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Beach-dune interactions and a new cycle of foredune evolution, Gulf County, Florida

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BEACH-DUNE INTERACTIONS AND A NEW CYCLE OF FOREDUNE EVOLUTION, GULF COUNTY, FLORIDA

A Dissertation

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Agricultural Mechanical College
in partial fulfillment of the
requirements for the degree of
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in

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by
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To my family…
thank you for everything.

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Abstract

Coastal foredunes are important natural resources that serve as nature's first line of defense against powerful storms, protecting inland development and human populations. With the ever-increasing possibility of sea-level rise and the potential for increased frequency of major tropical storms, coastal mapping and understanding foredune development are important tools that coastal stakeholders can use to aid in policy planning.

The currently predominant beach-dune interaction models are inadequate as comprised and do not apply globally. The models currently in use lack sufficient quantitative data and have poorly defined variables to support their underlying concepts, and as a result, they are difficult to verify in field conditions.

An extensive field study was conducted in Gulf County, Florida, a location that has experienced relatively little anthropogenic impact. The study sites were chosen for their variety of erosion/accretion rates, exposure to wind and waves, and foredune heights. Topographic surveys, vegetation surveys, wave data, and archival research were all used to analyze the locations. The accumulated data were applied to the predominant models in an attempt to verify their applicability and accuracy. The results showed the insufficiency of the predominant models. Additional variables, including wave climate, vegetation, and antecedent geology were included in a new model that more fully explains foredune development.

The newly developed cycle of foredune evolution has several potential benefits. First, the cycle places foredunes on a continuous spectrum rather than in distinct categories. Second, the cycle can be tested and verified with quantitative data. Finally, the cycle can potentially be applied to foredunes in a wide range of coastal environments.

Chapter 1
Introduction

1.1 Introduction

Coastal geomorphology includes an examination of the evolution, development, and destruction and dynamics of coastal landforms and the processes involved that shape those landforms. This dissertation will examine some of the processes that shape beach and dune landforms found on the coastline of Gulf County, Florida. Traditionally, wave-dominated moderate to high-energy beaches and wind-dominated dunes have been examined as distinct and separate systems (Sherman and Bauer, 1993, Sherman, 1995). While studies conducted about these actually codependent systems reveal important findings, it is essential to also consider interdependent relationships between the two. While a few models of beach-dune interactions have been developed, none have examined the interaction between these forms and how they relate specifically to the development and morphology of foredunes on a spit.

1.2 Research Objective

The broad objective of this study is to document the changes to Gulf County beaches and foredunes and examine these in relation to the prevailing models describing beach dune-interactions (Short and Hesp, 1982; Psuty, 1984, 2004; Sherman and Bauer, 1993). After examining whether these models apply or not to Gulf County, a modified or new beach-dune interaction model will be proposed.

A further objective is to document the interrelationships between foredune vegetation and beach-dune dynamics. A portion of the research will also explore if the vegetation present on a foredune provides a key to understanding foredune development and dynamics, and whether or not vegetation should be included as part of a more complete beach-dune development model.

Additional objectives include the documentation and examination of wave energy along the study region to ascertain the effects of wave energy difference along various sections of the coasts, their effect on dune landform change in the study area, and the identification of the possible effects of tropical storms on beach and dune forms from historical records.

1.3 Research Purpose

1.3.1 Beach-Dune Interaction Models and Management Decisions

Beach-dune interaction models can be invaluable tools for land managers and policymakers. Models found in the literature, such as Psuty's (1988) sediment supply matrix may be used as a foundation for making informed coastal resource decisions. However, if the models are inaccurate, land use policies may be designed based on false pretences or assumptions. This could lead to poor land management, long-term erosion and sustainability issues, and increased difficulties maintaining the dynamic coastal systems that the policies were designed to protect. Therefore, it is essential that managers have the best information available for maintaining the coast.

Through developing a better understanding of beach-dune interactions in Gulf County, the community, state, park managers and planners will have a sound foundation for making management and land use decisions for the county's shoreline, in both the developing sections as well as the protected regions of St. Joseph Peninsula State Park. Demonstrating that beach-dune models such as Short and Hesp's (1982), Psuty's (1988), and Sherman and Bauer's (1993) models may or may not work for the study region will highlight that these models may not apply to all coastal systems. It is critical for coastal land managers to realize that alternative models and research may be necessary to better understand their respective section of coastline, which may, for example, include vegetation dynamics on the beach and foredune.

Gulf County, Florida provides an opportunity to test wave (or surfzone)-beach-dune interaction models for a variety of shoreline orientations and dune types and their respective vegetation zonation and diversity. Although Gulf County is dominated by low wave energy micro-tidal conditions, the findings from this research could be applied and extrapolated to higher energy sandy beach environments of the Gulf of Mexico coast. Additionally, the research results may be applicable to various sandy barrier coasts around the world.

1.3.2 Implications for Disaster Science and Management

Predictions by the Intergovernmental Panel on Climate Change (IPCC) indicate that in the next 100 years there will be a 1.4 to 5.8° Celsius temperature increase relative to 1990 (IPCC, 2001). The projected temperature increase will raise mean sea level by an estimated 0.49 meters by 2100 (Houghton et al. 1996), or a range of 0.18 – 0.59 m (Church and White, 2006; IPCC, 2007). The sea-level rise, combined with potential increases in extreme events such as tropical storms (IPCC, 2007), adds to the growing need for coastal scientists to have a greater understanding of beach-dune interactions and responses to intense storm events. Hurricanes Ivan, Dennis and Katrina, of recent years, are examples of the type of devastating storms that the Gulf coast will continue to face in the future. These storms, built on an increased relative sea-level, will create scenarios that will undoubtedly increase risk to the sustainability of our coastal ecosystems, create a higher risk to human safety, and cause great economic losses to Gulf states.

Coastal managers and scientists, hazard/disaster managers, as well as regional planners can potentially apply geomorphic and ecologic results from this research for making pre- and post-storm management decisions, as well as assist in creating regional setback plans and management decisions before anthropogenic influences further promote the destruction of barrier dunes.

1.4 Dissertation Structure

Several chapters will be broken into different key concepts relating beach-dune interactions in Gulf County, Florida.

The purpose of chapter 2 will be to identify the key literature that will illuminate the nature and scope of this project as it pertains to Gulf County, Florida. The initial focus of the chapter will be examining the basic concepts of foredune initiation, growth, and classification. This will be followed by a section describing coastal foredune vegetation dynamics and the role vegetation plays in developing coastal dunes and this is preceded next by an explanation of the development of foredunes on the Peninsula.

Chapter 3 will outline the methods used to achieve the overall research objectives. The chapter will first provide an introduction of the basic physiography of Gulf County, followed by sections outlining the methodology used to obtain results.

Chapter 4 will identify the variability in wave heights reaching the Gulf County coast and model the sediment transport regimes along the shoreline in order to better ascertain the morphodynamic nature of these shorelines.

Chapter 5 examines beach and dune profile changes in the Cape San Blas - St Joseph Peninsula region from 1973 to 2007 and will provide descriptions regarding the spatial and temporal variability of the profile volume changes.

Chapter 6 will examine the nature of vegetation presence/absence, diversity, and richness on the foredune profile lines discussed in Chapter 5.

Chapter 7 will examine conditions discussed in Gulf County that necessitate the development of a new model that can be applied to the study region. The new cycle of foredune evolution developed herein will take into account more unique features of the beach-dune system in Gulf County, thus providing a more accurate tool for future analysis of similar areas.

Chapter 2
Literature Review

2.1 Introduction

This chapter identifies the key literature that focuses on the nature and scope of this project as it pertains to Gulf County, Florida. The initial focus of the chapter will be examining the basic concepts of foredune initiation, growth and classification. This will be followed a by a section describing coastal foredune vegetation dynamics and the role vegetation plays in developing coastal dunes. An explanation of the development of a spit as an aid in explaining the variability in development of the foredunes on the Peninsula follows.

2.2 Foredunes

Foredunes are shore parallel ridges formed on the top of the backshore (Figure 2.1) by aeolian sand deposition within vegetation (Hesp, 2002; 245). Foredunes range from large convex ridges to flat terraces maintaining low elevations (Hesp, 2002). However, the most seaward coastal dune is not necessarily a foredune. The are two main types of foredunes: 1) Incipient foredunes, or embryo dunes, which are new or developing sand accumulations within pioneer plant communities, and 2) established foredunes, which have greater morphological complexity, height, volume and intermediate to climax plant species than incipient forms (Hesp, 2002).

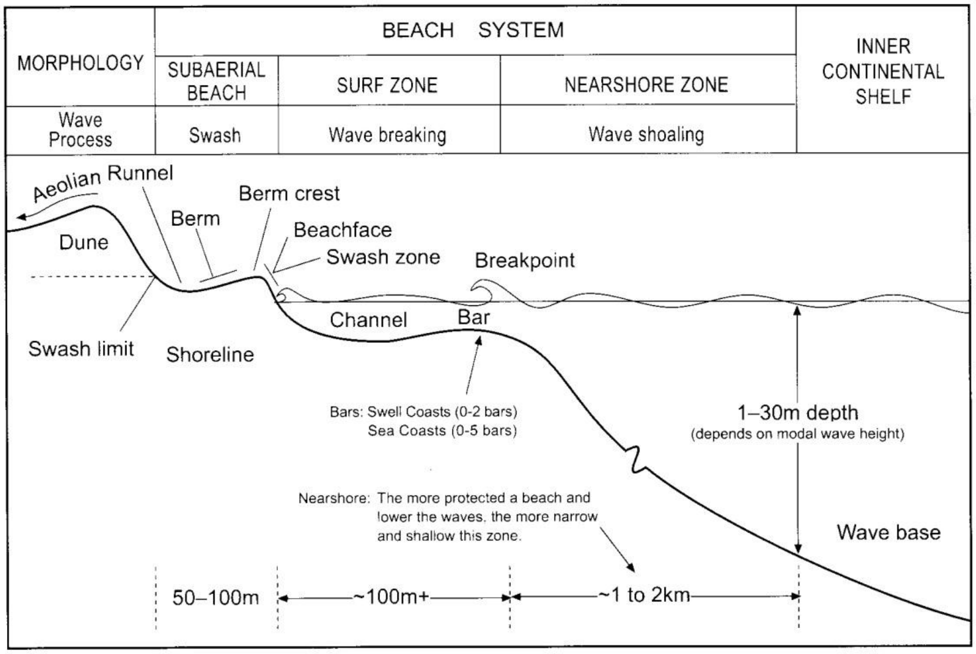


Figure 2.1 - Conceptual sketch of a beach system including from dune to the offshore zone (Short, 1999; 4). The sand dune or foredune is at the back of the beach formed from aeolian deposition of beach materials.

2.2.1 Incipient Foredunes

Incipient dunes form on the backshore through to back-barrier flats within individual plants or clumps of vegetation (Hesp, 1999). As approaching winds reach vegetation, flow rapidly decelerates below threshold velocities, and flow accelerates around the plants (Bressolier and Thomas, 1977; Hesp, 1981; Greely and Iversen, 1985; Nickling and Davison-Arnott, 1990). The decreased wind speeds resulting from the roughness element (vegetation) results in decreasing sediment transport and deposition (Hesp, 1981). The development of the incipient form depends on the plant density, height and cover, wind velocity, and rate of sediment transport (Hesp, 1999; 155), and can be characterized by their form being discrete or laterally continuous, or *Type 1* and *Type 2* incipient dunes (Hesp, 1989). Tall, dense vegetation, such as *Ammophila,* promotes the growth of taller hummocky and asymmetric dunes compared to rhizomatous plants, such as *Ipomoea,* which produce lower, less hummocky dunes (Hesp, 2002). Incipients formed within tall, dense vegetation tend to have a shorter seaward slope due to the intensely reduced sand transport on the windward edge of the vegetation (Hesp, 1999). Lower and less dense vegetation reduces flow and sediment transport more slowly downwind, and are more prone to have a shorter slope on the downwind side of the incipient (Hesp, 1984). The overall range of incipient dune morphologies results from variations in density, distribution and types of vegetation, sediment supply, and frequency of storm inundation relative to the vegetation on the embryo forms (Ranwell, 1972; Davies, 1972; Carter, 1988; Nickling and Davidson-Arnott, 1990; Carter and Wilson, 1990; Packham and Willis, 1997; Hesp, 1984, 1989, 1999). Gulf County, Florida has a range of highly eroding to highly prograding beaches with different aeolian sediment transport potentials and varying vegetation types on the beaches and foredunes. The variability provides the potential for a wide range of shapes and sizes of incipient dune forms, which have not been identified or investigated in this region. Identification of incipient foredunes (types 1a, 1b, 2a and 2b, after Hesp, 1984) from topographic surveys can be used to track the erosion of incipients, or the growth of incipients to established foredunes, and how they've played a role in the development of Gulf County surface morphology.

