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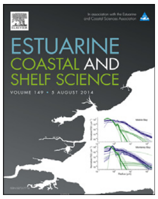

Seabed texture and composition changes offshore of Port Royal Sound, South Carolina before and after the dredging for beach nourishment

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ABSTRACT

Beach nourishment has been a strategy widely used to slow down coastal erosion in many beaches around the world. The dredging of sand at the borrow site, however, can have complicated physical, geological and ecological impacts. Our current knowledge is insufficient to make accurate predictions of sediment infilling in many dredging pits due to lack of detailed sediment data. Two sites in the sandy shoal southeast of Port Royal Sound (PRS) of South Carolina, USA, were sampled 8 times from April 2010 to March 2013; one site (defined as 'borrow site') was 2 km offshore and used as the dredging site for beach nourishment of nearby Hilton Head Island in Beaufort County, South Carolina, and the other site (defined as 'reference site') was 10 km offshore and not directly impacted by the dredging. A total of 184 surficial sediment samples were collected randomly at two sites during 8 sampling periods. Most sediments were fine sand, with an average grain size of 2.3 phi and an organic matter content less than 2%. After the dredging in December 2011–January 2012, sediments at the borrow site became finer, changing from 1.0 phi to 2.3 phi, and carbonate content decreased from 10% to 4%; changes in mud content and organic matter were small. Compared with the reference site, the borrow site experienced larger variations in mud and carbonate content. An additional 228 sub-samples were gathered from small cores collected at 5 fixed stations in the borrow site and 1 fixed station at the reference site 0, 3, 6, 9, and 12 months after the dredging; these down-core sub-samples were divided into 1-cm slices and analyzed using a laser diffraction particle size analyzer. Most cores were uniform vertically and consisted of fine sand with well to moderately well sorting and nearly symmetrical averaged skewness. Based on the analysis of grain size populations, 2 phi- and 3 phi-sized sediments were the most dynamic sand fractions in PRS. Mud deposition on shoals offshore of PRS presumably happens when offshore mud transport is prevalent and there is a following rapid sand accumulation to bury the mud. However, in this borrow site there was very little accumulation of mud. This will allow the site to be used in future nourishment projects presuming no accumulation of mud occurs in the future.

1. Introduction

Beaches are common sandy sedimentary environments on many continental margins worldwide. The condition and stability of these beaches form an integral part of coastal economies, primarily by providing support for local tourism and infrastructure protection, particularly for the East and Gulf Coasts of the USA. Coastal erosion along developed shorelines, however, can have adverse effects on beaches and beach-related recreational and economic benefits. Like many tropical and subtropical areas around the world, the East and Gulf Coasts of the USA have a rich history of tropical storms and hurricanes. Depending on the pathways, timing, and intensities of storms, coastal erosion during these extreme meteorological and oceanographic conditions can be severe, resulting in a significant amount of sediment eroding from the

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beach to the offshore inner continental shelf, and/or onshore into the back-barrier system as overwash. In addition, relative sea-level rise during the past several decades has exacerbated the beach erosion problem in many areas around the world.

Besides hard structures like jetties, groins, breakwaters and sea walls, many coastal states in the USA have adopted beach nourishment as the predominant strategy for addressing adverse effects of coastal erosion. Although there are various definitions, beach nourishment in South Carolina is generally defined as '*the artificial establishment and periodic nourishment of a beach with sand that is compatible with the existing beach in a way so as to create a dry sand beach at all stages of the tide*' (DHEC, 2010). A typical nourishment project consists of dredging and transferring beach-compatible sand from offshore sites (often called 'borrow' areas) to the beach. An ideal borrow location should be close to the beach to minimize the transferal costs, and generally consists of high quality sediment, e.g., >90% of sand, well sorted, low shell content and low organic matter (Bergquist et al., 2009).

The dredging for beach nourishment, however, can have complicated physical and biological impacts on the borrow areas. For example, drastic bathymetric changes may cause localized scouring and hydrodynamic variation in the borrow pits; this needs to be considered in diving, fishing and navigation activities. The borrow pits may lead to collapse or mass failure of nearby seafloor, which is a potential geological hazard to manmade structures like gas pipelines and oil platforms; therefore, a setback buffer zone needs to be defined in many borrow areas to minimize the impact of borrow areas to nearby manmade structures (Nairn et al., 2005). In the southeastern US, dredging nearshore shoals often leads to the filling of the borrow sites with mud, thereby changing the physical and ecological characteristics of the sites (Bergquist et al., 2009). Benthic communities are generally totally removed by the dredging process, and it may take months to years for benthic communities to be reestablished to pre-dredge conditions, potentially impacting fishery resources that rely on those benthic fauna (Bergquist et al., 2009).

The focus of this study is South Carolina, which shares its similarity with many states in the Gulf and East Coasts of USA. South Carolina has a rich history of hurricanes and storms, with thirty severe storms making landfall in coastal areas of South Carolina between 1871 and 1999 (Gayes, 1990). Since 1985, at least 24 nourishment projects have occurred in South Carolina, with a total of over 21 million m^3 of sand added to beaches at a price of nearly $225 million U.S. dollars. Hilton Head Island, Myrtle Beach, and Folly Beach of South Carolina have had the most sand applied, representing a combined 76% of the South Carolina's total (DHEC, 2010). However, coastal sand resources in South Carolina suitable for beach nourishment are limited; efficient and low-impact use of those resources is therefore important to the sustainability and management of future nourishment projects.

Previous monitoring efforts have shown that borrow areas near Hilton Head Island and Myrtle Beach can fail to refill in a timely manner, occasionally refill rapidly with sand, refill with high concentrations of mud, or refill with laminated mud and sand (e.g., Bergquist et al., 2009; McCoy et al., 2010). Refilling with mud and very slow refilling can prevent the sustainable reuse of the borrow area, forcing future projects to seek sand sources further offshore at greater cost, and impacting the ecology of additional areas of seafloor. Seabed texture and composition as well as the location and design of the borrow pits may influence the rate of infilling, source and type of sediments refilling the pit, and the recolonization of disturbed sediments by background fauna. Unfortunately few studies have monitored the seabed sediment texture and composition changes *repetitively* both before and after the dredging activities, and our current knowledge is insufficient to make accurate predictions of infilling processes after the dredging activities.

During the past several decades there have been many physical, geological, and biological studies at both nourished beaches and borrow areas in South Carolina (e.g., Kana, 1988; Bruun, 1988; Van Dolah et al., 1992; Van Dolah et al., 1998; Jutte et al., 2001; Byrd, 2004; Bergquist et al., 2009; McCoy et al., 2010; Obelcz et al., 2010). In addition, many scientists have been using modeling and observational (e.g., geophysical surveys, corings, moorings, and tripods) methods to study sediment transport processes in estuary, marsh, inlet, and shelf sedimentary environments (Ojeda et al., 2004; Gardner and Kjerfve, 2006; Murphy and Voulgaris, 2006; Wargo and Styles, 2007; Schwab et al., 2008; Haas and Warner, 2009; Wren et al., 2011; Kumar et al., 2011; Warner et al., 2012). Although many beach nourishment projects conducted in South Carolina have been monitored, most of the post-dredge monitoring has been limited to the first year of post-nourishment recovery (DHEC, 2010). In order to improve future beach nourishment monitoring in South Carolina, DHEC (2010) suggested '*pre- and post-monitoring for all beach nourishment projects, for both offshore (borrow area) and onshore (beach and surf zone) areas, including downdrift shoreline changes*'.

