EVALUATING PROXIES OF SUBAERIAL BEACH VOLUME CHANGE ACROSS VARIOUS TIME SCALES AND MORPHOLOGIES AT ONSLOW BEACH, NORTH CAROLINA, USA.

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A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Department of Marine Sciences

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ABSTRACT

ETHAN JOHN THEUERKAUF: Evaluating proxies of subaerial beach volume change across various time scales and morphologies at Onslow Beach, North Carolina, USA.
(Under the direction of Dr. Antonio B. Rodriguez)

Proxy methods for measuring beach volume change, such as beach-profile surveys and measuring shoreline change are commonly used in place of three-dimensional surveys. These methods are used at all types of beach morphologies and time frames, but it is unclear whether these measurements represent the true volume change. This study assesses the impact of transect placement on volume change measurements and the performance of the shoreline change proxy at varying time frames (0.5-3.5 years) and morphologies (e.g. beach cusps, nourishment). Results indicate that transect placement is important over both short- and longer-time frames at beaches with high-along-beach morphologic variability, high temporal variability in shoreline position, and periodic nourishment. Transect placement does not impact volume change measurements over longer (~3.5 year) time scales at beaches with rapid and consistent volume change. The shoreline change proxy works best at beaches with low temporal variability in shoreline position and where there are no significant morphologic changes to the backshore (e.g. beach cusp formation/destruction).

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LIST OF ABBREVIATIONS AND SYMBOLS

FEMA	Federal Emergency Management Agency
RTK-GPS	Real Time Kinematic-global positioning system
LIDAR	Light detection and ranging
DEM	Digital elevation model
m	Meter(s)
km	Kilometer(s)
s	Seconds
cm	Centimeter(s)
NAVD88	North American Vertical Datum of 1988
NE	Northeast
SW	Southwest
~	Around
MHW	Mean High Water
U.S.	United States of America
NCDCM	North Carolina Division of Coastal Management
R^2	Coefficient of determination
DSAS	Digital Shoreline Analysis System
r_c	Concordance correlation coefficient

Chapter 1

Impacts of Transect Location and Variations in Along-Beach Morphology on Measuring Volume Change

1.1 Introduction

Mapping complex beach morphology is one of the foundations of coastal research and management and is essential for understanding the response of beaches and barrier islands to changes in storminess and sea-level rise (Nicholls et al., 2007). A variety of survey methods are available for mapping beach morphology and quantifying volume changes (Emery 1961; Morton et al., 1993; Shrestha et al., 2005; Stockdon et al., 2002); however, beach profile surveys are most commonly used. Beach profile surveys are used in a variety of applications where accurate measurements of morphologic change are needed, including assessing the impact of tropical and extratropical storms on the beach profile and shoreline (Lee, Nicholls, and Birkemeier, 1998; Stone et al., 2004; Zhang, Douglas, and Leatherman, 2002), assessing temporal and spatial variability in shoreline and beach profile changes (Hansen and Barnard, 2010; Larson and Kraus, 1994), developing littoral cell sediment budgets (Patsch and Griggs, 2008; Ruggiero et al., 2005; Swales, 2002), establishing the foundation for beach management plans and determining Federal Emergency Management Agency (FEMA) funding for poststorm beach renourishment (FEMA, 1988), monitoring and modeling beach nourishment performance (Benedet, Finkl, and Hartog, 2007; Bocamazo, Grosskopf, and Buonuiato, 2011; Browder and Dean, 2000; Elko and Wang, 2007; Miller and Fletcher, 2003), measuring long-term and short-term shoreline change rates (Smith and Zarillo, 1990), developing and testing shoreline change models (Ruggiero et al., 2010), and developing and validating new methods for measuring subaerial beach volume change (Farris and List, 2007; Smith and Bryan, 2007).

One of the most common profile survey methods utilizes a differential global positioning system (GPS) or a Real Time Kinematic Global Positioning System (RTK-GPS) to map beach topography, at high accuracy and precision, along profiles oriented perpendicular to the shoreline (e.g. Baptista et al., 2008; Dail, Merrifield, and Bevis, 2000; Farris and List, 2007; Harley et al., 2011; Jackson, Cooper, and del Rio, 2005). Subaerial beach volume is calculated from RTK-GPS profile surveys by integrating under the profile, using mean high water or mean sea level as a base, and multiplying this area by the profile spacing (Sonu and Van Beek, 1971). Volume change is calculated by differencing beach volumes between two surveys. Beach surveys based on profiles of x-, y-, and z-data points collected with an RTK-GPS are time and cost efficient and significantly improve upon older ground-survey methods, such as rod-and-level surveys (Morton et al., 1993). Previous studies aimed at determining the optimal transect spacing for beach surveys suggest that a spacing of at least 50 m is generally acceptable for analyzing shoreline response (Dolan, Fenster, and Holme, 1992; Phillips, 1985); however, it is questionable whether these widely spaced beach profile surveys can be used to accurately quantify volume change along a shoreline where beach topography is variable and affected by nourishment.

Beach profiles are commonly collected at an along-beach spacing of more than 100 m to quantify volume change over a given period (Benedet, Finkl, and Hartog, 2007; Creaser, Davis, and Haines, 1993; Elko and Wang, 2007; Farris and List, 2007; Harley et al., 2011; Park, Gayes, and Wells, 2009). The implied assumption is that morphologic variations at a scale below the profile spacing are negligible. Widely spaced beach profiles generally do not capture small-scale (10-100 m) along-beach morphologic variations, such as those associated with beach nourishment and/or bed forms (e.g. beach cusps, ridges, and runnels), which results in over- or underestimation of beach volume (Bernstein et al., 2003; Swales, 2002). Pietro, O'Neal, and Puleo (2008) found that volume-change measurements derived from beach profiles along a recently nourished 0.5-km stretch of Rehoboth Beach, Delaware— a wave-dominated-passive margin shoreline— can be up to 8% different from measurements using terrestrial light detection and ranging (LIDAR), which produce extremely high-resolution Digital Elevation Models (DEMs) based on ~1 million x-, y-, and z-data points per 50 m^2 (Heritage and Large, 2009). For the beach fill monitored at Rehoboth Beach, 8% translates into 8369 m^3 over an along-beach distance of 0.5 km, which may be an acceptable margin of error for beach profiles there; however, 8% miscalculation of volume change could be more problematic at other beaches, where small amounts of volume loss translate into severe erosion problems (e.g. narrow, transgressive beaches).

The purpose of this study is to quantify the performance of beach profiles in measuring volume change with respect to variable beach morphology. Onslow Beach in eastern North Carolina is an ideal site for this type of study, because it contains both transgressive and regressive zones (Benton et al., 2004) and areas with beach cusps and beach-fill material, making results presented here applicable to many other barriers and beaches globally. We compare three groups of beaches with distinct morphologies: (1) beaches with ephemeral cusps, (2) beaches with negative volume change distributed uniformly across the site, and (3) beaches with positive and negative volume changes distributed bimodally across the site (e.g. erosion along one half of a site, while the other half changes little). The error associated with employing beach profiles to measure volume change for the three groups of beaches is assessed by comparing against a benchmark volume-change measurement, which is derived from terrestrial laser scanner data. The ultimate goal is to help beach managers, engineers, and researchers assess the morphologic conditions under which beach profiles can and cannot be used to effectively measure volume change.

1.2. Study Area

Onslow Beach, located at Marine Corps Base Camp Lejeune in Eastern North Carolina, is a wave-dominated, 12-km-long and 90- to 600-m-wide barrier island bordered by Brown's Inlet to the NE and the New River Inlet to the SW (Figure 1.1). The island is microtidal, with a mean tidal range of 1 m and, based on the National Oceanic and Atmospheric Administration's National Data Buoy Center Station 41035 located ~8 km offshore, the nearshore average significant wave height and wave period are 0.91 m and 7.4 s, respectively.

Barrier morphology is highly variable along Onslow Beach (Figure 1.1). The island is divided into a northern zone, which is characterized by well-developed, more than 6-m-high dunes; a wide beach; and a stable to accretionary shoreline, and a southern zone, which is characterized by 2- to 4-m-high dunes, a narrow beach, and an erosional shoreline with multiple washover fans (Foxgrover, 2009; Figure 1.1). Subdivision of the beach into two morphologic zones is a result of Oligocene submarine rock ridges that intersect Onslow Beach at the point where shoreline evolution transitions from transgression (to the SW) to regression (to the NE; Benton et al., 2004; Riggs, Cleary, and Snyder, 1995; Figure 1.1). Overall, adjacent barriers tend to follow the same pattern, being regressive to the north (toward Cape Lookout) with higher topography (Timmons et al., 2010) and transgressive to the south with lower topography and a preponderance of washover fans (Riggs, Cleary, and Snyder, 1995).

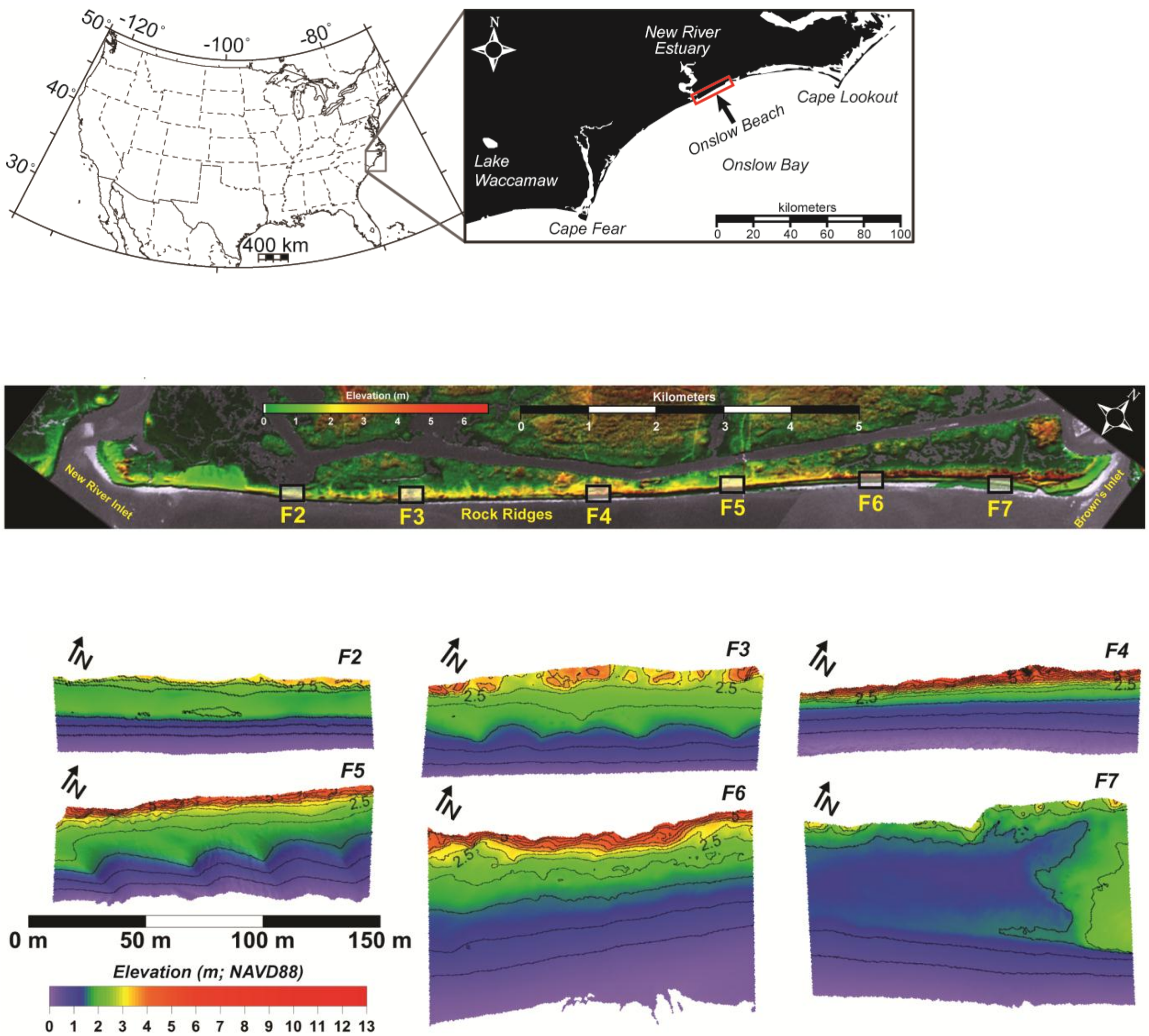

Figure 1.1 - Study area maps. (Top) Regional study area map showing the location Onslow Beach, North Carolina. (Middle) Map of elevations overlain on a black-and-white aerial photograph, highlighting the six focus sites used in this study and the variable along-barrier morphology. (Bottom) DEMs of the focus sites derived from terrestrial laser-scanning data obtained in May 2008 (shown with a 0.2-m contour interval).

1.3. Methods

1.3.1. Field-Data Acquisition

Six focus sites were selected to represent the diverse beach morphologies along Onslow Beach: F2 and F3 in the southern transgressive zone and F4 to F7 in the northern regressive zone (Figure 1.1). Topographic data were collected using a Riegl three-dimensional LMSZ210ii Terrestrial Laser Scanner. The scanner was mounted onto a truck and rotated 360° while collecting ~ 2 million spatial (x, y, and z) data points from laser returns. RTK-GPS-surveyed reflectors, positioned within the scan area, were used to georeference the data points to a global coordinate system (Universal Transverse Mercator). Two scan positions were occupied at each focus site, resulting in ~200 m of coverage along the beach (~4 million points per site per survey). Beach surveying was restricted to 2 hours before and after low tide to maximize subaerial beach coverage. Error in the three-dimensional topographic data is estimated to be ±3.0 cm, which includes a ±1.5-cm factory-estimated maximum instrument error and an average ±1.5-cm RTK-GPS error. The RTK-GPS error is reported from the instrument as horizontal and vertical error and varies based on factors such as number of satellites, position of satellites, and cloud cover. Each focus site along the island was scanned biannually in association with an ongoing beach monitoring program (May 2008, September 2008, and May 2009), and one of the sites (F3) was scanned before and after a nor'easter in September 2008 that was associated with a ~4-m maximum significant wave height and ~0.3-m maximum increase in water level.

1.3.2. Data Processing

Ground points (x-, y-, and z-data points) were isolated from the raw data using an algorithm in the Terrasolid software package and by manual editing. Surface-grid models were created from ~125,000 ground points for sites with narrow cross-shore widths (e.g. F4) and ~500,000 ground points for sites with wide cross-shore widths (e.g. F7) using Delaunay triangulation. Woolard (1999) and Woolard and Colby (2002) suggest that DEMs derived from airborne LIDAR data most accurately represent coastal topography with a spatial resolution of 1-2 m. Given the high density of points derived from the laser scans at each site in this study, 0.5-m grid spacing was used. This 0.5-m grid spacing is generally much larger than the spacing of the laser returns; thus, each grid node is based on an average of several topographic measurements. Areas of the focus sites greater than 5 m^2 with no laser returns, which only occurs in the dunes, were not included in the surface model (i.e. the areas were defined with blanked grid nodes) because the limited data would not depict the ground surface accurately at the desired resolution. Surface-grid files were imported into Golden Software's Surfer 10.0 to generate contour maps and DEMs.