2.2.2 Established Foredunes

Established foredunes develop from incipient foredunes and are characterized as having intermediate plant species and greater morphological complexity and volume than their incipient counterparts (Hesp, 1999). Established foredunes range in height from less than a meter to larger dune complexes over 30 meters in height (Short and Hesp, 1982; Hesp, 2002). Foredune morphology is dependent on many factors, which are listed in Table 2.1.

Table 2.1 – Factors that affect the development of established foredunes, modified from Hesp, 2002.

Factors affecting development	**Role of factor in development**	**Sample research**
sand supply	sediment available for transport is required to build foredunes; in negative budget conditions dune erosion may occur	Psuty, 1988, 1992, 2004; Nickling and Davidson-Arnott, 1990; Sherman and Bauer, 1993; Davidson-Arnott and Law, 1996, Aagard et al., 2004
sediment transport rate	sediment transport potential into and over the foredune, often limited by sediment transport conditions including beach width, wave inundation and beach moisture content, lag deposits, vegetation and other obstacles to flow	Nickling and Davidson-Arnott, 1990; Sherman and Lyons, 1994; Namikas and Sherman, 1995; Bauer and Davidson-Arnott, 2002; Davidson-Arnott et al., 2005; Bauer et al., 2009 Namikas et al., 2010; Delgado-Fernandez, 2011
wave and wind forces	wave conditions affect the beach types and subsequent flow and transport conditions	Short and Hesp, 1982, Hesp, 1988; Carter and Wilson, 1990; Ruz and Allard, 1994
wind flow over dunes	variations in sediment transport, erosion and deposition are related to slope angles, incident wind angles, and presence and percent cover of vegetation on foredunes	Jackson and Hunt, 1975; Rasmussen, 1989; Hsu, 1977; Arens et al., 1995, Arens, 1996; Bauer and Davidson-Arnott, 2002, Hesp et al., 2005a; Walker et al., 2006
long-term beach state	eroding, stable, or prograding beaches can lead to different scarping, building or stranding of the foredune from beach processes	Carter, 1988; Psuty, 1988, 1992; Saunders and Davidson-Arnott, 1990; Davidson-Arnott et al., 2005
occurrence and magnitude of storm events	storms, including tropical storms and hurricanes, play a significant role in beach and dune inundation, scarping and overwash	Orford et al, 1991; Ritchie and Penland, 1990; Davidson-Arnott and Law, 1996; Giles and McCann, 1997; Sallenger, 2000, Morton, 2002
vegetation cover	the amount of vegetation cover will affect sediment transport potential over the dune; different species will exist in varying biogeographical regions	Hesp, 1984, 1988; Ruz and Allard, 1994; Arens et al., 1995, Arens, 1996; Martinez et al., 2001, Miot da Silva et al., 2008
human impact and use	vegetation destruction and erosion may be induced by foot traffic and recreational vehicles	Davies, 1980; Psuty, 1990; Nordstrom, 1994; Arens and Wiersma, 1994

Sediment drift potential (Fryberger and Dean, 1979) estimates direction of sediment transport, and therefore locations with multiple beach and dune orientations (such as Gulf County, Florida) may have variable sediment potential reaching the foredunes on different beach orientations. However, many other factors play a pivotal role in sediment delivery to the dunes, which add to the variability in dune heights in Gulf County. To continue developing into established foredunes, there needs to be an adequate dry sediment source to transport into the foredune and wind speeds above threshold velocities for the sediment available (Sherman and Bauer, 1993; Davidson-Arnott and Law, 1996; Bauer and Davidson-Arnott, 2002). The sediment available is directly related to the beach width and the fetch. However, wind-driven sediment transport has been shown to reach limiting conditions regardless of the wind velocity. Factors that limit the wind-driven sediment transport, such as sediment properties, moisture, and beach geometry can be more important than the wind velocity (de Vries et al., 2012, 41.)

The sediment available is directly related to the beach width, and the length across the beach (Nickling and Davidson-Arnott, 1990, Bauer and Davidson-Arnott, 2002). Short and Hesp (1982) showed that this is tied directly to beach-surfzone type: Dissipative beaches tend to have wider, flatter beaches and therefore maximum sediment transport potential; reflective beaches tend to be smaller, more aerodynamically rough and therefore have less potential for sediment transport and smaller foredunes (Hesp, 1988; Sherman and Bauer, 1993; Ruz and Allard, 1994). Beach width and surfzone, in addition to wind and wave energy, also affect the amount of salt aerosols across the beach (Hesp, 1988). Higher salt aerosols will in turn decrease vegetation potential and limit the species that may initiate and develop the foredunes (Hesp, 1988, 1989).

Reduced wind speed and flow stagnation occurs at the toe of a foredune (Walker et al. 2006). The decrease in flow and sediment deposition is increased when vegetation is present (Hesp, 1984, 1989; Rasmussen, 1989; Arens et al., 1995; Arens, 1996). Flow is accelerated due to compression over the dunes, especially up the stoss slope where potential sediment transport increases (Hsu, 1977; Sarre, 1989; Arens et al., 1995, 2002; Hesp et al., 2005a). The flow structure is dependent on plant density, height, wind speed, approach angle and slope (Arens, 1996; Frank and Kocurek, 1996; Walker et al., 2006). Beyond the crest of the dune, this accelerated flow jets over the crest and separates from the bedform (Arens et al., 1995; Frank and Kocurek, 1996; Rasmussen 1989; Hesp et al., 2005a). Leeward of the crest, a zone of flow expansion and separation exists and a point of reattachment exists down the lee side of the dune. Deceleration and separation at the dune crest can also lead to deposition on the lee side of coastal dunes (Arens et al., 1995; Frank and Kocurek, 1996; Rasmussen 1989; Hesp et al., 2005a). Vegetation on coastal dunes alters the flow to cause greater drag forces: the greater the density of vegetation produces increased drag, and thus an increase in deposition in the areas of densest vegetation (Arens et al., 1995; Hesp et al., 2005a). The amount of sand transported per unit beach width per unit time is related to the cube of the shear velocity (Bagnold 1941; Cooke and Warren, 1973; Hsu, 1973; Sherman and Lyons, 1994). However, actual sediment transport can vary widely depending on moisture levels, rainfall, fetch, vegetation cover and species presence, and ice and snow cover (Ruz and Allard, 1994; Namikas and Sherman, 1995; Davidson-Arnott and Law, 1996; Arens, 1997; Hesp, 2002; Bitton and Byrne, 2002; Aagaard et al., 2004; Hesp et al., 2005a; Anthony et al., 2006). Psuty (1992) used the foredune crest location to monitor change and make estimated to foredune volume changes. More recently, Miot da Sliva et al., (2008) utilized the crest to the seaward limit of vegetation to monitor foredune sediment budget change (Figure 2.2). However, the variations in flow and potential sediment deposition change from the seaward limit of vegetation to the crest and further landward. This would suggest that a cross-section of the foredune from the seaward limit of vegetation to the leeward point of inflection should be used for monitoring foredune sediment supply and geomorphic change.

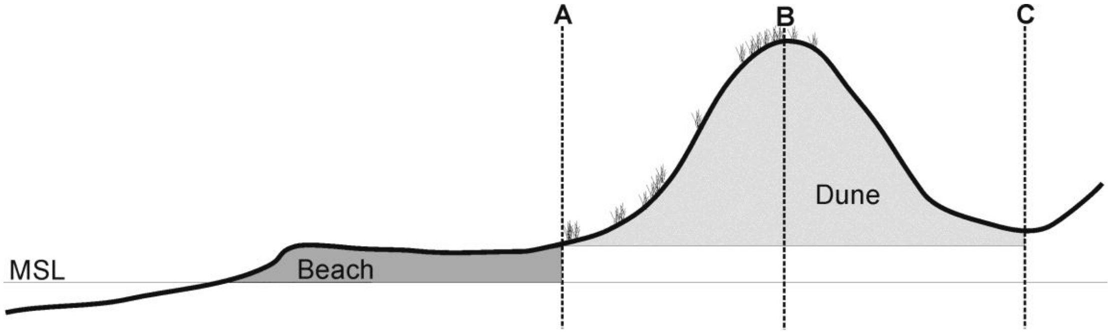


Figure 2.2 - The division between beach and dune volumes. Miot da Silva et al., (2008) calculated volume from seaward limit of vegetation (A) to the crest (B). However, the flow across the foredune varies from the initial vegetation and past the crest where flow separation occurs and more sediment may be deposited. Line C could represent the break in slope at which point the elevation increases in the landward direction where a new dune or beach ridge is found, and a better end point to estimate foredune volume.

Wind direction also plays a pivotal role in sediment transfer and deposition to a foredune via topographic steering (Svasek and Terwindt, 1974; Rasmusseen, 1989; Hesp, 2002; Walker et al., 2006). Winds approaching at oblique angles tend to be deflected normal to the foredune crest (Arens et al., 1995; Walker et al., 2006). Highly oblique winds (>60) are generally deflected parallel to the foredune (Hesp, 2002, Walker et al., 2006). Localized accretion on the upwind slope and crest of foredunes often result, thereby increasing topographic variability (Hesp, 2002; 249). Offshore winds also contribute to topographic variability by transporting sediment from lee slopes and crests to the stoss and beach (Svasek and Terwindt, 1974; Arens et al., 1995) and offshore wind flow reversals on the stoss side of foredunes can transport sediment up the foredune face (Hesp, 2005). The effects of topographic steering contribute to the difficulty of measurement and modeling of beach-foredune sediment budgets (Walker et al., 2006). All of these principles make it difficult to examine actual sediment budget change to beaches and foredunes, thus more micro-scale research is needed before total sediment transport can be incorporated into a beach-dune model of development.

2.2.3 Sea Level, Storms and Sediment Budget

As stated earlier, beach and surfzone type plays a critical role in sediment availability and transport across a beach and to the foredune (Short and Hesp, 1982). Additional factors such as beach width, fetch, moisture content, and vegetation also play a critical role in limiting the sediment available for transport (Nickling and Davidson-Arnott, 1990; Sherman and Lyons, 1994; Namikas and Sherman, 1995; Hesp, 1999, 2002; Bauer and Davidson-Arnott, 2003; Davidson-Arnott et al., 2005; Miot da Silva et al., 2008). When sea (or lake) levels are rising, the foredune stoss slope may erode and form blowouts, the crest may increase in height, and the foredune will transgress landwards (Hesp and Thom, 1990; Saunders and Davidson-Arnott, 1990, Rithcie and Penland, 1990; Thors and Boulton, 1991; Psuty, 1992; Hesp, 2002; Christiansen and Davidson-Arnott, 2004). The foredune may also become scarped and destabilize, forming blowouts, parabolics, sand sheets, and transgressive dunefields (Hesp, 2002; 251). This may occur under conditions of regional high wind conditions as well (Hesp, 2002). If beach progradation occurs despite sea level rise, a series of foredune ridges may form (Psuty, 1992; Davidson-Arnott and Law, 1996; Hesp and Short, 1999).

If sea (or lake) level falls, beach width will typically increase, unless sediment sources are cut-off (Firth et al., 1995, Hesp, 2002; Orford, 2005;). Under these positive-beach sediment conditions, new incipients and established foredunes will form similar to prograding beaches with stable sea level (Hesp, 1984; Psuty, 1988; Saunders and Davidson-Arnott, 1990). If the foredune is scarped prior to sea/lake fall (or during extreme stormy conditions), pioneering vegetation may be absent and a phase of foredune erosion and instability may result forming blowouts, parabolics and transgressive dune sheets (Carter, 1988; Saunders and Davidson-Arnott, 1990, Orford et al., 1999; Hesp, 2002).