The overall objectives of this study are to: 1) collect sediment samples *inside* and *outside* of borrow areas repetitively *before* and *after* the dredging on multiple sites offshore of Port Royal Sound, South Carolina; 2) determine the changes of surficial sediment texture and composition (e.g., carbonate and organic matter) in response to dredging; 3) investigate down-core sediment texture variations to see if mud-sand laminations can be preserved; and 4) determine whether mud preservation occurred at the borrow site on the sandy shoal. We chose Port Royal Sound as our study site because: i) this area was used for beach nourishment of Hilton Head Island where multiple beach nourishments have been performed; ii) substantial data have been collected in the area over the past two decades; iii) South Carolina Department of Natural Resources (SCDNR) staff associated with this study had worked with the contractor responsible for the PRS borrow site design to configure it so that the potential accumulation of mud in the borrow site was minimized; and iv) ebb tidal deltas are often the targeted areas for beach nourishment and large volumes of sand can be exchanged among the ebb-tidal deltas, tidal channels, and adjacent beaches (Miner et al., 2009). Our findings from this study may shed some light on the studies in other borrow areas near the ebb tidal deltas around the world, and can help the design and permitting processes of future beach nourishment projects in South Carolina and elsewhere. In addition, our data can be used to validate or calibrate the morphological or sediment transport models for the predictions of borrow pit infilling process in the future.

2. Background

Hilton Head Island (HHI, Fig. 1), located in Beaufort County of southwestern South Carolina, USA, is a barrier island with ~20 km of sandy beach shoreline next to the Atlantic Ocean. The island supports a population of approximately 34,000 residents and a tourist industry worth nearly one billion dollars annually. Major sedimentary environments include sandy "drum-stick" barrier islands, tidal inlets, tidal creeks (mostly muddy sand and sandy mud) and muddy marshes as well as a sandy ebb tidal delta (half-circle shaped, over 15 km wide, Fig. 1). East of HHI is Port Royal Sound (PRS), which is a large well-mixed estuary in southwestern South Carolina. The PRS receives only a small freshwater input from the Coosawhatchie River and consequently has high salinity throughout (Crotwell and Moore, 2003). The PRS bottom is underlain by fine- and coarse-grained sand; the percentage of mud

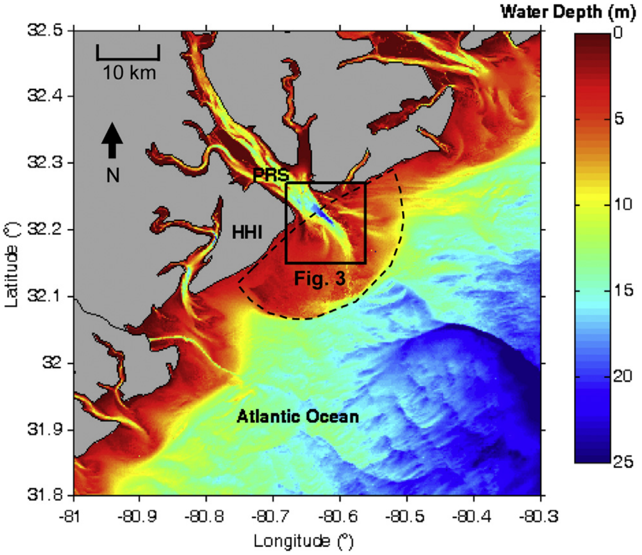

Fig. 1. Study area of Port Royal Sound (PRS) of South Carolina, USA. Bathymetry data are from NOAA National Geophysical Data Center. Dashed half circle is the ebb tidal delta offshore of PRS. HHI, Hilton Head Island.

normally is 5% or less in open water areas of the PRS but increases dramatically near marshes or headwaters of tidal creeks (SCWRC, 1972). Milliman (1972) reported that the inner shelf offshore of PRS is covered by very-fine to medium-fine sand, with 0–25% of carbonate and 11–25% of feldspar/(feldspar + quartz) ratios in minerals. A recent usSEABED study by the U.S. Geological Survey showed that over 80% of surficial sediment inside of PRS and in the nearby inner continental shelf is composed of sand (Fig. 2; Reid et al., 2005), although their sampling spacing was approximately 10 km, which is not high enough to investigate the detailed seabed changes for dredging activities.

In PRS and the nearby coastal waters, dominant wind directions change during four seasons of a year. Strong winds are typically alternating in the longshore direction (southwest to northeast) through the winter, spring and fall, with summer winds being relatively calm. Records from a nearby NOAA NDBC buoy at Fripp Nearshore (FRP 2, http://www.ndbc.noaa.gov/station_page.php?station=41033, about 30 km east of HHI), for example, show an average wind speed of 5.6 m/s, with peak speeds around 15 m/s. This region is dominantly controlled by tides and waves. Mean spring tidal range in the area is about 2.1 m based on the NDBC tidal station at Capers Island, SC (http://tidesandcurrents.noaa.gov/noaatidepredictions/NOAATidesFacade.jsp?Stationid=8668837); tidal currents are energetic, especially near the PRS tidal inlet. Because of its large tidal prism, this area is notoriously difficult to observe, with diving only being able to be performed during slack water periods. Wave fields in the area change quickly because of rapid wave refraction and shoaling around the ebb tidal deltas before approaching the top of the complex sandy shoals (Fig. 1).

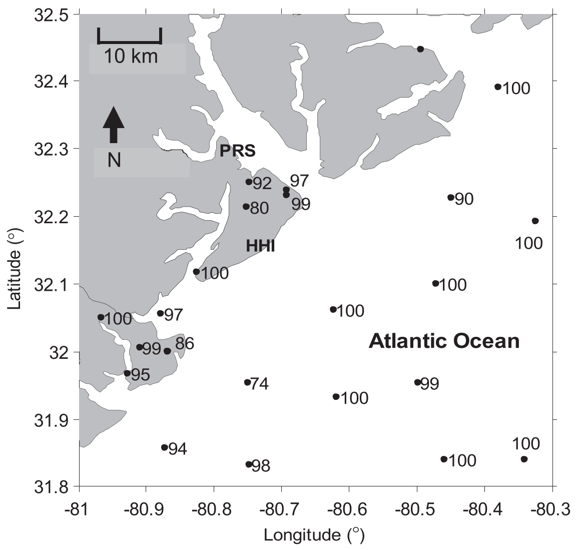

Fig. 2. Sand percentages (%) of surficial sediment samples based on the usSEABED report (Reid et al., 2005). Sand content in the study area is generally greater than 80%. PRS, Port Royal Sound; HHI, Hilton Head Island.