The position of the laser scanner was not the same for each reoccupation of the focus sites due to changes in barrier morphology and unavoidable circumstances (e.g., beachgoers and Marine Corps training activities). This caused the mapped area of a site to be slightly different for each survey. To account for this, DEMs were cropped to reflect only areas of overlapping survey coverage, resulting in an along-beach extent of ~150 m for each focus site. The data points also extend further landward at sites with low-elevation dunes and overwash fans (e.g. F3), but these data are patchy landward of the foredune crest because of shadowing. Portions of the dune landward of the foredune crest were cropped out of the maps to normalize coverage across the beach among surveys. The seaward boundaries on the maps were cropped at 0-m North American Vertical Datum of 1988 (NAVD88) to normalize coverage across the beach caused by differences in tidal height (the laser does not penetrate the surface of the water) among surveys.

The cropped maps were subtracted from one another at three timescales: annual (May 2008 - May2009), seasonal (May 2008 - September 2008), and event (nor'easter September 17 - September 30, 2008; Figure 1.2 and Table 1.1). A subset of these DEM-subtraction maps was used in the study with the aim of including the range of net volume changes and morphologic beach responses across the barrier. Accretion, erosion, and net volume change (accretion - erosion) were calculated for each subtraction map (Figure 1.3). The volume changes are not reported with an error estimate because here we define the "true" morphology of the beach as being equal to the DEMs. The DEMs are the benchmark that the volume change based on the beach profiles is measured against.

1.3.3. Deriving Beach Profile Data from the DEMs

Beach profile data were generated using Surfer 10.0 to sample the surface grids along user-defined transects. Transects are oriented shore normal and spaced every 0.5 m along the beach (equal to the grid spacing), resulting in ~300 transects for each focus site. Transect locations are kept constant at each focus site. Volume change was derived from all transects, resulting in ~300 volume measurements per site per time step. Each volume measurement is derived by integrating the area between profiles at a transect location and translating this area across the focus site (150 m). Specifically, beach profile data are used to measure volume change using:

$$\sum_{i=1}^{n} Y \Delta Z_i \, (X_{i+1} - X_i)$$

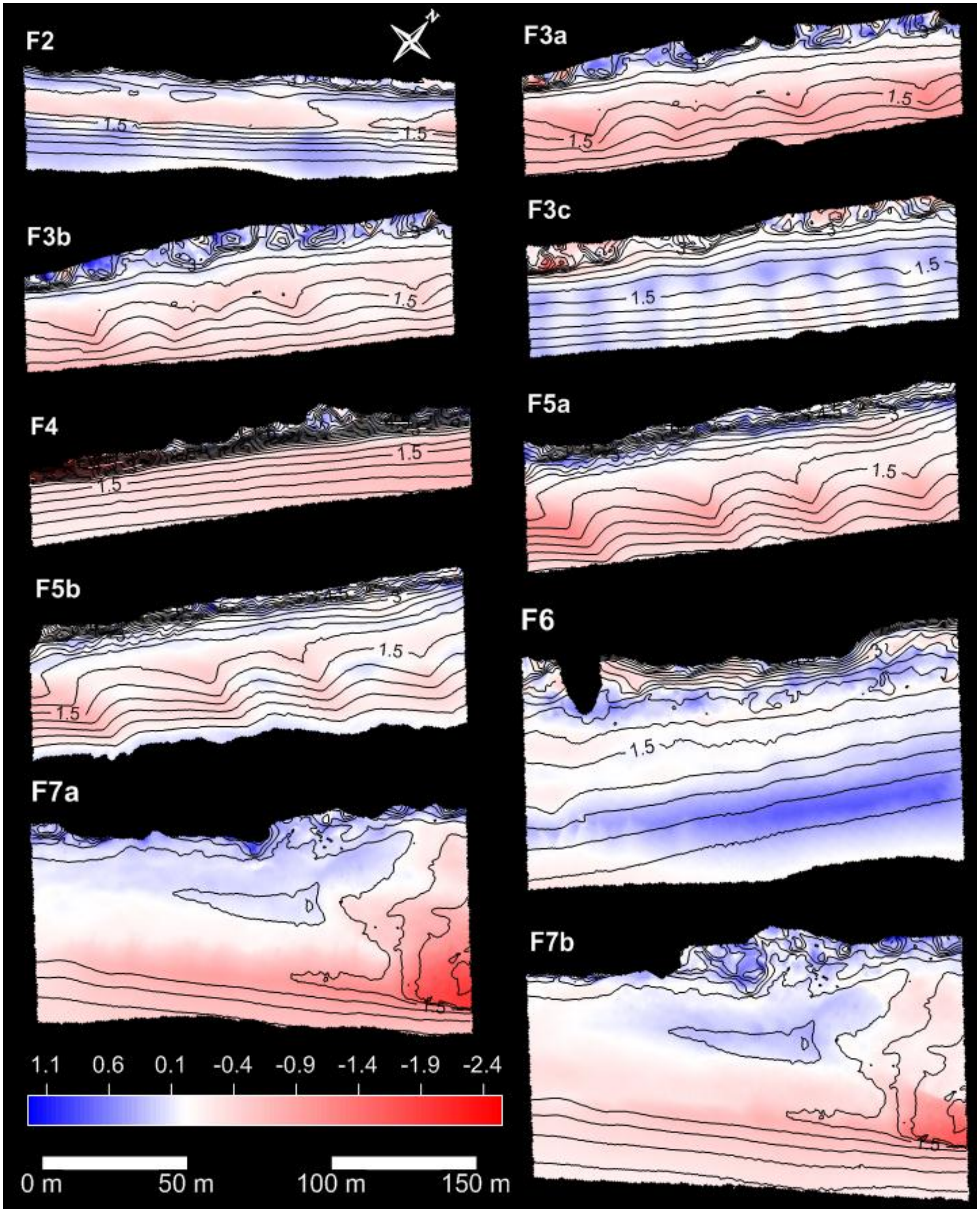

Figure 1.2 - DEM subtraction maps derived from terrestrial laser-scanning data. Elevation contour lines of the DEM of the first survey are displayed on each map to highlight the morphologic changes among surveys (May 2008 contour lines for all surveys except F3c, which is September 2008).

Subtraction Map	DEM Dates
F2	May 2008-September 2008
F3a	May 2008-May 2009
F3b	May 2008-September 2008
F3c	September 2008-post nor'easter 2008
F4	May 2008-May 2009
F5a	May 2008-May 2009
F5b	May 2008-September 2008
F6	May 2008-May 2009
F7a	May 2008-May 2009
F7b	May 2008-September 2008

Table 1.1 – Dates of DEMs used to create subtraction maps.

In this equation, n is the total number of grid cells the transect intersects, Y is the along-beach transect spacing (150 m), ΔZ is the change in elevation at a given grid cell, and X is the across-beach distance a cell is from the first (most landward) grid cell in the transect. The along-beach transect spacing of 150 m (Y = 150 m) was chosen for this study because this is a typical spacing used for beach-profile studies (e.g. Creaser, Davis, and Haines, 1993). The ~300 volume changes measured from transects at each site were then compared to the net volume change measured from laser-scanning data to assess the performance of beach profiles.

1.4. Results and Interpretations

1.4.1 Focus Site Morphology

The DEMs of each focus site detail the variable morphology along Onslow Beach (Figure 1.1 and Table 1.2). Sites in the southern portion of Onslow Beach (i.e. F2 and F3) are characterized by beach widths ranging from ~22 to ~39 m (measured from 0-m NAVD88 to the base of the foredune) and by ~3- to 4-m-high discontinuous foredunes, with multiple washover fans (e.g. site F3; Figure 1.1). Site F4, in the middle of the island, has an average beach width of ~19 m and ~6.5-m-high foredunes. Northern Onslow Beach sites (i.e. F5-F7) are characterized by beach widths ranging from ~30 to ~81 m and by ~5.5- to ~8.5-m-high continuous foredunes. Maintenance dredging of the Intracoastal Waterway near Brown's Inlet occurs every other year, and in March 2008 this beach-quality sand was disposed of near F7. The dredge material was not graded, and the SE end of the mound is clearly visible in the earliest DEM of F7 (Figure 1.1).

Beach cusps, which are crescentic features of the foreshore characterized by steep seaward-protruding extensions (horns) and gently sloping landward extensions (embayments; van Gaalen et al., 2011), have variable morphologies at Onslow Beach. Cusps at sites F2 and

DEM	Average Beachface Width (m)	Standard Deviation of Along-beach Slope	Maximum Foredune Height (m)	Morphologic Features
F2 May 2008	25.58	0.0137	3.40	N/A
F2 September 2008	23.92	0.0169	3.72	Beach cusps
F3 May 2008	36.75	0.0185	3.72	Beach cusps
F3 September 2008	32.04	0.0107	3.94	N/A
F3 May 2009	22.81	0.0092	4.11	N/A
F3 Post-Storm	39.78	0.0240	4.02	Beach cusps
F4 May 2008	23.54	0.0071	6.52	N/A
F4 May 2009	14.23	0.0059	6.75	N/A
F5 May 2008	33.34	0.0214	5.60	Beach cusps
F5 September 2008	42.00	0.0095	5.80	N/A
F5 May 2009	30.45	0.0079	5.83	N/A
F6 May 2008	65.98	0.0174	7.43	N/A
F6 May 2009	51.15	0.0123	7.47	N/A
F7 May 2008	81.46	0.0197	8.84	Dredge spoil at northeast end
F7 September 2008	68.73	0.0149	7.32	Dredge spoil at northeast end
F7 May 2009	60.68	0.0133	7.65	N/A
N/A * = No Backshore				

Table 1.2 – Beach parameters measured from the DEMs derived from terrestrial laser scanning.

F3c only exist in the second survey and are evenly spaced ~35 and ~20 m, respectively (Figures 1.1 and 1.2). Sites F3a, F3b, F5a, and F5b have irregularly spaced beach cusps with spacings ranging from ~20 to 40 m and from ~30 to 50 m, respectively (Figure 1.1) and only exist in the first survey (Figure 1.2).

1.4.2 Volume Changes Derived from Laser Scanning

All focus sites and time steps experienced varying degrees of accretion (positive volume change) and erosion (negative volume change) ranging from 1750 m^3 at F6 to -3650 m^3 at F7a (Figures 1.2 and 1.3), making results presented here applicable to a range of beach responses to sediment-transport processes. Net volume change indicates whether the focus site experienced overall erosion or accretion between time steps and ranges from -3020 m^3 (net erosion) to 1470 m^3 (net accretion; Figure 1.3). Sites that experienced similar values of erosion and accretion between surveys result in net volume changes that are close to zero, but these sites still have a high degree of morphologic variability. For example, both F2 and F3c have low net volume changes resulting from similar values of erosion and accretion, but these sites developed cusps between surveys (Figures 1.2 and 1.3). Several sites experience unidirectional erosion or accretion, which can result in large net volume changes (e.g. F7a) or modest net volume changes (e.g. F4).

The DEM-subtraction maps detail a high degree of spatial and temporal variability at each focus site (Figure 1.2). Contour lines on the DEM-subtraction maps depict the morphology of the beach during the earliest survey, and this overlay facilitates recognition of morphologic changes that occurred between surveys. Based on the subtraction maps, three groups of beaches with distinct morphologies are recognized: (1) ephemeral beach cusps, (2) uniform beach change, and (3) bimodal beach change. Those sites with beach cusps that eroded between surveys (F3a and b; F5a and b) and developed between surveys (F2 and F3c)

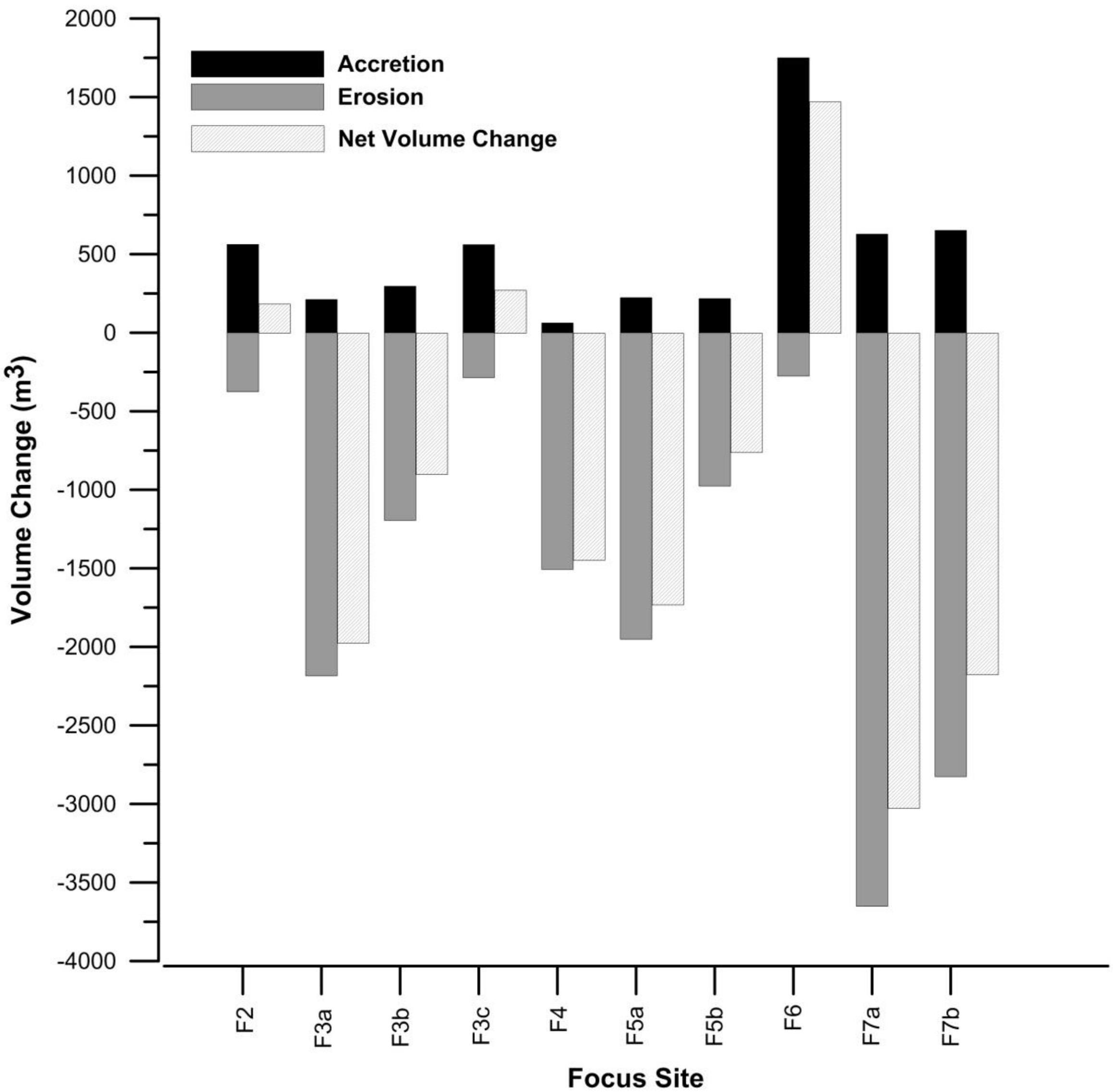

Figure 1.3 - Volume changes at each focus site and time step, including accretion (black), erosion (gray), and net volume change (hatched).

are included in the beach-cusp group. Site F4 shows negative volume change distributed uniformly across the beach and is the only uniform beach-change site. The effects of nourishment can be seen in the DEM-subtraction maps for F6, F7a, and F7b. Erosion of the dredge-material disposal mound at the NE end of F7 is evident in F7a and F7b, and accretion of the lower beach at F6 is likely the result of SW transport of the eroded material. These three sites have positive and negative volume changes that encompass about half of their areal extent and are included in the bimodal beach-change group.