Since sea level has remained relatively stable over the past 2000 years in Gulf County, Florida (Otvos, 2005), large tropical storms and hurricanes play a larger role in foredune change (Thieler and Young, 1991; Sallenger, 2000; Morton, 2002; Morton and Sallenger, 2003; Nott, 2006; Houser and Hamilton, 2009). Morton et al. (1994) found that post-storm recovery of beaches and foredunes involved accretion of the beach face, followed by backshore building, incipient dune formation and foredune size increases as vegetation continued to grow. Foredune recovery is initiated when pioneer vegetation is able to re-establish with sufficient density to trap sediment delivered via aeolian transport during fair-weather conditions (Hesp, 2002). Only in the absence of storm activity is vegetation able to establish and foredunes develop on the beach (Stallins and Parker, 2003; Stallins, 2005; Houser and Hamilton, 2009). The beachface can recover through sediment transport of the sand that was stored directly offshore in the bars and in the upper shoreface (Morton et al., 1994). As this sediment supply is transported back to the beach face, the beach widens, aeolian transport may begin, and incipient dune formation may occur. Gulf County foredunes will be impacted by any large storm, as in the case of Hurricane Ivan, which affected over 300 km of shoreline (Wang et al., 2006). While short and long-term changes to foredunes post-storm have been documented (e.g. Wang et al., 2006), long-term impacts on the overall geomorphology of spits and their incipient and established foredunes have not been well documented.

2.2.4 Established Foredune Classification

Foredunes have been classified based on different factors including origin (Hesp, 1984), morpho-ecological states (Carter, 1988), long-term state of accretion, stability or erosion (Arens and Wiersma, 1994), and their response to water level and change and storm action (Carter and Stone, 1989; Saunders and Davidson-Arnott, 1990; Law and Davidson-Arnott, 1990; Ritchie and Penland, 1990).

Pye (1983) divided coastal dunes into two types. First, there are *impeded* dunes, including embryo or incipient dunes, foredunes, platforms, hummocky dunes, and nebkhas, which are all essentially fixed in position. Second, there are *transgressive* dunes, which migrate landward through aeolian processes. Short and Hesp (1982; Hesp, 1988) classified foredunes into five states based on the percent vegetation cover and their morphology related to the beach states. The classifications ranged from 90-100% vegetation cover topographically continuous foredunes (Stage 1), to hummocky topography and decreasing vegetation cover (Stages 2-4), to remnant knobs, blowouts and sand sheets with only 5-20% vegetation cover (Stage 5). Carter (1988) devised a similar five stage classification based on Short and Hesp's (1982) morpho-ecological states ranging from vegetation dominated multi-ridge forms to landforms characterized by wind forms such as barchanoid dunes and transverse blowouts, with limited to no vegetation and intermediate foredune states in between. Similar to Short and Hesp (1982), Arens and Wiersma's (1994) foredune classifications incorporated coastline dynamics, including beach sediment supply and regressive, stable and prograding states, into their foredune classifications. Arens and Wiersma (1994) also included aeolian erosion and deposition to the foredune and the amount of foredune management, from completely natural dunes to foredunes completely managed through artificial sediment supply and revegetation. Some beach nourishment and vegetation plantings have modified the natural dune development in some areas of Gulf County. However, this project will focus on the natural development of the beaches and dunes in the study region.

Hesp (1999, 2002) synthesized the models of Hesp (1988), Carter (1988), and Arens and Wiersma (1994) into one classification based on foredune morpho-ecological states, with temporal changes to the foredunes (Figure 2.3).

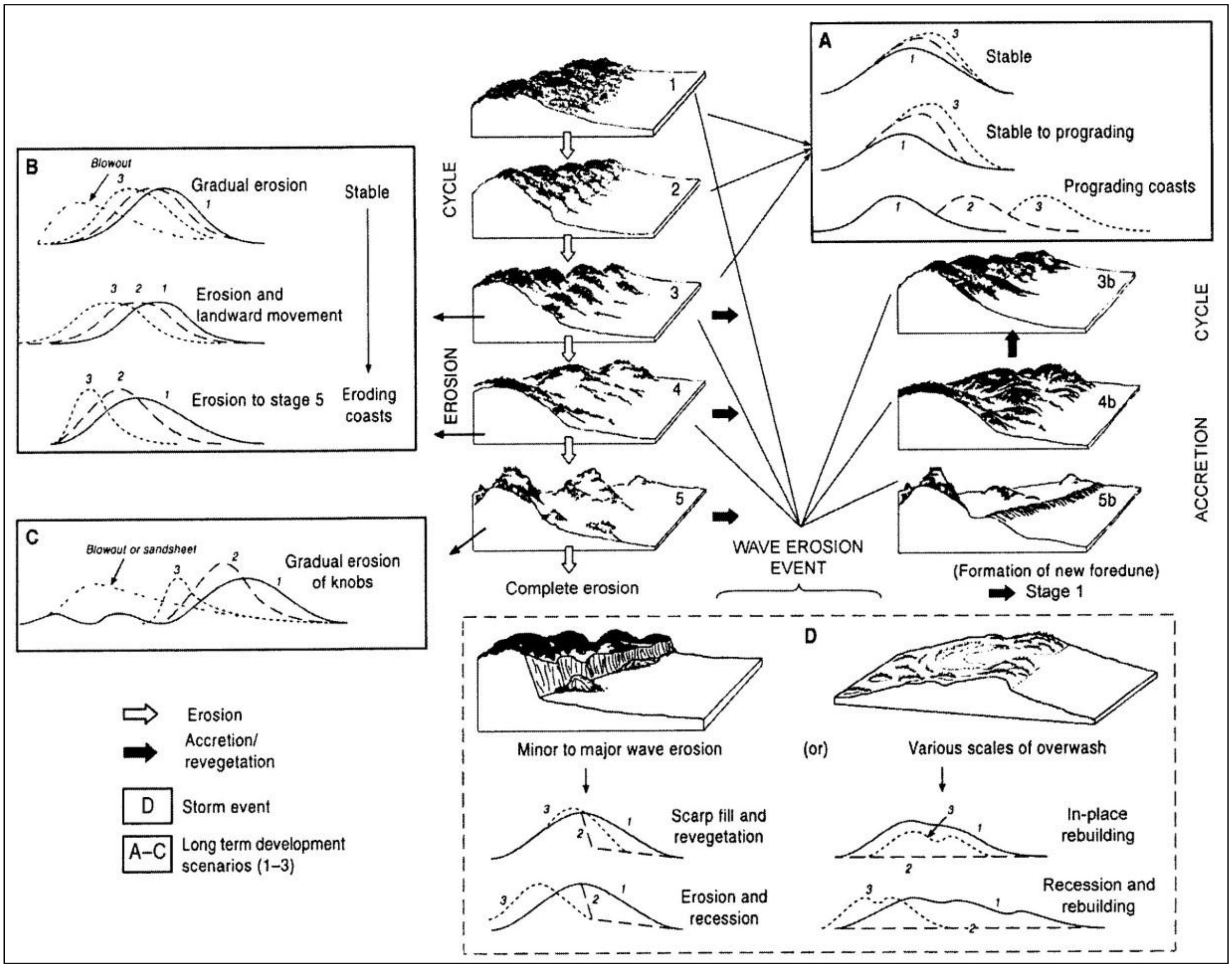


Figure 2.3 - Hesp's (2002; 253) foredune classification model based on temporal change and morpho-ecological states.

The evolutionary process from a stabilized well vegetated continuous dune (Hesp *Stage 1*) to a dune that has been eroded via aeolian processes, vegetation loss, and possible wave attack, to the last stage which contains remnant knobs and blowouts, and minimal vegetation cover (Hesp *Stage 5*) is the core of the classification diagram. Potential long-term changes can be inferred from the stages that occur between the initial five stages. Additionally, the foredune crest migrations can be inferred from Boxes A through C. A period of stability and/or beach progradation may lead to the building of a new foredune and revegetation (stages *5b* to *3b*) may occur. Box A shows a cross-section development model of the formation of multiple new ridges that may occur on a prograding coast (Short and Hesp, 1982; Psuty, 1988; Arens and Wiersma, 1994). Box B shows the landward migration of the foredunes under erosional conditions from Hesp's original stage *2* through *4* foredunes, and box C displays the long-term effects of erosional conditions to the *Stage 5* hummocky, highly erosional forms. Box D highlights the importance of wave scarping during storms, and in more extreme cases lead to overwash conditions (Cleary and Hosier, 1979; Carter and Stone, 1989; Ritchie and Penland, 1990; Carter et al., 1990; Giles and McCann, 1997). This can also occur under conditions of rapid lake (or sea) level changes (Saunders and Davidson-Arnott, 1990; Davidson-Arnott and Law, 1990). The five foredune types (stages *1* through *5* and *3b*-*5b*) can be used as a way to define the morpho-ecological states of foredunes, and the foredune change can be predicted or hindcasted using the classifications scheme for a specific region if the beach (sediment supply) and erosional storm history is known. This collective classification scheme may also be used to aid in creating a globally applied beach-dune interaction model and for making management decisions.

2.2.5 Foredune Plains and Beach Ridges

Foredune plains are a series of parallel foredunes that form from a foredune becoming isolated from a seaward developing new incipient foredune, which may become an established foredune (Hesp, 2002). In planform, a series of foredune ridges may look similar to a series of beach ridges. However, beach ridges, defined as being built by wave processes (e.g., Johnson 1919; Psuty, 1965; Tanner and Stapor, 1971) are morphogenetically distinct from foredunes (Hesp *et al*., 2005b).

Table 2.2 – Formation of beach ridges or foredune plains adopted from summaries by Taylor and Stone (1996), and Hesp *et al*. (2005b).

Genesis of ridges	**Example Research**
High wave-energy beach ridges	-Thom (1964) and Psuty (1965) found low energy waves transported sediment to the nearshore, but larger storm waves built the beach ridges
Swell condition beach ridges	-Davies (1958) "cut and fill" hypothesis that during storms the berm ridge was cut, and infilled during swell conditions. Vegetation of the berm would follow.
Swash condition beach ridges	-Tanner and Stapor (1971; Tanner and Stapor, 1972) showed internal structure of beach ridges indicate a gradual growth from longshore and offshore sediment, to create a berm which may prograde seaward.
Emergent bar beach ridges	-Bigarella (1965) and Curray et al., (1969) demonstrated emerging offshore bars initiate beach ridge development -Hine (1979) showed similar development of beach ridges on an elongating spit, in which emergent recurves exhibited ridge forms.
Foredunes	-McKenzie (1958) showed incipient ridges form at the seaward limit of vegetation -Hesp (1983, 1984, 1999) described incipient foredunes to form on the backshore in vegetation; berms were not a prerequisite for ridge development.
Beach-foredune ridges	Hesp (1999) names ridges initiated by beach ridge processes, but capped by aeolian deposited sediment, as beach-foredune ridges.
Chenier	-Price (1955; Otvos and Price, 1979) showed that during periods of large fluvial discharges mud flats deposits occur, but during periods of low sediment input, chenier (higher sand and shell content) ridges formed.

Beach ridges have been defined as linear, mound-shaped ridges roughly paralleling the coast (Stapor, 1975). The origin and modes of construction (Table 2.2) have been debated by many authors, and reviewed by Taylor and Stone (1996), Otvos (2000), Hesp (2004), and Hesp, *et al*., (2005b). Taylor and Stone (1996; 619) summarize that beach ridges are formed by swash in low or high wave-energy conditions, the emergence of offshore bars, or through a combination of wind and wave processes. However, Hesp (1983, 1984, 1999) has shown that no wave processes are necessary for the development of ridges, and that "beach-ridges" can be formed entirely by aeolian deposition in vegetation.

Beach ridge form is directly related to sediment availability: Rapid deposition results in low closely spaced ridges, while slower deposition resulted in characteristically longer ridges with wider profiles (Johnson, 1919; Davies, 1958; Taylor and Stone, 1996). Psuty (1988, 2004) postulates that under high sediment supply conditions, more lower beach ridges will form compared to slower prograding beaches that will have taller foredunes. According to Tanner and Stapor (1972), beach ridge development is increased under higher tidal ranges and increased wave energy levels, which will increase the berm height and the subsequent beach ridge. Stone and Stapor (1996) have also shown during periods of low sediment supply, aeolian deposition has increased the foremost dune, and the landward beach ridges were capped with aeolian sediment from intervening swales. While these statements are true for beach-ridges and beach-foredune-ridges, *foredune plains* (Hesp, 1983, 1984, 1999) develop as *incipient foredunes* at the seaward limit of vegetation and continue to develop via aeolian sediment deposition until a new seaward incipient foredune forms.

To add clarity to the morphogenetic debate between beach ridges and foredune plains (which includes the active foredune and the landward relict foredunes) Hesp et al.(2005b) redefined beach ridges as, "swash aligned, swash and storm *wave* built deposits or ridges formed primarily of sand, pebbles, cobbles or boulders, or a combination of these sediments" (Hesp, 1999; Hesp et al., 2005b; 500). In contrast, "foredunes are genetically and morphodynamically distinct from beach ridges… [and] are the foremost vegetated sand dune formed on the backshore zone of beaches by *aeolian* sand deposition within vegetation." (Hesp *et al.,* 2005b; 500) [italics added].