Like many other beach cities along the eastern U.S. coast, the Town of HHI has been maintaining healthy beach conditions principally through sand restoration and nourishment. To date, the Town of HHI has completed four major beach nourishment projects in 1990, 1997, 2006–2007 and 2011–2012, respectively. The recovery of the borrow areas for pre-2007 projects varied substantially from slow to rapid infilling, and from little to substantial changes in sediment composition and biological community structure (Van Dolah et al., 1992; Van Dolah et al., 1998; Jutte et al., 2001; Bergquist et al., 2009). A common problem observed before 2007, however, was the accumulation of muds in the borrow pits, which prevented the future reuse for beach nourishment.

Between 2007 and 2011 Olsen Associates, Inc. (www.olsen-associates.com/) worked with the Town of HHI, and led multiple comprehensive studies to identify a new borrow area (polygon in Fig. 3B) east of PRS tidal inlet, including bathymetric surveys, vibracoring, seismic profiling, sediment analyses, numerical modeling and others. Olsen (2009) collected 55 vibracores in this borrow area, and reported that sediment is mainly sandy, with numerous mud (i.e., silt/clay) patches interspersed with sand. Based on this vibracoring study and additional seismic profiling survey, Olsen (2009) concluded that complex buried tidal channel sediment was mixed with some estuarine inputs in the geological depositional history. In 2011, this borrow area was approved by the State of South Carolina and the US Army Corps of Engineers to serve as a sand source for HHI beach nourishment in 2011–2012. The borrow area was designed to mine sands from the shoal at the edge of the PRS entrance channel using a configuration that was hoped to minimize the accumulation of muds through natural ebb and flood tide scouring of the borrow pit. The dredging began in December 2011 and was completed in January 2012. The project included the removal of about 0.76 million m^3 of sand from the sandy shoals (Olsen, 2013). The shoals were dredged to an absolute elevation of −6.1 m National Geodetic Vertical Datum of 1929 (NGVD29) that resulted in an average deepening of the seabed of about 3.0 m. Olsen (2013) performed bathymetric surveys 14 months after the dredging and found that between January 2012 and March 2013 there was ~1.2 m sediment deposition near the central part of borrow area and ~1.2 m sediment erosion along the northern edge.

3. Methods

The borrow area for 2011–2012 HHI nourishment is about 2 km offshore of the PRS and is defined as the ‘Borrow Site’ in this study (polygon in Fig. 3B). Another study site is about 10 km offshore of PRS and was selected to have the same shape and size as the borrow site. This site is defined as the ‘Reference Site’ because no

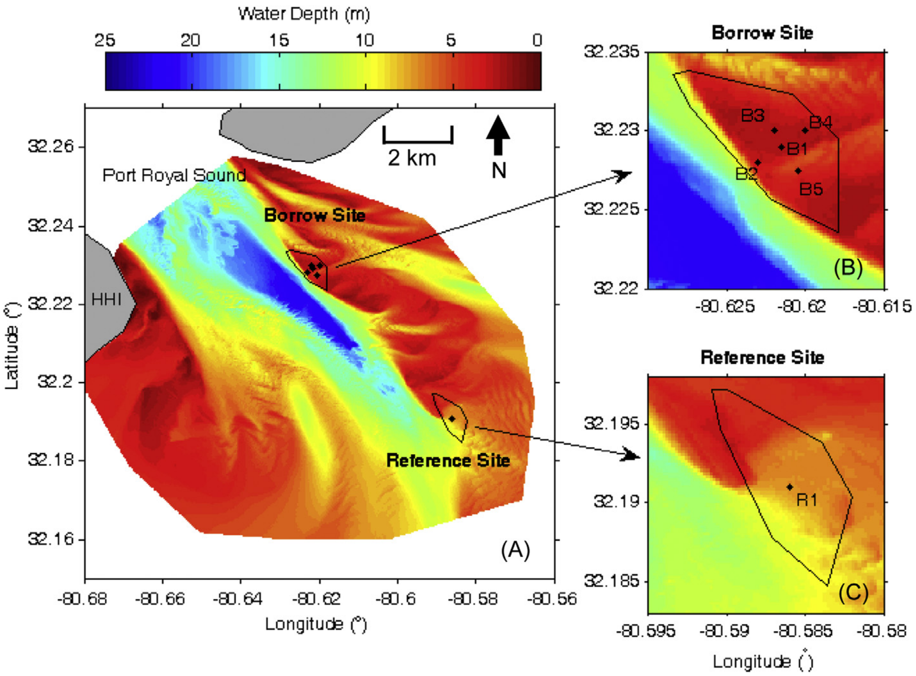

Fig. 3. (A) Bathymetry offshore of the Port Royal Sound (PRS). Bathymetric data were provided by Olsen Associates, Inc and collected in 2007/08. Complex sandy shoals are northeast and southwest of the tidal inlet of PRS. Two polygons at borrow and reference sites are the study areas. (B–C) Stations B1–B5 and R1 are at borrow and reference sites, respectively. HHI, Hilton Head Island.

dredging activities were conducted in this area (polygon in Fig. 3C).

Two strategies were used in sediment sampling: ‘random’ and ‘fixed’. During each cruise, 10 samples were collected within the boundaries of borrow and reference sites, with the longitudes and latitudes of the samples randomly selected using ArcGIS, a Geographic Information System (GIS) program. All random sampling locations at borrow and reference sites are shown in Fig. 4. A Young grab sampler was used to collect the seabed sediment up to approximately 10 cm deep (Fig. 5), and sediment samples were

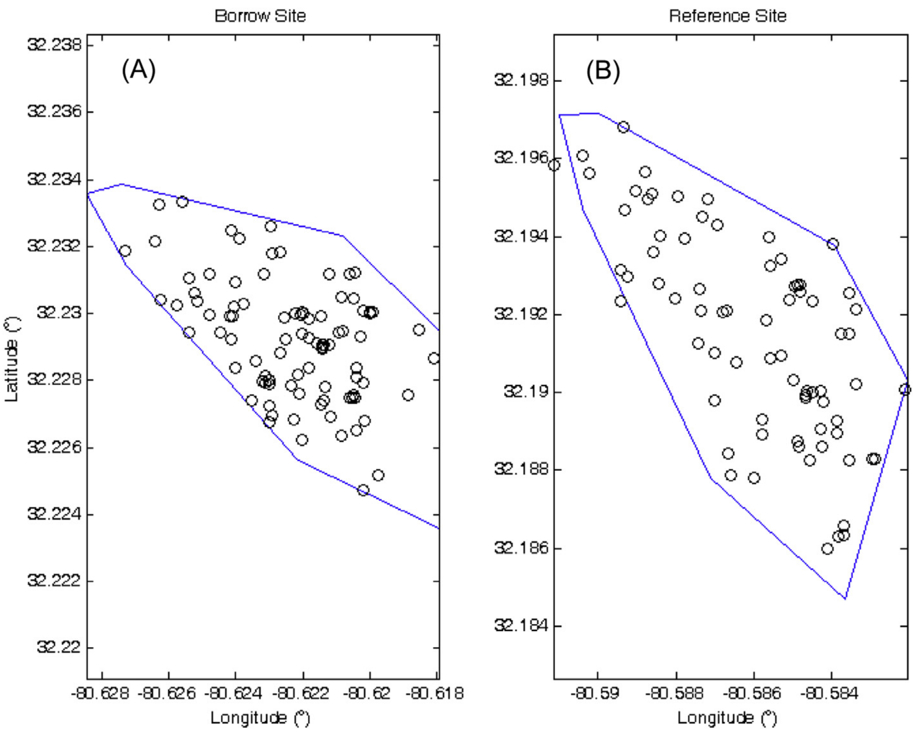

Fig. 4. Random sediment sampling locations at borrow (A) and reference (B) sites during 8 periods: 18, 6 and 0 months before dredging as well as 0, 3, 6, 9 and 12 months after the dredging.