1.4.3 Volume Changes Derived from Beach Profiles

At each site and time step, comparisons were made between the range of volume changes measured from each transect (~300 separate measurements of volume change) and the true volume change (based on the DEMs derived from laser-scanning data; Figure 1.4). Where the difference between the volume change measured from profiles and the true volume change is high, the suitability of that transect for measuring volume change for the entire site is low. The accuracy of using beach profiles to measure volume change for all sites and time steps highly depends on transect placement, as evidenced by the scattered spatial distribution of the transects that yield accurate volume change. Differences in beach morphologies between sites and time steps influences the importance of transect placement for accurately measuring volume change from beach profiles and the following highlights the importance of morphology on profile performance.

1.4.3.1. Beach Cusps

Sites with beach cusps (F2, F3a-F3c, F5a, and F5b) have a range of volume changes based on measurements from the transects, including overestimation and underestimation (Figure 1.4). Accuracy of volume change is a function of where the transect is located with respect to cusp morphology. Transects located on the horns and

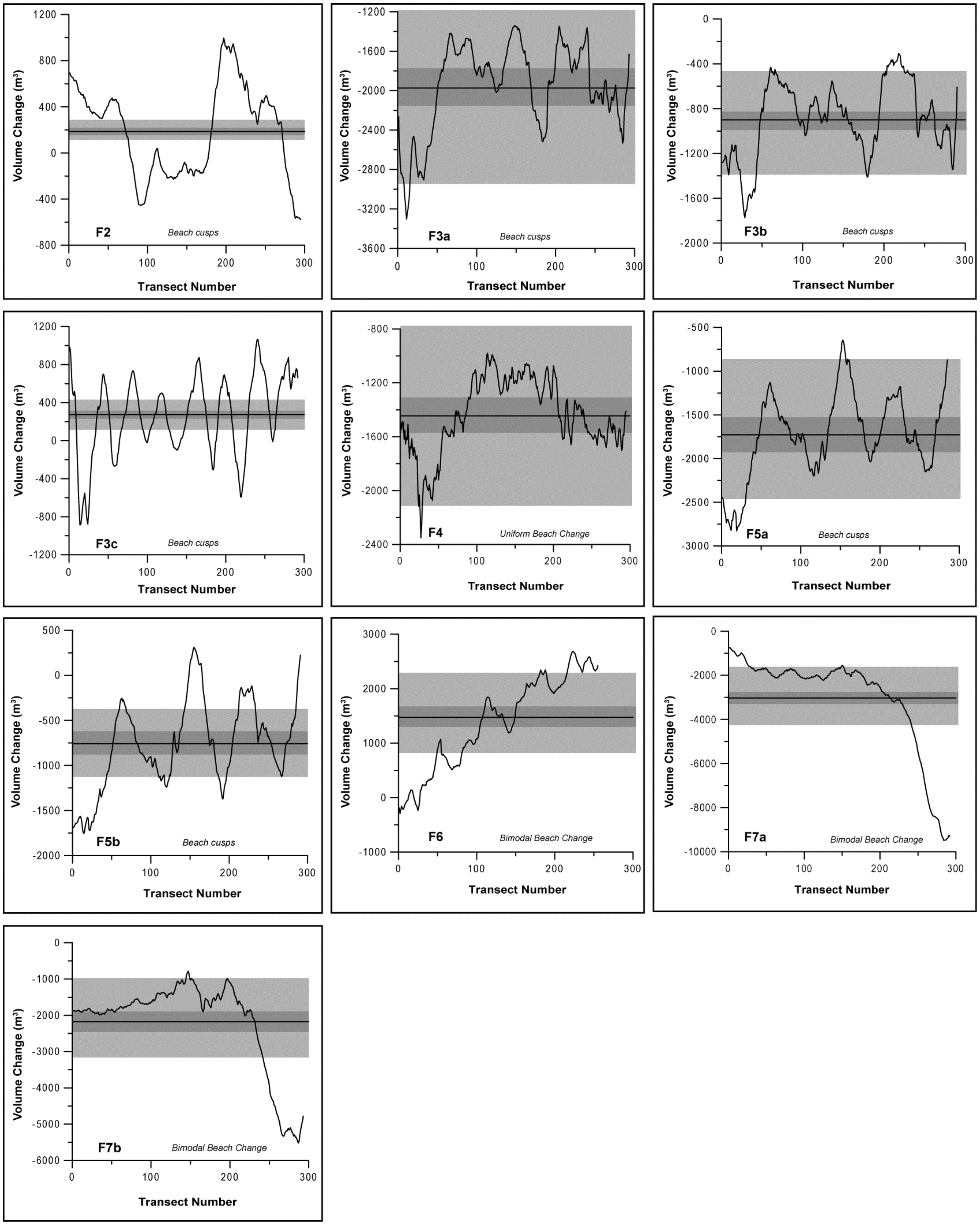

Figure 1.4 - Along-beach variability in volume-change measurements at each focus site. Volume-change measurements for each beach transect are plotted from the SW (transect 0) to the NE (transect 300) and connected by a line. The y-axis of each map is scaled differently based on the range of volume-change

measurements. The "true" volume-change measured from laser-scanning data is indicated by the horizontal black line. The volume-change measurements within ± 10 and ± 50% of the true volume change are denoted by dark gray and light gray shading, respectively. The morphologic group that the survey belongs to is denoted on each graph.

embayments of beach cusps result in the largest overestimation or underestimation of volume change. If cusps erode between surveys, overestimation of volume change generally occurs when transects are located in the cusp embayments and underestimation occurs if profiles are located on the cusp horn (e.g. F3a, F3b, F5a, F5b). If cusps develop between surveys, overestimation of volume change generally occurs when profiles are located on the cusp horn and underestimation occurs when profiles are located in the cusp embayment (e.g., F2 and F3c). Profiles appear to only accurately measure volume change when they are located on a small section of the cusp flanks, the inflection point where the net morphology change is low and reflects the true volume change— regardless of whether the cusp forms or is destroyed among surveys.

1.4.3.2. Bimodal Beach Change

The sites characterized by bimodal beach change have more than 75 profiles along one end of the beach that overestimate or underestimate volume change (F6, F7a, and F7b; Figure 1.4). Volume-change measurements based on transects along F7a and F7b display continuous erosion along the beach with transects located toward the NE (transect numbers >200) showing increasing and more extreme erosion than transects located around the SW end of the site. Erosion of the dredge-spoil disposal mound at the NE end of F7 is the cause for this zone of higher erosion. Volume-change measurements at F6 show continuously increasing values of accretion from SW (transect 0) to NE (transect 300). This accretion pattern likely resulted from erosion of the dredge-spoil mound at the adjacent site (F7) and redistribution of this sediment along the NE part of F6.

1.4.3.3. Uniform Beach Change

The beach response at the uniform beach change site (F4) is characterized solely by erosion and no beach cusps (Figure 1.2). Despite this apparent low variability in beach response across the F4 subtraction map (Figure 1.2), volume change derived from transects encompass a large range of values (~1400-m^3 variability), which reflects the high variability in the foredune response across the site (Figure 1.4). Site F4 is missing a prominent backshore zone (Figure 1.1), which likely resulted in undercutting, erosion and slumping of the foredune from waves during high tide. These factors led to the high variability of the foredune response.

1.5 Discussion

The suitability of using beach profiles spaced 150 m apart to measure volume change for a particular project largely depends on the accuracy requirements of the project; however, beach morphology also strongly influences the accuracy of volume-change measurements based on profiles. For better assessment of error and appropriate application of volume-change measurements based on profiles, it is necessary to determine the beach morphologies that are not conducive to this method. The percentage of transects that measure volume change within ±10, 20, and 50% of the true volume change is used to assess the applicability of using profiles to measure volume change for the various beach morphologies of Onslow Beach (Figure 1.5). Profiles do not quantify volume change well (i.e. they perform poorly) at sites where a low percentage of transects measure the true volume change to within the specified accuracy windows (i.e. ±10, 20, and 50%).

1.5.1. Beach Cusps

Transect placement is important for quantifying volume change at beaches with cusps and only a small fraction of transect locations result in values similar to the true volume change. Transect location, with respect to a cusp and the morphology of the beach cusp, determines the degree profiles over- and underestimate volume change, regardless of whether the beach cusps are erosional (e.g., F3a, F3b, F5a, and F5b) or accretional (e.g., F2 and F3c). Volume change measured from transects along the horn or embayment of a beach cusp under- or overestimate the true volume change. This inaccuracy is exacerbated at sites with cusps that have a short wavelength (e.g., F3c; ~20-m wavelength). The effects of cusp wavelength on volume-change measurements at F5a and F3c are readily apparent in Figures 1.4 and 1.5; a higher percentage of transects approximate the true volume change at F5a than the percentage at F3c. Beach cusps in both of these surveys had similar heights, but the cusp wavelength at F5a (~40-m wavelength) was ~50% greater than F3c, resulting in more transects along the cusp flanks. The transects along the cusp flanks more closely approximate the true volume change because these values are intermediately between the maximums of erosion and accretion. Sites with broader and more gently sloping cusp flanks (e.g., F3a, F3b, F5a, and F5b) have more transects that measure the true volume change because more transects are located on the flanks. The accuracy of using profiles to measure volume change at sites with beach cusps can be increased if the profile spacing is less than the wavelength of the beach cusps, allowing for more profiles to

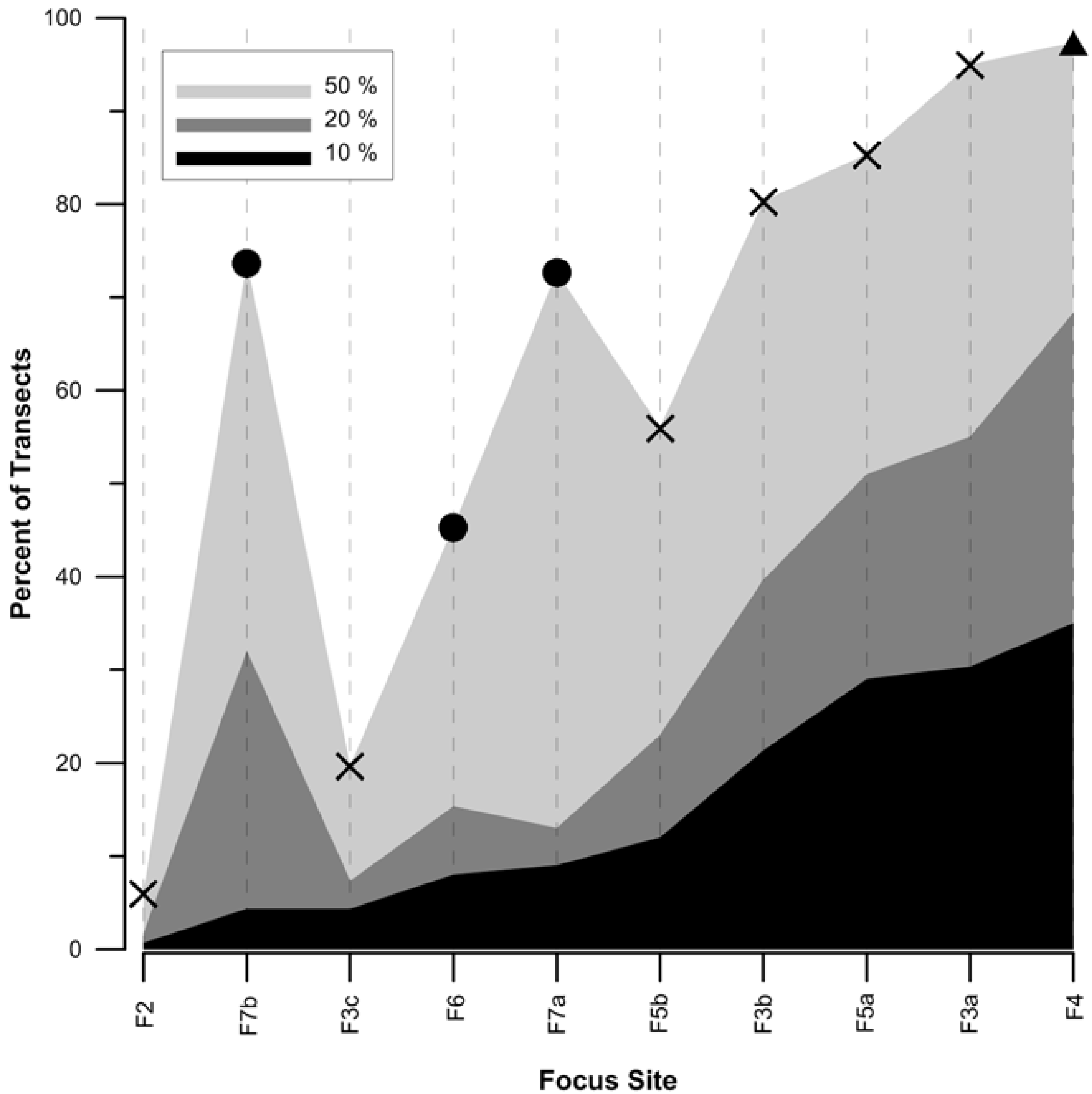

Figure 1.5 - Percentage of transects that measure the true volume change within a specified percentage accuracy window. Surveys are ordered from lowest (poorest) to highest (best) percentage of transects that accurately measure the volume change to within ±10% of the true volume change. Morphologic groupings are denoted by the symbols × (beach cusps), ● (bimodal beach change), and ▲ (uniform beach change).

be located on the flanks, but decreasing the profile spacing is not always practical. The performance of beach profiles in accurately measuring the true volume change strongly depends on the morphology of the beach cusps, rather than simply the presence of beach cusps.

1.5.2. Bimodal Beach Change

Transects spaced 150 m apart poorly approximate volume change at sites with bimodal beach changes. Only transects placed at the interface between the two responses accurately measure volume change; all other profile placements either overestimate or underestimate volume change because the extreme values are not accounted for. Sites that are generally responding in one direction (erosion or accretion), but have an anomalous region of strong response in the opposite direction (e.g., F7a and F7b) have few transect placements that accurately approximate the true volume change. Sites where half of the beach responds one way and the other half responds another way also have a true net volume change in the middle of these extremes, resulting in few transect placements that accurately measure the true volume change (e.g., F6). All bimodal beach response surveys do not perform well at the ±10% accuracy window, but some perform better at the ±20 and ±50% windows (Figure 1.5). Surveys that perform better with the larger accuracy windows have variability in volume-change measurements that is close to or lower than the window (e.g., F7b), which varies among sites depending on the amount of net erosion or accretion that occurred. Once this variability threshold is crossed, beach profiles reasonably measure the true volume change. This threshold performance is unique to the bimodal beach response group.