Otvos (2000; 84) defined beach ridges as, "relict, semiparallel, multiple ridges, either of wave or wind origin," and has described the Gulf County mainland coast being dominated by beach ridge strand plains (Otvos, 2005). By Otvos's (2000) definition, the multiple ridges in Gulf County may be formed by different processes. Rizk (1991) identified portions of St. Joseph Peninsula to be beach ridges, but without clearly defining the interpretation of wave versus aeolian building processes. Stapor (1975) asserts that most of the beach ridges on the peninsula are of swash origin, yet in all locations on the modern beach, beach ridges are not formed by swash, but are aeolian in origin. While utilizing Otvos's (2000) broad definition to delineate areas with beach ridges is straightforward, it does not assist in describing the geomorphic development of Gulf County.

2.2.6 Beach-Dune Interaction Models

Several authors have attempted to examine the long-term spatial and/or temporal development of beach and coastal dune interactions and the development of the coastal foredune under specific conditions (e.g. Short and Hesp, 1982; Psuty 1988, 2004; Sherman and Bauer, 1993, de Vries et al., 2012). While the Psuty (1986,1988) sediment supply matrix has dominated coastal literature, quantitative data have not verified this model.

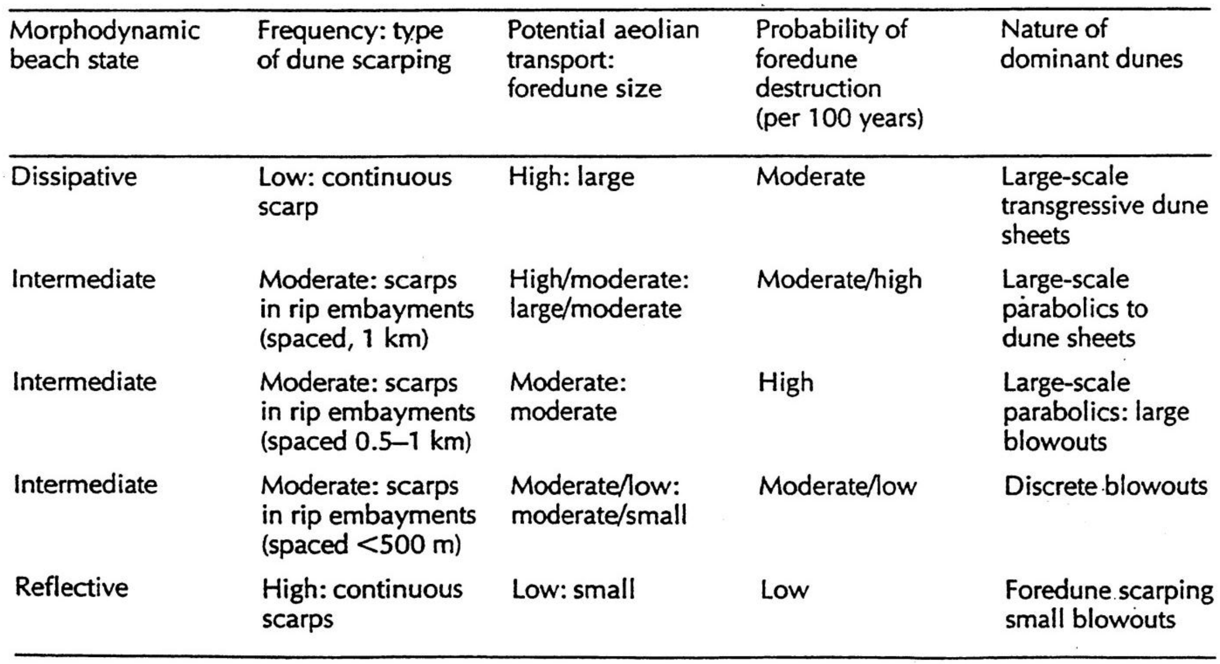
2.2.6.1 Short and Hesp

Short and Hesp (1982) studied beach-dune interaction with an emphasis on the morphodynamic response to wind and wave energy of the foredunes adjacent to modal beach states as described by Short (1979), in south-eastern Australia's micro-tidal environments.

The dissipative beach typically exists in the modally highest wave-energy conditions. For this reason, a much larger volume of sand is moved onto the dissipative beach than onto intermediate and reflective beaches. On the beach, the grains dry and can be moved further inland by onshore and onshore-oblique winds (Davidson-Arnott and Law, 1990). The wind strength necessary to move different sized grains is determined by grain density and size and can be limited by in beach sediment transport reviews by Nickling and Davidson-Arnott (1990), Davidson-Arnott and Law (1990), Sherman and Lyons (1994). The typical fine to medium grain sediment on a dissipative beach is more readily transported than coarser grains, which are typically found on reflective beaches due to lower threshold velocities needed to initiate and continue movement. The wide, dissipative beach provides ample sediment to be transported into the dune system, thus acting as a potentially large source of sediment for dune growth. Additionally, the wide, dissipative beach has greater fetch lengths and flatter topography, which are also crucial in achieving maximum sediment transport rates. Subsequently, Short and Hesp (1982) found the tallest sand dunes on modally dissipative beaches.

The Short and Hesp (1982) model study has underlying conditions that may limit the model to regional applications. These regional conditions include shore normal sediment transport, large volumes of sediment being supplied to the coast during the Holocene transgression, and the shoreline having been stable to slightly retrogradational during the last 1000-2000 years (Short and Hesp, 1982). These conditions are not globally consistent and may

Table 2.3 - Summary of Short and Hesp (1982) wave-beach-dune interactions based on morphodynamic beach state (from Sherman and Bauer, 1993; 52).



Morphodynamic beach state	Frequency: type of dune scarping	Potential aeolian transport: foredune size	Probability of foredune destruction (per 100 years)	Nature of dominant dunes
Dissipative	Low: continuous scarp	High: large	Moderate	Large-scale transgressive dune sheets
Intermediate	Moderate: scarps in rip embayments (spaced, 1 km)	High/moderate: large/moderate	Moderate/high	Large-scale parabolics to dune sheets
Intermediate	Moderate: scarps in rip embayments (spaced 0.5–1 km)	Moderate: moderate	High	Large-scale parabolics: large blowouts
Intermediate	Moderate: scarps in rip embayments (spaced <500 m)	Moderate/low: moderate/small	Moderate/low	Discrete blowouts
Reflective	High: continuous scarps	Low: small	Low	Foredune scarping small blowouts

give rise to variations in beach-dune states. Due to this model assuming a minimum sediment supply, it does not include possible variations in dune type if there is a very high sediment supply for dissipative through reflective beach states, or a very low (or negative) sediment supply through all beach states. Short and Hesp did provide a global model that included additional wave-wind environments as described by Davies (1964). However, this model has not been tested in different global settings such as the U.S. Gulf of Mexico coast.

The most significant factor influencing sand transport is wind velocity, although other factors, such as sand size and grain shape, are also important in total sediment transport (Willetts et al. 1982). Short and Hesp (1982) make reference to dune size being representative of wind-wave energy:

> … the largest dunes occur in lee of high energy dissipative intermediate beaches exposed to onshore mid-latitude westerlies; …moderate dune development is characteristic of moderate energy intermediate beaches particularly along east

> coast swell and trade wind environments; …low dunes are associated with low wind velocities and reflective beaches. (Short and Hesp, 1982; 282).

However, this assumption may be inaccurate in low wave energy conditions that were a result of short fetch length, larger grain sizes, or climatic regions that do not have vegetation species that aid in promoting dune growth, not actual slow wind speeds. Hesp (1988) found that regardless of total wind exposure, the dune forms reflected the characteristics of the beach stage whether reflective, intermediate or dissipative in southeast Australia. This, however, was a regionally specific example.

2.2.6.2 Psuty Sediment Supply Models

Psuty's (1986) first presentation of a conceptual matrix of dune positive and negative sediment budgets versus beach positive and negative sediment budgets divided into four quadrants by lines of equilibrium (Figure 2.4:A). The diagram is conceded as being a qualitative diagram and there is an emphasis on dune morphologic expressions in this interaction model (1986; 14). In this matrix, the beach-ridge topography occurs in the beach positive and dune negative quadrant. When the beach budget becomes slightly negative, the diagram denotes a period of maximum dune development. This is a result of dune scarping combined with lee side deposition. Within the dune positive and beach negative quadrant the shaded area highlights the conditions for "present day dune development". The negative dune – negative beach quadrant begins with dune attenuation and as the variable becomes more negative, the resulting morphologic conditions are washover forms. In 1988, Psuty also expands the extremely negative beach sediment supply from having washover morphology to including "a lack of foredune coherence" and hummocky remnants of the foredunes (1988, 294).

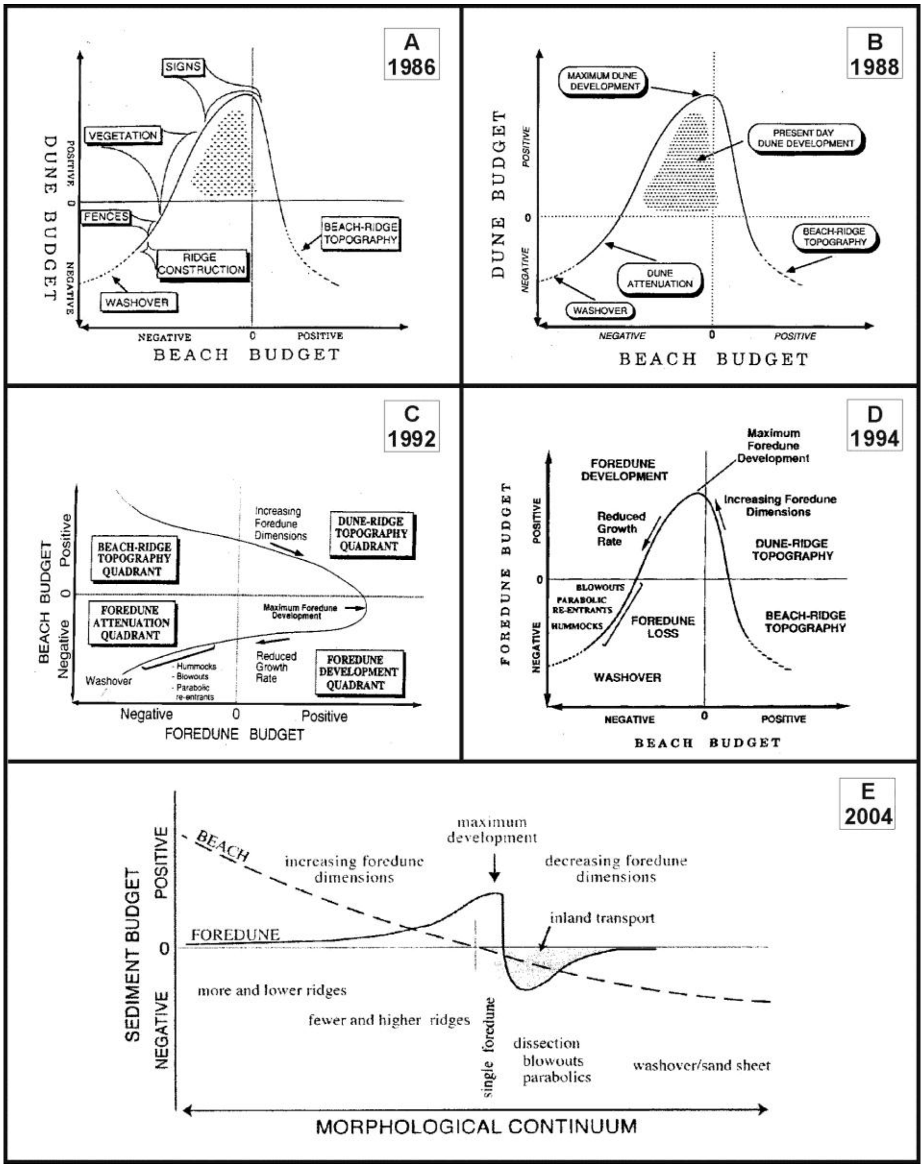


Figure 2.4 - The evolution of the Psuty beach dune interaction conceptual model. The 1986 (A) matrix was initially designed to aid land and resource managers. The matrix contains beach and foredune sediment budgets, and is divided by lines of equilibrium. The 1988 (and near identical 1989 matrix not shown,) added the position of maximum foredune development and eliminated the proposed project plans for managers. The 1992 model was rotated and flipped such that the beach and foredune budgets were on opposite axis but the positive budgets remained to the top and left respectively. Psuty identified the quadrants based on the sediment supply and expected resultant dune forms. In 1994 (D) the matrix returned to its original layout. The foredune attenuation quadrant of 1992 was changed to foredune loss and washover. The morphological continuum (2004) was presented in a new format, still focussing on beach and dune sediment budgets but the format changed. (Psuty, 1986; 14: 1988; 4: 1992; 5: 1994; 44: 2004; 23)

While Psuty's beach-dune sediment budget models have been widely cited, especially the 1988 and 1992 adaptations of the model, there are attributes of the models that remain unclear. This is partly due to a lack of qualitative description and quantitative evidence to support the models.

