chopping results in the introduction and re-suspension of “rock flour”, the clay-like material that caused the most concern during the Phase III dredging (Water & Air 2017). Inadequate CSD suction flow can result in “spillage” (i.e., failure to remove the material) of 5 - 40% of the material (Dekker et al. 2003). A zero suction flow, as applied in Miami, would result in higher spillage rates. There were also no restrictions on the overflow of fine material[5] from the dredge hopper or hopper barge. Of note, USACE committed to prohibiting rock chopping and overflow (in dredge areas in close proximity to coral reef habitat) or restricting overflow (in dredge areas more distant from reefs) in a separate port expansion being planned in southeast Florida at Port Everglades (USACE 2020; USACE 2022).

Our study examines impacts to coral reefs from sediment accumulation to supplement data collection efforts from other groups. This is a follow-up study to Miller et al. (2016) that presents findings of data collected by NMFS divers in 2015. This study was done to support quantification of the coral habitat impacted using data collected by NMFS in 2015 and 2016

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[5] Fine material refers to the cut-point between coarse silt and very fine sand on the Wentworth (1922) grain-size scale. Fines are generally < 0.063 mm in diameter.

and evaluated independently and in the context of data and observations collected by other groups, including the FDEP-permit required monitoring. The coral reef and hardbottom habitats discussed in our study are designated Habitat Areas of Particular Concern under the Magnuson-Stevens Fishery Conservation and Management Act and Critical Habitat for corals listed as threatened under the Endangered Species Act (ESA).

2.0 Methods

We surveyed the coral reefs adjacent to the Port Miami Entrance Channel during December 7, 9, 10, and 11, 2015, and April 12 to 15, 2016. Representatives of Dial Cordy and Associates (USACE contractors) accompanied us on April 14 and 15, 2016. A subset of our sampling included locations also sampled by the USACE, Port Miami, and their contractors to comply with the permit issued by the State of Florida.

Throughout this report, the term “area” refers to broad geomorphological features (e.g., Outer Reef, Inner Reef, or Nearshore Ridge Complex) often modified by adding North or South to indicate position relative to the Entrance Channel (e.g., Inner Reef North or Inner Reef South) (Figure 1). While sampling occurred in all of these areas, this report focuses on results from the Inner Reef because this is where most impacts were believed to have occurred and staff resources for sampling were limited. The term “location” refers to a specific point along the reef where sampling occurred, measured in meters from the Entrance Channel. Sampling locations were grouped based on their purpose. For example, we refer to the locations used as a reference collectively as reference locations, and locations examined for potential impacts from the dredging we refer to collectively as sediment assessment locations. Where Walker and Klug (2014) show both Linear Reef and Ridge Reef occurring at a location, we established one sampling “site” in each reef type. At each site, our sampling was done along transects, and specific points along the transects are sometimes noted. Throughout the report, the naming convention for locations is derived from the area and the location’s distance from the Entrance Channel. For example, we named the sediment assessment location on Inner Reef North at 1,050 m as IRN-1050. The naming convention for sites adds the reef type to the location name. For example, the site IRN-1050-LR is on the Inner Reef North at 1,050 m in the Linear Reef.

2.1 Sample Locations on the Inner Reef

We conducted sediment surveys at 13 different locations to the north and south of the channel. Sediment survey locations were spaced at 100-m intervals north and south from the channel for the first 300 m, then at variable intervals up to 9,500 m from the channel (Figure 2 and Table 1). Our surveys of the Inner Reef had six sediment assessment locations north of the Entrance Channel and four sediment assessment locations south of the Entrance Channel. Additionally, we had one reference location north of the channel, and two reference locations south of the channel. Most survey locations were composed of two sites, one on the Ridge Reef and one on the Linear Reef. However, only the Linear Reef was sampled at the sediment assessment locations IRN-1050 and IRN-700. Similarly, only the Linear Reef site was sampled at the reference location IRS-2200. Table 1 provides the names of the sites surveyed, distances from the channel, date of survey, and purpose in this study (reference or sediment assessment).

2.2 Transects for Examining Bottom Cover and Sediment Depth

Transects were used to collect information on bottom cover and sediment depth (i.e., thickness of the sediment layer above underlying hardbottom). For the transects conducted during December 2015 and April 2016, we followed the methods described in Miller et al. (2016). At each site, we deployed from the surface at predetermined site coordinates a dive weight attached to a temporary marker buoy. Divers then deployed two 50-meter-long transects originating at the dive weight and running in opposite directions. Transects were oriented east-west when coral habitat extended at least 50 m beyond each end of the transect. When this was not the case, we oriented the transects in a north-south direction. These determinations of orientation were made before going into the field and were done using Google Earth Pro and the Walker and Klug (2014) reef habitat maps. Transects were sampled at 1.0 m intervals (50 points per transect and two transects per site yielding 100 points per site) for bottom cover class. In two instances, only a single 50-m transect was fully conducted at the survey site. At IRS-200-RR, only the east transect was surveyed due to weather conditions shortening sampling time. At IRS-1375-RR, both transects were conducted, but sediment depth was only recorded on the east transect.

Table 2 provides the bottom cover classes noted in the field during each survey and used for statistical analyses. In December 2015, coral phylogenetic groups were not differentiated and recorded as the bottom cover class “Coral”. In April 2016, divers recorded different coral phylogenetic groups, but they were pooled into a single category prior to analysis and comparison to December data. A number of bottom cover classes that were not regularly observed in the field were pooled into a single category (“other”) for analysis. The bottom cover class “sand”, as described in NMFS (2016), described points along the transect exhibiting no indication of hardbottom being present (i.e., no octocoral or sponges were emerging from sand), and included sand patches within reef habitats (Miller et al. 2016). “Sand channel” describes features within spur and groove habitats or relict grooves. “Sand channels” are narrower and more linear than sand patches or sand habitats described as “sand.” The bottom covers “sand channel” and “sand” were combined from the April 2016 dataset to allow comparisons to the December 2015 data. Both “sand” and “sand channel” bottom cover classes contribute to the “other” category used in analyses. “Sediment over hardbottom” was defined as a visible accumulation of sediment over underlying hardbottom, including turf algae laden with sediment.

Miller et al. (2016) describes the method for measuring sediment depth every 5.0 m along the transects. During December 2015, one measurement of sediment depth was made at each 5.0-m point. During April 2016, at least three measurements were made at each 5.0-m point with the divers recording the minimum, maximum, and median sediment depth. These three measurements were made within approximately 10 cm of each other. For analysis, the average of the maximum and minimum sediment depths was calculated and used as the measurement of sediment depth at that point.

In addition to recording bottom cover and sediment depth, sampling of the transects included notes on potential indicators of stress to coral reef biota from sedimentation, such as recent partial mortality (i.e., minimally encrusted skeleton in which individual calyces were still discernible, 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 were no noticeable signs of stress present.

2.3 Data Analysis

We used observations of bottom cover from transects made during December of 2015 and April of 2016 to assess potential impacts to coral from sedimentation. We pooled some observations of bottom cover from April 2016 to enable comparisons with the December 2015 data due to refinements in the sampling approach (Table 2). Differences in bottom cover on the Inner Reef were first analyzed using nMDS ordination, ANOSIM, and SIMPER analyses using the *vegan* (Oksanen et al. 2020) and *ade4* (Dray and Dufour 2007) packages in R. Ordinations used Bray-Curtis dissimilarity and three dimensions to reduce stress. For these analyses, we treated each transect separately to account for differences between reef types and any differences between divers. Observations of bottom cover on sediment assessment transects (n = 35) were compared to those on reference transects (n = 10). This analysis also examined differences in bottom cover between transects north (n = 24) and south (n = 21) of the Entrance Channel, and between the Linear Reef (n = 26) and Ridge Reef (n = 19) reef types present on the Inner Reef. Because the majority of sites north of the channel were only sampled during December 2015, and all of the sites south of the channel were only sampled during April 2016, we cannot distinguish between survey efforts and the two sides of the Entrance Channel. Any dissimilarities in observed bottom cover could reflect differences between these areas (perhaps due to differences in local hydrodynamics), seasons, the passage of time, or other factors.

Based on the results of the SIMPER analysis, the two bottom cover classes contributing most to dissimilarities, “sediment over hardbottom” and “algal turf”, were further analyzed for differences in relative prevalence among locations with a one-way ANOVA, using specified orthogonal contrasts to specify comparisons made in hypothesis testing. Prior to hypothesis testing, data were examined for heteroskedasticity and normality assumptions. Average percent cover was compared between sediment assessment (n = 10) and reference (n = 3) locations, and between the north (n = 6) and south (n = 4) sides of the channel, for sediment assessment locations only. Previous analyses indicated percent cover did not differ on the basis of reef type, so this factor was excluded from the analysis. In addition, data were only recorded for a single transect at the IRS-200-RR site, therefore it was excluded from analyses.

Measurements of sediment depth from the December of 2015 and April of 2016 transects were also used to examine potential impacts to coral from sedimentation. As previously noted, in December, a single measurement of sediment depth was recorded at each 5.0-m point along the transect, while multiple measurements were made at each 5.0-m point during

April. For the April survey, divers recorded the maximum, minimum, and the apparent median sediment depth; however, for analysis, the maximum and minimum sediment depths were averaged, and we used the average for comparisons with the December data. Differences in sediment depth among locations were analyzed with a one-way ANOVA, using specified orthogonal contrasts. Prior to hypothesis testing, data were examined for heteroskedasticity and normality assumptions. Sediment depth was compared between sediment assessment ($n = 10$) and reference ($n = 3$) locations, and between the north ($n = 6$) and south ($n = 4$) sides of the channel, for sediment assessment locations only. Previous analyses indicated that sediment depth did not differ on the basis of reef type, so that factor was excluded from the analysis. Data were only recorded for a single transect at the IRS-200-RR site therefore it was excluded from analyses.

3.0 Results

Field observations of bottom cover, and measurements of sediment depth on the Inner Reef were analyzed to examine potential damage from sediments to coral reefs. Sediment assessment locations experienced more severe impacts than reference locations, with both more observations of the bottom cover class “sediment over hardbottom” and deeper sediment depths. Analyses of bottom cover and sediment depth were also used to determine the spatial extent of potential impacts. All sediment assessment locations on the north side of the Entrance Channel were impacted, and moderate to severe impacts are estimated to have extended 600 m from the Entrance Channel on the south side of the Entrance Channel.

3.1 Bottom Cover

At the Inner Reef sediment assessment locations, the bottom cover class “sediment over hardbottom” was the most prevalent, on average making up 42% of observations (Figure 3). The bottom cover class “coral[6]” was the next most prevalent at 19%. At reference locations, the bottom cover class “algal turf” was most prevalent, representing an average of 36% of the observations. “Coral” was again the second most prevalent observation at 25%. At reference locations “sediment over hardbottom” represented an average of only 7% of bottom cover classes observed.

The relative prevalence of bottom cover classes on sediment assessment transects were significantly dissimilar (ANOSIM; $R = 0.46$, $p < 0.001$) from reference transects (Figure 4). The bottom cover classes “sediment over hardbottom” and “algal turf” were the primary drivers of this dissimilarity (Table 3). The sediment assessment locations exhibited a significantly higher prevalence of the class “sediment over hardbottom” than reference locations (ANOVA; $Df = 1$, $F = 37.57$, $p < 0.001$), with an average (± S.E.) of 42 ± 4% compared to 7 ± 4% (Figure 5A). Sediment assessment locations also had a significantly lower prevalence of the class “algal turf” than reference locations (ANOVA; $Df = 1$, $F = 39.01$, $p < 0.001$), with an average cover of 11 ± 2% compared to 36 ± 4% (Figure 5B).

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[6] Coral phylogenetic groups (stony, octocoral, and hydrocoral) were pooled into a single category.

The prevalence of bottom cover classes also differed between transects on the north and south sides of the channel (ANOSIM; R = 0.14, p = 0.002). Sediment assessment locations on the north side of the channel had significantly higher prevalence of the class "sediment over hardbottom" (Figure 6A) than locations on the south side of the channel (ANOVA; Df = 1, F = 7.40, p = 0.010). There was no difference in the prevalence of the cover class "algal turf" (Figure 6B) between assessment locations north or south of the Entrance Channel (ANOVA; Df = 1, F = 0.33, p = 0.569). Finally, the prevalence of bottom cover classes did not differ between transects in different reef types (ANOSIM; R < -0.01, p = 0.524).

3.2 Sediment Depth

Sediment depth was significantly deeper at sediment assessment locations compared to reference locations (ANOVA; Df = 1, F = 8.17, p = 0.007), with an average depth of 1.4 ± 0.1 cm compared to 0.6 ± 0.1 cm (Figure 7). Sediment depth did not significantly differ between locations north (Figure 8A) and south (Figure 8B) of the channel (ANOVA; Df = 1, F = 2.32, p = 0.138). However, the deepest sediment deposits were found at the IRN-200 and IRN-700 locations with average depths of 2.9 ± 0.7 cm and 2.1 ± 1.4 cm respectively. Comparable sediment deposits on the south side of the Entrance Channel were found only at the IRS-100 location with an average sediment depth of 2.0 ± 0.7 cm.

3.3 Sedimentation Impact Index

The potential severity of impacts to coral and coral reef habitat was examined further by creating an index comparing the prevalence of the bottom cover class "sediment over hardbottom" with the average sediment depth at each site. First, sites were ranked based on the prevalence of "sediment over hardbottom" relative to the reference location average. Next, sites were ranked by the average sediment depth. Combining the two rankings grouped sites into general impact categories ranging from unimpacted to severe impacts (Table 4).