1.5.3. Uniform Beach Change

The percentage of transects that accurately measure the true volume change is generally higher for the site with uniform beach changes. At the ±10% accuracy window, however, only 35% of transects approximate the true volume change at site F4 (Figure 1.5). This relatively low percentage, despite a generally uniform beachface response, is the result of small-scale variability in the foredune. When the accuracy window is increased to ±20% a higher percentage of transects accurately measure the true volume change, and at ±50% almost all transects accurately measure the true volume change because all small-scale volume-change variability along the foredune is accounted for. When the scale of the volume-change variability is low compared to the net volume change, beach profiles reasonably measure the true volume change.

1.5.4. Profile Performance with Varying Beach Width and Along-Beach Slope

Determining the amount of beach erosion or accretion that could potentially be ignored from profile surveys given a particular set of beach parameters is important for beach managers and researchers who require accurate volume-change measurements and are deciding which survey method to employ for a project. Assessment must rely on beach parameters that are readily available from existing data sets and field observations, such as beach width and along-beach variations in morphology.

Previous beach profiling studies assert that volume is proportional to beach width (Dingler and Reiss, 2002; Thom and Hall, 1991). This suggests that beach width may be an important component in the performance of transects in deriving volume change. To assess the influence of beach width on the accuracy of profile-derived volume changes, the average beach width is plotted against the performance of beach profiles in measuring the true

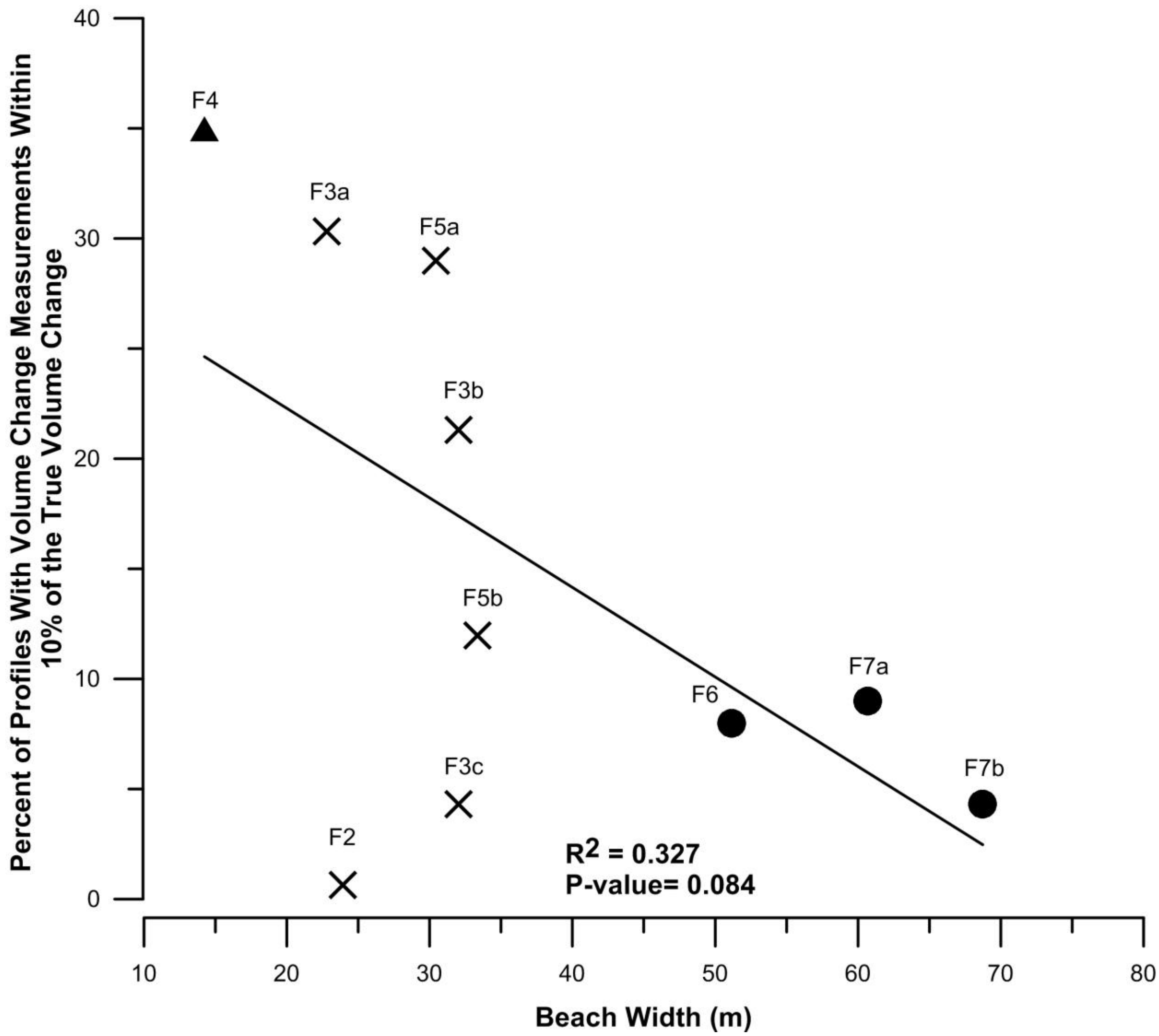

Figure 1.6 - Relationship between beach width and percentage of transects that accurately measure volume change to within ±10% of the true volume change. Morphologic groupings are denoted by the symbols ×(beach cusps), ● (bimodal beach change), and ▲ (uniform beach change).

volume change to within ±10% (Figure 1.6). The smaller DEM for each time step was used for measurements of beachface width because the smaller map is always the same size as the subtraction map (only overlapping grid nodes can be subtracted). This analysis suggests that no significant relationship exists between the beach width and the percentage of transects with volume-change measurements within ±10% of the true volume change ($R^2 = 0.327$; P value = 0.084); thus beach width cannot be used as a reliable predictor of profile performance. Generally, large beach widths (>50 m) perform poorly and small beach widths (<20 m) perform well, but there is a range of performance values for beach widths between these end members. The percentage of profiles with volume-change measurements within ±10% of the true volume change has a large range (~1-30%) across a narrow range of beach widths (~20-30 m). Given that these sites all have beach cusps, along-beach variability in morphology is likely more indicative of profile performance than beach width.

Along-beach morphologic variability is the primary control on the accuracy and applicability of using profile surveys spaced 150 m apart for measuring volume changes. The standard deviation of the along-beach slope, i.e. the slope of the gridded surface measured in an along-beach direction, is used as a proxy for along-beach variability in morphology. In this study, the along-beach slope is derived from the second survey in each time step and is measured across grid nodes for the whole gridded surface using Surfer 10.0. This parameter could also be measured using RTK-GPS shore-parallel surveys. A high standard deviation in along-beach slope indicates more variable morphology, while a low standard deviation indicates smoother, less variable morphology. The standard deviation of along-beach slope is plotted against the performance of beach profiles in measuring volume change to within ±10 % of the true volume change (Figure 1.7). Only the

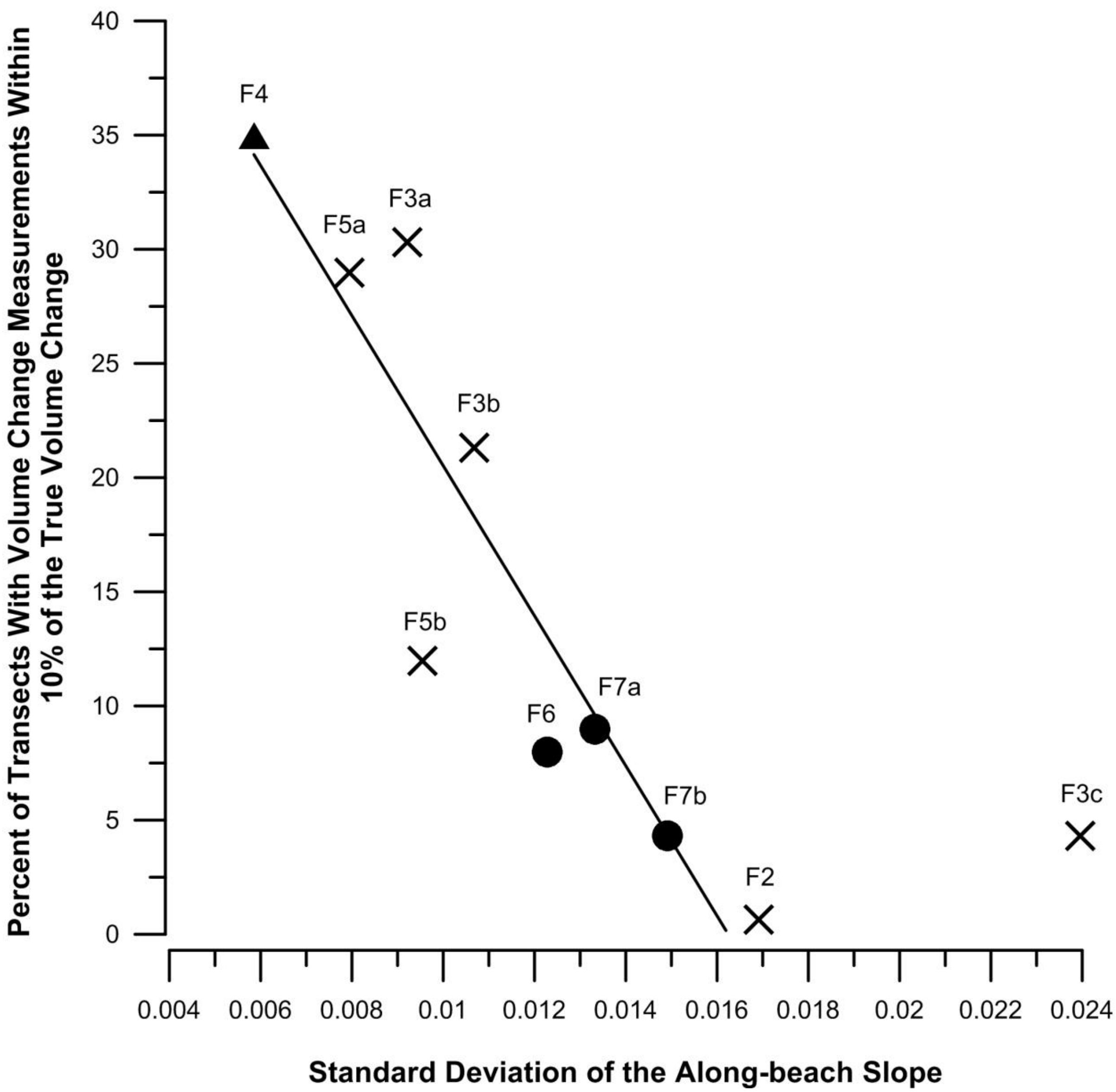

Figure 1.7 - Relationship between beach width and percentage of transects that accurately measure volume change to within ±10 % of the true volume change. Morphologic groupings are denoted by the symbols ×(beach cusps), ● (bimodal beach change), and ▲ (uniform beach change).

standard deviation of the along-beach slope for the beach is analyzed; however, the volume measurements include the foredune. Although the foredune represents a much smaller area of each focus site than the beachface, this does introduce variability and may explain some deviation from the regression line (Figure 1.7). A strong relationship exists between the standard deviation of along-beach slope and the performance of beach profiles ($R^2 = 0.842$; P value = 0.00049). Overall, beach profiles at sites with a high standard deviation in along-beach slope (e.g., F2, F6, F7a, and F7b) performed worst, while transects at sites with a low standard deviation in along-beach slope (e.g., F4) performed best. The standard deviation of the along-beach slope is highest at sites with short wavelength beach cusps (e.g., F2 and F3c) or anomalous zones of beach response (e.g., F7b) and lowest at sites with little variability in morphology (e.g., F4) or long wavelength beach cusps (e.g., F5a). Site F3c was not included in the regression because of its extremely high variability in along-beach morphology, which makes the data point an outlier. Based on where F3c plots on the graph, it is likely that beaches with extremely high variability in along-beach morphology will always have some locations where profiles measure the volume change to within ±10%. Likewise, beaches with low variability in along-beach morphology will have some locations where profiles will not accurately measure the volume change to within ±10%.

1.5.5. Implications for Coastal Management

These analyses suggest that a range of volume-change measurements can result from profile surveys, regardless of the beach morphology. Beaches with low along-beach morphologic variability are more suitable for using profile surveys to measure volume changes, but even these beaches can have large ranges in volume-change measurements depending on where the transect is located. Despite the large range in volume-change measurements for profile surveys, they are still the most commonly used method for validating beach models and determining how much sand is eroded from a beach after a storm event.

Change in shoreline position is commonly used to calculate beach volume change (Dail, Merrifield, and Bevis, 2000; Farris and List, 2007; Sallenger et al., 2002). Farris and List (2007) argue that the change in shoreline position, defined as the location of the mean high water datum, is a valid proxy for subaerial volume change and support this notion with volume change measurements based on profiles at Cape Cod, Massachusetts; Assateague Island; and the Outer Banks of North Carolina. Transect spacing ranged from 10 m at Assateague Island (extracted from airborne LIDAR data) to ~1 km along the Outer Banks of North Carolina. The Farris and List (2007) study presents significant correlations between shoreline change and subaerial volume change (correlation coefficients range— 0.71-0.96) for different beaches, and correlation coefficients are generally high when along-coast variability in profile shape is low. The results from our study show that beach cusps and other along-beach variations in morphology make measurements of volume change inaccurate when they are based on profiles spaced 150 m apart. For example, fewer than 20 of the 300 measurements of volume change based on profiles at F2 are within ±50% of the true volume change. Even sites with the lowest along-beach morphologic variability have fewer than 105 of the 300 measurements of volume change based on profiles that are within ±10% of the true volume change. Measuring volume change from widely spaced profiles can yield erroneous results and should never be used as a benchmark for evaluating proxies of volume change; thus, it is likely that the correlations between change in shoreline position and true volume change are actually weaker than those reported in the Farris and List (2007) study.

Profile surveys are commonly used to assess the erosional impacts of storms and to determine how much FEMA aid a community receives for beach renourishment. For instance, Bogue Banks, a barrier island located ~14 km NE of Onslow Beach, with a similar morphology to the northern end of Onslow Beach, utilized RTK-GPS surveyed profiles spaced more than 1 km apart to measure the volume of beach eroded from Hurricane Ophelia in 2005 (Coastal Science & Engineering Staff, 2005). More than $13 million in FEMA beach renourishment funding was given to Bogue Banks to replenish the estimated 847,000 m^3 of sediment lost to Hurricane Ophelia. Results presented here suggest that it is unlikely that the profiles accurately quantified the beach response from that hurricane because of the large profile spacing. If three-dimensional methods, such as airborne LIDAR or terrestrial laser scanning, were used to evaluate beach response to the hurricane, the volume of sediment lost would be more accurately and precisely quantified, which would result in more effective beach renourishment. The additional funds necessary to collect these types of data represent a small percentage of the poststorm restoration cost. The large spread of volume-change measurements from profile surveys in our study suggests that this survey design is not suitable for making measurements of beach volume changes for beach research and management.

1.6. Conclusions

The accuracy of beach profile surveys in measuring volume change is strongly related to the amount of along-beach morphologic variability, which can be quantified using the standard deviation of along-beach slope. Beach profiles measure volume change most accurately at sites with low along-beach morphologic variability; however, profile placement, spacing, and the accuracy required for the project are important factors. All sites at Onslow Beach have transect locations that would erroneously measure volume change, but the accuracy required for a study determines whether these anomalous regions are problematic. If the accuracy required is high (e.g. ±10% of the net volume change), then these regions can greatly affect volume-change measurements based on profiles. In most cases, even if low accuracy is required, the along-beach variability will cause transect placement to be the most important factor in how closely measurements of volume change, based on profiles, reflect the true volume change. In the absence of hindsight, picking ideal locations for transect placement at many beaches is a difficult task.