Psuty's matrices (Figure 2.4:A-D) have beach and dune-ridge forms building, yet the dune sediment budget is negative. In contradiction to this, this sequence is explained in Psuty's 2004 (Figure 2.4:E) continuum to have a very slightly positive dune budget while the beach is strongly positive when ridges are forming. However, even in the 2004 model the relationship between the beach and foredune sediment budgets are not clearly stated: It is not explained if the relative ratio between high beach progradation or high sediment input into the beach (which may move from the backshore to the dunes while the shoreline maintains position) explains the low beach ridges versus foredune growth.

Clear definitions of beach-ridge versus dune-ridge topography may help discern the difference between the two beach positive quadrants. For example, if the beach-ridge quadrant contains purely wave built forms with no overlying aeolian deposition, then perhaps it could be clearly distinguishable from dune-ridges and consequently the dune budget could be represented as zero. However, this still does not explain the *negative* dune budgets unless some force, such as strong aeolian forces and/or vegetation destruction, is eliminating former foredunes, yet the model only describes the active foredune.

In the Psuty (2004) continuum, as the beach sediment supply drops to a lower or negative sediment supply, the foredune sediment drops markedly followed by an unexplained increase in sediment supply. The slightly negative beach sediment supply relates to the occasional scarping of the foredune, after which a new sediment ramp can be built to increase the foredune dimensions. Presumably as the beach continues to decrease in sediment supply, the foredune will continue to erode by the same processes. Yet, in the model when the beach sediment supply decreases past this inflection point, or the state just beyond maximum decrease in sediment supply rate, the dune sediment budget inexplicably increases (Figure 2.4:E). At the point in the continuum where the beach is at its most negative supply rate, the foredune sediment supply rate is almost equal to the foredune sediment supply rate (near zero) when the beach is at a maximum, which seems implausible.

In Psuty's continuum (2004, Figure 2.4:E) the negative foredune budget never reaches a value of zero. If the foredune is constantly decreasing, by its end on the morphological continuum it should presumably reach a value of zero, at which point there would no longer be dune forms but rather washover/sand sheets that were differentiated in the previous model. However, the continuum suggests an ongoing loss of dune sediment.

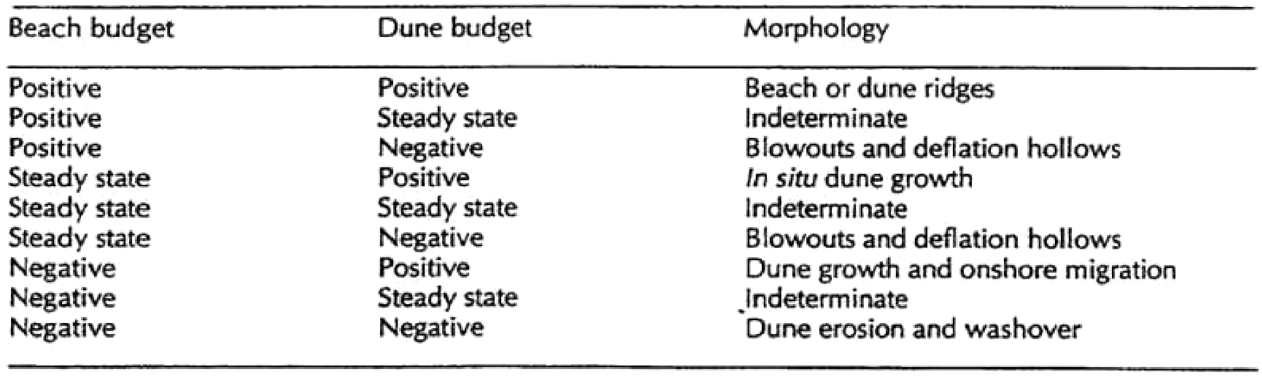
In addition to the conceptual problems, Psuty has only twice published empirical results testing the sediment supply matrices or the morphological continuum. In 1993 some of Psuty's findings concurred with the model, but a great degree of variability was presented in the results. Additional factors beyond sediment supply may be contributing to the variability found in this study. The Psuty model still has yet to be tested with conclusive results to support or dispute its various incarnations.

2.2.6.3 Sherman and Bauer

Sherman and Bauer's (1993) model was very similar to Psuty's (1986) model, with the inclusion of steady or equilibrium states between positive and negative in both the beach and dune sediment supplies and an expansion from four to nine conditions over meso-scale time frames. The relationships are summarized in Table 2.4. Similar to Psuty's models (although

Psuty did not explicitly assert this), the scheme assumes that vegetative factors within the dune system are secondary and that internal heterogeneities within individual beach and dune systems are unimportant (Sherman and Bauer, 1993).

Table 2.4 - Sherman and Bauer's (1993) conceptual model relating beach and dune sediment budgets.



Beach budget	Dune budget	Morphology
Positive	Positive	Beach or dune ridges
Positive	Steady state	Indeterminate
Positive	Negative	Blowouts and deflation hollows
Steady state	Positive	*In situ* dune growth
Steady state	Steady state	Indeterminate
Steady state	Negative	Blowouts and deflation hollows
Negative	Positive	Dune growth and onshore migration
Negative	Steady state	Indeterminate
Negative	Negative	Dune erosion and washover

Sherman and Bauer (1993) presented examples of the different beach states, but the model has not been field-tested. Sherman and Bauer also did not attempt to combine the sediment supply states with beach morphodynamic states that Short and Hesp (1982; Hesp, 1988) have shown to be critical in determining foredune types. Additionally, the model still has indeterminate dune morphologies (Table 2.4) and no reference to vegetation characteristics of the foredunes.

2.2.6.4 Additional Beach-Dune Models

Cleary and Hosier (1979) identified a cycle of spatial-temporal dune stages based on storms and washover topographies (Figure 2.5). They noted the variability in foredunes on the barriers of Bird Island, North Carolina was directly related to the incidence of erosional forms, which resulted from large storms. They found that the foredune forms were a function of the foredune rebuilding rates and storm return rates.

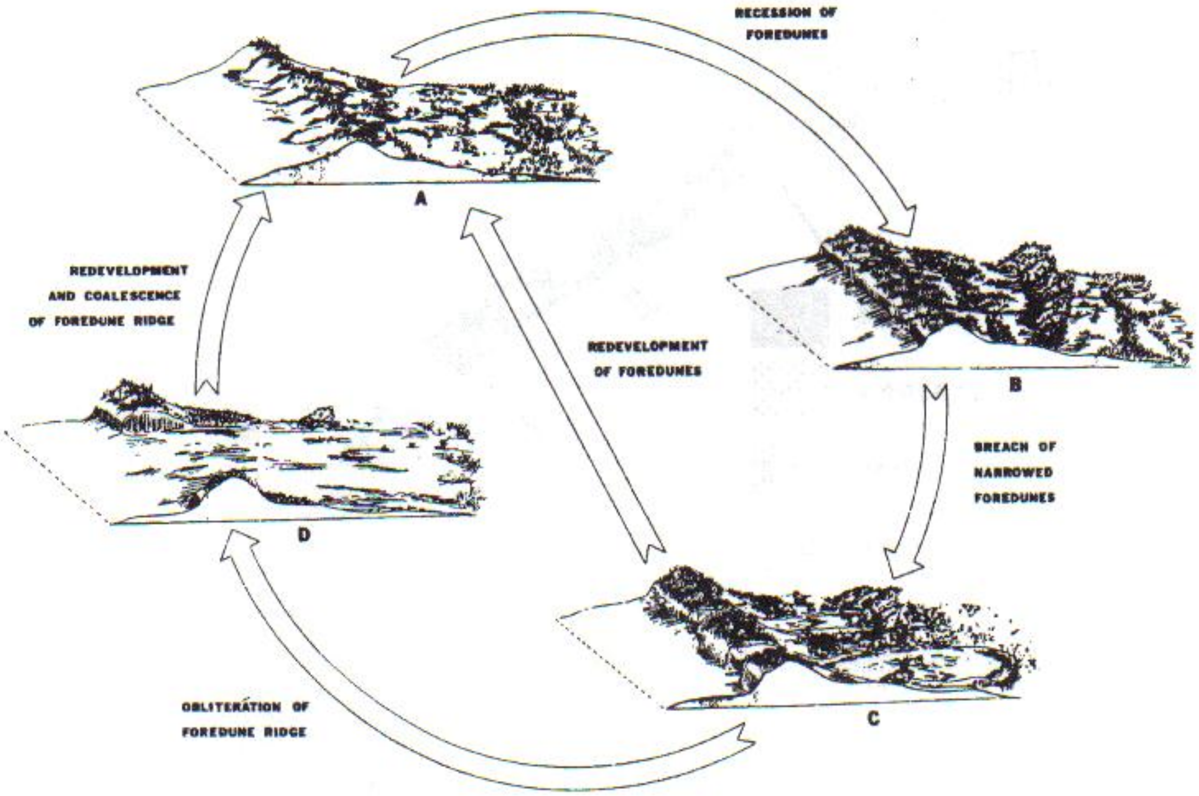


Figure 2.5 - Cleary and Hosier's (1979; 257) washover and foredune change model. From A, the foredune goes through a process of erosion due to wave scarping (B) and foredune breaching (C), to obliteration of the foredune (D). During calm periods the foredune can redevelop and coalesce to form a new foredune ridge.

Ritchie and Penland (1990) described barrier islands in southeastern Louisiana and found that hurricane impacts played a pivotal role in the development of barrier morphology. Similar to Cleary and Hosier (1979), the spatial sequences of the Louisiana barriers can change rapidly based on the variability and strength of both tropical and extra tropical storms. In the model (figure 2.6), the five dune stages described are directly related to the degree of severity of frontal passage storms, and ultimately return to washover states during major hurricanes.

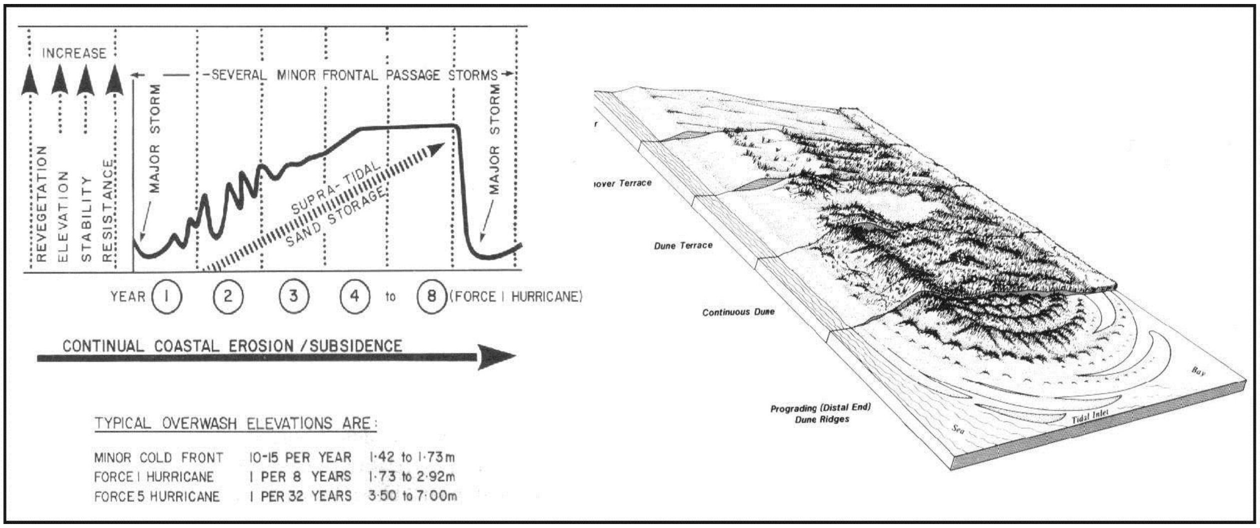


Figure 2.6 - Ritchie and Penland's (1990; 116, 119) cycle of overwash and resultant dune types found on Louisiana’s Gulf Coast. The diagram on the left indicates increasing dune characteristics over time until a major storm reverts the system back to the smallest dune forms and washover topography. The diagram on the left displays the typical dune forms found along the Louisiana coast, which are often reflective of time lag between storms.