We considered sites unimpacted when the prevalence of "sediment over hardbottom" was 0 - 0.5 times greater than the reference average and sediment depth was 0 - 0.5 cm. Sites were considered potentially impacted when the prevalence of "sediment over hardbottom" and sediment depth were both elevated one ranking (0.5 - 1 times greater than the reference average and 0.5 - 1 cm, respectively), but also when "sediment over hardbottom" was elevated up to two rankings (> 0.5 - 5 times greater than the reference average) and sediment depth was low (0 - 0.5 cm), and when "sediment over hardbottom" was low (0 - 0.5 times greater than the reference average) but sediment depth was elevated up to two rankings (> 0.5 - 2 cm). Similarly, moderate impacts occurred when both the prevalence of "sediment over hardbottom" and sediment depth were both elevated two rankings (> 1 - 5 times greater than the reference average and > 1 - 2 cm, respectively), but also when "sediment over hardbottom" was elevated up to three rankings (> 1 - 10 times greater than the reference average) and sediment depth was lower ranked (0 - 1 cm), and when "sediment over hardbottom" was lower ranked (0 - 1 times greater than the reference average) but sediment depth was elevated up to three rankings (> 1 - 4 cm). Finally, severe impacts occurred when both the prevalence of "sediment over hardbottom" and sediment depth were both elevated three rankings (> 5 - 10 times greater than the reference average and > 2 - 3 cm, respectively), but also when “sediment over hardbottom” was elevated up to four rankings (> 5 - 10 times greater than the reference average) and sediment depth was lower ranked (0.5 - 2 cm), and when “sediment over hardbottom” was lower ranked (0 - 5 times greater than the reference average) but sediment depth was elevated up to four rankings (> 2 - 5 cm) (Table 4).

Using these rankings, moderate to severe impacts from sedimentation occurred at all Inner Reef sediment assessment locations north of the Entrance Channel and at all but one sediment assessment location south of the Entrance Channel. Notably, one of the reference sites (IRS-1375-RR) also experienced moderate impacts. Potential impacts occurred at both sites of the Inner Reef South location 700 m from the Entrance Channel (IRS-700-RR and IRS-700-LR). Based on these impact rankings we estimate that moderate and severe sedimentation occurred on the Inner Reef at least 1,100 m north of the channel and approximately 600 m south of the channel (Figure 9) representing an impact area of 278.6 acres of reef using the coral maps from Walker and Klug (2014). We chose 600 m for the southern boundary due to severe impacts at the next channel-ward station within this and the adjacent line of stations. We view this estimate as conservative because the area of potential impacts extended beyond our study locations north of the channel, and because sedimentation depths at reference sites 1,300 m or greater south of the channel were greater than the site 700 m south of the channel. Additionally, these impacts represent only the Inner Reef, and not the Outer Reef or Nearshore Ridge Complex.

4.0 Discussion

This study indicates sediment from the dredging of Port Miami resulted in significant differences in bottom cover and elevated sediment depths at assessment locations compared to reference locations. Our study demonstrates the sediment assessment locations differed substantially from the reference locations. Using percent cover of “sediment over hardbottom” and depth of sediment deposits, notable contrast is evident with the reference locations. At least 278 acres of Inner Reef habitat were covered or partially covered in sediment 8 to 12 months after dredging ended. Evaluation of our findings in the context of other peer-reviewed studies (i.e., Miller et al. 2016; Cunning et al. 2019), suggests significant impacts occurred along the Inner Reef. Assessing our findings in addition to other available data and studies contributes to understanding the severity and extent of sediment-related impacts to coral habitat resulting from the 17 months of dredging. Yet, our estimate in the spatial extent of damage to coral reef is likely an underestimate as sizable impacts to other habitats including the Nearshore Ridge Complex, artificial reefs constructed near the Entrance Channel to mitigate damage from the project, and patch reefs located between the Inner and Outer Reefs were not included in this study. It is possible dredged-related sedimentation damaged a much larger acreage of coral reef, if the spatial extent and severity of the sedimentation impact follows a similar pattern along the Nearshore Ridge Complex and Outer Reef.

The reefs examined are fishery habitats protected under the ESA and the Magnuson-Stevens Act. We conducted this study because the monitoring data collected in compliance with the permit issued by the FDEP (FDEP, #0305721-001-BI) assumed a smaller impact footprint, lacked pre-dredging baseline survey events[7], and methods to assess project-related sediment impacts on their own and cannot be solely relied on to evaluate project impacts. We implemented post-hoc sampling (i.e., ~8 months after dredging as described in Miller et al. (2016) and 12 months after dredging was completed) to supplement the FDEP permit required monitoring data.

4.1 Bottom cover in context of other available information and studies

As demonstrated in our study, dredging altered bottom cover at sediment assessment locations substantially. In the initial December 2015 assessment, NMFS authors concluded the mean prevalence of the bottom cover class "sediment over hardbottom" was 17.5- to 36.0-fold higher at Inner Reef North locations when compared to the reference location (Miller et al. 2016). Additional data collected in our follow-up study five months later (April 2016) revealed locations south of the Inner Reef with observations of "sediment over hardbottom" up to 5-fold higher at sediment assessment locations compared to the reference (Figure 6A). Photographs taken during the April 2016 survey illustrate the high prevalence of the bottom cover class "sediment over hardbottom" at one site located 100 m south of the channel (Figure 10).

Our observations of bottom cover found a higher prevalence of the bottom cover class "turf algae" and a lower prevalence of the class "sediment over hardbottom", inclusive of turf algae embedded with sediment, at the reference sites. By contrast, sedimentation assessment sites exhibited the opposite pattern (Figure 3). Turf algae, also called epilithic algal communities (Connell et al. 2014), can physically trap sediments on hard substrates associated with coral reefs and also prevent resuspension of sediment once trapped (Purcell 2000). Sediment accumulation within algal turfs enhances the ability of these assemblages to smother and overgrow other benthic biota (Steneck 1997). Algal turfs alone have not been shown to inhibit coral settlement; however sediment-laden algal turf can displace the available space on the reef for coral recruitment and significantly impede settlement for corals listed as threatened under the ESA (*Acropora palmata* and *Orbicella faveolata*) (Speare et al. 2019). Such changes in the turf communities could have long-lasting negative implications for coral recruitment and survival of new individuals to adulthood (Speare et al. 2019).

During FDEP-permit compliance monitoring, contractors sampled four permanent monitoring sites located within 50 m of the channel on the Inner Reef, and their corresponding references located 9,400 m to the north and 1,250 m to the south, no less than 30 times each during dredging. NMFS reviewed benthic functional group percent cover data produced from the FDEP-permit compliance monitoring (DCA 2015b, Appendix H; DCA 2017) in order to better understand the temporal duration of the increase in "sediment over hardbottom" observed on the Inner Reef. Initial surveys at both the channel-side assessment and reference sites conducted in November 2013 document low mean sediment cover (< 12%), followed by a

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[7] Data collection associated with the survey intended to serve as the FDEP-permit required baseline monitoring was not completed until 45-days after the dredging commenced.

substantial increase (greater than 4-fold) in sediment percent cover at the assessment sites during the first few monitoring events conducted after dredging was initiated. Sediment cover remained higher at the assessment sites compared to the reference sites throughout the duration of the dredging (Figure 11). Although assessment and reference sites began with similar levels of sediment, six months after dredging began sediment cover was always higher at the assessment sites relative to the reference sites. This disparity was particularly prevalent during the periods from April 2014 to March 2015 when sediment cover ranged from 30 - 80% sediment cover at assessment sites and 3 - 66% cover at reference sites. During the monitoring events in July 2015 (3 months after the completion of dredging), sediment cover at the channel-side monitoring sites was 36% higher in the north and 52% higher in the south compared to the initial surveys in November 2013. During the final monitoring events in August 2016 (16 months after the completion of dredging), sediment at the assessment sites had declined from July 2015, but was still 10% higher in the north and 38% higher in the south, compared to the initial surveys in November 2013. Sediment dominating the reef habitat more than a year after dredging was completed, suggests the dredge project caused major, lasting changes to bottom cover.

Cunning et al. (2019) extensively reviewed the data collected in accordance with the FDEP permit and reported high sediment cover on the reef. Specifically, they found the near channel areas, located within 50 m of the channel, naturally low in sediment cover prior to dredging (0 - 10%; Inner Reef and Outer Reef) became 50 - 90% covered in sediment for most of the duration of dredging. Monitoring from intermediate areas (1,250 - 2,500 m away), also experienced increases in sediment cover, peaking at 50 - 70% in late 2014 (Cunning et al. 2019). Conversely, the reference areas located 9,400 m away were typically less than 25% sediment, and never exceeded 50% (Cunning et al. 2019). Notably, their analysis was not limited to the Inner Reef and included other reef features such as the Outer Reef in addition to the Nearshore Ridge Complex.

From field observations made by multiple groups during dredging, sediment cover over hardbottom was qualitatively described over time on the Inner Reef and was referred to as heavy (DERM 2014), recently deposited (FDEP 2014), and severe (NMFS 2015), with the spatial extent spreading over 200 m north of the channel on the Inner Reef with no evidence of the sedimentation receding at this distance away from the channel (FDEP 2014; Miami WaterKeeper 2015). Qualitative observations recorded by divers during the FDEP permit-required monitoring also suggested bottom cover change was apparent early in the dredging project and in other coral reef areas located throughout the dredging project (see Appendix: Timeline). During the first week of dredging (CW1, November 23, 2013, HBS2-CP) a diver noted the conditions at one of the Nearshore Ridge Complex monitoring stations as "sedimentation snowing" at the site. The first completed monitoring event on the Inner Reef did not occur until 9 weeks into dredging (CW9, January 18, 2014, R2N1-RR), and a diver noted the presence of "very fine sediment layer" over the site with "sediment accumulating in coral grooves on most coral colonies." This monitoring site was visited again until April 15, 2014 (CW21) and a diver again recorded "fine white sediment" on the substrate. After 24 weeks of dredging, (CW24, May 6, 2014), a diver described an Inner Reef site (R2S1-RR) as "covered in fine white sediment." Divers recorded similar observations on field data sheets throughout the duration of the dredging project, suggesting the dredging caused substantial sedimentation resulting in visually apparent changes in bottom cover and covering the reef in sediment (see Appendix: Timeline).

4.2 Sediment depth over hardbottom in context of other available information and studies

Our study demonstrated sediment depth over hardbottom at assessment locations substantially changed as a result of nearby dredging. In the initial December 2015 assessment, sediment depths at Port Miami Inner Reef reference sites located north of the channel were low (mean 0.3 cm ±1 SE; Miller et al. 2016). Sediment depth was significantly deeper at Inner Reef North sediment assessment sites compared to the reference. Along the Inner Reef North, sediment depth was significantly higher, ranging from 2.7 - 10.0-fold higher compared to the measured reference (Miller et al. 2016) and along the Inner Reef South, sediment depth ranged from 0.7 - 3-fold higher compared to the measured reference. During the dredging, multiple groups reported deep sediment depths (Figure 12), and NMFS divers measured sediment depths up to 14 cm on the Inner Reef South in April 2016 (Figure 12E). The standing sediment levels measured at Port Miami are cumulative standing sediment levels that likely commenced with the beginning of dredging and are well-beyond the threshold of standing sediment representing severe stress and coral mortality (1 cm), described in Nelson et al. (2016). Deeper sediment deposits at the assessment sites compared to the reference sites could also be directly associated with the manner in which the dredging was conducted; i.e., with rock chopping and the absence of restrictions on overflow.

Based on a review of the data collected for the FDEP permit, including data products not analyzed by NMFS, Cunning et al. (2019) also determined deep sediment covered significant portions of the Inner and Outer Reef north of the channel. The highest prevalence of fine sediments deposited on the Inner Reef North and they determined there was a 10-fold decrease in fine material at the reference site located 9,400 m north. Cunning et al. (2019) notes that while sediment depth data were not collected pre-dredging, the very low sediment cover measured on the Inner Reef (0 - 1%; Fig. S5) suggests that depths at these locations must have also been near zero.

Water & Air (2018) completed for the USACE a sediment tracer study at Port Miami using tracers engineered to mimic the sediments liberated during the expansion dredging. They found high likelihood a chronic buildup of sediment on the Inner and Outer Reefs occurred during the dredging period, especially during calm ocean conditions. They asserted this buildup of sediment likely remained on the Inner and Outer Reefs for months at a time until ocean conditions were sufficiently energetic to resuspend and transport the material out of the project area.

Water & Air (2017) also provided USACE with a preliminary calculation that estimates stripping losses from a Cutterhead Suction Dredge; i.e., the amount of material liberated but not removed by the dredging process during rock chopping based on numerical modeling.

Using the estimated 216 acres of Inner Reef delineated as potentially impacted by sedimentation (DCA 2015a) as a benchmark for the extent of impacts, Water & Air (2017) determined sediment deposition of 33 cm over hardbottom could have resulted throughout this area. Based on an analysis of sediment samples collected in areas within 200 m of the channel in April 2016, the chemistry of the sediments was more representative of the layers penetrated during the dredging than the chemistry of surface reef sands (Swart 2016).

Multiple groups observed and qualitatively described sediment depth over hardbottom on the Inner Reef during dredging. The FDEP (2014) and Miami WaterKeeper (2015) described sediment depth over hardbottom as being of variable thickness. In addition, FDEP measured a sediment thickness of 1 - 14 cm in coral reef areas surrounding Port Miami in July 2014 (FDEP 2014). DERM measured approximately 1 cm of sediment thickness along the Nearshore Ridge Complex north of the channel and measured approximately 1 - 2 cm of sediment thickness on the Inner Reef North of the channel at two locations 27 - 34 m north of the Entrance Channel (DERM 2014). In January 2015, Miami WaterKeeper measured a sediment thickness of 5 - 7 cm along the Inner Reef North in an area that ranged from 100 - 250 m from the channel in (Miami WaterKeeper 2015). Excavations conducted by Miami WaterKeeper at these sites revealed coral reef substrate and coral skeletons [dead coral] beneath the sediment (Miami WaterKeeper 2015).

Observations recorded by divers during the permit-required monitoring also suggest deep pockets of standing sediment over the reef as early as four weeks into dredging (CW4, December 12, 2013) where the divers noted monitoring sites “buried” in fine sediment measuring approximately 3.8 cm on the Nearshore Ridge Complex. During week 16, divers noted “heavy sedimentation” and sediment depths ranging from 2 - 7.6 cm. During week 23, divers noted sediment depth ranging from 1 - 5 cm, in addition to recent partial mortality at the bases of corals. Divers recorded similar observations on field data sheets throughout the duration of the dredging project, suggesting the dredging project was responsible for the deep layers of sediment on the reef. These deep layers of sediment (Figure 8) caused an increased prevalence of partial mortality of corals throughout the project area (Figure 13).