Overall, beach profiles are least suitable for measuring volume change on beaches with large (>50 m) beach widths and complex along-beach morphologic variability (i.e. short wavelength beach cusps and/or pockets of anomalous erosion/accretion). Transect placement is important at these types of beaches and transects located along the horn or embayment of a beach cusp should not be used in volume-change measurements. If transects are used to survey a beach with cusps, they must be located on the cusp flanks to increase the accuracy of volume-change measurements. Surveying a beach with widely spaced transects is not an appropriate method for monitoring the edges of areas that were nourished because of the complexity of the beach response there. It is necessary to constrain the complexities of beach changes resulting from cusps and nourishment to accurately determine sediment budgets, which serve as input for morphodynamic models. These complexities are not likely to be captured by profile surveys, yet they are commonly used for many research and engineering projects, as well as the basis for FEMA funding of emergency beach restoration after a storm.

Profile surveys are employed on a range of timescales (event to decadal) to determine the magnitude and rates of shoreline and volume change on beaches and barriers worldwide. Results from this study suggest that beach profiles generally do not accurately measure volume change on short (event to annual) timescales, but it is unclear whether they are accurate on longer (decadal) timescales. At these longer time frames, the contribution of small-scale morphologic variations to the net volume change are dwarfed by the much larger volume changes associated with barrier transgression or regression; thus, profiles should perform better across longer time steps.

Chapter 2

Evaluating proxies of subaerial beach volume change across various short time scales and morphologies

2.1. Introduction

Accurate predictions of beach response to storms and short-term sea-level fluctuations (years to decades) rely on three-dimensional analyses of changes, such as beach volume. Three-dimensional datasets (e.g. LIDAR or terrestrial laser scanning), however, are commonly not available for many coastlines and/or at relevant time frames, thus beach researchers and managers normally rely on proxies. Changes in beach profiles and shoreline positions are universally-used proxies for deriving beach volume change when three-dimensional data sets are not available (Farris and List, 2007; Jarrett, 1991; Smith and Zarillo, 1990). The widespread use of those proxies makes it important to evaluate their utility for quantifying volume change across various time frames and beach morphologies that are relevant for coastal management.

The beach-profile method is employed by coastal researchers and managers for monitoring volume change, as well as tracking the performance of beach-nourishment projects (Benedet, Finkl, and Hartog, 2007; Bocamazo, Grosskopf, and Buonuiato, 2011; Browder and Dean, 2000; Elko and Wang, 2007; Miller and Fletcher, 2003; Norcross, Fletcher, and Merrifield, 2002; Smith and Bryan, 2007). Previous studies suggest that beach profiles do not accurately measure volume change on short-time scales (< 1 year) at beaches with high along-beach morphologic variability (Pietro et al., 2008; Theuerkauf and

Rodriguez, *In Press*). The inherent assumption with long-term studies (> 1 year) of volume change using beach profiles is that with increasing time the event to yearly variability of the beach volume is dwarfed by the overall trend (Dolan, Fenster, and Holme, 1991; Larson and Kraus, 1994). In addition, this suggests that along a beach with significant along-beach variations in morphology the importance of transect placement for obtaining accurate measurements of beach volume should also diminish as the time frame increases.

Shoreline change is a convenient proxy for subaerial volume change because it can be derived from easily accessible aerial photographs as well as LIDAR data, which is commonly archived and made publically available by state and federal agencies. The shoreline can be defined as either a datum-based shoreline- a specific elevation contour like the mean high water line (MHW), or a visually-interpreted shoreline such as the wet-dry line (Farris and List, 2007). The shoreline-change proxy assumes that the beach profile is in equilibrium, and the total volume change is simply equal to the height of the active profile multiplied by the horizontal movement of the shoreline (Bruun, 1962; Farris and List, 2007; Hanson, 1989). Although this assumption implies that the shoreline-change proxy works best over long time scales (decadal), many studies argue that it is also applicable over shorter time scales (yearly; Dail, Merrifield, and Bevis, 2000; Jarrett, 1991; Sallenger et al., 2002). Using volume change derived from beach profiles at several sites along the U.S. Atlantic Coast as a benchmark, Farris and List (2007) evaluated shoreline change (derived from the intersection of the beach profile with the elevation of MHW) as a proxy for volume change over yearly time scales and determined that the proxy is more reliable at beaches where profile shape does not change significantly over time.

Previous studies assert that morphologic complexities (i.e. profile variability, beach cusps, and nourishment) contribute to the poor performance of beach volume change proxies on short-time scales, but have less influence over longer time frames (Dingler and Reiss, 2002; Farris and List 2007; Theuerkauf and Rodriguez, *In Press*). While that may be true for beaches that are rapidly eroding or accreting, no indication is given for the duration a beach with variable or inconsistent morphologic change must be surveyed before proxy performance increases. This study addresses that lack of understanding by examining the effects of complex morphologic changes and varying observational time frames on the accuracy of using changes in beach profiles and the position of shorelines as proxies for subaerial volume change. Volume changes measured from high-resolution DEMs, derived from terrestrial laser scanning data, are the benchmarks that we use for assessing the proxies.

2.2. Study Area

The study area is Onslow Beach, located at Marine Corps Base Camp Lejeune in eastern North Carolina along the U.S. Atlantic Coast. This wave-dominated, microtidal (mean tidal range of ~1 m) barrier island is 12-km-long, 90-600-m wide, and is bordered by the New River Inlet to the SW and Brown's Inlet to the NE. Onslow Beach was chosen for the study because along-shore morphology and erosion rates are highly variable (Benton *et al*., 2004; Foxgrover, 2009; Rodriguez, Rodriguez, and Fegley, 2012; Figures 2.1 and 2.2) allowing the volume-change proxies to be evaluated at the same time frames across a

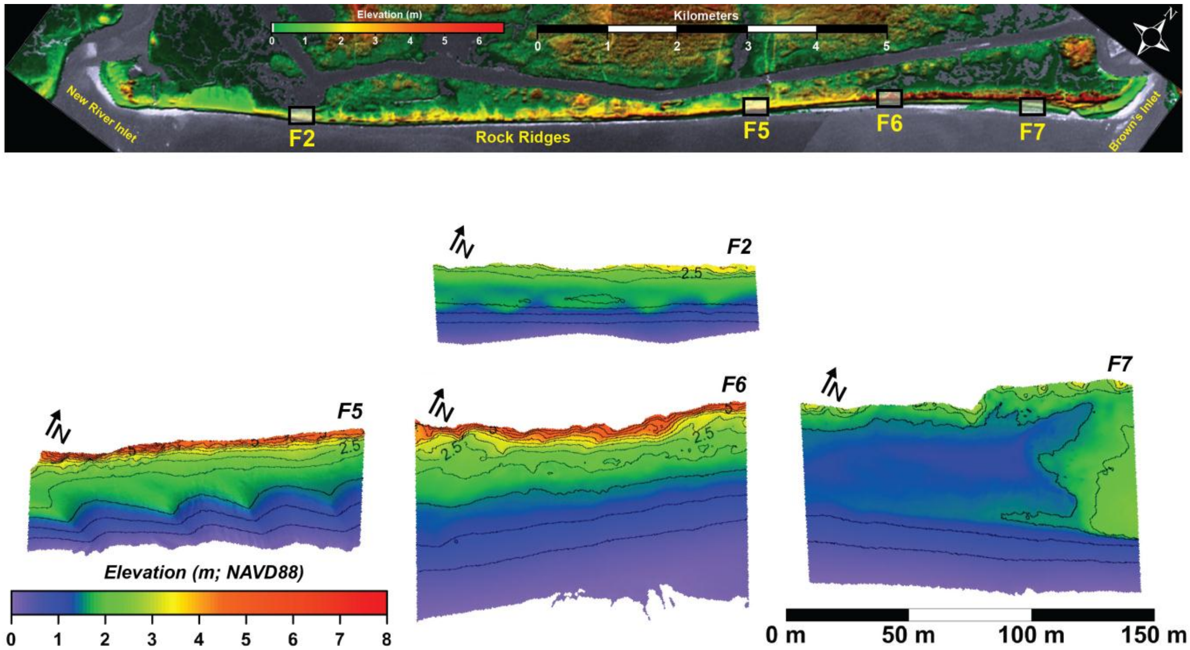

Figure 2.1.- Study area map highlighting the four focus sites used in this study and the variable along-barrier morphology. Examples of the high-resolution digital elevation models of the focus sites, derived from terrestrial laser-scanning data, are shown with a 0.2-m contour interval.

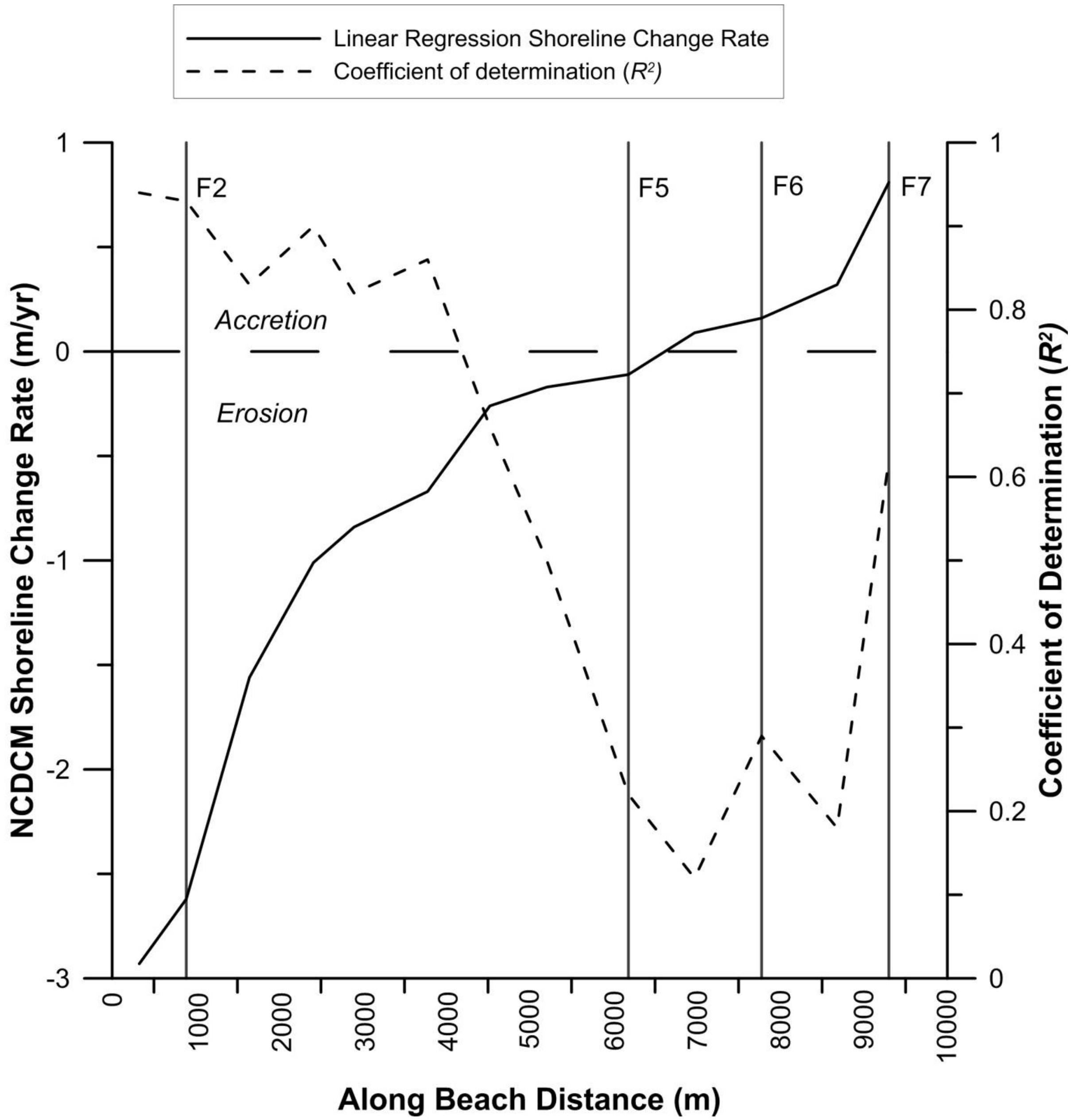

Figure 2.2.- NCDCM shoreline change rates (solid line) and interannual variability represented as the coefficient of determination R^2 (dashed line) at Onslow Beach. Along-beach distance is from the New River Inlet. Vertical lines indicate location of focus sites.

range of morphologies subjected to the same wave conditions. The southern portion of the island (toward the New River Inlet) is dominated by erosion on the decadal scale with 2- to 4-m high dunes, a narrow beach, and multiple washover fans (Figures 2.1 and 2.2). The northern portion of the island (toward Brown's Inlet) is dominated by accretion on the decadal scale with greater than 6-m-high dunes and a wide beach. Riggs, Cleary, and Snyder (1995) suggest that subdivision of these distinct zones is the result of Oligocene rock ridges that intersect the center of the island, where shoreline evolution transitions from transgression to regression. These zones represent beach morphologies of adjacent barriers to the north (regressive toward Cape Lookout; Timmons *et al*., 2010) and south (transgressive toward Cape Fear; Riggs, Cleary, and Snyder, 1995), as well as other wave-dominated barriers along passive margins.

2.3. Methods

2.3.1. Field-Data Acquisition

Focus sites (four) were selected along the barrier to sample the various directions and rates of shoreline movement, which were measured from the North Carolina Division of Coastal Management's (NCDCM) shoreline change dataset using the Digital Shoreline Analysis System (DSAS) and linear regression (Benton *et al*., 2004; Thieler *et al*., 2009; Figures 2.1 and 2.2). Site F2, in the southern zone, is characterized by rapid and consistent erosion (~-2.6 m/yr; R^2= 0.93). Sites F5 and F6, in the northern zone, are characterized by near-neutral rates of shoreline change (~-0.11 m/yr and ~0.16 m/yr, respectively) and high interannual variability in shoreline position (R^2= 0.22 and 0.29, respectively). Dredge-material disposal at the northern end of Onslow Beach occurs in the winter approximately every two years and the material is compatible, in terms of sediment texture, with the natural beach sediment (native: mean=2.18 phi, 1% gravel; material: mean=2.29 phi, 0% gravel). Site F7, which experiences consistent accretion on decadal scales (~0.81 m/yr; R^2=0.62), is located at the dredge-material disposal site and is used to represent nourished beaches. Sites F2 and F5 are also characterized by a high-degree of along-beach variability in beach morphology with beach cusps occurring repeatedly throughout the study period (Table 2.1).

Topography of the focus sites was surveyed with a Riegl three-dimensional LMSZ210ii terrestrial laser scanner, which collects around 2 million spatial (x, y, and z) data points per scan. Beach scans were conducted every fall and spring from November 2007 to May 2011, as well as before and after nourishment (dredge-material disposal) in February 2010. Each focus site was scanned in two locations ~200 m apart in the along-beach direction, and surveying was limited to the 2 hours before and after low tide to maximize data coverage of the foreshore. Data points were georeferenced to a global coordinate system (Universal Transverse Mercator) using RTK-GPS-surveyed reflectors. Topographic data is estimated to contain a ± 3.0 cm error, which is the sum of a ± 1.5 cm factory-estimated maximum instrument error and a ± 1.5 cm average RTK-GPS error that is reported from the instrument.