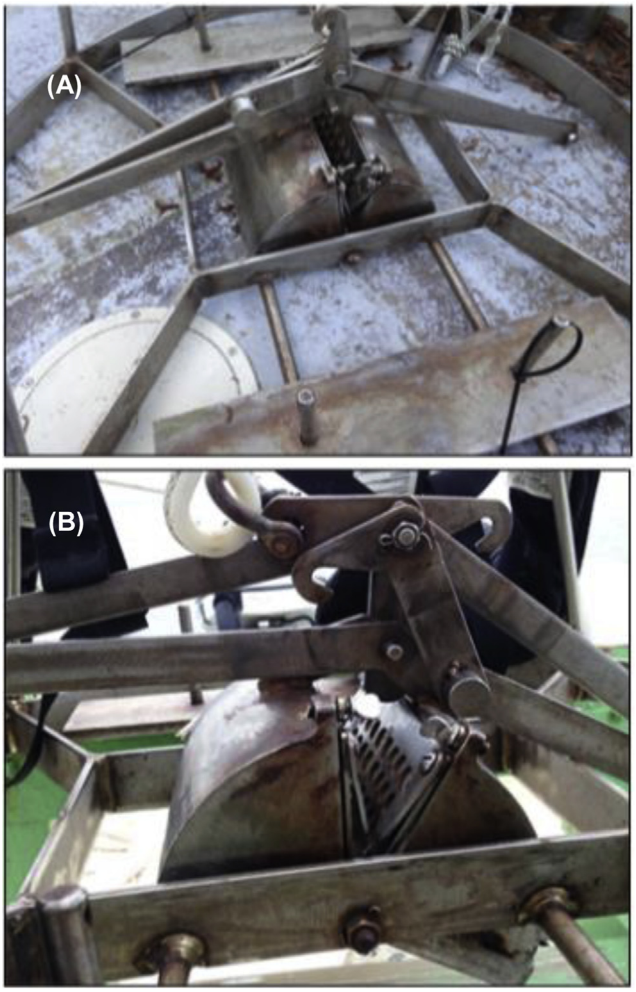

Fig. 5. (A) Top and (B) side views of the Young Grab used in sediment samplings.

transferred into sediment bags for sieve grain size, carbonate and organic matter analyses in the laboratory.

Sediment samples were also collected at 5 fixed stations (B1–B5, Fig. 3B) in the borrow site and 1 fixed station (R1, Fig. 3C) in the reference site, respectively. The same Young grab was used to collect the sediment, with open-end syringes pushed through the sediment (perpendicular to sediment surface) to collect small sediment cores at variable lengths of 5–10 cm. Sediment in the syringes was then sliced into 1 cm intervals and stored in sediment bags for laser grain size analyses in the laboratory.

Samples from random stations were analyzed for weight percentages of sand (−1 to 4 phi), silt (4–8 phi), clay (>8 phi), and calcium carbonate ($CaCO_3$) using procedures described in Folk (1980) and Pequegnat et al. (1981); phi scale was defined as $phi = -log_2$ *(grain diameter in mm)* according to the Udden-Wentworth phi classification (Brown and McLachlan, 1990). The calcium carbonate determination of only the sand fraction is conducted by acidification in 10% HCl. The sand fractions were dry-sieved using a Ro-tap Mechanical Shaker, and mean grain size was determined by using fourteen 0.5 phi-interval sieves (−2.0 phi pebble gravel to 4.0 phi very fine sand); mud fraction was analyzed using the pipette method. Total organic matter was determined by the ‘loss-on-ignition’ method, using a separate subsample by weighing a portion of the subsample after drying in a 70 °C oven for 24 h, combusting it at 550 °C in a muffle furnace for 2 h, and re-weighing it, following the methods described by Plumb (1981).

Samples from the fixed stations were analyzed using a Beckman–Coulter laser diffraction particle size analyzer (Model LS 13 320). About twenty ml of deionized water was added to ~1 g of sediments in a beaker and samples were soaked for 24 h. Then samples were treated on a Vortex Mixer for 5 min and transferred to a −1 phi (2000 μm) sieve to remove any particles (e.g., shell fragments) coarser than 2000 μm. Neither acid nor hydrogen peroxide was used to remove carbonate or organic matter in this analysis. When samples were loaded to the chamber of the laser analyzer, the sonication was turned on to ensure the complete disaggregation. This laser analyzer had a detection range of 0.02–2000 μm and produced grain size data in 1/8 phi resolution, compared with ½ phi intervals in the above sieve analyses for samples from random stations. Mean grain size, standard deviation, skewness, and kurtosis were calculated using the methods from Folk (1980).

Dredging of borrow area occurred over a 3 month period between October 2011 and January 2012. Three sampling efforts were conducted before the beginning of dredging: April 1, 2010, March 23, 2011, and October 13, 2011, defined as 18, 6 and 0 months pre-dredging, respectively. Five sampling efforts were conducted after the end of dredging: February 14, 2012, May 15, 2012, August 24, 2012, November 29, 2012 and March 5, 2013, defined as 0, 3, 6, 9, and 12 months post-dredging, respectively. The 0 month pre-dredging and 0 month post-dredging were about 4 months apart. Random samples were collected during all eight sampling periods, but fixed samples were collected only during the 5 post-dredging periods.