4.3 Biological indicator data in context of other available information and studies

In April 2016, non-halo partial mortality, halo mortality, and sediment accumulation on living stony coral colonies were all observed at sediment impact assessment sites. Differences in survey methods in December 2015 and April 2016, prevented direct comparisons between the sampling efforts. Figure 12 illustrates severe biological impacts to corals and octocorals at a site location 100 m south of the channel on the Inner Reef. Based on data collected by NMFS in December 2015, the prevalence of corals with recent partial mortality was significantly higher at sites located 100, 300, and 700 m north of the Entrance Channel on the Inner Reef (Miller et al. 2016). In addition there was up to a 3.1 to 5.1-fold increase in the prevalence of corals with recent partial mortality at sedimentation impact sites compared to reference sites. The occurrence of sediment accumulation on live coral tissue was 4.8 to 21.3-fold higher at sediment impact sites compared to reference sites. In addition, halo mortality (mortality at the base of colonies due to elevated levels of sediment) on corals ranged from 3 to 26-fold more frequent at sedimentation impact sites compared to reference. The tagged colonies at the channel-side location showed over 4-fold greater tissue loss on average than the reference colonies. In addition, 48% of reference colonies displayed positive growth over the course of the project, compared with only 18% of channel-side colonies based on a quantification of live coral tissue using photos from permanently tagged corals (collected as part of the FDEP-permit required monitoring) before and after dredging (Miller et al. 2016).

Observations of recent partial mortality of corals has been used as a biological indicator of sediment impacts by several organizations involved in assessing the expansion of the Port Miami Entrance Channel (e.g., DCA 2015a; Miller et al. 2016; and Cunning et al. 2019). Within sediment assessment sites, partial mortality was observed on 33 - 47% of corals, compared to 7 - 8% at reference sites (DCA 2015a; Cunning et al. 2019) (Figure 13), strongly suggesting sediment impacts from Port Miami expansion increased partial mortality of corals along the Inner Reef.

Cunning et al. (2019) also describes frequent observations of partial mortality due to sedimentation, especially in areas located within 50 m of the channel. The authors conclude a significant reduction in the density of corals ≥3 cm in all reef areas within ~20 m from the channel two years after dredging. These reductions in coral density ranged from ~26 - 43% (Inner Reef South, Outer Reef South, Inner Reef North) up to 50 - 64% (Nearshore Ridge Complex North, Nearshore Ridge Complex South, and Outer Reef North). Further reductions in the density of small corals (1 - 2 cm diameter) resulted near the channel two years after dredging. Notably, coral density of small corals declined by approximately 80% on the Inner Reef North, Inner Reef South, and Outer Reef North. They estimate over 500,000 corals within 500 m of the channel were killed during the dredging period. Since impacts extended beyond 500 m (Barnes et al. 2015; Miller et al. 2016; Cunning et al. 2019), the actual amount of coral lost as a result of dredging is likely much higher (i.e., millions of colonies) (Cunning et al. 2019). This pattern is also consistent with the results of Pollock et al. (2014), which showed extended exposure to dredging project-related sediment plumes was a significant driver of increased occurrence of compromised conditions of reef corals.

By contrast, Gintert et al. (2019), reported a negligible loss of corals from the FDEP-permit required monitoring. Specifically, the authors reported 2% (7 of 336) of corals monitored as part of the FDEP permit died (complete mortality) from sediment stress related to the project. Gintert et al. (2019) did not evaluate changes in sediment depth or cover on the reef nor the chronic sediment stress to corals that occurred throughout the project duration. Instead, the authors used a binary approach to report coral condition (unaffected vs one of 30 categories of coral stress[8]) (DCA 2015a, 2015b, 2017). This approach does not account for a cumulative loss of live tissue throughout the duration of the dredge project, as illustrated in Figure 14. Since a binary system was used and the majority of the codes were not direct indicators of sediment

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[8] 30 categories of coral stress included sediment-stress indications and conditions not likely attributed to sediment stress (e.g., fish bites) (DCA 2017)

stress, the ability to differentiate between dredge-related sediment stress from natural background stress was masked (Water & Air 2017).

In order for NMFS to obtain a better understanding of sediment stress over time, we re-entered the field data collected associated with the FDEP-permit required monitoring, but filtered out coral stress codes not directly pertaining to sediment stress. This effectively replaced the binary system for reporting coral stress. In instances where stress was reported, we provided additional resolution directly from the field data, substituting one of nine possible coral conditions (in order of severity: “sediment dusting”, “sediment accumulation”, “partial burial of coral”, “complete burial of coral”, “partial mortality from sediment”, “partial mortality and other sediment stress”, “coral disease”, “coral disease and other sediment stress”, and “complete mortality”). To visualize trends, we further summarized these data to determine the percent prevalence of each general type of coral stress (Figure 15). In this data set, instances of “coral disease” and “coral disease and other sediment stress” were rare until the last few weeks of dredging and were not included in this visualization.

The permit-required data collected on biological indicators of sediment stress clearly show the progression of sediment impacts experienced at Inner Reef monitoring sites closest to the channel (Figure 15). Biological impact indicators were generally higher than those at reference sites, with the exception of “unaffected” or “normal” condition[9], which were consistently higher at the reference sites. During the first four months of dredging, the average percent prevalence of unaffected observations declined and sediment accumulation increased (Figure 15A-B). During compliance events completed in mid-January 2014, (nine weeks into dredging), sediment accumulation was present on 100% of sediment assessment sites north of the channel and 96% of sediment assessment sites south of the channel. The next completed survey event occurred three months later in April 2014 (21 weeks into the dredge project); where the conditions were unchanged. By months six and seven of project operations, coral burial increased (Figure 15C). This represents a more severe impact as sediment deposits were becoming more frequent and sufficient to partially or completely bury corals. A severe warm thermal stress event (Eakin et al. 2016; Manzello 2015) occurred in the Fall of 2014. On September 12 and September 17, 2014 (week 43 of the dredge project), Gintert et al. (2019) conducted surveys pursuant to FDEP permit requirements and reported bleaching on 82% (89 of 109) and 75% (213 of 285) of corals surveyed that day. Bleached corals are less capable of removing sediments from their surfaces, and sediment can accumulate 3 to 4-fold more than on normally-pigmented corals and result in partial mortality (Bessell-Browne et al. 2017). After a full year of project dredging, recent partial mortality of corals from sediment increased (Figure 15D).

Multiple groups observed sediment stress to corals early on in the project. Contractors visited four of the seven monitoring sites required by the FDEP permit along the Nearshore Ridge Complex during the first week of dredging. Contractors did not report sediment accumulation or partial burial at three of the four sites during the four baseline sampling events completed at

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[9] RFI tracker “Cross Site Code Crosswalk” tab

HBN2-CR, HBN3-CP, and HBS2-CP between October 20, 2013 and November 7, 2013[10]. However, during the first week of dredging, all tagged corals at these sites exhibited sediment accumulation or partial burial from sediment (CW1, November 23, 2013, HBN2-CP, HBN2-CR, HBN3-CP, HBS2-CP). The Terrapin Island, a trailing suction hopper dredge, was working in the area between the jetties at the entrance of the port and west of the channel elbow on November 20, 21, and 23, 2013. The most plausible explanation for the sediment stress was the nearby dredging operations with no restrictions on overflow.

Divers from Miami-Dade County observed stony coral colonies with 100% mortality attributed to sedimentation at locations within 150 m of the Entrance Channel during dredging (DERM 2015). In addition, groups commonly reported burial of the base of octocorals (Miami WaterKeeper 2015; NMFS 2016a). Images of impacts to staghorn coral (*Acropora cervicornis*), which is listed as threatened under the ESA, show partial mortality or complete mortality from sedimentation along the Inner Reef 150 - 220 m north of the channel (Miami WaterKeeper 2015; NMFS 2015). Images also show staghorn coral branch tips dipping into sediment (Miami WaterKeeper 2015), not a normal pattern of growth for staghorn coral, and therefore attributed to sedimentation.

4.4 Impact map and impact index

Data collected on the Inner Reef by NMFS in December of 2015 and April of 2016 indicated that moderate to severe coral impacts extended 1,100 m north of the channel, and 600 m south of the channel (Figure 9; Table 4). This area encompasses all of our sediment assessment locations north of the Entrance Channel, the furthest of which was at 1,050 m. On the south side of the channel, moderate to severe impacts were experienced at sediment assessment locations up to 300 m from the Entrance Channel. Sediment assessment locations more distant from the channel (700 m) ranked as potentially impacted as well. Average sediment depth at 700 m was less than 1 cm and the average prevalence of the bottom cover class “sediment over hardbottom” was 7%. In determining a southern limit to our estimate of impacts we used a distance 100 m closer to the channel than this location. Notably, based on these rankings, moderate impacts occurred at one of the reference sites at IRS-1375-RR. The average sediment depth was less than 1 cm, and average prevalence of “sediment over hardbottom” was 14%, which is more than double the reference location average. Use of IRS-1375-RR as a reference, knowing moderate impacts occurred is another reason to consider our estimate of impacts as an underestimate. Since we used this site to calculate the reference site average, it influences the standard by which impacts were determined. Sites designated as impacted exhibited a mean of 1 - 5 cm mean standing sediment and greater than 5 (and up to 10) times more sediment cover compared to the reference sites.

This impact area (Figure 9) is entirely within the remotely sensed sediment plumes detectable by satellite and examined by Cunning et al. (2019) who found higher plume frequencies in the areas located within 2,000 m of the channel. Specifically, after dredging commenced in late 2013, plumes occurred with high frequency (77 - 92% of days) near the channel on the

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[10] This component of the sampling intended to serve as baseline was conducted prior to dredging

Nearshore Ridge Complex and the Inner Reef, on the Outer Reef (58% of days), and in monitoring areas located within 1,250 - 2,000 m (33 - 50% of days) required by the FDEP permit. By contrast, Cunning et al. (2019) detected sediment plumes on only 14 - 17% of days during the same time period 9,400 m away, the location of the Inner Reef North reference area. In 2014 through the end of dredging in 2015, authors almost never detected sediment plumes (3 - 4% of days) 9,400 m away, but plumes still occurred with variable and high frequency at all intermediate distance monitoring areas (16 - 38% of days) and channel-side areas (53 - 65% of days).

Although NMFS surveyed sites on the Nearshore Ridge Complex and the Outer Reef, we limited our analysis to the Inner Reef. Due to time constraints of staff in the field, the NMFS was unable to collect data from enough sites required to draw firm conclusions for other reef areas (Outer Reef and Nearshore Ridge Complex). Expanding our analysis and attempting to quantify the total area of sedimentation impacts on neighboring reefs (i.e., Outer Reef and Nearshore Ridge Complex) is complicated when solely using the data NMFS collected. Impacts to corals occurring landward of the Inner Reef (Nearshore Ridge Complex) are particularly difficult to quantify because of the non-uniform size and orientation of the reefs. However, when considering this study in context of multiple other studies (Barnes et al. 2016; Water & Air 2017; Water & Air 2018; DCA 2015a; Miller et al. 2016; Swart 2016; Cunning et al. 2019), there is strong evidence the source of the material deposited on the reefs was sediments from the dredging project. Furthermore, Cunning et al. (2019) examined remotely-sensed sediment plumes and the FDEP-permit in-situ data and found a significant positive correlation among metrics in permanent monitoring areas, including sediment accumulation, benthic sediment, coral burial, and coral mortality. They conclude high positive correlations among the metrics. Areas where authors found sediment plumes more frequent had higher rates of sediment trap accumulation, higher proportions of the benthos covered in sediment, higher probabilities of corals being partially or completely buried in sediment, and higher rates of coral partial mortality (Cunning et al. 2019).

5.0 Stony Coral Tissue Loss Disease implications

A highly lethal coral disease, referred to as Stony Coral Tissue Loss Disease (SCTLD)[11], emerged in the Port Miami area with the first observation likely occurring 28 weeks into the dredging at a monitoring location within the Nearshore Ridge Complex South (May 30, 2014, *Pseudodiploria clivosa,* HBSC1 T3 C5); the FDEP permit required monitoring at this location. By the fall of 2014, outbreak levels of SCTLD (generally defined as a prevalence of more than 5% above background levels) were observed at locations south of Port Miami (the FDEP permit required monitoring at these locations) and has since spread north and south along the Florida Reef Tract (reported in Precht et al. 2016) and to coral reefs found along at least 25 Caribbean countries or territories (Kramer et al. 2022). Over 20 species are affected by

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[11] SCTLD Case Definition. 2018. Florida Coral Disease Response Research & Epidemiology Team. Accessed: September 15, 2022. Link: https://floridadep.gov/sites/default/files/Copy%20of%20StonyCoralTissueLossDisease_CaseDefinition%20final%2010022018.pdf.

SCTLD, with some susceptible species reduced to less than three percent of their initial population densities (Precht et al. 2016); regional declines have been reported in coral densities and live tissue as a result of SCTLD (Walton et al. 2018).

Sediments can play a role in SCTLD transmission. In transmission experiments with sediments collected from southeast Florida, Studivan et al. (2022) found sediments acted as a disease vector in coral species present in the Port Miami area (*Orbicella faveolata* and *Montastraea cavernosa*). Infection could occur rapidly (in under 24 hours) and without direct contact with diseased coral or disease-inoculated water (Studivan et al. 2022). Pollock et al. (2014) studied coral disease incidence along a gradient of in situ sedimentation and turbidity associated with dredging activities on the Great Barrier Reef, Australia. The researchers found a significant positive relationship between overall coral disease prevalence and the length of time the reefs were exposed to sediment plumes. In Studivan et al. (2022), no other anthropogenic or environmental parameters produced a significant relationship, providing strong evidence that dredge-related sedimentation was driving coral disease prevalence. There are two additional studies that support this relationship. Voss and Richardson (2006) observed increased incidence of coral disease at sites with higher sedimentation in the Bahamas, but the authors drew no firm conclusions on causation. In an exercise to improve the predictive capability of statistical modeling related to coral disease spatial patterns, Williams et al. (2010) found a statistical relationship between the presence of disease in *Porites* spp. (manifests as growth anomalies) and turbidity in Hawaii. It is possible that concurrent stressors, including sedimentation from Port Miami dredging, contributed to the emergence of this disease (Aeby et al. 2019).