2.3.2. Data Processing

Ground points (x-, y-, and z-data points) were isolated from the point cloud and used to create surface-grid models (using Delaunay triangulation) with 0.5-m grid spacing using Terrasolid software. Surface-grid models were imported into Golden Software's Surfer 10.0 to generate contour maps and DEMs. Areal laser coverage at each site varied between surveys due to unavoidable circumstances, such as beachgoers, Marine Corps training activities, variations in the location of the scanner, variations in dune morphology, and sea level. To correct for variations in areal coverage, each DEM was cropped to the maximum extent of overlapping coverage. Resulting maps extend ~150 m in the along-beach direction for each focus site. The DEMs were cropped at the foredune crest to normalize the landward boundary and 0 m North American Vertical Datum of 1988 (NAVD88) to normalize the seaward boundary for variations in sea level (principally tidal height) among surveys.

Volume change between two times were quantified by subtracting DEMs in Surfer 10.0 using two schemes: (1) each DEM was subtracted from the first survey (November 2007 for F2, F5, and F6; May 2008 for F7) and (2) each DEM was subtracted from the survey immediately prior (e.g. November 2007-May 2008; May 2008-September 2008; Figure 2.3). Error in volume change measurements are not reported with these DEM-subtraction maps because the "true" morphology of the beach is assumed to be equal to the DEMs; i.e. volume change derived from the DEMs is the benchmark that volume change derived from beach profiles and shoreline change will be measured against.

DEM	Backshore Width (m)	Beach Cusps	Nourishment
F2 November 2007	2.16	Yes	No
F2 May 2008	7.71	No	No
F2 September 2008	5.83	Yes	No
F2 May 2009	14.67	Yes	No
F2 September 2009	4.50	Yes	No
F2 May 2010	0.00	No	No
F2 September 2010	0.00	No	No
F2 May 2011	0.00	No	No
F5 November 2007	23.69	Yes	No
F5 May 2008	9.09	Yes	No
F5 September 2008	18.26	Yes	No
F5 May 2009	12.81	No	No
F5 September 2009	5.52	Yes	No
F5 May 2010	20.00	No	No
F5 September 2010	8.86	Yes	No
F5 May 2011	5.27	Yes	No
F6 November 2007	16.57	No	No
F6 May 2008	24.50	No	No
F6 September 2008	25.54	No	No
F6 May 2009	32.76	No	No
F6 September 2009	23.81	Yes	No
F6 May 2010	11.03	No	No
F6 September 2010	12.95	Yes	No
F6 May 2011	0.00	No	No
F7 May 2008	51.82	No	Yes
F7 September 2008	41.90	No	Yes
F7 May 2009	35.44	No	Yes
F7 September 2009	24.34	Yes	Yes
F7 January 2010	40.22	Yes	Before spoil dispoal
F7 February 2010	52.80	No	Immediately after spoil disposal
F7 March 2010	41.52	No	After spoil disposal
F7 May 2010	23.70	Yes	Yes
F7 September 2010	8.92	No	Yes
F7 May 2011	10.97	No	Yes

Table 2.1.- Beach parameters for each DEM used to create the subtraction maps.

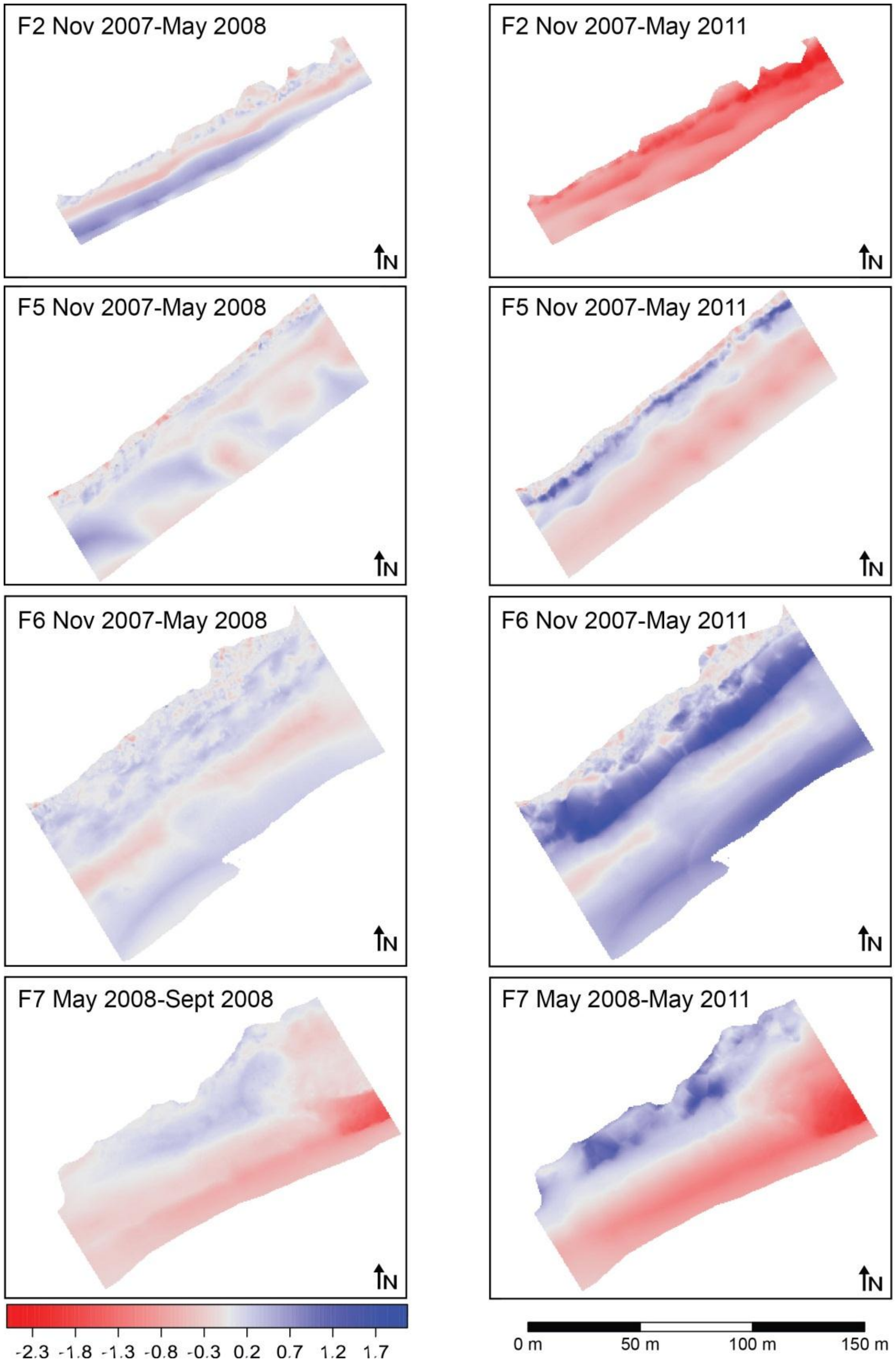

Figure 2.3.- DEM subtraction maps derived from terrestrial laser-scanning data. The shortest (November 2007-May 2008 for all sites except F7, where surveying began in May 2008) and longest time steps are shown as examples. Negative values shown in red are erosion and positive values shown in blue are accretion.

2.3.3. *Beach-Profile Data*

Beach-profile data were derived from the DEM-subtraction maps by extracting grid-node values along shore-perpendicular transects positioned every 0.5 m along the beach using Surfer 10.0 (~300 transects per site). Volume change is derived from the profiles using Equation 1:

$$\sum_{i=1}^{n} Y\Delta Z_i \left(X_{i+1} - X_i\right)$$

In this equation, n is the total number of grid cells the transect intersects, Y is the along-beach transect spacing (150 m), ΔZ is the change in elevation at a given grid cell, and X is the across-beach distance a cell is from the first (most landward) grid cell in the transect (Theuerkauf and Rodriguez, *In Press*). A transect spacing of 150 m was chosen because that is a common spacing for beach-profile studies (*e.g.*, Creaser, Davis, and Haines, 1993). Volume change calculations from the profiles were compared to the benchmark at each time step to assess the accuracy of beach profiles at measuring volume change and whether accuracy increases as the time step increases (Figure 2.4).

2.3.4. *Shoreline-Change Data*

Shoreline change was measured using the mean high water (MHW) line, which is 0.36 m NAVD88 at Onslow Beach (Weber, List, and Morgan, 2005). The MHW line was contoured from the DEMs and exported as a shapefile into ArcGIS. Shoreline change was measured using DSAS, an extension in ArcGIS that computes shoreline change by calculating the distance each shoreline is away from a known baseline (Thieler *et al*., 2009). The difference between those distances is equal to shoreline displacement for a given time

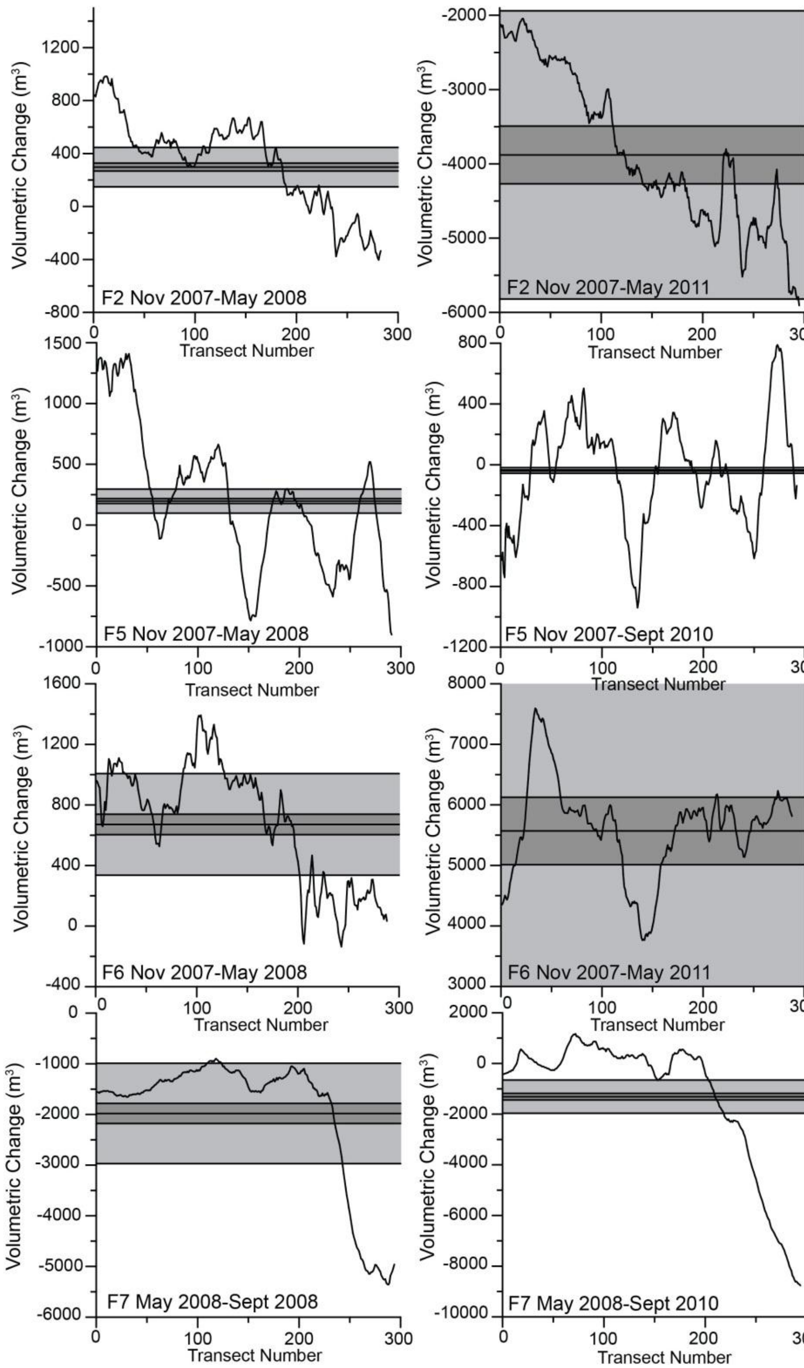

Figure 2.4.- Along-beach variability in volume-change measurements derived from beach profiles spaced every 0.5 m along the beach at each focus site. Measurements for each transect from the SW (transect 0) to the NE (transect 300) are plotted. The true volume change from laser scanning data is indicated by the horizontal black line. Volume change measurements within ±10% and ±50% of the true volume change are denoted by dark gray and light gray shading, respectively. The shortest survey length and a longer survey length are shown as examples and correspond with Figure 2.3.

step. Shoreline change was computed at Sites F2, F5, and F6 for 7 periods ranging from 0.5 to 3.5 years and Site F7 for 6 periods ranging from 0.5-3.0 years. Shoreline change was plotted against the true volume change, derived from the DEMs, to evaluate the proxy at each site.

2.4. Results and Interpretations

2.4.1. Impact of Transect Placement on Volume Change Over Time

Profile-measured-volume change calculated from the middle transect correlates well (R^2=0.91) with the true (laser-derived) volume change when all sites and periods are analyzed together (Figure 2.5). This, in itself, should not be interpreted to indicate that profile-based volume changes are accurate everywhere along Onslow Beach because the accuracy of the volume-change calculation is dependent upon the transect position, the period between observations, and the magnitude of the change, which are not taken into account. Volume change measurements from each site are compared to the true volume change using the concordance correlation coefficient (r_c; Lin, 1989). An r_c value of 1 indicates that there is a 1:1 relationship between profile-measured volume change and the true volume change, while an r_c value of 0 indicates that there is no correspondence between the two measurements. Each r_c value is reported with 95% confidence limits. Profile-measured volume changes from the center transect at Sites F5, F6, and F7, analyzed individually, do not compare well with the true volume change and have r_c values that are lower than what is obtained when all the sites are analyzed together (Figure 2.5). In contrast, Site F2 has a high r_c value, similar to all the points analyzed together. To evaluate the large differences in r_c values between sites the importance of transect placement on the accuracy and precision of the volume change measurements over varying time frames (0.5 to 3.5 years) is assessed by computing the percent of transects that measure volume change to within 10% and 50% of the true volume change (i.e. the 10% and 50% window; Figure 2.6). A time frame with a low percentage of transects that approach the true volume change indicates that measurements based on the beach-profile method perform poorly and have low accuracy and precision.