4. Results

4.1. Samples from random stations

A total of 184 surficial samples were collected at random stations. Not surprisingly most samples were comprised of sand and

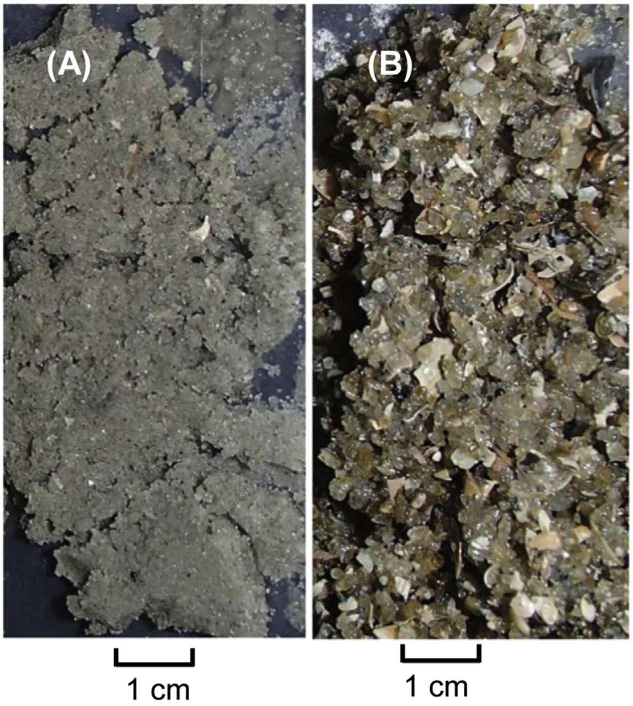

Fig. 6. Pictures of sandy (A) and shelly (B) sediment samples collected at borrow site offshore of Port Royal Sound. Courtesy of Martin Levisen from South Carolina Department of Natural Resources.

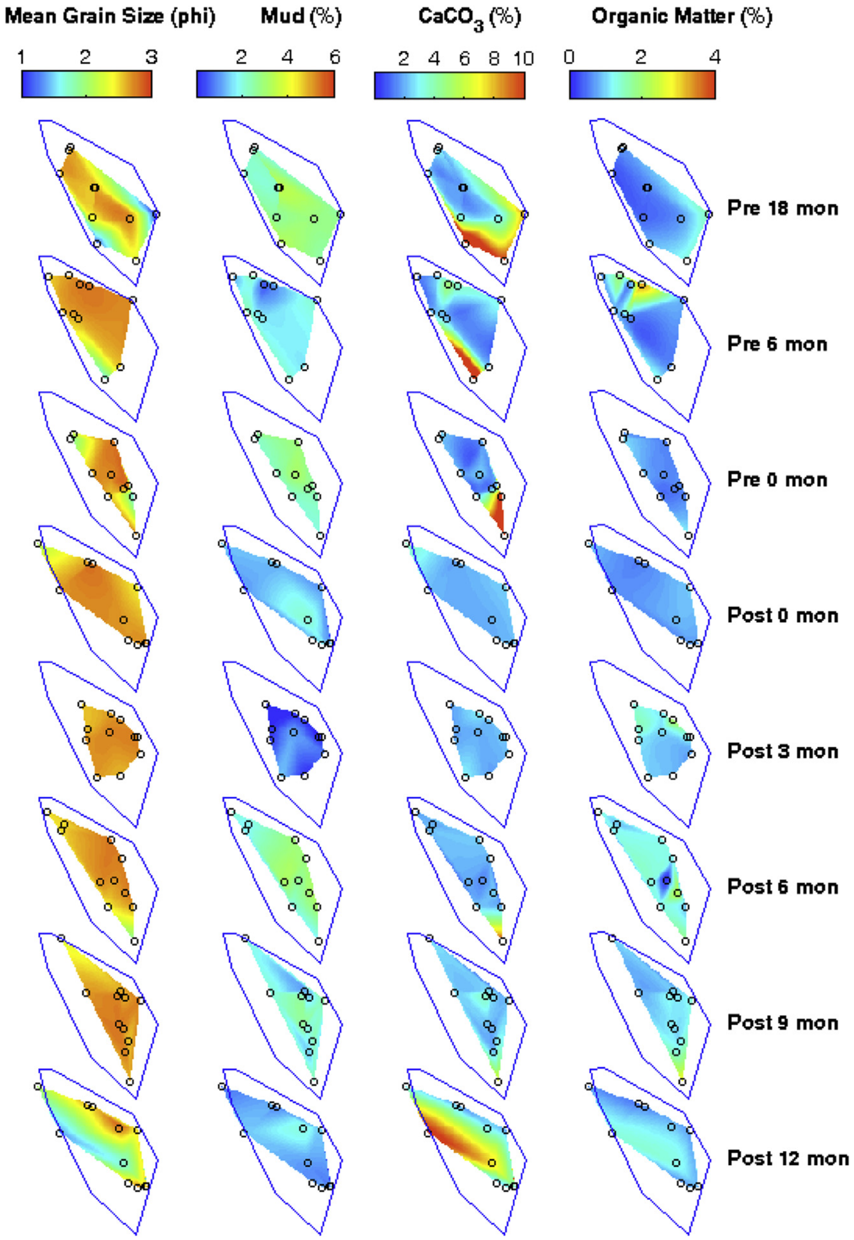

Fig. 7. Reference site variations of mean grain size, mud, $CaCO_3$ and organic matter percentages during 8 periods: 18, 6 and 0 months before dredging as well as 0, 3, 6, 9 and 12 months after the dredging. Circles represent the sampling locations.

the average mean grain size of these 184 samples was 2.3 phi (fine sand); a typical sediment sample can be seen in Fig. 6A. Average carbonate percentage of all 184 samples was 4.8%, however, 3 out of 184 samples contained more than 20% carbonate; a high carbonate example is shown in Fig. 6B. Average organic matter of all samples was only 1.1%, and the highest was 3.7%.

4.1.1. *Reference site*

Mean grain size was fairly homogeneous, varying between 2 phi and 3 phi from 18 months before the dredging to 12 months after the dredging. Fig. 7 shows both temporal and spatial variations of mean grain size, mud content, carbonate and organic matter at the reference site. Mud content was generally less than 3% throughout most of our study periods. Carbonate content was less than 5% during most periods, except the three pre-dredging and the 12 month post-dredging periods. Organic matter content was always less than 3%.

4.1.2. *Borrow site*

Temporal and spatial variations at the borrow site are shown in Fig. 8. Coarse sand (around 1 phi) was found in the northwestern side of borrow site before the dredging. After dredging, seabed sediments became finer (around 2.3 phi). Mud content averaged 6% in the entire borrow site 18 months before the dredging but it decreased to <2% 12 months later, and stayed low for the rest of the study period. Carbonate was very patchy in space and highly variable in time: many samples contained more than 10% carbonate and 3 samples were composed of >20% carbonate. Carbonate decreased dramatically 0 and 3 months after the dredging (Fig. 8). Organic matter stayed below 3% all the time, but it decreased to