Saunders and Davidson-Arnott (1990) proposed a model for Long Point, Canada, where Lake Erie water levels vary on long-term (decadal) changes, annual fluctuations, and periods of hours based on storm surges and wind seiche events. This model outlined morphological changes to the foredune in relation to water levels and sediment supply. The model contained three scenarios including: neutral or negative sediment budgets with 1) severely cliffed foredune, and 2) breached (overwash and blowout initiation or reactivation) foredune; and 3) when there is a positive sediment budget, or is in a depositional zone.

Their first scenario describes the changes to the foredune in an erosional zone. During rising water level conditions the foredune toe may be scarped. At peak water levels the foredune is (further) scarped. During lower water levels the sediment supply (beach width) increases, but if no vegetation is introduced no embryo dunes will form.

The second scenario describes changes in an erosional zone as well. Typically the foredune is completely breached by overwash, or severely breached by rising or peak water levels. During peak water levels, or when the foredune is breached, seeds and rhizomes move landward with the sediment. These seeds/rhizomes will grow and initiate embryo dune growth as water levels recede, and the beach widens. This ultimately decreases wave run-up, which may destroy embryo forms. In the model, embryo dune forms will continue to grow and possibly coalesce into a foredune while water levels remain low.

Scenario 3 exists in a depositional zone. As lake levels rise, the foredune may be scarped slightly, but remain intact. Storm waves do not reach as far inland in this zone because of the wider/widening beach due to sediment deposition. Similar to the second scenario, as lake levels drop, embryo dune forms may develop, but in this case, in front of the foredune. Before the embryo dunes are formed, some of the sediment reaches the foredune to assist in rebuilding the foredune that may have been scarped during peak water levels.

Giles and McCann (1997) documented a series of foredune types on Iles de Madeleine in Canada. While highlighting different foredune features, they attempted to compare their results with the Short and Hesp (1982). Interesting in this example, Giles and McCann found in opposition to the Short and Wright's (1984) beach stage models that beach types and sediment sizes were opposite, and "the relationship between beach width and foredune size postulated by Short and Hesp (1982), does not hold and there is no apparent correlation between the two variables," (Giles and McCann, 1997; 1475). However, "the range of beach widths in the Iles de Madeleine is insufficient to impart a characteristic imprint on foredune size," (Giles and McCann, 1997; 1475). Additionally, Giles and McCann's research was conducted on a transgressing barrier with dunes that were continually subject to wave attack.

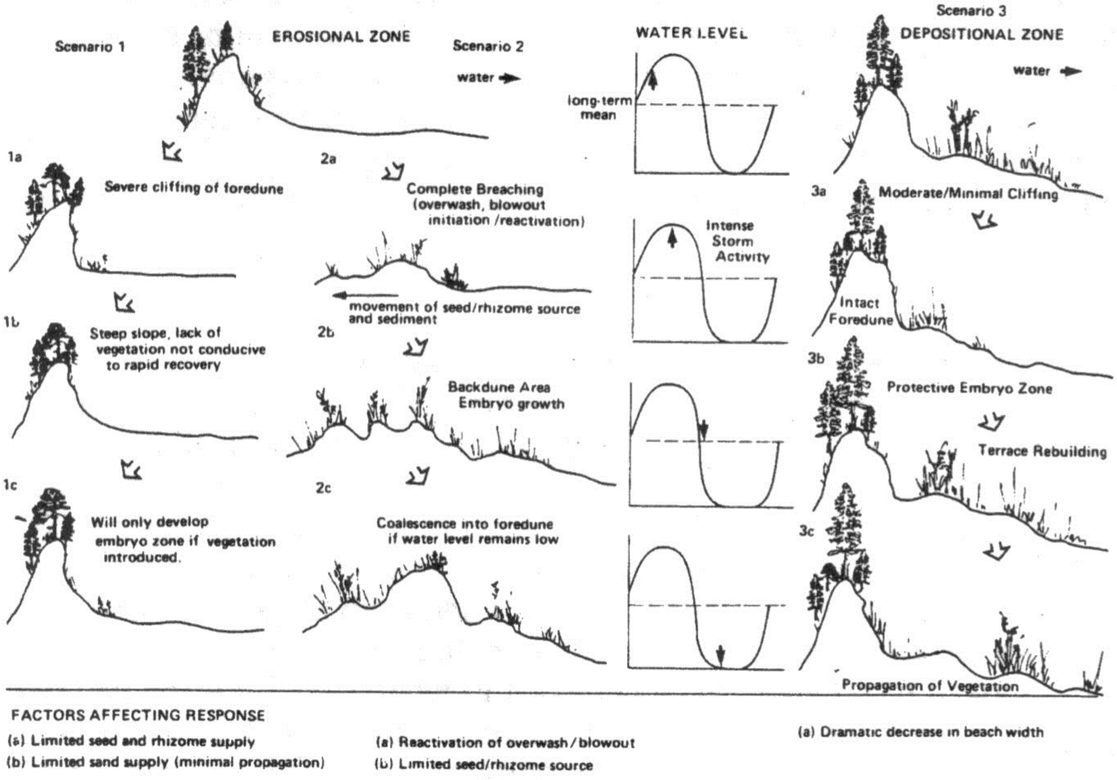


Figure 2.7 - Saunders and Davidson-Arnott's (1990; 343) model of dune response to water level change at Long Point, Lake Erie. The model's three major scenarios include: 1) neutral or negative sediment budgets with severely cliffed foredunes, 2) neutral or negative sediment budgets with breached and overwashed foredunes; and 3) a positive sediment budget, or depositional environment.

2.2.7 Foredune Vegetation

It has long been recognized that sediment accumulation requires the existence of vegetation on the beach (Cowles, 1899; Olson, 1958; Ranwell, 1972; Oertel and Larsen, 1976; Hesp, 1984). This colonizing vegetation diminishes wind speed closer to the ground and thus promotes sediment accumulation at this seaward limit of vegetation (Hesp, 1983, 1984, 1988; Goldsmith, 1989, Kuriyama et al., 2005). These initially hummocky forms may eventually coalesce to form a continuous foredune (Oertel and Larsen, 1976; Hesp, 1984).

Vegetation presence/absence, species growth habitat and morphology, species richness and diversity, cover, and the vegetation zonation are all critical factors affecting coastal foredune development, among others (e.g. van der Valk, 1974a; 1974b; Pye, 1983; Hesp, 1988, 2002; Arens, 1996; Giles and McCann, 1997; Hesp et al., 2005; Pye, 1983; Hesp, 1988, 1991, 2002; Arens et al., 1995; Giles and McCann, 1997; Hesp et al., 2005a; Miot da Silva et al., 2008; Hesp and Walker, in press). Sediment supply, beach-surfzone morphodynamic state (dissipative to reflective), and beach state (erosional, stable, accretional) are additional factors that may strongly influence foredune evolution and morphology (e.g. Short and Hesp, 1982; Davidson-Arnott and Law, 1990,1996; Davidson-Arnott, 2010). Gulf County, Florida has a wide range of beach states from highly erosional to highly progradational (Foster and Cheng, 2001), which make it an ideal location to study foredune and dune vegetation associations and shoreline state (eroding to stable to accreting).

Coastal plant species usually tolerate high salinity, high temperatures, wind abrasion, and extremes of soil moisture conditions (Hesp, 1991; Craig, 1991). The most critical factors in coastal dune vegetation zonation are salt-spray, (Oosting and Billings, 1942; Sykes and Wilson, 1991) and sand burial (van der Valk, 1974, 1974b; Moreno-Casasola, 1986) (Dech and Maun, 2005; Maun, 2009). However, swash inundation and ponding, dryness, light intensity, high temperatures, sand salinity, and nutrient deficiency are all stress factors in which coastal vegetation must have specific adaptations to survive (Hesp, 1991; Martinez et al., 2001). We know little, however, about how coastal plant associations and species respond to varying moderate to long-term levels of beach and dune erosion and accretion (Hesp and Martinez, 2007).

Doing (1985) described six successional vegetation zones based on sand movement, salinity, and depth of water table. Variations in these factors are directly related to the topography. Tinley (1985) summarized four major vegetation zones where rainfall is sufficiently high and the shoreline is stable to prograding. Brown and McLachlan (1990) summarized the four zones (Figure 2.8), which include: 1) Pioneer Zone (which included Doing's (1985) beach and embryo dune zones); 2) Shrub community or dune heath; 3) Scrub-thicket zone; and 4) Thicket or Forest.

The pioneer zone is closest to the sea (Zone 1, Figure 2.8), characterized by creeping grasses and succulent herbs with rhizomatous and stoloniferous growth (Hesp, 1983, 1984; Doing, 1985; Moreno-Casasola, 1986; Brown and McLachlan, 1990). These plants are ephemeral and may be removed by extreme storms (Ranwell, 1972; Hesp, 1989). However, their rhizomes, stolons, or seedlings may be transported back to the same shoreline position where they may quickly regenerate, establish new populations, and subsequently rebuild embryo dunes (Maun, 2004). Inicpient forms are often monospecific, (Brown and McLachlan, 1990), but multiple species may appear as the incipient foredune grows (Hesp, 1989). The first pioneers may be rhizomatic, (*Ammophila*) or stoloniferous, (*Ipomoea*) (Bird, 1969). Tall, dense vegetation, such as *Ammophila,* promotes the growth of taller hummocky and asymmetric dunes compared to *Ipomoea*, which produce lower, less hummocky dunes (Hesp, 2002). Low creeper species often dominate incipient forms in the tropics, whereas taller grasses and sedges dominate incipient forms in temperate regions (Hesp, 2004). The species in the pioneer zone are the most salt tolerant, making them well suited to survive and prosper when buried by sand, and are often succulent species that best store water (Brown and McLachlan, 1990). *Uniola paniculata,* *Panicum amarum, Ipomoea pes-caprae, Cakile edentula* and *Sesuvium* sp. are commonly found pioneer species in Gulf County, and are ideally suited for the county's environmental conditions.

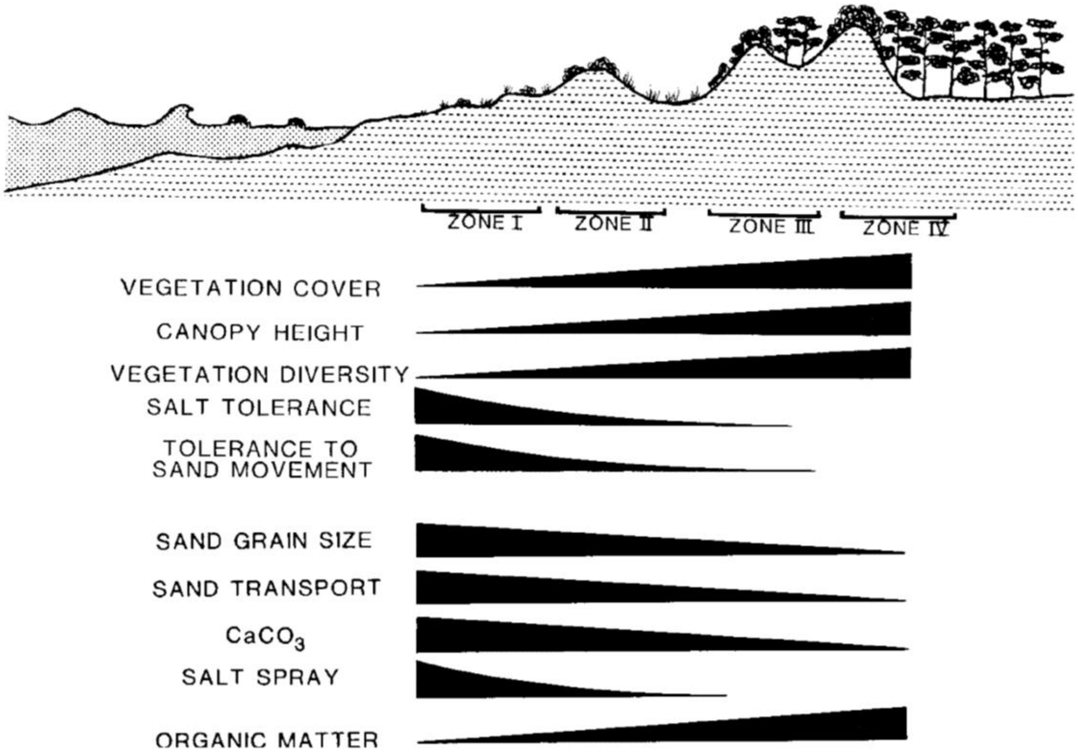


Figure 2.8 – Vegetation zones and key factors affecting vegetation development (modified from Brown and McLachlan, 1990; 254, 256). Vegetation cover, canopy height, and diversity increase landward, and species tolerance to salt spray and sand movement decreases landward.