6.0 Conclusions

This study provides empirical field-based evidence linking deeper sediment deposits and changes in coral reef bottom cover to dredging that occurred at Port Miami from 2013 to 2015. Impacts to the Inner Reef caused by dredging and sedimentation are estimated to be 278 acres; compared to the EIS estimate of 3.3 acres of impacts (from direct removal of the Outer Reef). The differences between the Port Miami impact prediction and during-dredging compliance monitoring illustrates the need to carefully evaluate existing practices to plan for and detect impacts from large scale dredging projects in coral reef environments. The NMFS is committed to working with FDEP and USACE on improving monitoring conducted to assess impacts to coral reefs during dredging projects required by FDEP permits and described in Biological Opinions, completed by NMFS under Section 7 of the ESA.

The USACE is currently planning two additional large-scale, multi-year port expansions in southeast Florida, including additional work at Port Miami, referred to as Phase IV, and an expansion at Port Everglades, located approximately 37 km north of Port Miami. Several substantial lessons learned from the Port Miami dredging have been memorialized in planning documents associated with Port Everglades expansion, including USACE commitments to prohibit rock chopping, prohibit or restrict of overflow, and adaptive management based on near real-time measurements of water quality and environmental conditions (USACE 2020;

USACE 2022). The development of additional lessons learned and translation to dredging project best practices near coral reefs or other sensitive habitats is warranted.

Establishing frequent iterative feedback loops between federal and local sponsors, resource trustees, entities conducting the environmental monitoring, and dredge contractors would help ensure the implementation of lessons learned from Port Miami dredging. Future port expansions cannot further contribute to the downward trajectory of the condition of Florida's Coral Reef and must be in the public interest. The coral reef impacted by Port Miami dredging once supported all coral species listed as threatened under ESA. The NMFS designates coral reefs as critical habitat to ESA-listed corals and the South Atlantic Fishery Management Council designates coral habitat as Essential Fish Habitat and Habitat Areas of Particular Concern for species managed under fishery management plans for snapper-grouper, spiny lobster, and coral. Implementing compensatory mitigation is essential to jump-start recovery of this invaluable ecosystem.

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8.0 Tables

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Table 1: Locations surveyed on the Inner Reef North (IRN) and Inner Reef South (IRS). Location indicates approximate distance from the channel in meters. Site indicates the reef type surveyed (LR = Linear Reef, RR = Ridge Reef). The site naming convention reflects the area, location, and site (i.e. IRN-9500-RR). Purpose indicates if a location was used as a reference or for assessing sediment impacts. Transects surveyed at each site had east-west orientations except for those marked with a *; these were north-south.

Area	Location	Site	Name	Date	Notes	Purpose
IRN	9500	RR	IRN-9500-RR*	12/10/15		Reference
		LR	IRN-9500-LR*	12/10/15		
	1050	LR	IRN-1050-LR	4/14/16	No RR present	Sediment Assessment
	700	LR	IRN-700-LR	12/11/15	RR present but not surveyed	Sediment Assessment
	500	RR	IRN-500-RR	12/9/15		Sediment Assessment
		LR	IRN-500-LR	12/9/15		
	300	RR	IRN-300-RR	12/9/15		Sediment Assessment
		LR	IRN-300-LR	12/9/15		
	200	RR	IRN-200-RR	12/11/15		Sediment Assessment
		LR	IRN-200-LR	12/11/15		
	100	RR	IRN-100-RR	12/10/15		Sediment Assessment
		LR	IRN-100-LR	12/10/15		
IRS	100	RR	IRS-100-RR	4/12/16		Sediment Assessment
		LR	IRS-100-LR	4/12/16		
	200	RR	IRS-200-RR	4/15/16	Only east transect surveyed due to weather conditions	Sediment Assessment
		LR	IRS-200-LR	4/12/16		
	300	RR	IRS-300-RR	4/12/16		Sediment Assessment
		LR	IRS-300-LR	4/15/16		
	700	RR	IRS-700-RR	4/15/16		Sediment Assessment
		LR	IRS-700-LR	4/15/16		
	1375	RR	IRS-1375-RR	4/12/16	Sediment depth not measured on west transect (diver lost ruler)	Reference
		LR	IRS-1375-LR	4/12/16		
	2200	LR	IRS-2200-LR	4/14/16	RR present but not surveyed	Reference

Table 2. Bottom cover classes recorded from transects in December 2015 and April 2016. Colors and order correspond to Figure 3 Table 3, and Appendix.

December 2015	April 2016	Notes
Algal Turf	Algal Turf	
Coral	Stony	Phylogenetic groups differentiated in April were pooled into a single category for analysis and comparison to December.
	Octocoral	
	Hydrocoral	
Sponge	Sponge	
Palythoa	Palythoa	Contributes to “other” in Figure 3
Cyanobacteria	Cyanobacteria	Contributes to “other” in Figure 3
Crustose Coralline Algae	Crustose Coralline Algae	Contributes to “other” in Figure 3
Dead Coral	Dead Coral	Contributes to “other” in Figure 3
Dead Sponge	Dead Sponge	Contributes to “other” in Figure 3
Sand	Sand	Sand and Sand Channel from April were pooled into single category and contributes to “other” in Figure 3
	Sand Channel	
Hardbottom	Hardbottom	Contributes to “other” in Figure 3
Macroalgae	Macroalgae	
N/A	Rubble	No rubble was recorded in December
Sediment Over Hardbottom	Sediment Over Hardbottom	
Deep Sediment Over Hardbottom	Deep Sediment Over Hardbottom	Subcategory of Sediment over Hardbottom recorded when sediment depth measured greater than 4.0 cm

Table 3. Results of the SIMPER analysis indicating the degree each bottom cover class contributes to dissimilarity between assessment and reference locations, standard deviation, and significance. Colors and order correspond to Figure 3, Table 2, and Appendix.

Bottom Cover Class	Percent Contribution	Standard Deviation	p value
Algal Turf	12.29	6.9	0.001
Coral	5.17	4.1	0.099
Sponge	3.82	2.9	0.848
Other	3.72	2.8	0.496
Macroalgae	4.66	4.2	0.089
Rubble	3.85	6.8	0.686
Sediment Over Hardbottom	18.58	10.5	0.001

Table 4. Ranking of sites by average sediment depth and times greater percent sediment cover, compared to the reference site average. Sites with no sedimentation impacts are in the top left corner. Sites with highest impacts are in the bottom right corner. ^{R} indicates reference site. Color and notation indicate severity of impact and correspond to Figure 9: yellow and ^{P} indicate potential impact, orange and ^{M} indicate moderate impact, red and ^{S} indicate severe impact. From Swart (2016): ^{1} indicates native sediment, ^{2} indicates dredged sediment, ^{3} indicates inconclusive source.

Sediment Depth (cm)	Times Greater Percent Sediment Cover (vs. Reference Average)				
	0 - 0.5	> 0.5 - 1	> 1 - 5	> 5 - 10	> 10
0 - 0.5	IRN-9500-RR ^{R,1}	🟨	IRS-700-LR ^{P,3}	🟧	🟧
	IRN-9500-LR ^{R}	🟨	🟨	🟧	🟧
	IRS-2200-LR ^{R,1}	🟨	🟨	🟧	🟧
> 0.5 - 1	🟨	IRS-700-RR ^{P,3}	IRN-300-RR ^{M}	IRN-500-LR ^{M}	🟥
	🟨	IRS-1375-LR ^{R,P}	IRS-1375-RR ^{R,M}	IRN-300-LR ^{M}	🟥
	🟨	🟨	🟧	IRS-200-RR ^{M,2}	🟥
> 1 - 2	🟨	🟧	IRN-500-RR ^{M}	IRN-1050-LR ^{S,3}	🟥
	🟨	🟧	IRS-100-LR ^{M}	IRN-100-RR ^{S,2}	🟥
	🟨	🟧	🟧	IRN-100-LR ^{S,2}	🟥
	🟨	🟧	🟧	IRS-200-LR ^{S}	🟥
	🟨	🟧	🟧	IRS-300-RR ^{S}	🟥
	🟨	🟧	🟧	IRS-300-LR ^{S,2}	🟥
> 2 - 3	🟧	🟧	🟥	IRN-700-LR ^{S}	🟥
	🟧	🟧	🟥	IRN-200-RR ^{S}	🟥
	🟧	🟧	🟥	IRS-100-RR ^{S,2}	🟥
> 3 - 4	🟧	🟥	🟥	🟥	🟥
> 4 - 5	🟥	🟥	🟥	🟥	IRN-200-LR ^{S,2}

9.0 Figures

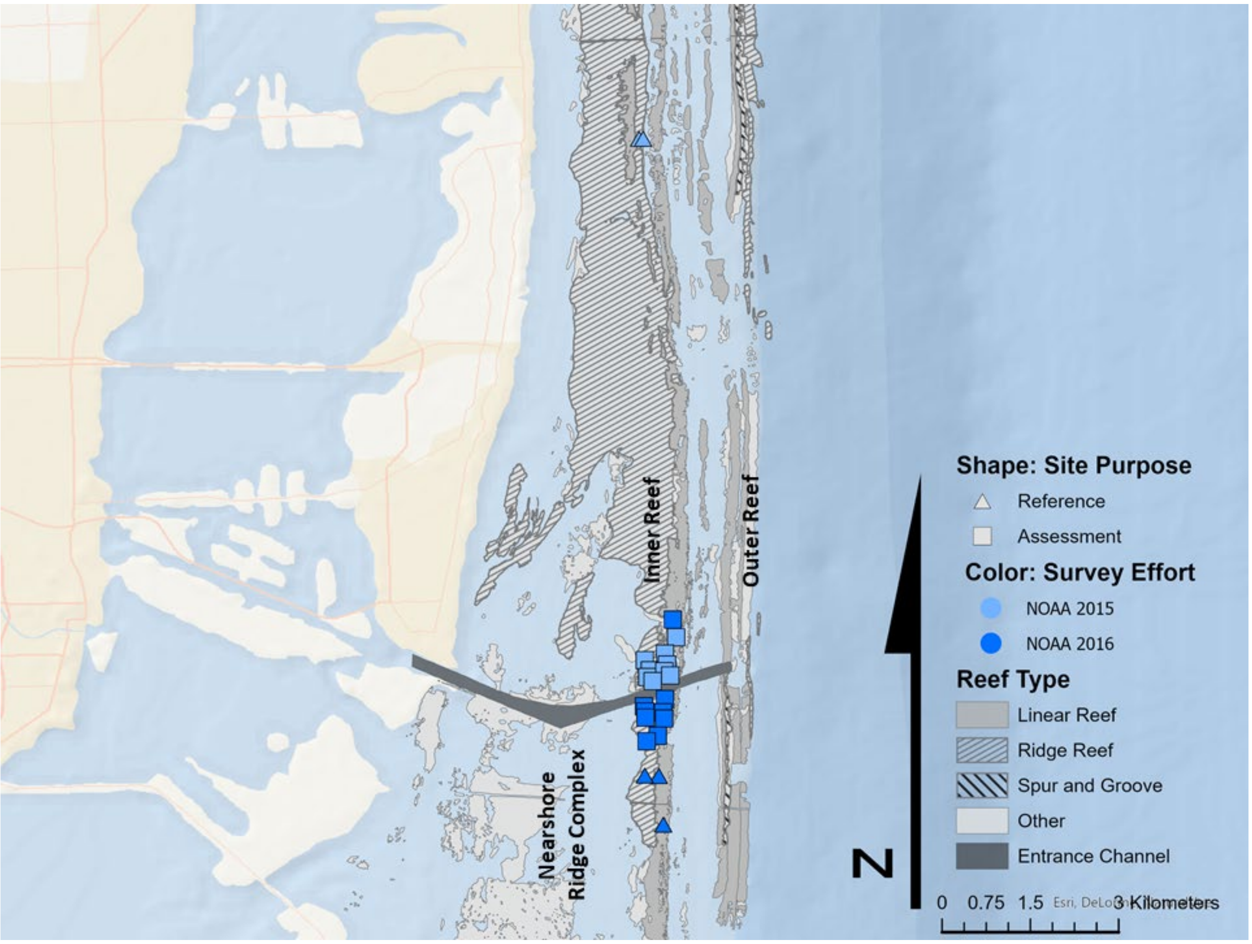


Figure 1. Map of the study area including the Port Miami Entrance Channel and nearby coral reef systems: the Nearshore Ridge Complex, Inner Reef, and Outer Reef. Different reef habitats are indicated by shading and hatching. Symbols on the Inner Reef represent each of the 23 sites NOAA divers surveyed, representing six assessment locations and one reference location north of the entrance channel, and four assessment locations and two reference locations south of the entrance channel. The shape of the symbol distinguishes between assessment and reference sites. The color of the symbol distinguishes when the site was sampled.