Site F2 experienced rapid and consistent beach erosion over the 3.5 year study, which corresponds with the decadal shoreline record (Figures 2.2 and 2.6). Overall, profile performance increases as the time steps increase, reaching a maximum within 3 years. After 2.5 years, around 100% of the profiles measure volume change to within 50% of the true

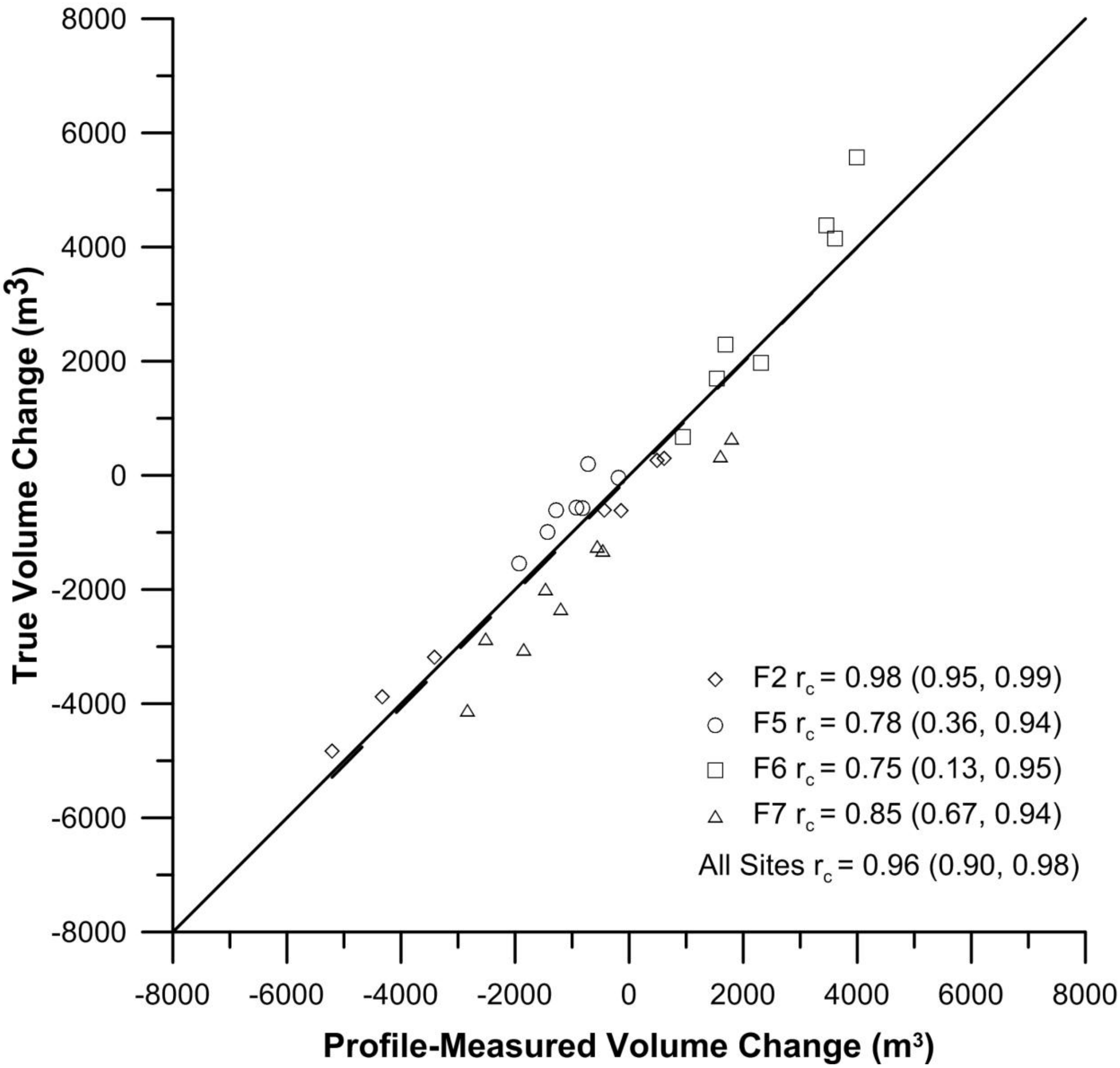

Figure 2.5.- Comparison of profile-measured volume change to volume change derived from terrestrial laser scanning (the benchmark). The center transect (transect 150) was used to compute volume using Equation 1. The solid line indicates a 1:1 relationship between profile-measured volume change and the benchmark. The dashed line is the regression line through all of the points. The concordance correlation coefficient (r_c) indicates departure from the 1:1 line; r_c= 1 indicates no departure from the 1:1 line. 95% confidence limits for the r_c values are shown in parenthesis.

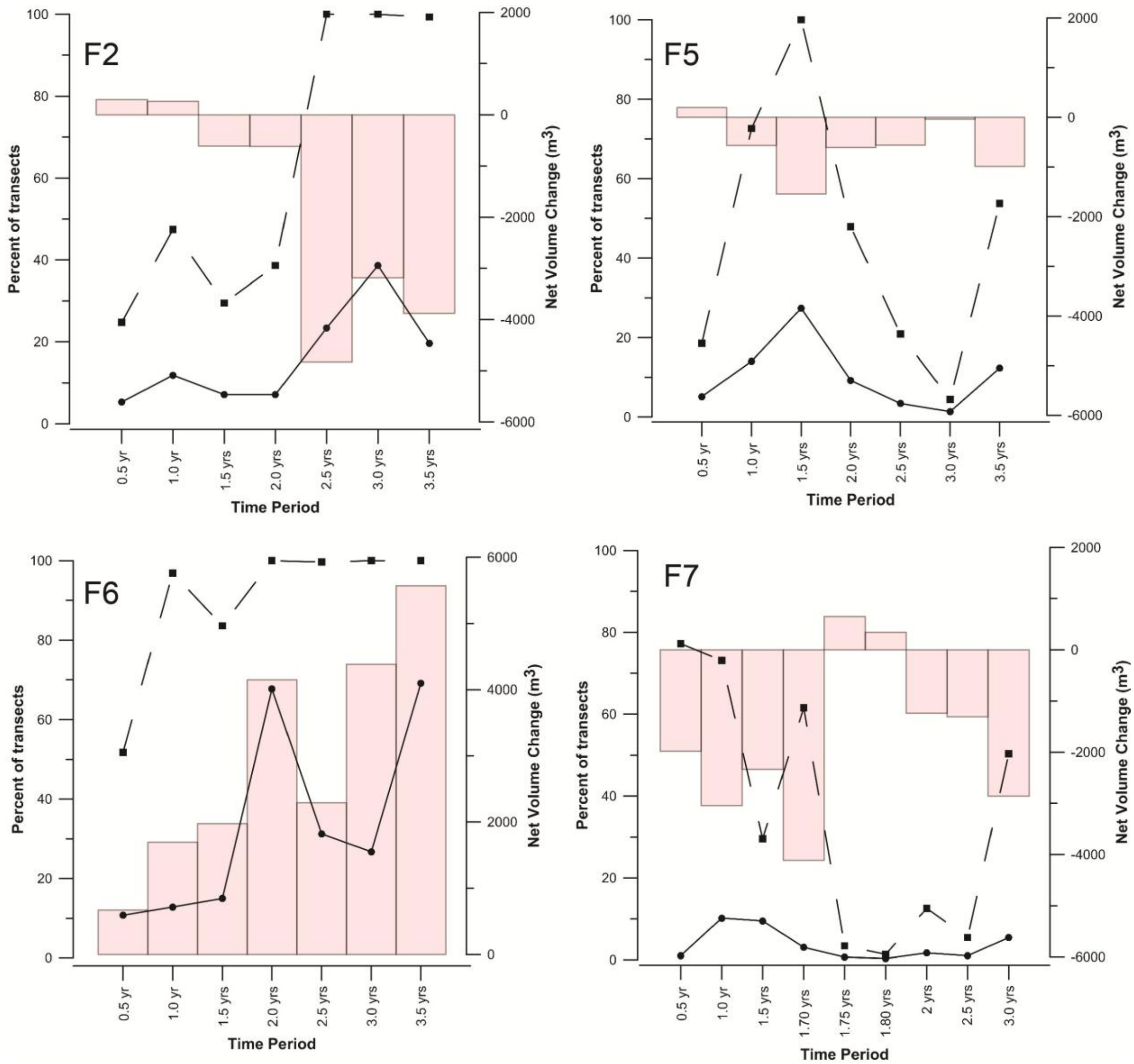

Figure 2.6.- Beach profile performance with increasing time steps at sites F2, F5, F6, and F7. The solid line indicates the percentage of transects that measure volume change within ±10% of the true volume change and the dashed line indicates the percentage of transects that measure volume change within ±50% of the true volume change. Red bars indicate the net volume change since the initial survey. Periods start from November 2007 at sites F2, F5, and F6 and May 2008 at Site 7.

change, but only around 20-40% of the profiles measure volume change to within 10% of the true change. Performance scales with net volume change, i.e. the best performing time periods correspond with the largest net volume changes and because this site is consistently eroding, profiles across time steps >2.5 years provide the most accurate measures of volume change.

At Site F5, net volume change over the 3.5 year study was low and exhibited high interannual variability in both the magnitude and direction of change (Figure 2.6), which corresponds with the decadal record of shoreline change (Figure 2.2). From 0.5-1.5 years, the transect-performance increased rapidly to ~30% of transects calculating volume change within 10% of the true volume change and 100% of transects calculating volume change within 50% of the true volume change. From 1.5-3.0 years, the transect-performance decreased rapidly, but increased again from 3.0-3.5 years to ~10% at the 10% window and ~55% at the 50% window. Profile performance did not systematically increase with increasing time; rather it covaried with net volume change, which oscillated greatly throughout the study. Site F5 varies between erosion and accretion at 0.5 year time scales making the net volume change at the larger periods similar in magnitude to the shorter time frames and profiles not being a reliable measure of volume change at any of the time scales examined.

Low rates of shoreline change and high interannual variability are noted at Site F6 in the decadal shoreline change record (Figure 2.2); however, over this 3.5 year study, net volume changes were, overall, consistently high and positive (accretion; Figure 2.6). Similar to Site F2, profile performance increased consistently with increasing time. Maximum profile performance, ~70% for the 10% window and ~100 % for the 50% window, occurs in association with large net volume changes and the 2 and 3.5 year time steps.

The decadal record shows that Site F7 is consistently accreting (Figure 2.2); however, over this study period, high variability in both the magnitude and direction of net volume change was observed in response to biennial beach nourishment (Figure 2.6). Profile performance is consistently low at the 10% window and high variability in profile performance at the 50% window is observed throughout the study. Profiles performed poorly at both the 10% and 50% windows after beach nourishment during the winter of 2010, which corresponds with a large increase in net volume change between the periods 1.70 and 1.75 years. Nourishment also occurred in the winter of 2008, prior to the first survey in this study (May 2008). The site consistently erodes between nourishment events until a volume of sand equal to what was eroded is artificially placed back on the beach resetting the system to a near-neutral volume change. Variations between erosion and accretion at 2.0-year time scales makes the net volume change at the larger periods similar to the shorter periods and profiles not being a reliable measure of volume change, which is similar to what was observed at Site F5.

2.4.2. Shoreline Change as Proxy for Volume Change

Shoreline change correlates well with the true volume change at Onslow Beach (R^2 = 0.82; *P* value = 4.73 E-26; Figure 2.7) when all sites and time frames are analyzed together. The coefficient of determination for the correlations between shoreline change and volume change is lower for surveys spanning less than or equal to one year (0.78; *P* value = 1.22 E-12), which suggests that the performance of shoreline change as a proxy for volume change increases across longer time periods (Figure 2.7). Some site measurements cluster on the graph (e.g. F5) suggesting that the regression line cannot be used to model volume changes accurately from shoreline movements at those sites. Clustering could be the result of along-beach variations in morphology and/or short-term changes in volume and the position of the shoreline that are at a similar magnitude to long-term changes. Comparing shoreline change to volume change at the individual sites provides a more detailed examination of the utility of this proxy.

Shoreline change highly correlates with volume change at the rapidly and consistently eroding site F2 (R^2 = 0.83; *P* value = 1 E-06) and the nourished site F7 (R^2 = 0.96; *P* value = 1.53 E-14; Figure 2.8). Unlike beach profiles, this proxy performs well with surveys conducted before and after beach nourishment. A lower correlation exists at site F6 (R^2 = 0.63; *P* value = 0.00025), where accretion was relatively consistent throughout the surveys, but decadal scale variability in the shoreline position is high (Figure 2.2). Shoreline change does not correlate well with volume change (R^2 = 0.27; *P* value = 0.041) at site F5 where volume change was relatively low and exhibited high inter-annual variability. The correlation coefficients at Sites F2, F5 and F6 are higher for the regression lines through the points that represent periods >1 year than the regression lines through the points for all time periods up to 3.5 years. This suggests that increasing the time frame improves the shoreline-position proxy, which is most apparent at Site F5. The correlation coefficient at Site F7 is high (≥ 0.9) for all of the periods examined here (Figure 2.8).

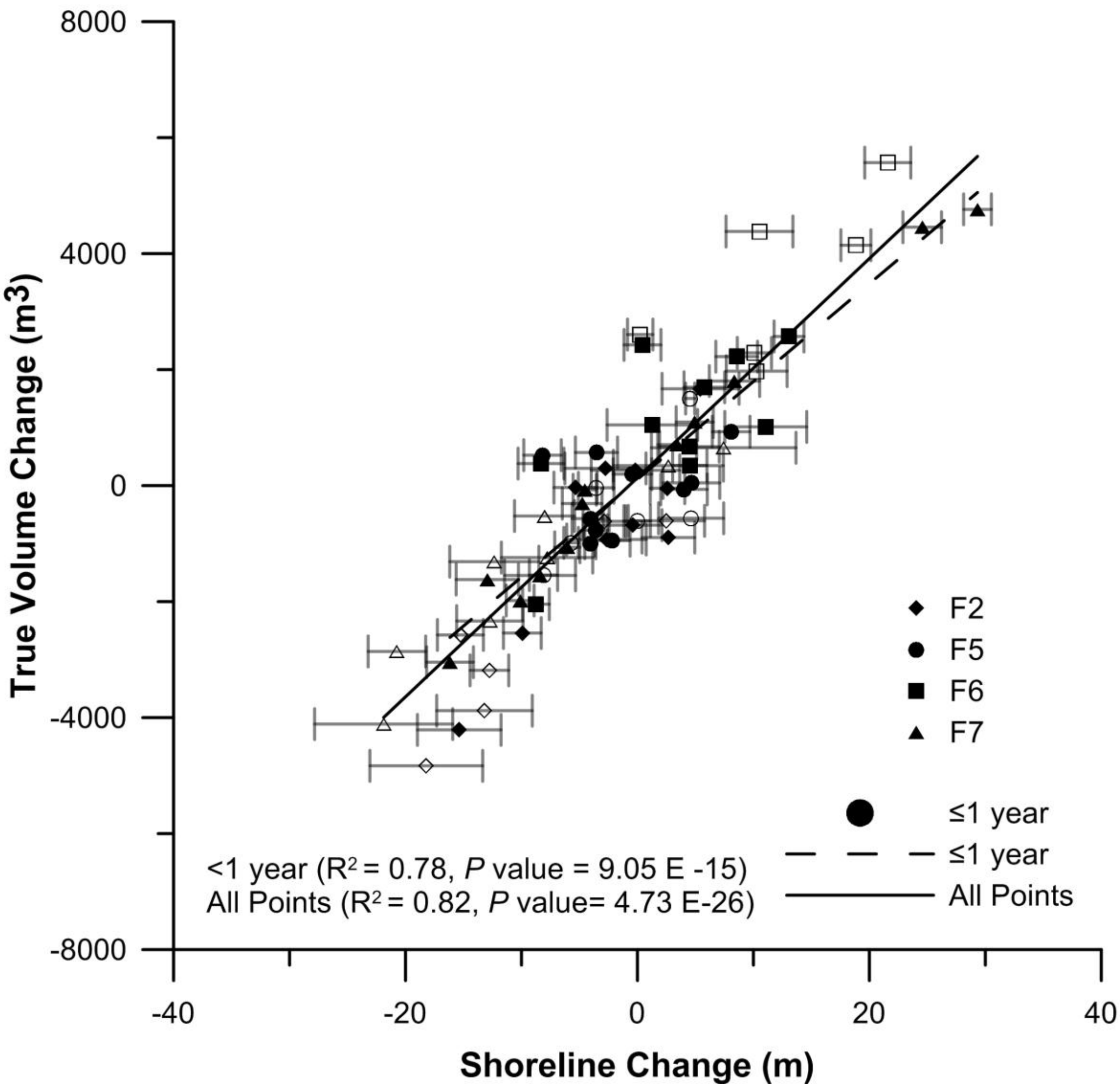

Figure 2.7.- Relationship between MHW shoreline change and the volume change derived from terrestrial laser scanning at all sites and time intervals. The solid line is the regression line through all of the data points. Bars around each data point indicate the standard deviation of shoreline change measurements.