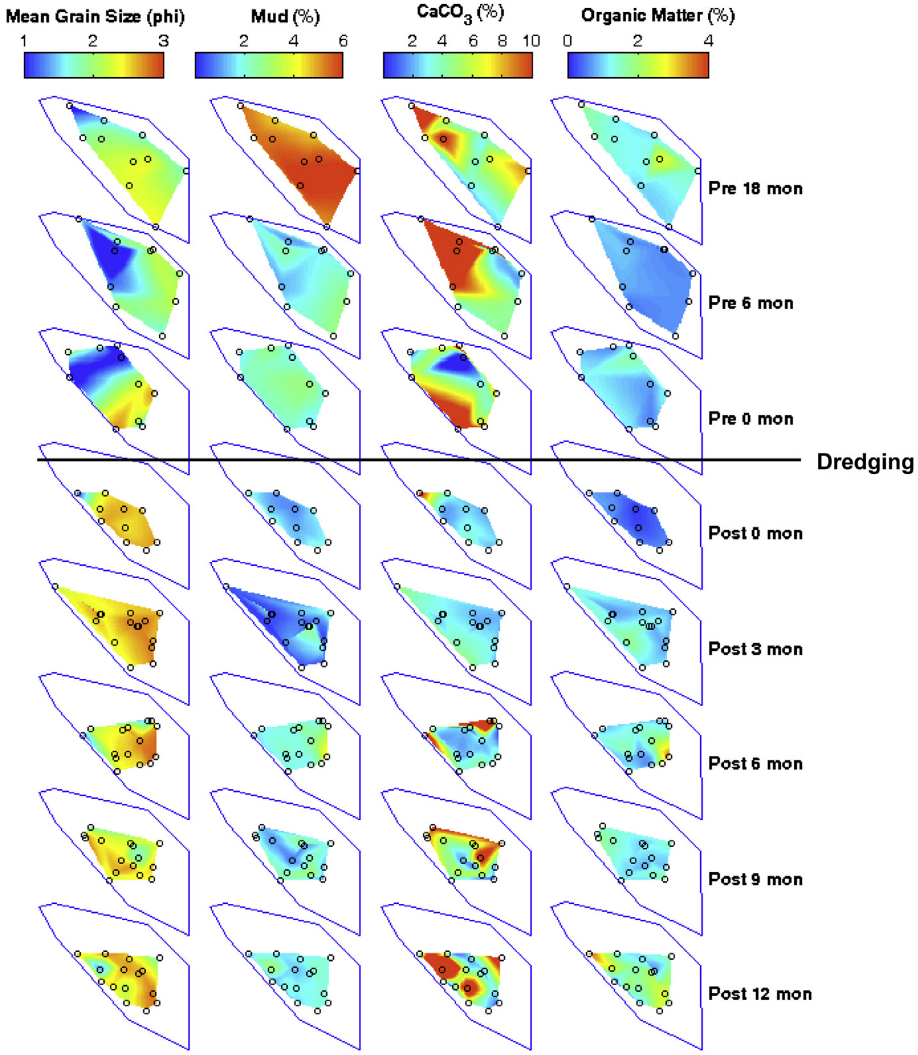

Fig. 8. Borrow site variations of mean grain size, mud, CaCO$_3$ and organic matter percentages during 8 periods: 18, 6 and 0 months before dredging as well as 0, 3, 6, 9 and 12 months after the dredging. Circles represent the sampling locations, and the horizontal line indicates the dredging from November 2011 to January 2012.

almost 0% immediately after dredging and restored back to pre-dredging levels 9–12 months later (Fig. 8).

4.2. Samples from fixed stations

Mean grain size was about 2.2 phi from the top to the bottom of most cores at the fixed stations, but slightly coarser sand of about 1.8 phi was found at stations B3 and B4 about 9 and 12 months after the dredging, respectively. A thin layer of mud-sand mixture was found at the bottom of station B2 in the period of 12 months after the dredging (Fig. 9). Station R1 at the reference site has the most consistent grain size among six fixed stations with literally no variation in mean grain size with depth.

Standard deviation was in the range of 0.35–0.71 phi in most stations, indicating well to moderately well sorted sediment, according to the definition of Folk (1980). The mud-sand mixture layer at the bottom of station B2 was found to have the highest standard deviation of 2 phi and thus very poor sorting. Skewness was highly variable, both positively and negatively skewed, but the down-core averages seemed to be within the range of +0.10 to −0.10, which is nearly symmetrical (Folk, 1980). Kurtosis was in the range of 1–2 for most core samples.

Detailed grain size distributions can be seen in Fig. 10. Prominent orange bars in the color plots reveal the dominant peaks on the grain size distribution curves as well as the well sorting of sediment. The peak of the mud-sand mixture layer at the bottom of station B2 shifted to about 6 phi, indicating the presence of medium silt in sediment (Fig. 10). Mosaic colors can be seen around 0 phi in many plots (e.g., 3 months post-dredging), indicating the random presences of coarse sand particles.

5. Discussion

5.1. Comparison of borrow with reference sites

Although the borrow and reference sites share the same size and shape, they are 2 and 10 km seaward of the shoreline, respectively (Fig. 3). Because of its close proximity to the PRS estuaries, the borrow site is more likely to be impacted by estuarine inputs. Eighteen months before the dredging, for instance, the mud content was approximately 6% throughout the borrow site, but no mud was found at the reference site (Figs. 7 and 8). Mud at the borrow site, however, disappeared in the next sampling period, reflecting the dynamic nature of the seabed in such an