Rapid beach progradation often leads to the development of wide-terrace like incipient dunes, especially if the vegetative species are aggressively colonizing the new beach material (Hesp, 1989). If the rate of progradation decreases, sand terraces will become more ridge-like as more sediment is trapped in the foremost vegetation (Hesp, 1983, 1989; Sarre 1989; Kuriyama et al., 2005). During erosion (storm) events, if the beach is inundated, the foredune may be scarped and the most seaward vegetation will be removed. This allows for species still present on the foredune to trap more sediment and thus build the foredune (Psuty, 1988; Hesp, 1989, 2002;

Maun, 2004). As vegetation cover increases, late colonizers (for example *Schizachyrium*) take root leeward of the maximum sedimentation area (Martinez et al., 2001).

Shrub communities or dune heaths (Zone 2, Figure 2.8) occur above intertidal waters, which include a mixture of plants from the pioneer zone, together with species which are less salt tolerant and less adapted to sediment transport and burial, such as *Croton punctatus* and *Iva imbricata* (Oertel and Larson, 1976). In this successional zone, vegetation cover may increase, and therefore decreases sediment transport across the foredune.

The scrub-thicket zone (Zone 3, Figure 2.8) is characterized as having little to no sand movement, and therefore a host of new vegetation species that cannot survive burial may now co-exist with the same species that are found in zone 1 and zone 2. These secondary species may out-compete the pioneering species. These plant communities may include dwarf trees and shrubs with little understory, but a distinct litter layer may be present (Brown and McLachlan, 1990). In Gulf County, Florida, *Quercus spp.* and *Ceritola ericoides* are found on tall foredunes fronted by eroding shorelines.

Thicket or forest (Zone 4, Figure 2.8) only develops in areas of high rainfall behind the shelter of larger dunes (Brown and McLachlan, 1990; 255). Thicket or forest may be seen in relict foredune plains or beach ridges in areas no longer affected by salt spray (Moreno-Casasola and Espejel, 1986). While these areas only develop when stranded a distance from the beach, extensive shoreline erosion may bring forest, or thicket (zone 4, as well as zone 3) closer to the shoreline, and even leeward of the foremost dune as seen in Gulf County.

Zonation is often most commonly related to the amount of vegetation burial by sand (Moreno-Casasola, 1986; Maun, 2004; Dech and Maun, 2005). While successive vegetation zones may overlap across gradients, in some areas succession is clear-cut, consisting of shore parallel bands, which are often associated with dune ridges and swales (Olson, 1958; Carter, 1980; Hester *et al.*, 2005). However, the studies mentioned have all focused on prograding to stable shorelines. Examinations of changes to successional zonation on eroding beaches and dunes with secondary to climax species have not been conducted.

Johnson (1997) found that *Uniola paniculata* and *Panicum amarum* were the dominant species just west of Gulf County, on Crooked Island, Florida. *Uniola paniculata* dominated foredunes up to eleven years and *Panicum amarum* only maintained dominance for the foredunes' first five years (Johnson, 1997). *Chrysoma pauciflosculosa* dominates older dunes, and *Ceratiola ericoides* would become the dominant dune species after 52 years (Johnson, 1997). Stapor (1971) also found that foredunes with *Ceratiola ericoides* have potentially been stable for at least 50 years. However, *Ceratiola ericoides* exists on the crests of the foremost dune in parts of St. Joseph Peninsula State Park. Johnson (1997) found *Smilax auriculata* only on ridges protected from the coast for over 20 years on Crooked Island, yet *Smilax auriculata* exists on the foredune crests in St. Joseph Peninsula Park as well. Johnson's (1997) study focused on transects that highlighted the beach progradational and vegetation successional stages. Vegetation zonation on eroding coasts has not been documented for Gulf County and the surrounding region.

Patterns of succession in natural coastal communities have been described by many authors over the past century, including the seminal work of H. C. Cowles (1899), studying plant succession across the Lake Michigan shoreline and dunes. Successional zonation of species is related to sediment movement (Moreno-Casasola, 1986; van der Maarel, 1996; Maun and Perumal, 1999; Maun, 2004). However, sand movement is not the only factor that explains vegetation zonation (Martinez et al., 2001). Martinez et al. (2001;370) showed that abiotic (sand mobility) and biotic (species dominance) conditions, which change over time, were both very important in describing vegetation dynamics on coastal dunes. In addition, they showed that there is high variability in species presence or absence within the United States and Mexico gulf coasts (Martinez et al., 2001). At even smaller spatial scales, Miot da Silva et al., (2008) demonstrated high variability on one beach in Brazil based on the variations in morphodynamic beach state. Hesp (1988) showed similar vegetation variability to be directly related to sediment supply and salt spray on the different surfzone-beach morphodynamic types in Australia.

Biological diversity encompasses all levels of natural variation and includes patterns up to the landscape level (Huston, 1994; 1).   Diversity can be used as an indicator of coastal dune ecosystems (Magurran, 1988). Huston (1994) points out that diversity is better understood using groups of species in functional plant types. Garcia-Mora et al. (2000) found that using functional plant types based on similar structure, function, and response to environmental conditions could be used to assess coastal dune vulnerability in Portugal, and this could be translated to apply to other geographical contexts. This methodology could be valuable to assess species vulnerability and change to the foredunes on the Florida panhandle once functional species types have been identified.

2.3 Spit Morphodynamics

Spits are depositional sand or shingle features built along the shore usually ending in one or more landward recurves (Bird, 1969). Ridges along the spits, especially the distal ends, indicate former shoreline position, tracing the evolution of the spit (Davis and Fitzgerald, 2004). This results from the addition of sediment to the spit’s distal end.

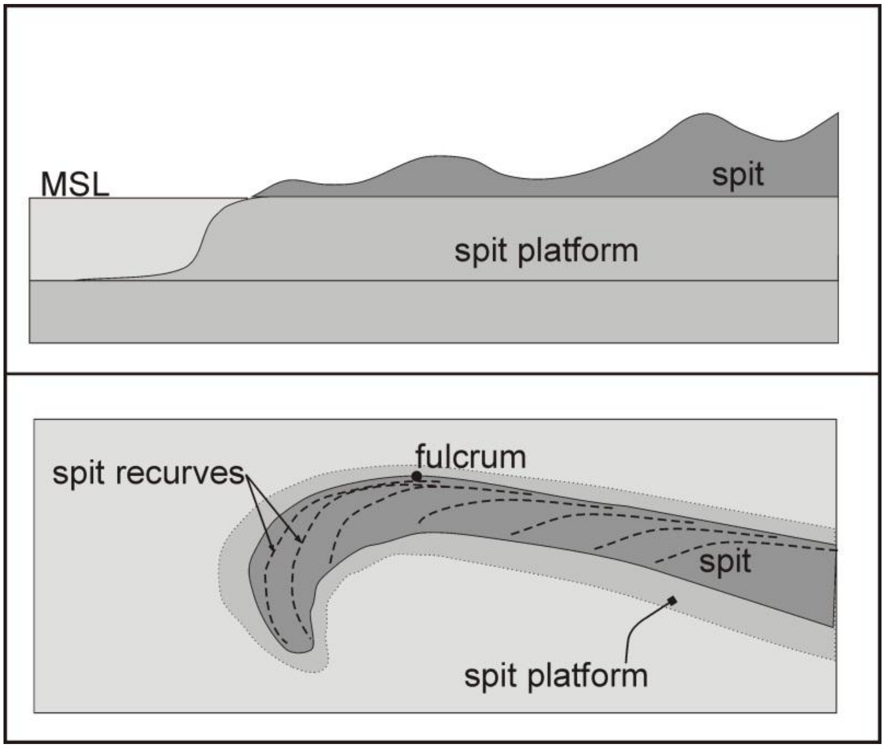


Figure 2.9 - Conceptual diagram of a spit in cross-section (above) and planform (below) view. The spit is an elongated depositional form extending into open water, from a landward attachment (the distal end) to the prograding (proximal) end.

2.3.1 Spit Initiation

Gilbert (1885) first noted that when a coastline turns abruptly, the currents do not turn with it, but rather pass into deeper water. When the current diverges from the coastline, the sediment will continue to be transported by the current and transport to the deeper water, where it will accumulate as the current slows (Gilbert, 1885). This process will continue with more sediment accumulating until a ridge of sediment is built, and ultimately a beach and barrier similar to the attached beach will form.

The spit platform (Figure 2.9) is an embankment elevated above the shelf but below mean low-water level in which the subaerial spit is built (Meistrel, 1966). Meistrel found that the spit platform was a precursor to any spit and that platform building was an ongoing process. Unlike the process described by Meistrel (1966), Kharin and Kharin (2006) found that not all spits were built on a longshore sediment transport built platform. For example, the Curonian Spit was built across a moraine that followed the former shoreline (Kharin and Kharin, 2006).

The spit itself can be a temporary structure, even if the platform is stable. However, both the spit and platform are only temporary structures with regard to overall coastal development (Meistrel, 1966; 23). Similar to other barrier forms, spits may translate landwards across the spit platform while maintaining their general shape. Salt marshes frequently found on the landward side of spits and between recurves on the landward side are established on the subaqueous platform (Bird 1969). Under landward retreat, a spit will overtop the adjacent salt marsh material providing layers with higher biogenetic material (Bird, 1969), which may be found in the southern portion of St. Joseph Peninsula if landward migration is occurring.

Ollerhead and Davidson-Arnott (1993) demonstrated that the spit platform was an integral component in the variations between the distal ends of Buctouche Spit and Long Point in Canada. The platform forced waves to shoal further offshore at Buctouche and, as a result, local wind generated waves were a greater factor in recurving the distal end. Vinther (2006) also found that a loss in the spit platform (due to channel dredging) led to erosion of the tip of Skalligen spit, Denmark. This was due to high wave energy and a decreased sediment accumulation at the tip of the spit itself. This resulted from longshore transported sediment refilling the dredged area, and thus retarding the platform rebuilding process (Vinther, 2006). A similar situation may halt the elongation and possibly increase erosion of St. Joseph Peninsula’s distal tip if the Intracoastal Waterway into St. Joseph Bay has to be dredged due to continued spit and subaqueous platform elongation.

2.3.2 Spit Elongation

Spits represent subaerial accumulations of sand or gravel that result from longshore transport (Woodroofe, 2002; 301). This subaerial feature may take the form of a spit, hook, bar, or a loop (Gilbert 1885; 29). In Gulf County, St. Joseph Peninsula is a spit elongating from Cape San Blas northwards that possess landward recurves (Otvos, 2005). There is an additional detached free form extending eastward from the mainland in Gulf County. However, this eastern arm does not display the same landward recurves found at the tip of St. Joseph Peninsula, but rather southeastward trending ridges which extend into Indian Pass.

Gilbert (1885) and Johnson (1919) described the movement of sediment by longshore currents, and the growth of spits resulting from this sediment transport. Kidson (1963) believed that counter drift, which is alternating sediment transport cells described by Steers (1948), could explain variations in spit growth direction. Opposing direction sediment transport cells described by Stone and Stapor (1996) may cause the varying beach progradation of the south facing stretch of Gulf County's coast. Additionally, reversing cellular transport may aid in explaining the building and erosion of the Cape San Blas foreland.

Evans (1942) found that the rate of growth of spits directly correlated to the strength of the winds and waves. The rapidly changing spits studied by Evans (1942) also showed that waves coming from opposing directions or perpendicular to the axis of the spit tended to erode the landform. However, this occurred on short time scales that may not be detected in historical records for most regions, including those of Gulf County, Florida. Hine (1979) demonstrated that the building of the tip may occur as a result of successive berm-ridges with intervening runnels, thus creating a step-wise building of the spit tip, rather than a continuous development of alongshore sediment flow first described by Johnson (1919) and Evans (1942). The Hine

(1979) model of spit development may describe the development of St. Joseph Peninsula, while continual swash supplied sediment transport may describe the development of the Gulf County's south facing shore. If the flow of material is disrupted as a result of a change in the trend of the coastline or from a reduction in sediment supply, new deposition and accumulation forms may occur (Zenkovich, 1967). Seasonal wind and wave variability and tropical storm occurrence may play a significant role in altering sediment budgets, yet their effect on spit elongation rates has not been documented.