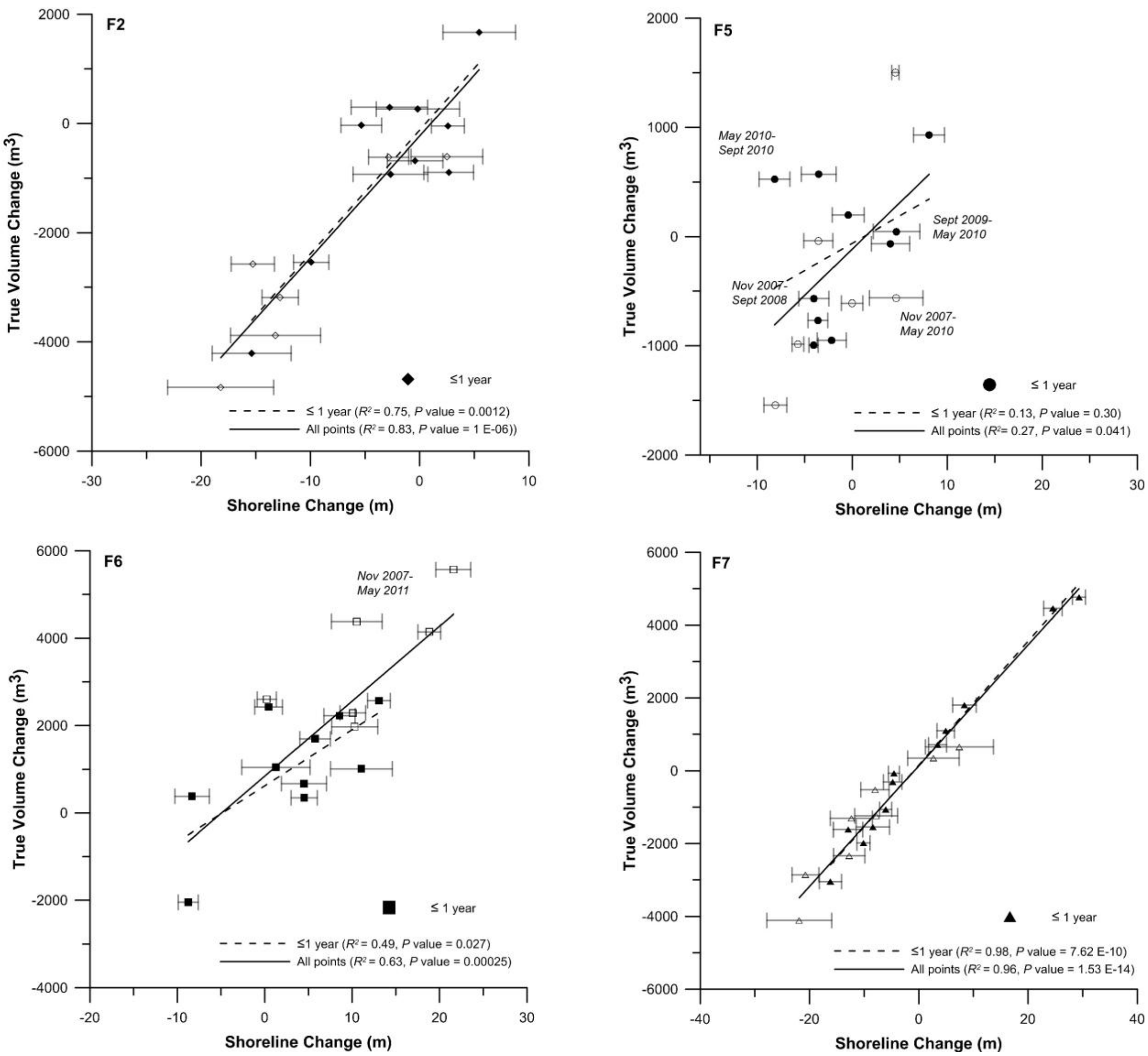

Figure 2.8.- Relationship between MHW shoreline change and true volume change at each site. Best-fit lines through each data series are shown to highlight proxy performance through time. Bars around each data point indicate the standard deviation of shoreline change measurements.

2.5. Discussion

2.5.1. Profile Performance over Time

The profile method for measuring beach volume change assumes that the relative importance of variability in the shape of profiles at short temporal and spatial scales is minimal in comparison to the magnitude of change on longer time scales. This suggests that at longer time scales the importance of transect placement decreases and performance of beach profiles in measuring volume change increases. At Sites F2 and F6, beach profile performance improved with increasing time, while this was not observed at Sites F5 and F7 (Figure 2.6). This difference is mainly because the net volume changes at Sites F2 and F6 are relatively high magnitude and show overall consistent erosion and accretion, respectively, which minimizes the relative influence of the small-scale short-term spatial variability on profile performance. At Site F2, the small-scale spatial variability is produced mainly by ephemeral beach cusps (Table 2.1). The ephemeral beach cusps decrease the performance of beach profiles at short time scales, but as the length of survey time increases at F2 (> 2 years), the effect of beach cusps on profile performance decreases. Similar to Site F2, profile performance at Site F6 improves greatly with increasing time steps because over the 3.5 year time frame, F6 is consistently accreting at a high magnitude.

Profiles at F5 and F7 did not perform better with increasing time steps, which is likely due to high interannual variability in the direction and/or magnitude of beach response. At yearly and decadal scales, F5 is characterized by a low rate of shoreline change and high variability in the position of the shoreline through time ($R^2 = 0.22$; Fig. 2.2 and 2.6). Beach cusps are common at F5 (Table 2.1) and affect the performance of profiles at interannual time scales because the magnitude of the volume change they introduce is similar to the variability of the net volume change at the 0.5-3.5 year time scales examined here.

Although the decadal record indicates accretion at F7 is consistent (R^2=0.62), there is a considerable amount of variability in net volume change throughout this study resulting from beach nourishment in March 2008 and February 2010. The biennial beach nourishment began less than 10 years ago, which is why it is not reflected in the decadal record of shoreline movement. Nourishment sand strongly influences the interannual beach response by producing beach accretion followed by erosion, which results in poor profile performance at the 10% and 50% windows. The performance of profiles does not increase as time increases at this regularly nourished beach.

2.5.2. Shoreline Change as a Proxy for Volume Change

Shoreline change is an accurate proxy for volume change at Site F2, where the shoreline consistently moved in one direction because over time, the magnitude of volume change relative to the magnitude of variability increases, suggesting that an equilibrium beach profile is consistently approximated at Site F2 (Figure 2.8). This confirms the findings of previous studies that indicate this proxy works best when the beach profile is in equilibrium (Farris and List, 2007; Jarrett, 1991). In addition, proxy performance at Site F2 improves with time indicating that the ability of this proxy to accurately measure volume change increases with time (Figure 2.8). Proxy performance improves slightly at sites F5 and F6 with time, but remains low indicating that shoreline change is not a reliable proxy for volume change at these sites. The slight decrease in performance at Site F7 for time periods greater than a year is the result of large interannual variability in volume change associated with multiple nourishment events.

The shoreline-change proxy should not be used at sites where the foreshore and backshore respond in different directions and/or at sites with high decadal variability in shoreline change, such as F5 and F6. A poor relationship between shoreline change and volume change was observed at Site F5 at time scales ≤1 year (≤1 year R^2= 0.13; *P* value = 0.30), although the relationship does improve with time (R^2 = 0.27; *P* value = 0.041 for all time scales); Figure 2.9). There are several instances when beach erosion is associated with seaward movement of the shoreline and when beach accretion is associated with landward movement of the shoreline. The mean high water shoreline (MHW) at Onslow Beach is located below the berm along the foreshore, thus shoreline movements may not capture volume changes in the backshore. The shoreline moves in the opposite direction from the true volume change when the volume change is mainly isolated to the backshore, which is commonly related to the formation or erosion of beach cusps and/or aeolian transport. Site F5 is generally characterized by a well-developed berm and a backshore with ephemeral beach cusps. When beach cusps form or are destroyed the volume change data indicates accretion and erosion, respectively but the average shoreline movement can be in the opposite direction because the MHW line is located at a lower elevation and is not influenced by these features (e.g. May 2010 to September 2010; November 2007 to May 2010; Figure 2.9).

The shoreline proxy can also over predict accretion or erosion when the foreshore and backshore responses are in opposing directions. The positive shoreline change at Site F5, across the September 2009 to May 2010 time step, is associated with foreshore accretion, but backshore erosion that is not captured by the proxy resulted in a near-zero net volume change. Between November 2007 and May 2011, Site F6 experienced foreshore accretion in response to sediment received from upstream beach nourishment, while the backshore experienced little or no volume change. The shoreline proxy performance decreases when changes in the backshore are in opposing directions and/or magnitudes to changes in the foreshore and when decadal variability of the shoreline position is high. Increasing time will not improve the performance of the proxy at sites where there is high decadal variability in shoreline position and the rate of movement is close to zero (Sites F5 and F6) because the magnitude of longer-term net volume changes will always be at the same as the magnitude of small-scale morphologic variability.

Shoreline change corresponds well with volume change at Site F7, where beach nourishment occurred. This proxy likely worked well at F7 because the beach is very wide and generally lacks a berm and backshore (Table 2.1), thus more closely resembling the equilibrium profile. This is in contrast to the poor performance of beach profiles in representing the beach volume at site F7 in association with nourishment. The MHW shoreline produces reliable estimates of volume change at this nourished beach and could be used as an alternative to beach profiles or three-dimensional methods for monitoring nourishment performance at beaches with morphologies similar to F7.

2.5.3. Comparison of Proxy Methods

In the absence of three-dimensional datasets for measuring volume change, it is useful to determine the proxy method that produces the most accurate volume change measurements for a specific type of beach morphology and evolution. At site F2, where rapid and constant erosion occurs, shoreline change and beach profiles both reasonably measure the true volume change (Figures 2.5, 2.6, and 2.8). This is shown by the high correlation coefficient between shoreline change and the benchmark volume change (R^2=0.83) and the high concordance correlation coefficient between the beach-profile proxy volume change and the benchmark volume change (r_c=0.98). In addition, profile performance significantly increased with time regardless of transect placement (Figure 2.6), confirming that beach profiles can produce accurate volume change measurements at beaches with temporally consistent beach response. The equilibrium beach profile assumption is valid at Site F2 where the relative influence of small- scale morphologic variability diminishes through time because of consistent beach erosion.

Shoreline change is also a good proxy for volume change at the nourished Site F7, but the beach-profile method did not perform as well. Although the center transect reasonably measured volume change at Site F7 (r_c=0.85; Figure 2.5), that result would not have been achieved if the transect were placed in a different location because Figure 2.6 shows large fluctuations in the percent of transects that measure volume change to within 50% of the true volume change through time. Profile measured volume change using the center transect corresponds with the benchmark volume change at Site F5 (r_c=0.78; Figure 2.5), but similar to Site F7, that result is highly dependent upon transect placement (Figure 2.6). The high concordance correlation coefficient exaggerates the utility of profiles as a proxy for volume change at Sites F5 and F7 because the along-beach morphologic variability associated with beach nourishment and cusps indicates that transects placed in other locations would yield lower concordance correlation coefficients (Figure 2.6). The 95% confidence limits for Sites F5 and F7 further indicate the exaggeration of profile performance. Although the r_c value is relatively high for these sites, the 95% confidence limits indicate relatively low confidence in the r_c values. Volume change measured using the center beach profile at Site F6 corresponds well with the benchmark (r_c=0.75) as would be expected given that transect placement has little influence on the volume-change measurement at periods >1.5 years (Figure 2.6). The shoreline change proxy does not perform well at Site F6 because of different magnitudes and directions of backshore and foreshore volume change, and high interannual variability in the position of the shoreline.

At Site F7, the high-degree of along-beach morphologic variability coupled with a ramp-like morphology in the cross-beach direction, for most observations, makes the shoreline change proxy more useful than the profile method for constraining changes in beach volume. At Site F5, the high-degree of along- and across-beach morphologic variability in addition to yearly fluctuations in erosion and accretion, which are at similar magnitudes to the morphologic variability, makes only three-dimensional data appropriate for obtaining accurate measurements of volume change. At Site F6 the low along-beach morphologic variability, high across-beach variability in erosion and accretion, and the high temporal variability in shoreline position makes changes in beach profiles more useful for measuring volume change than the changes in shoreline positions.

As previously outlined, the performance of both proxy methods varies over time depending on the morphology of a site. Generally, the proxies improve over relatively short time scales (<3.5 years), but at a site where the shoreline position and the along-beach morphology is highly variable, like Site F5, the observation length was not long enough to see significant improvement in both proxies. Unless the degree of morphologic variability at a site like F5 decreases, the proxies will continue to do a poor job of evaluating beach volume change, regardless of the observational time frame.

2.6. Conclusions

Proxy methods for measuring subaerial volume change, such as changes in beach profiles and shoreline positions, are commonly used in coastal research and management without consideration of the performance of these methods at varying time frames and beach morphologies. Proxy methods for measuring volume change are convenient alternatives to expensive and time-consuming laser methods and for many time intervals are the only data types available. Management decisions and research results may be adversely influenced by inaccurate depictions of beach volume change that were based on a proxy that is not well suited to that particular beach. Results from this study show that changes in beach-profiles and shoreline positions at time scales >1 year approximate volume change most accurately at beaches that erode or accrete consistently and at a large magnitude over time. For those beaches, the assumption that the morphology approximates the equilibrium beach profile is valid and relative influence of small-scale and short-duration (seasonal-year) volume changes are minimal compared to the high magnitude longer-term (multi-year) volume change. Changes in shoreline position should not be used as a proxy for volume change at beaches with high interannual variability in shoreline positions at time scales < 3.5 years and where there are significant morphologic changes to the backshore. Berm erosion/accretion, and beach cusps above the MHW line are not captured by analyzing shoreline changes. Beach profiles should not be used to measure volume changes at beaches where there is a large degree of along-beach morphologic variability, which can be introduced by beach cusps and nourishment. Changes in beach profiles and shoreline positions are poor proxies for volume change at beaches that oscillate between erosion and accretion making the net volume change over longer time scales (>2 years) low. At those beaches, the magnitude of small-scale changes in beach volume will always be similar to the long-term net change making data collection with three-dimensional methods essential.

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