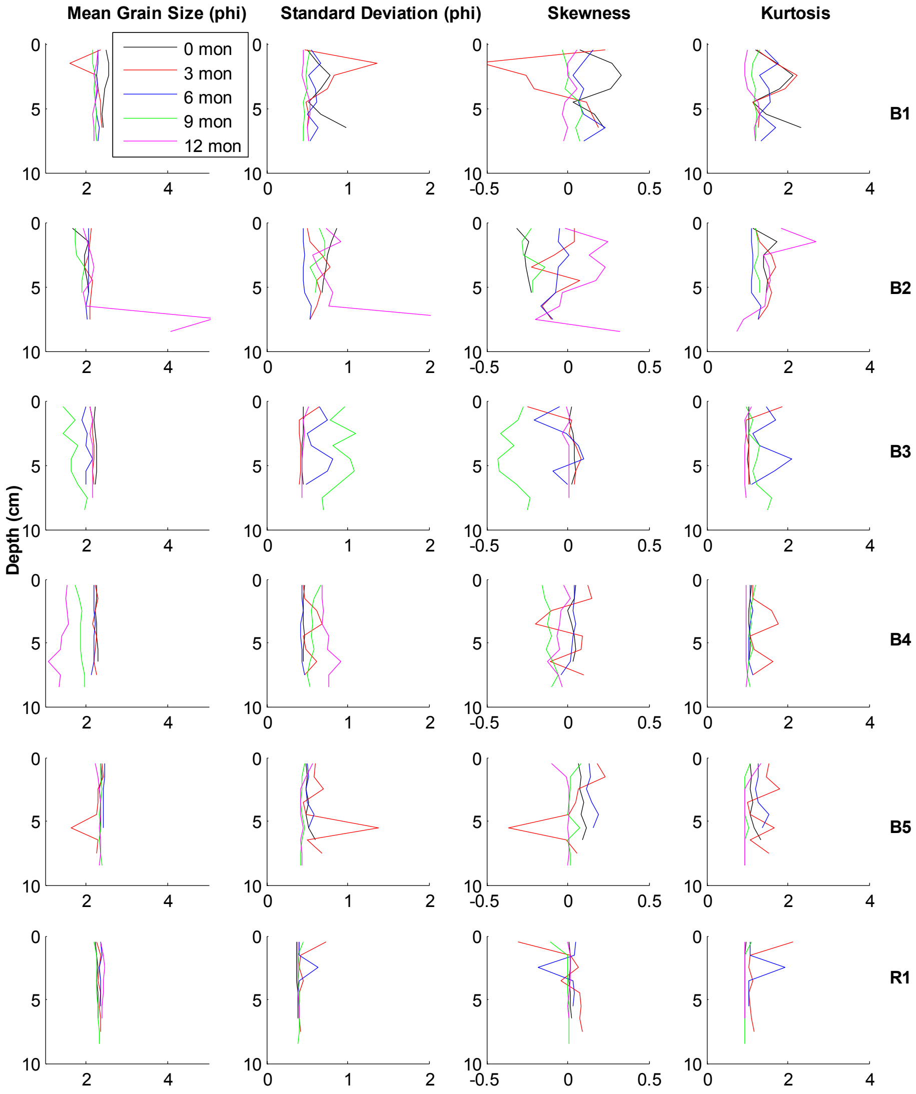

Fig. 9. Borrow and reference sites down-core changes in mean grain size, standard deviation, skewness and kurtosis at 0, 3, 6, 9 and 12 months after the dredging. See Fig. 3 for the locations of B1–B5 and R1.

energetic environment. In addition, the carbonate content of the borrow site was generally higher and more variable than that of the reference site (Figs. 7 and 8). Thus, natural carbonate and mud variations seem to be more prominent in the borrow site than in the reference site.

Grain size distribution curves from the center of borrow site at Station B1 can be compared with these from the center of reference site at Station R1 (Fig. 11A and B), and these curves can be used to calculate various parameters (e.g., mean grain size, standard deviation and skewness). Standard deviation of the grain size is a mathematical representation of the sediment sorting, i.e., a measure of the range of grain size distribution and the magnitude of the spread or scatter around the mean size. The standard deviations at the reference site were generally smaller than the five stations at the borrow site, indicating better sorting at the reference site. Skewness is a definition of the degree of asymmetry in a grain size histogram; positively skewed samples reflect grain sizes that are skewed to the positive end of the phi scale, which corresponds to finer grain sizes. Samples at the fixed stations were either positively or negatively skewed, but the averages of the stations seemed to be close to 0, i.e., nearly symmetrical. Kurtosis is the ratio between the spread in the middle part and the spread in the tails of the distribution curves. Most samples' kurtosis values were leptokurtic (between 1.1 and 1.5), meaning that the curves have more acute peaks around the means and fatter tails.

The variations on grain size distribution curves can also be used to study the sediment transport processes. Xiao et al. (2006), for instance, used the ‘grain-size vs. standard deviation’ method to identify the grain size intervals with the highest variability in sedimentary records. Following their method, we compiled data from the samples collected during 5 post-dredging periods at stations B1 and R1, respectively (Fig. 11A and B), and calculated the standard deviations of the grain size intervals, from −1 to 6 phi with a 1/8 phi spacing. Peaks of standard deviations were around 2 phi and 3 phi at both stations B1 and R1 (Fig. 11C and D), representing a population of grains with the highest variability throughout the one year sampling period after dredging. This indicated that 2-phi and 3-phi sized sands are the most dynamic fractions, transported frequently within the PRS study areas. The troughs between two peaks of 2 phi and 3 phi (Fig. 11C and D) were located around 2.4-phi, which was a relatively stable

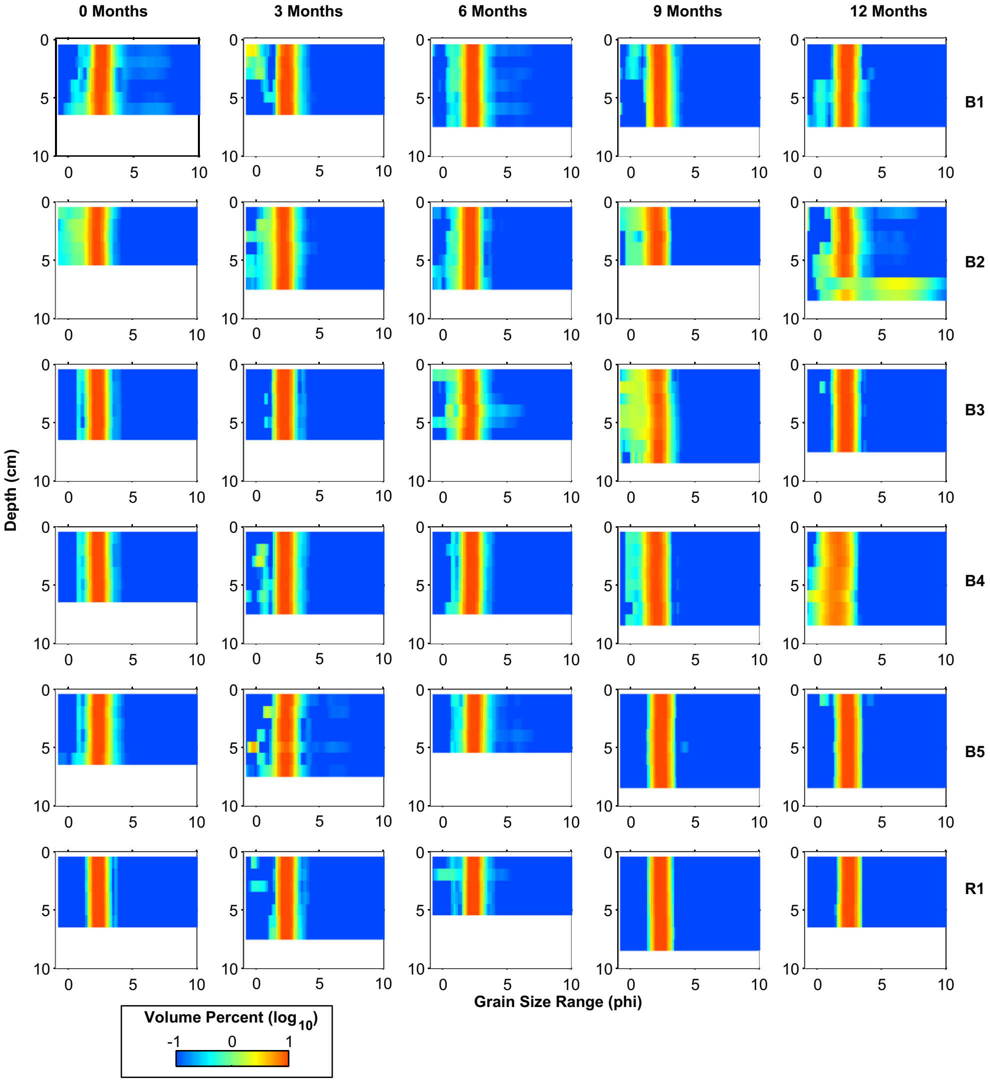

Fig. 10. Borrow and reference sites down-core grain size distributions at 0, 3, 6, 9 and 12 months after the dredging. See Fig. 3 for the locations of B1–B5 and R1.

fraction. The standard deviation peaks of Station B1 were taller than these of Station R1. This reflects a more dynamic nature in the borrow site than at the reference site, and indicates that the borrow site was not in an equilibrium status immediately after the dredging. Another peak can be seen around 0 phi in Fig. 11C and D, and this is the fraction composed of coarser sand and some shell fragments.