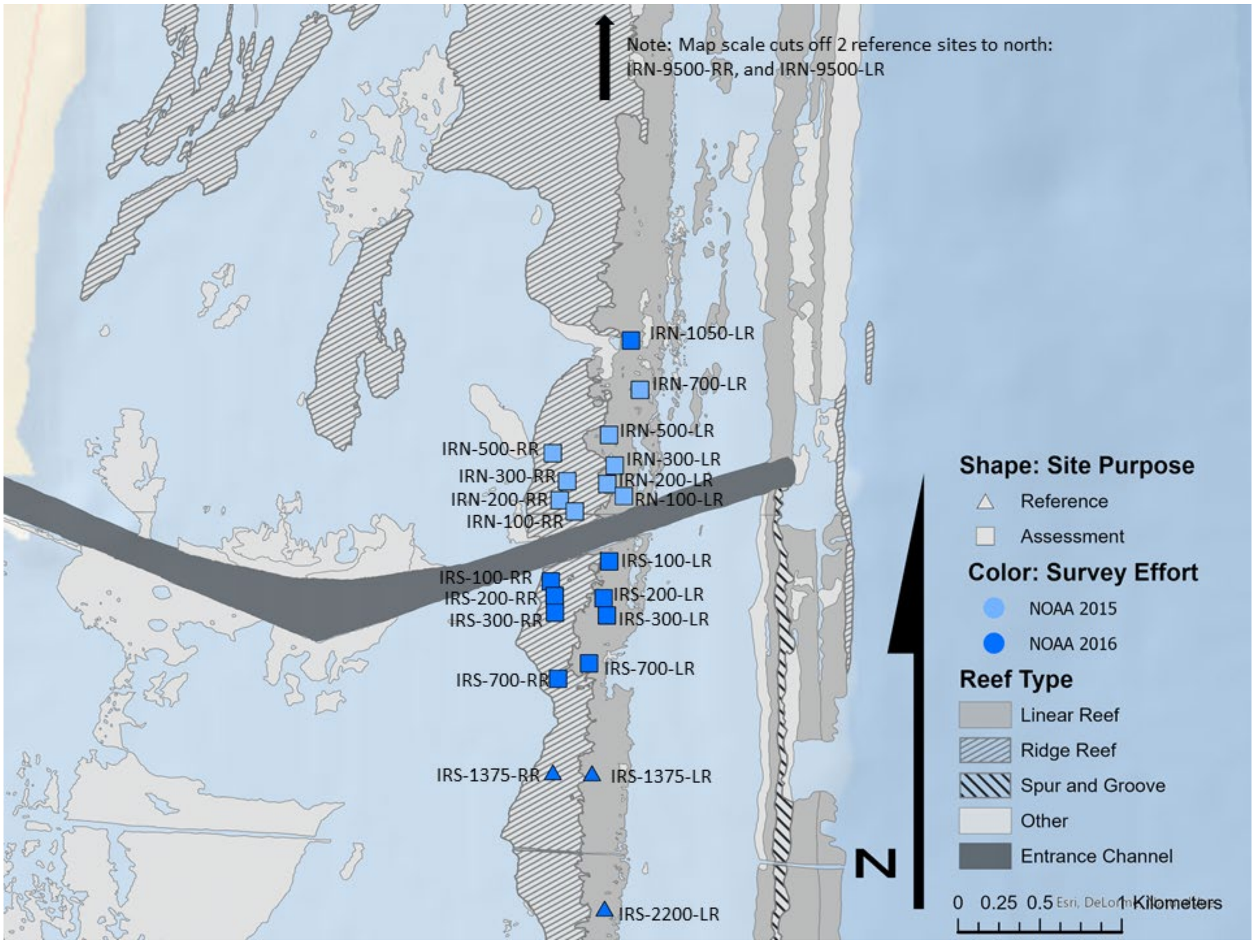


Figure 2. Detailed map of the Inner Reef study area indicating each of the 23 sites NOAA divers surveyed. The shape of the symbol distinguishes between assessment and reference sites. The color of the symbol distinguishes when the site was sampled.

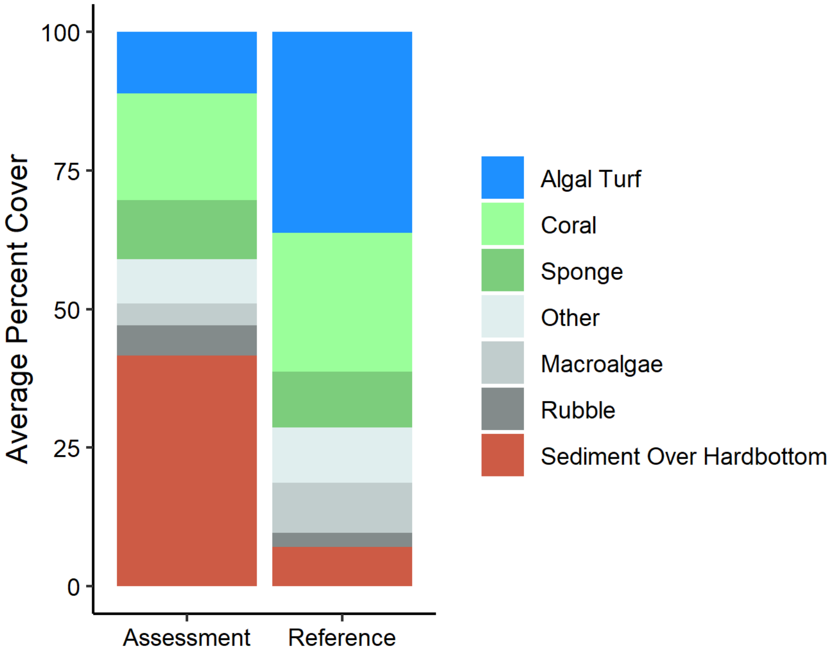


Figure 3. Average percent cover by cover class among assessment and reference locations on the Inner Reef. As presented in Table 2, coral phylogenetic groups (stony, octocoral, and hydrocoral) were pooled into a single category. Colors and order correspond to Table 2, Table Table 3, and Appendix.

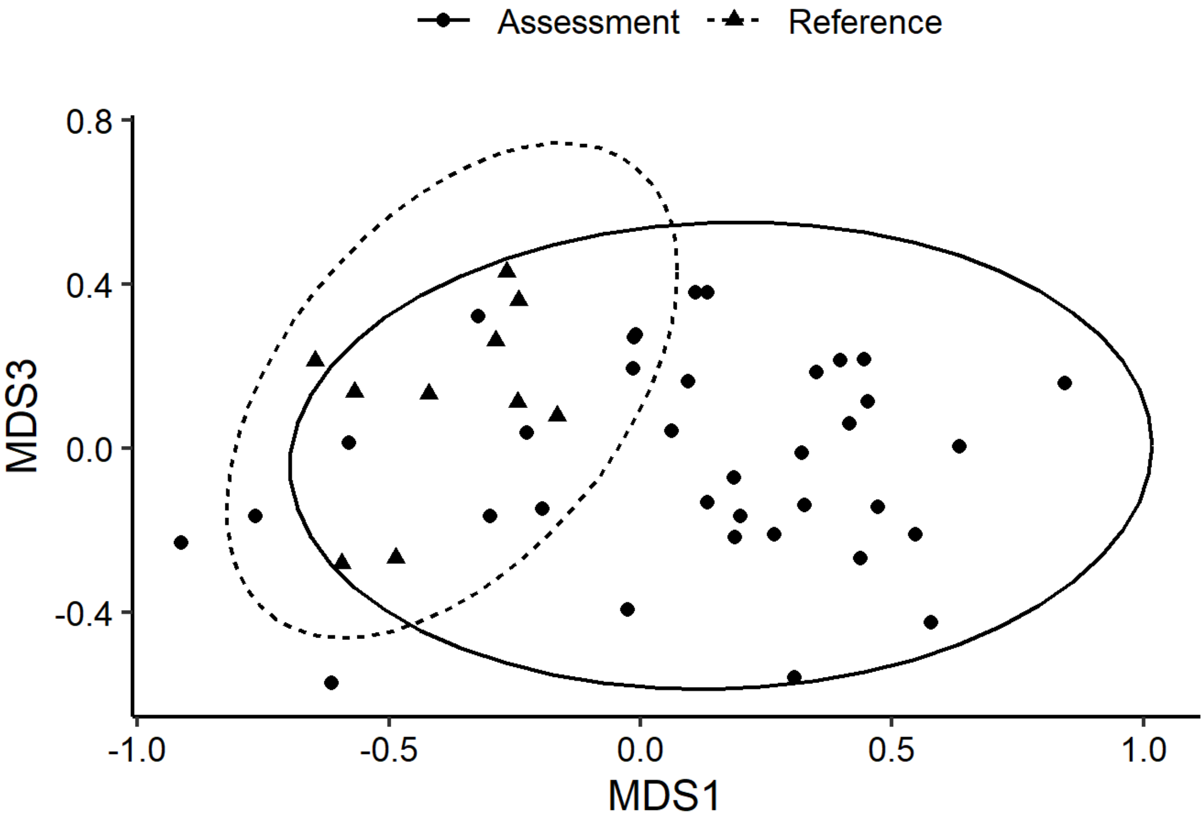


Figure 4. nMDS ordination (distance = Bray-Curtis, dimensions = 3, stress = 0.10) showing grouping of Inner Reef sediment assessment (n = 35) and reference (n = 10) transects based on similarity of bottom cover classes. Bottom cover at reference locations was significantly dissimilar from assessment locations (ANOSIM; R = 0.46, p < 0.001).

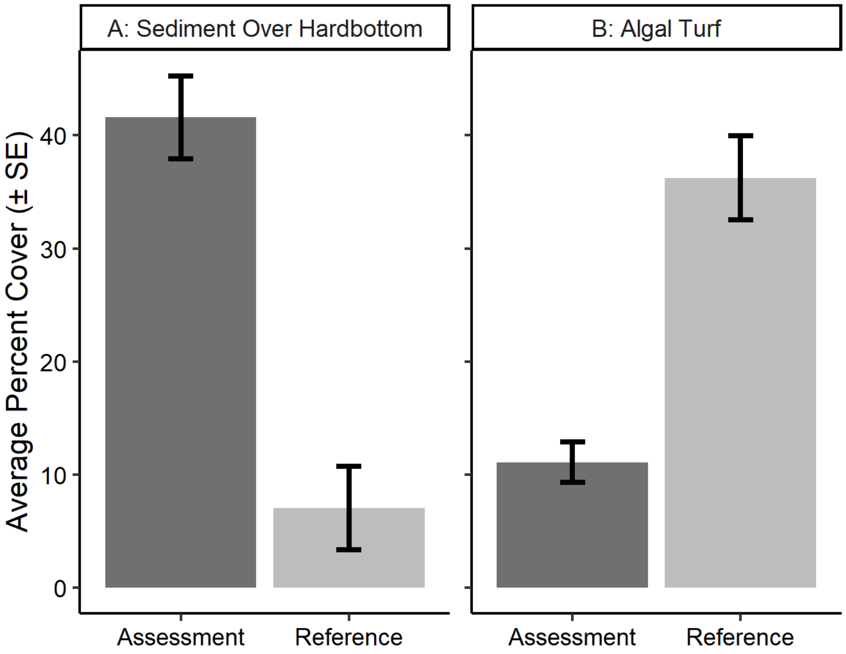


Figure 5. Average percent cover (± standard error) of the bottom cover classes “Sediment Over Hardbottom” (A) and “Algal Turf” (B) among Inner Reef sediment assessment (n = 35) and reference (n = 10) transects.

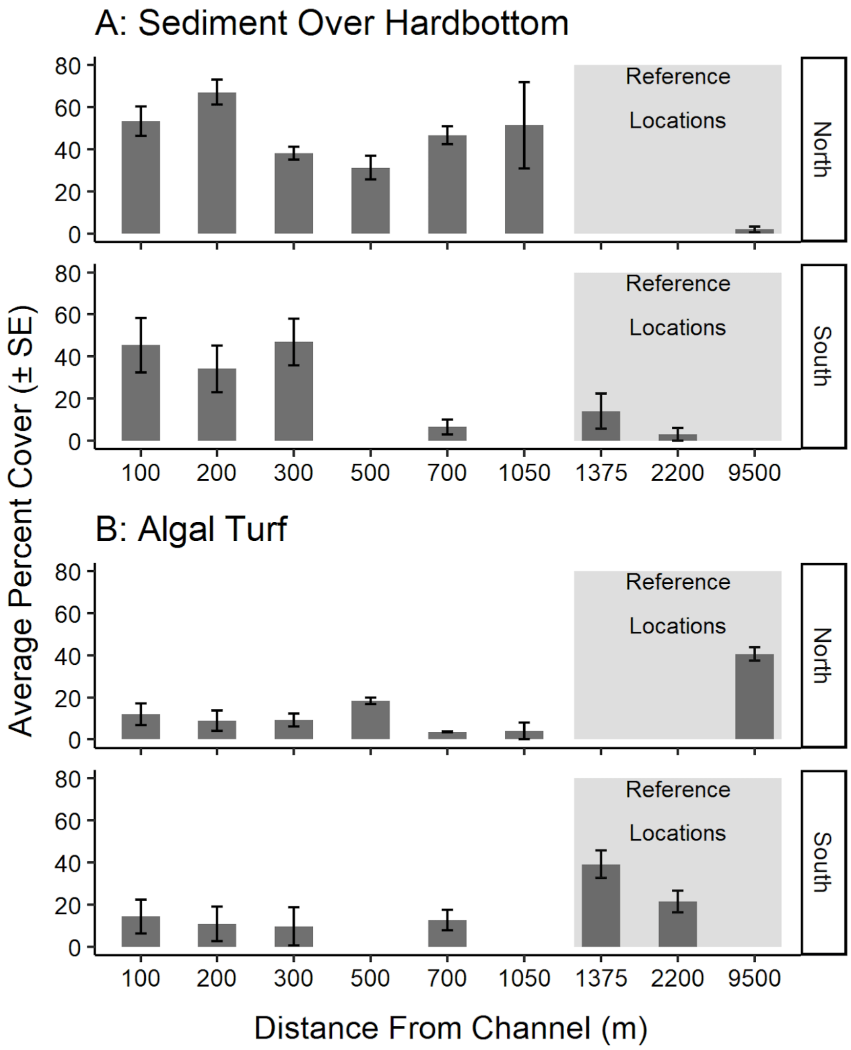


Figure 6. Average percent cover (± standard error) of the bottom classes “Sediment Over Hardbottom” (A) and “Algal Turf” (B) on Inner Reef locations north and south of the channel.

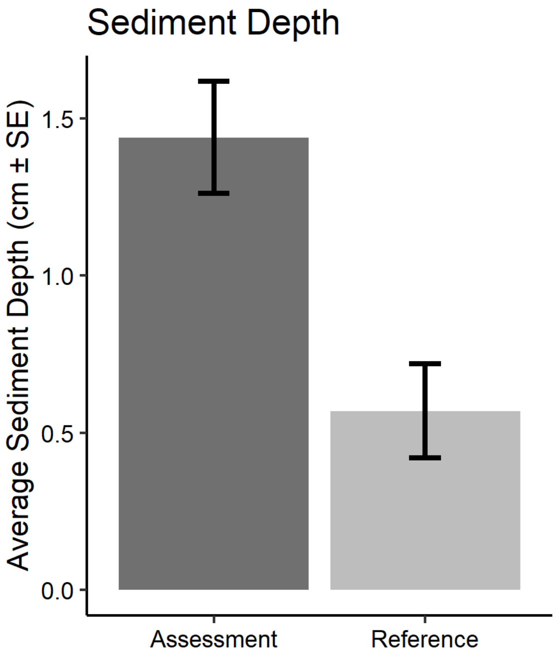


Figure 7. Average depth (cm ± standard error) of sediment deposits measured on Inner Reef sediment assessment (n = 35) and reference (n = 9) transects.