5.2. Mechanism of mud accumulation and burying

Preservation of mud in the borrow pit is not desirable if the borrow site is to be used again as a sediment source for future beach nourishment projects. Based on vibracoring data, Olsen (2009) reported mud patches that were interspersed with sand and were preserved on the sandy shoals of borrow site. Our data showed that little mud was preserved in the top 10 cm of seabed in the borrow site during the 12 months period after the dredging, except for the limited mud-sand mixture layer at Station B2 (Figs. 9 and 10).

During four field cruises in 2012 SCDNR divers reported that the water column visibility of the reference site was usually better than that of the borrow site, indicating higher turbidity and more estuarine influence at the borrow site. Both borrow and reference sites are in energetic tidal environments. In such environments, if mud is deposited on seabed surface for a short period of time, it will likely be resuspended and transported within the next tidal cycle unless large amounts are rapidly deposited or the mud is buried by sand. In addition, the shape of the borrow area at the borrow site created a ‘topographic plateau’, not a steep trench, and therefore no shielding or low-energy zone was formed on top of this plateau to facilitate mud preservation on seabed surface. Since the only nearby mud source is from the muddy PRS estuaries, the preconditions for mud preservation in borrow site should be: 1) significant offshore transport of muds from PRS or other nearby estuaries, 2) accumulation of mud, probably during low-energy slack tides or neap tides conditions, and 3) rapid and significant sand deposition to bury mud if the mud was not displaced by currents.

5.3. Impact from the dredging

The most significant impacts of dredging to the borrow site were observed in grain size and carbonate content. Before the dredging coarse sand (1 phi, 500 μm) was present in the surficial seabed

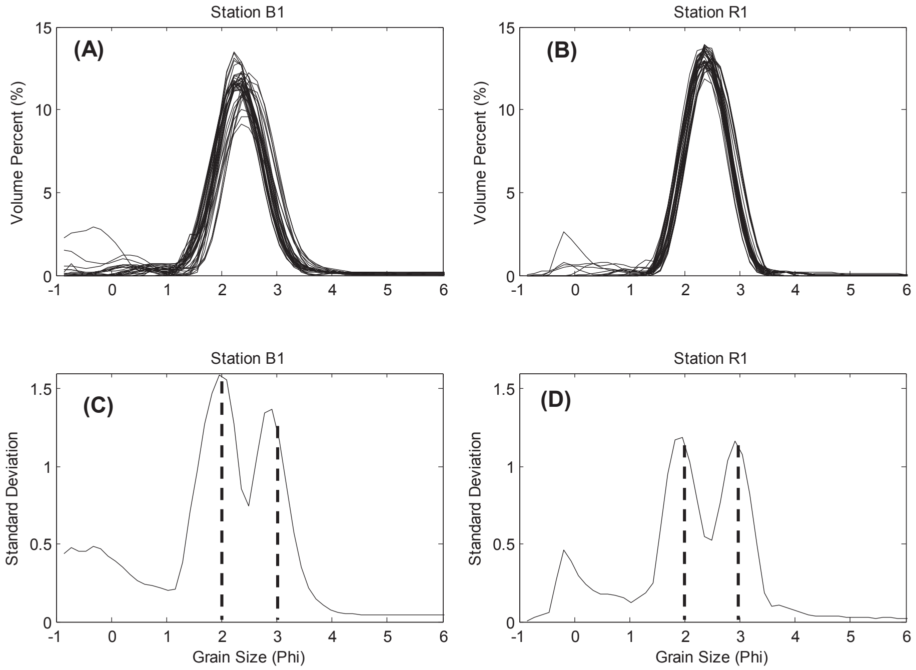

Fig. 11. Volume percentages (A) and their standard deviations 1σ (C) of station B1 down-core sediment samples collected 0, 3, 6, 9 and 12 months after dredging. Volume percentages (B) and their standard deviations (D) of station R1 down-core sediment samples collected 0, 3, 6, 9 and 12 months after dredging.

sediments. After the dredging finer sand (2.3 phi, 203 μm) was observed (Fig. 8). Generally speaking, mud content less than 10% is considered to be acceptable for dredging and the post dredging infilling sediment samples contained less than 3% mud. Thus, the lack of significant mud accumulation, combined with the accumulation of sands that can be used for future beach nourishment projects, indicates that this borrow site configuration was successful.

Carbonate content is an important parameter of seabed composition, which was highly variable in time and space (Fig. 8). By nature, the analyses of carbonate are challenging because selections of sediment subsamples can randomly include or exclude big shells in the sediment bags, and this can impact the results significantly. Little carbonate was found 0 and 3 months after the dredging at the borrow site (Fig. 8), presumably indicating the removal of carbonate by the dredging. The appearance of carbonate in 6, 9, and 12 months after dredging indicated the gradual reestablishment of $CaCO_3$ in the borrow site after dredging.

5.4. *Ongoing and future work*

Olsen (2013) reported that 14 months after the dredging there was about 1.2 m sediment accumulation in the center of the borrow site, further indicating that this site may accumulate sands at a rapid enough rate for the site to be re-used as a borrow area. Although it is well known that long term net longshore sediment transport direction in the region is toward the southwest, the local sediment transport direction in the borrow site has been poorly understood. Waves, tides and currents data were recently collected as part of this overall study to address this deficiency using multiple acoustic sensors at both borrow and reference sites in 2012 (Wren et al., 2014). In addition, a three-dimensional sediment transport model is being developed by the authors of this article for this study area. Future work should also be focused on 3-D morphological modeling prediction as well as the ecological impact of benthic community in the borrow site.

6. Conclusions

The seabed of most ebb tidal shoals offshore of Port Royal Sound are mainly composed of well sorted sand, with patchy carbonate distribution, low organic matter and low mud contents. Based on the analyses of our surficial sediments completed to date, mud content averaged 6% in the entire borrow site 18 months before the dredging and decreased to <2% about 12 months later, and stayed low for the rest of the study period. This indicates that the borrow site used for this nourishment project has been successful in minimizing the accumulation of muddy sediments, making this a favorable borrow site in the future for excavating beach-quality sand because mud accumulation has been mostly precluded. The sediments that were observed during the partial refilling of this borrow site, were finer in phi size, with the two most dynamic sand fractions being 2 phi and 3 phi based on the ‘grain-size vs. standard deviation’ method. These sediments will likely be suitable for the borrow site as nourishment material given the natural fine grained sediments that are present on the receiving beach. Similarly, the re-accumulation of $CaCO_3$ material in the borrow site was more similar to pre-dredge conditions prior to the dredging operation and should not be detrimental for use in future nourishment projects.

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