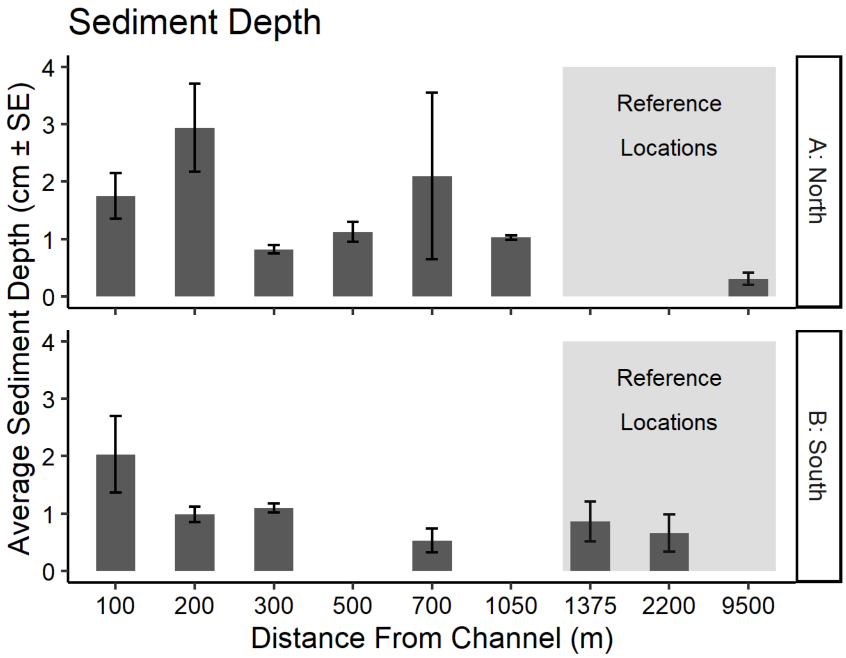


Figure 8. Average depth (cm ± standard error) of sediment deposits measured on Inner Reef locations north (A) and south (B) of the channel.

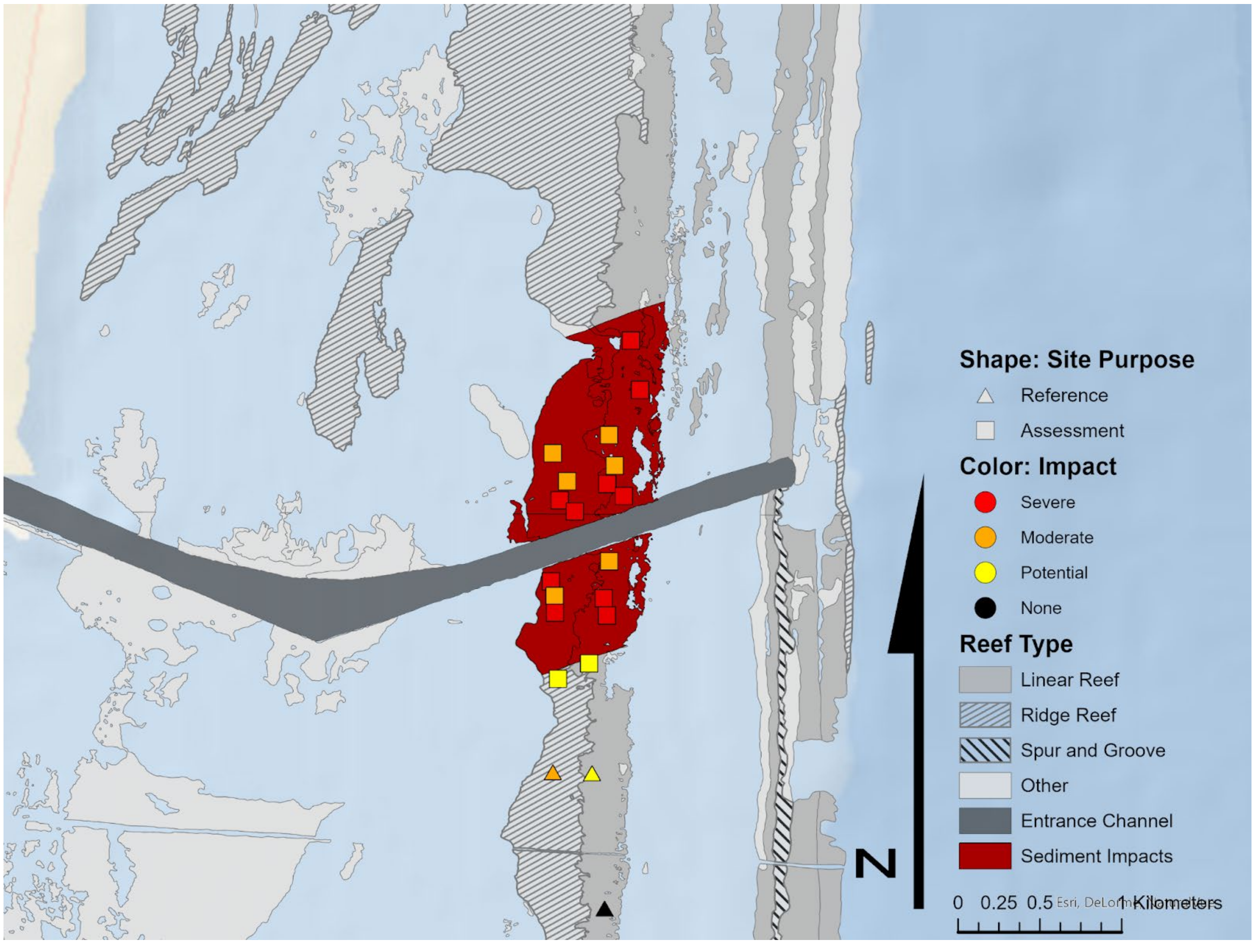


Figure 9. Estimated area of moderate to severe sedimentation impacts. Corresponds to Table 4 (Impacts Ranking). The area of sediment impacts was determined to reach 1,100 meters north of the channel and 600 meters south of the channel encompassing an area of 278.6 acres of coral reef habitat. The reference sites IRN-9500-RR and IRN-9500-LR are cut off by the map scale, and were not impacted (Table 4).

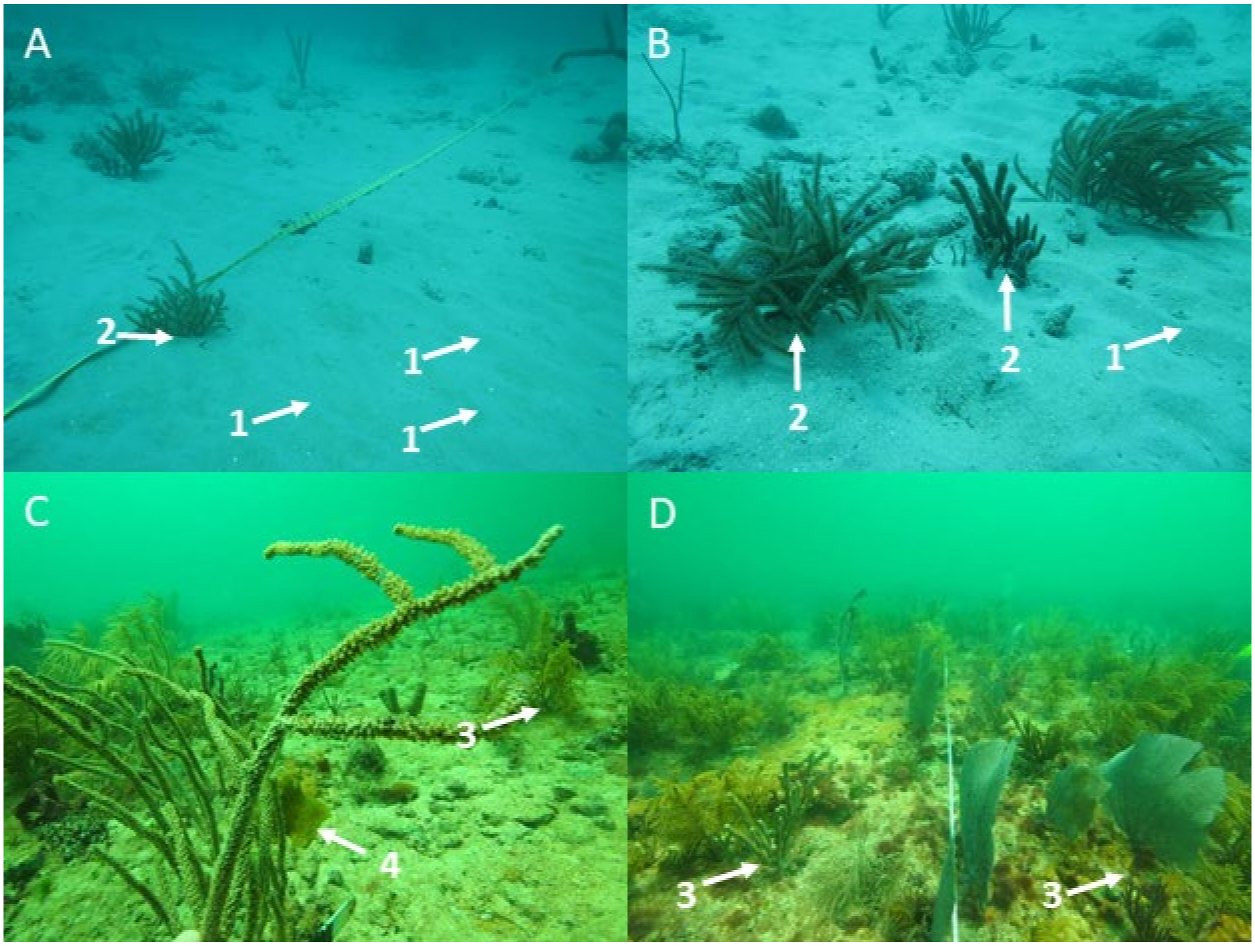


Figure 10. Panels A and B are photos from the Inner Reef south located 100 meters from the channel (IRS-100-RR, April 12, 2016, photo credit NMFS). This site was mapped reef habitat (Walker and Klug 2014) prior to the dredging project. Arrows indicate important details in the photos and the numerical labels relate to the following observations. The presence of sand waves (1) over the reef is clearly an indicator of severe impact due to sediment loading. The attachment points for octocorals to the reef are not visible (2) due to extreme burial. No stony corals are visible and are presumably buried. Mean sediment depth (cm ± standard error) at IRS-100 was 2.03 ± 0.67 cm and ranged from 3.9 - 0.72 cm. By contrast, panels C and D are photos from the Inner Reef South reference sites located 1375 meters from the channel (IRS-1375-RR and IRS-1375-LR, respectively). In April 2016, mean sediment depth (cm ± standard error) at IRS-1375 was 0.86 ± 0.35 cm and ranged from 1.52 - 0.35 cm. No sand waves are present on the reef at this location. Attachment points of octocorals are visible (3). Stony coral edges are also visible (4). Photo credits DCA April 2017, Appendix A (August 10, 2016).

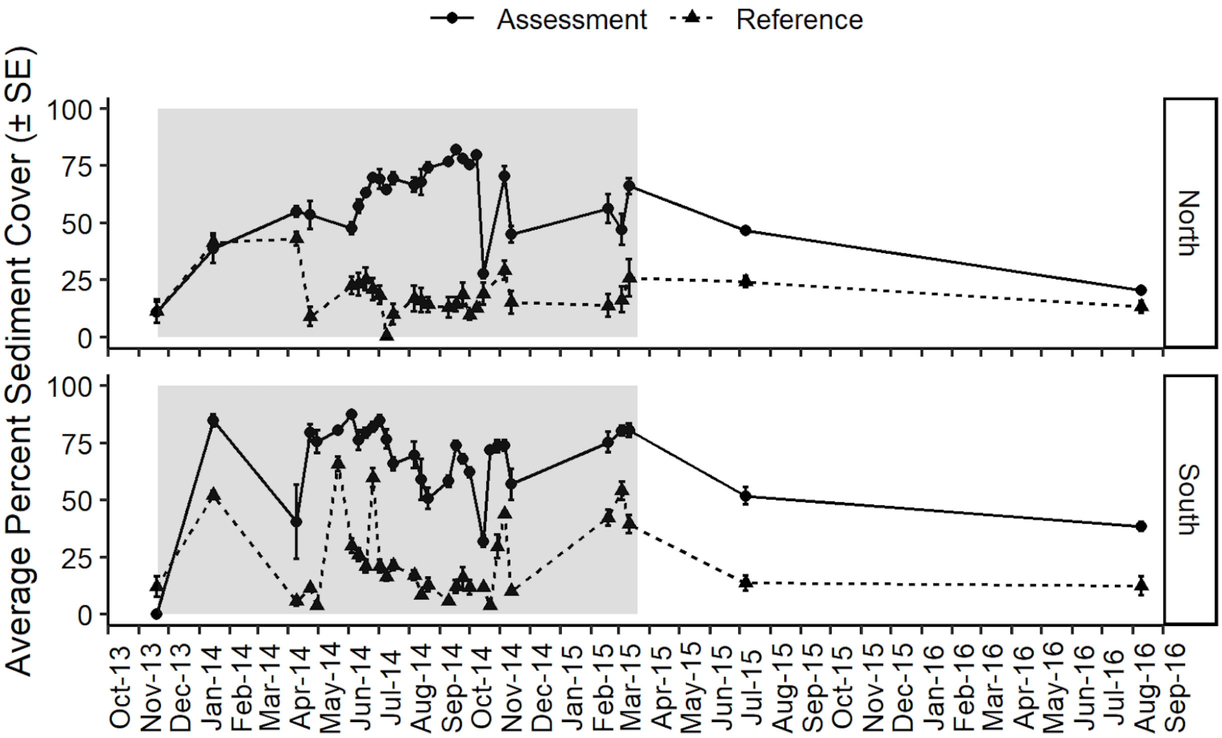


Figure 11. Average percent sediment cover (± standard error) at Inner Reef channel-side compliance sites monitored by DCA from November 2013 through the duration of the dredge project (DCA 2015b) in addition to post-dredge data collected in accordance with the FDEP permit (DCA 2017). The gray background indicates when dredging activities were occurring. Circles connected by a solid line represent assessment sites and triangles connected by dashed lines represent reference sites. At each site DCA surveyed three 20-meter transects. Data points are only presented when the north and south sites were sampled during the same week. The last data points are from the FDEP permit required surveys that occurred June to July 2015 and August 2016 to December 2017.

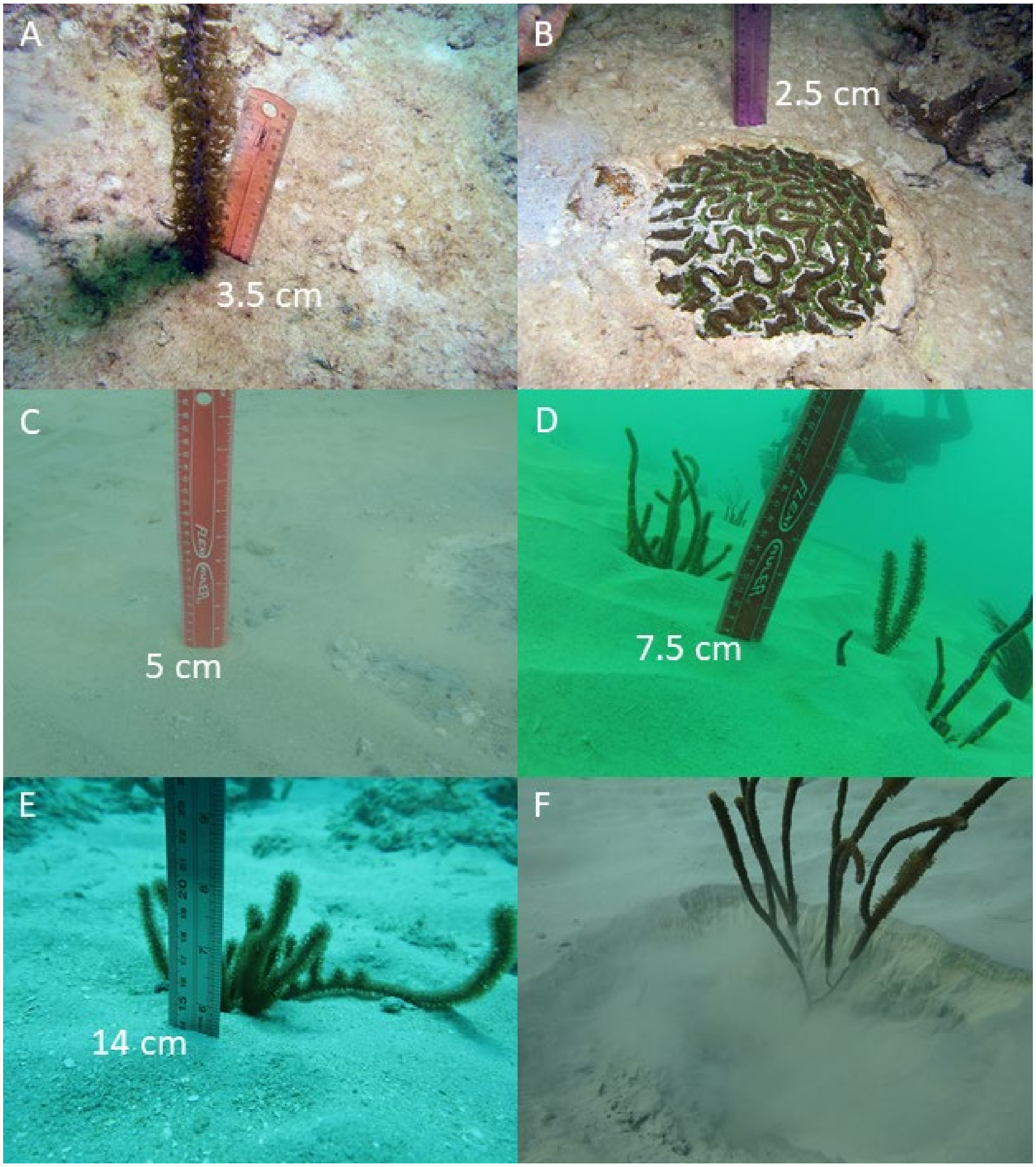


Figure 12. Octocoral buried in approximately 3.5 cm sediment (A) at the compliance monitoring location HBS4 along the Nearshore Ridge Complex on July 22, 2014 (FDEP 2014). Stony coral (left, *Stephanocoenia intersepta*) almost completely buried and stony coral (right, *Colpophyllia natans*) with sediment burial of the base (B). Ruler shows approximately 2.5 cm of sediment depth (FDEP 2014). Sediment thickness between 5 cm (C) and 7.5 cm (D) on the Inner Reef north in an area that ranged from 100 to 250 meters from the channel in January 2015 (Photo credit: Miami WaterKeeper 2015). Sediment deposits as deep as 14 cm (E) were recorded at IRS-100-RR (Photo credit: NMFS 2016). Sediments fanned away from the base of an octocoral 200 meters north of the channel on the Inner Reef in December 2015 (F, Miller et al., 2016).

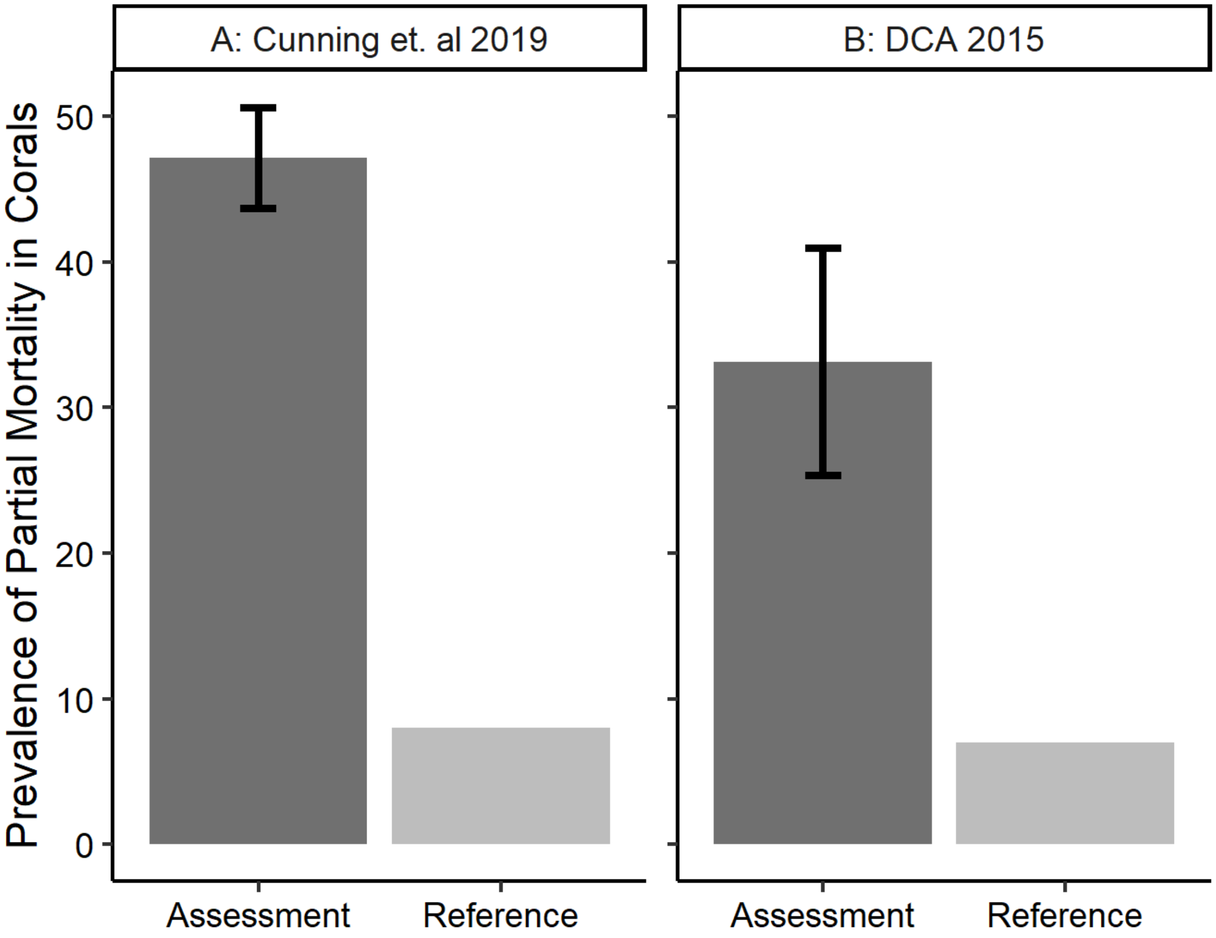


Figure 13. Average prevalence (± standard error) of recent partial mortality in corals on inner reef impact and reference sites as reported by, Cunning et al. (A), and DCA (B). Prevalence reported by Cunning et al. (2019) is an estimated probability.

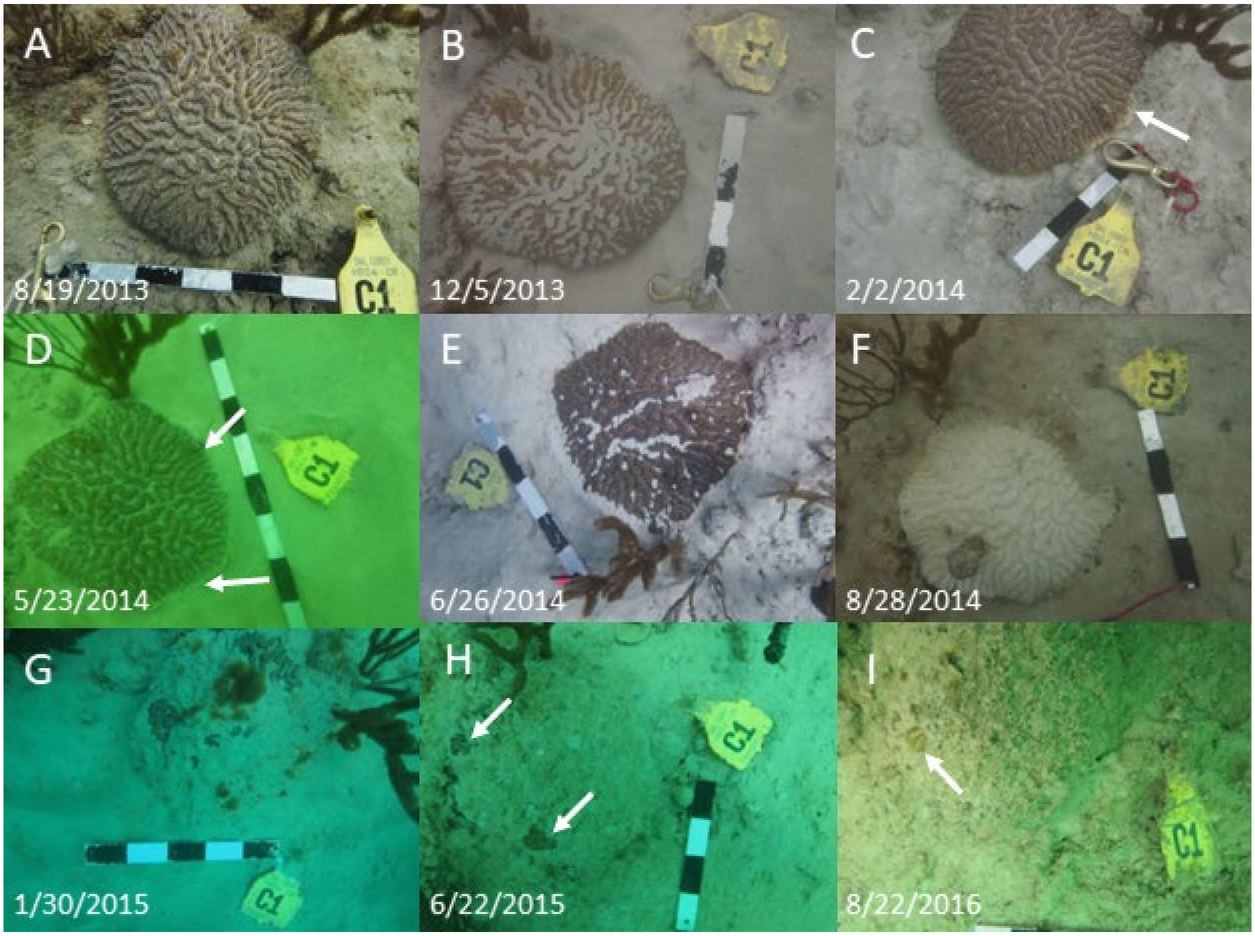
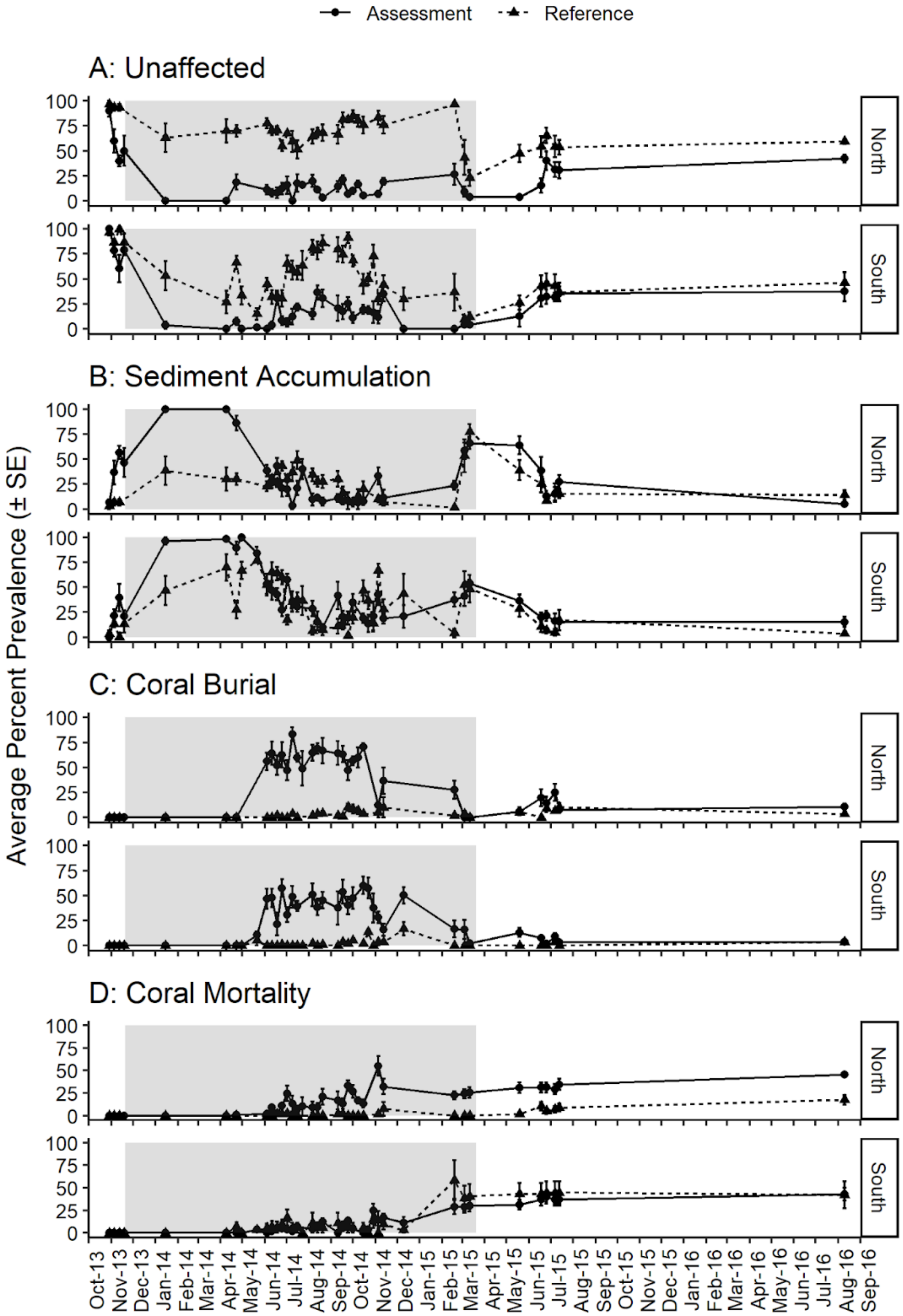


Figure 14. Abbreviated time-series to illustrate coral partial mortality from sediment in a *Meandrina meandrites*. No sediment-associated stress was present during the baseline survey (A). Three weeks into the dredging, the coral is partially buried in sediment (B). During subsequent monitoring, partial mortality from sediment is noted (C, see arrow). Additional sediment accumulation or burial events occurred throughout monitoring (D, E). The coral bleached during a regional warm weather event in August 2014 (F). However, additional sedimentation resulted in considerable partial mortality (G). In June 2015 (H) and August 2016 (I) only a few square centimeters of live tissue remain (see arrows).



Assessment
Reference
A: Unaffected
B: Sediment Accumulation
C: Coral Burial
D: Coral Mortality
North
South
Average Percent Prevalence (± SE)
0
25
50
75
100
Oct-13
Nov-13
Dec-13
Jan-14
Feb-14
Mar-14
Apr-14
May-14
Jun-14
Jul-14
Aug-14
Sep-14
Oct-14
Nov-14
Dec-14
Jan-15
Feb-15
Mar-15
Apr-15
May-15
Jun-15
Jul-15
Aug-15
Sep-15
Oct-15
Nov-15
Dec-15
Jan-16
Feb-16
Mar-16
Apr-16
May-16
Jun-16
Jul-16
Aug-16
Sep-16

Figure 15. Average percent prevalence (± standard error) of four indicators of coral health (A: Unaffected, B: Sediment Accumulation, C: Coral Burial, and D: Coral Mortality) at Inner Reef channel-side compliance sites monitored by DCA from October 2013 through the duration of the dredge project in (DCA 2015b, Appendix A) in addition to post-dredge data collected in accordance with the FDEP permit (field data sheets supplied by USACE with DCA 2017). Circles connected by a solid line represent assessment sites and triangles connected by dashed lines represent reference sites. At each site DCA surveyed 3 transects. The gray background indicates when dredging activities were occurring. Data points only presented when the north and south sites were sampled during the same week. The last two black data points are from the FDEP permit required surveys that occurred June to July 2015 and August 2016 to December 2017.

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*Sean Griffin, Ph.D., also
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*Tom Moore also
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11.0 Acknowledgements

The report preparers greatly appreciate the contributions from the following individuals from NMFS Southeast Fisheries Science Center (SEFSC), NMFS Southeast Regional Office (SERO) Habitat Conservation Division (HCD) and Protected Resources Division (PRD), NMFS Office of Habitat Conservation Restoration Center (RC), and NOAA’s Atlantic Oceanographic and Meteorological Laboratory (AOML). Funding for this work was provided, in part, by NOAA’s Coral Reef Conservation Program.

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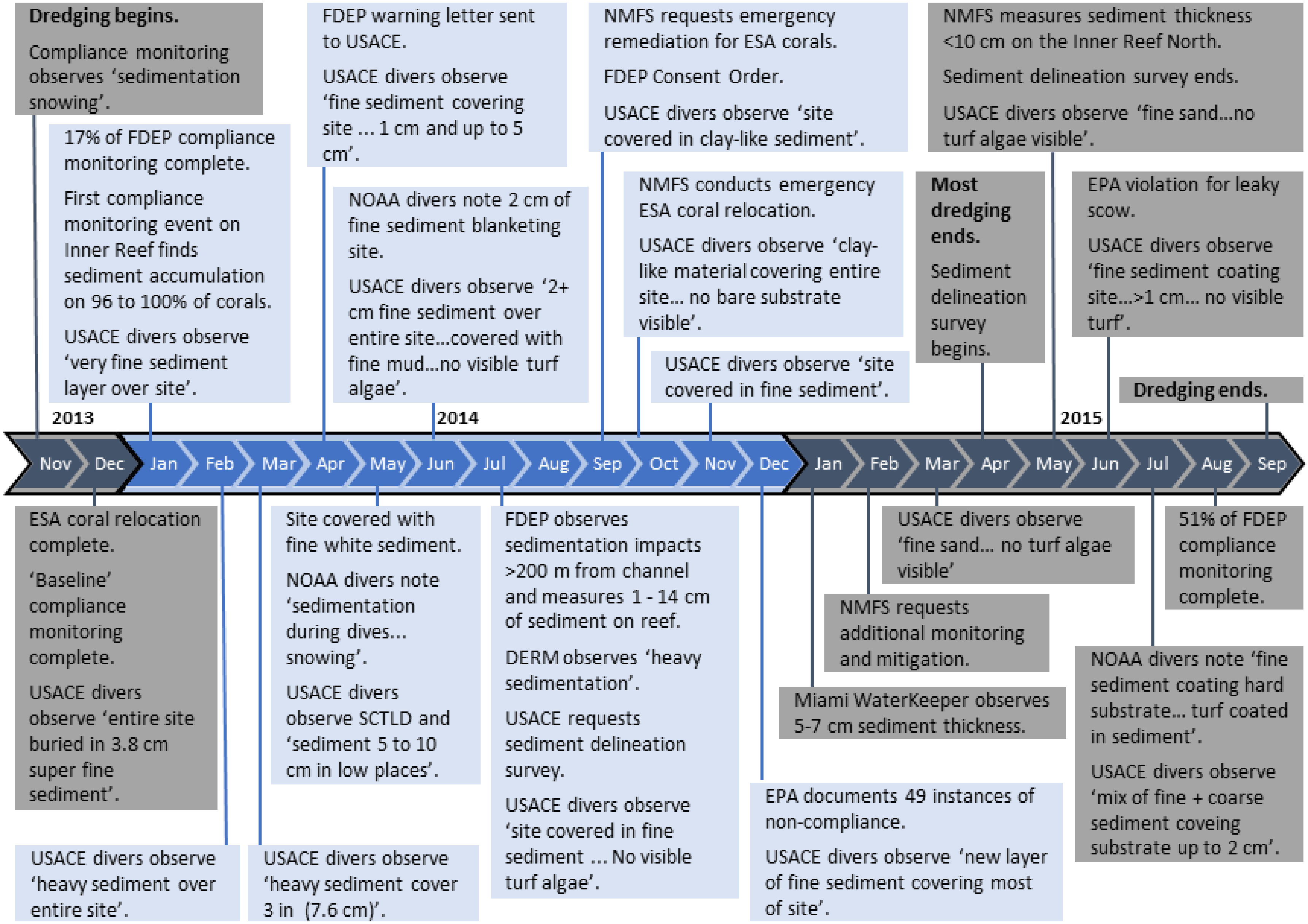
12.0 Appendix

There are two items in this Appendix. The next page contains an abbreviated timeline of events during Port of Miami Phase III dredging, November 2013 through September 2015. Events include required regulatory actions, agency actions, agency/NGO observations, as well as sediment delineation and contract diver observations at FDEP channel-side compliance sites. Events in bold represent dredge project milestones. The following page contains the table referred to as Appendix in Figure 3, Table 2, and Table 3.



Dredging begins.

Compliance monitoring observes 'sedimentation snowing'.

17% of FDEP compliance monitoring complete.

First compliance monitoring event on Inner Reef finds sediment accumulation on 96 to 100% of corals.

USACE divers observe 'very fine sediment layer over site'.

FDEP warning letter sent to USACE.

USACE divers observe 'fine sediment covering site ... 1 cm and up to 5 cm'.

NOAA divers note 2 cm of fine sediment blanketing site.

USACE divers observe '2+ cm fine sediment over entire site...covered with fine mud...no visible turf algae'.

NMFS requests emergency remediation for ESA corals.

FDEP Consent Order.

USACE divers observe 'site covered in clay-like sediment'.

NMFS conducts emergency ESA coral relocation.

USACE divers observe 'clay-like material covering entire site... no bare substrate visible'.

USACE divers observe 'site covered in fine sediment'.

Most dredging ends.

Sediment delineation survey begins.

NMFS measures sediment thickness <10 cm on the Inner Reef North.

Sediment delineation survey ends.

USACE divers observe 'fine sand...no turf algae visible'.

EPA violation for leaky scow.

USACE divers observe 'fine sediment coating site...>1 cm... no visible turf'.

Dredging ends.

ESA coral relocation complete.

'Baseline' compliance monitoring complete.

USACE divers observe 'entire site buried in 3.8 cm super fine sediment'.

USACE divers observe 'heavy sediment over entire site'.

USACE divers observe 'heavy sediment cover 3 in (7.6 cm)'.

Site covered with fine white sediment.

NOAA divers note 'sedimentation during dives... snowing'.

USACE divers observe SCTLD and 'sediment 5 to 10 cm in low places'.

FDEP observes sedimentation impacts >200 m from channel and measures 1 - 14 cm of sediment on reef.

DERM observes 'heavy sedimentation'.

USACE requests sediment delineation survey.

USACE divers observe 'site covered in fine sediment ... No visible turf algae'.

EPA documents 49 instances of non-compliance.

USACE divers observe 'new layer of fine sediment covering most of site'.

Miami WaterKeeper observes 5-7 cm sediment thickness.

NMFS requests additional monitoring and mitigation.

USACE divers observe 'fine sand... no turf algae visible'

NOAA divers note 'fine sediment coating hard substrate... turf coated in sediment'.

USACE divers observe 'mix of fine + coarse sediment coveing substrate up to 2 cm'.

51% of FDEP compliance monitoring complete.

Average percent of observations of each bottom cover class (percent cover) and average sediment depth (cm) at each of the 23 sites. Bolded site names indicate reference sites. Colors and order of cover classes corresponds to Figure 3, Table 2, and Table 3.

Name	Algal Turf	Coral	Sponge	Other	Macro-algae	Rubble	Sediment Over Hardbottom	Sediment Depth (cm)
IRN-9500-RR	45	38	9	4	1	0	3	0.32
IRN-9500-LR	36	36	11	5	11	0	1	0.30
IRN-1050-LR	4	17	6	7	9	5	52	1.03
IRN-700-LR	4	23	23	4	0	0	47	2.10
IRN-500-RR	19	34	16	5	0	0	26	1.30
IRN-500-LR	17	26	13	8	0	0	37	0.95
IRN-300-RR	14	28	17	8	0	0	33	0.92
IRN-300-LR	5	20	13	19	0	0	43	0.73
IRN-200-RR	14	18	4	6	0	0	58	1.68
IRN-200-LR	4	11	5	3	1	0	76	4.20
IRN-100-RR	14	15	14	7	0	0	50	1.86
IRN-100-LR	10	18	9	4	2	0	56	1.65
IRS-100-RR	12	9	14	2	0	2	61	2.81
IRS-100-LR	17	19	12	12	7	3	30	1.26
IRS-200-RR	2	20	7	23	0	10	38	0.80
IRS-200-LR	15	22	10	13	8	0	32	1.08
IRS-300-RR	19	16	14	9	2	0	39	1.16
IRS-300-LR	0	19	5	7	11	4	55	1.04
IRS-700-RR	8	11	6	7	19	44	6	0.74
IRS-700-LR	18	17	2	11	11	34	8	0.32
IRS-1375-RR	38	13	11	9	7	4	19	0.71
IRS-1375-LR	41	21	9	16	4	0	10	0.94
IRS-2200-LR	21	16	11	17	23	9	3	0.66