The spatial variability of dune types on elongating spits was described by Psuty in 1992 (Figure 2.10). St. Joseph Peninsula has been prograding northward and appears to be developing a series of ridge forms similar to Psuty's (1992) model. The alongshore variability described by Psuty states that "beach ridges" are found at the distal tip along recurve features, and erosional forms, or variable dune types based on the Psuty matrix (1988) can be found along the peninsula.

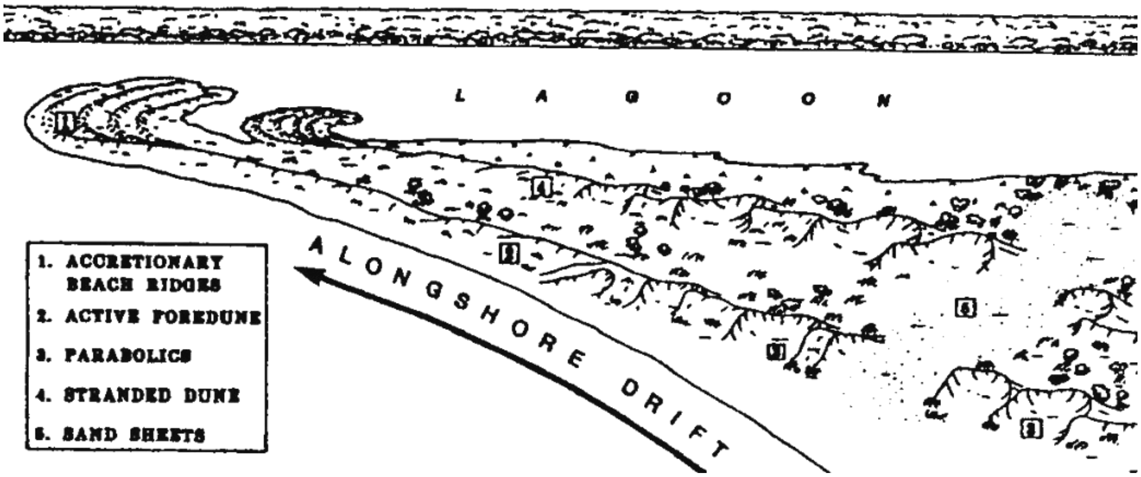


Figure 2.10 - Psuty's elongating spit diagram, indicating changes in dune types along a morphological continuum (1992; 11). St. Joseph Peninsula can potentially be used to identify the landforms associated with the Psuty model based on spatial variability of an elongating spit.

2.3.3 Spit Recurves

Spits usually end in one or more landward hooks or recurves (Bird, 1969). Spit recurves often result from the refraction of waves around the spit's distal tip (Evans, 1942). Ridges may also recurve resulting from varying onshore wave directions (Evans, 1942). Ebb and tidal flow can also control the direction of spit recurves if the local tidal currents paramount over the wave conditions (Oertel, 1985). Gulf County's micro-tidal (Foster and Cheng, 2001) conditions may play a small role on the alignment of St. Joseph Peninsula's recurves.

King and McCulluagh (1971) showed that deeper water off the distal end of a spit will be refracted more, and ultimately cause a large radius of curvature at the distal tip. When the longshore sediment transport decreases due to a decrease in wave energy as it refracts around the spit, the sediment follows this recurved path of the waves (Carter, 1988). A zone of accumulation results where the sediment flow decreases and the spit will often exhibit recurve forming ridges in the direction of sediment flow. Ridges along the spits indicate former shoreline position tracing the evolution of the spit (Davis and Fitzgerald, 2004). The changes in sediment supply and ridge curvature may be a result of the alteration of wave systems with different parameters and from various directions or from variations in sediment supply related to climatic or physiographic conditions (Zenkovich, 1971; 114), which may explain the variability in ridge curvature on St. Joseph Peninsula. Carter (1988) described the cannibalization of the ridges as providing a sediment supply for longshore sediment transport to elongate the spit, but limited descriptions and no quantification of the sediment supply of the cannibalization of dunes to build larger foredune complexes has been documented for spits.

Shoreline erosion may occur if longshore and offshore sediment supplies decrease. While sediment transport by waves is ongoing, progradational spits may be starved of sediment and thus become erosional features (Carter, 1988). Héquette and Ruz (1991) showed that the variability in sediment supply rates was the controlling factor in spit progradation and retreat rates in the Canadian arctic. This is in agreement with findings by Kidson (1963), Aubrey and Gaines (1982), and Ollerhead and Davidson-Arnott (1995), who showed that the proximal portion of a spit with low sediment supply would erode or may be breached, while the distal end (a sediment sink) continued to grow. Similar to other barrier forms, spits may translate landwards while maintaining their general shape (Carter, 1988). Understanding sediment volumes and supply rates may be crucial in determining shoreline erosion and deposition patterns of St. Joseph Peninsula.

2.3.4 Spit Alignment

Most spits grow in the direction of predominant longshore sediment transport while other spits depart from the trend of the coast and align themselves nearly at right angles to the prevailing wave direction (Komar, 1988; 26). Zenkovich (1967) identified that under high-angle wave conditions spits should grow at an angle approximately 45° to the shoreline trend. Oblique waves tend to form drift-aligned spits, whereas swash-aligned spits are more common in shore-normal conditions or on swash-aligned coasts (Ashton et al., 2001, 2007).

Zenkovich (1967) conceptualized the response of spits to variations in wave direction. He showed that waves under more oblique wave conditions will lead to greater spit widths than will more acute angled waves (Figure 2.11*Ia*). Refraction will only be affected at the distal tip: The wave field will become thinner but the spit will continue to grow in the same direction as the oblique wave approach (Zenkovich 1967; 415). If the wave angle becomes even more obtuse, such that waves approach the spit from an opposing direction, the currents will in turn force the accumulation of sediment to arc toward land (Figure 2.11*Id*). If the wave field returns to the original direction, the spit will return growing in its original direction, stranding the recurved portion.

If waves approach from the opposing direction (Figure 2.11*II*), the tip will be eroded and the sediment will potentially be translated down both sides of the spit. This material may create a secondary form on the landward side of the spit (Zenkovich, 1967; 416). If these conditions continue for extended periods of time, the recurved distal end will continue to extend back towards the proximal end of the spit (Figure 2.11*III*). The variations in planform widths of St. Joseph Peninsula may result from the variations in wind directions as described in situation I and II (Figure 2.11) by Zenkovich (1967). This is highlighted when examining the ridge sets on Edith Hammock near the proximal end of St. Joseph Peninsula, which appear to align normal to the shoreline. However, other factors such as breaches, overwash, and landward transgression due to beach erosion may also be important variables to consider when examining the width variation of the spit.

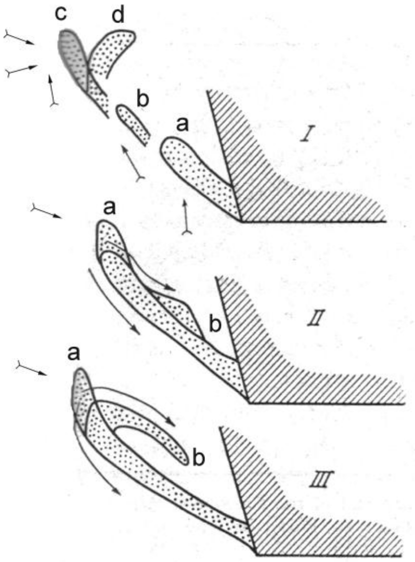


Figure 2.11 – Complexities due to changing wind angles in the growth of a spit: *I*- Alteration in the thickness of the spit (a,b) and in orientation (c,d) in relation to changing wave directions; *II*- Erosion of the distal end of the spit and formation of a secondary projection on the inner side; *III*- Formation of elongated curved on the spit (Zenkovich 1967; 415).

W. M. Davis (1909) first identified a fulcrum point on Cape Cod Massachusetts in which the spit maintained its position between an eroding cliff and the downdrift spit extension. At Buctouche Spit, from the point of mainland attachment to the fulcrum point, the spit experienced a landward transgression, and progradation from the fulcrum to the distal end (Ollerhead and Davidson-Arnott, 1993, 1995). Raper et al. (1999) point out that these sections may be divided into different littoral cells and different sediment pulses, with greater erosion on the shore parallel section, and deposition on the more shore normal section. Locating the fulcrum point, which may set apart variations in sediment supply and transport conditions, is important for predicting morphological changes to different portions of the spit. The occurrence and origin of longshore sandwaves (Saunders and Davidson-Arnott, 1990) have not been linked to fulcrum points. However, a slight change in beach orientation may provide a catalyst for longshore sandwave development. The recurves beyond the fulcrum point at the distal end of Buctouche Spit were not a result of wave refraction because the waves did not refract around the spit (Ollerhead and Davidson-Arnott, 1995). Rather, the recurve orientation was a result of less frequent local storm generated waves as described by Evans (1942) and supported by computer simulations by King and McCullaugh (1971).

Oblique waves give rise to the northward longshore sediment transport and the ultimate drift-alignment of St. Joseph Peninsula (Davies, 1980). St. Joseph Peninsula has a potentially large enough fetch off the northern distal tip for wind and waves to potentially recurve the ridges of the spit as described above. However, the shallow water depths allow for wave refraction patterns to potentially be the controlling factor in recurve orientation.

In comparison, Gulf County’s eastern spit extension into Indian Pass may have limited wind and wave effects because of the shorter fetch lengths from the east, as well as opposing tidal currents at the distal tip. This may limit the potential for recurved ridges from being located on this free form. A higher frequency of shore normal waves will give rise to a shore-aligned barrier (Davies, 1972), which may explain the slight seaward convex nature of this section of coast. Stapor (1971) found there to be minimal exchange of sediment into or out of this stretch of shoreline, which would support Davies (1972) hypothesis that the shore-aligned stretch is in, or near, equilibrium if the waves are swash aligned.

2.3.5 Spit Response to Sea-Level Change

Landward translations of spits may result from changes in sediment supply to the spit as well as (or independently from) a result of sea level rise acting as a forcing mechanism to the spit (Hoyt and Henry, 1967; Carter, 1988). Carter (1988) discovered changes to spits were directly related to changes in sea level. Carter (1988) observed that truncated recurves are often related to changes in sea level, which can change the wave and sediment transport dynamics of a system. Zenkovich (1971; 95) noted that sediment transfers into accumulation zones may be aided by a transgressing sea through reworking sediment into the accumulation zones in accordance with topographic and hydrodynamic conditions. Firth et al. (1995) showed that in Dornoch, Scotland, decreasing sea level aided spit development. However, in regions with decreased cliff face erosion resulting from sea level drop, the sediment supply feeding the longshore currents decreased, and spits in these locations were eroding (Firth et al., 1995).

Increased sea level may lead to the reworking of sediment at the proximal end of spits, leading to breaching at the proximal end and the formation of barrier islands with spit tips at both ends of the island (Carter, 1988). Thors and Boulton (1991) found that spits in Northern Iceland would retreat landward under relatively fast sea level rise if the current wave and substratum slope did not change, but spit elongation occurred under slower rates of sea-level rise under similar wave and sediment conditions. Otvos (2005) described spits that form and elongate in western Florida despite a slow sea level rise as well. Regarding the Florida panhandle barriers, Otvos (2005; 153) stated: "…strandplain development is not associated exclusively with stable or slowly declining sea levels." This is observed in the southern (east-to-west) coastline of Gulf County. While Otvos (2005) promotes the idea of an asymptotic rise in sea level for the Gulf of Mexico, Tanner et al., (1989) and Blum et al., (2002) contend that sea level has maintained near present levels for the past 5000 years. Tanner et al., (1989), detailed a highstand around 5000 kPA and a second highstand approximately 2000 kPa. Despite the disagreement in sea level, it can be postulated that sea level on the Gulf County coast has been rising to stable since the inception of St. Joseph Peninsula (< 2000 kPa); luminescence dates by Otvos (2005) indicate that the study region has all formed since 2000 kPa. Thus, it can be inferred that the Peninsula has been built during this period of slightly rising to stable sea level through the very recent Holocene.

2.4 Chapter Summary

The preceding literature outlined describes foredune and spit dynamics and was essential background information for fully understanding the morphodynamics of Gulf County, Florida. Subsequent chapters will utilize this material to help understand the morphologic changes occurring in the study region.

Chapter 3
Study Site and Methods

3.1 Introduction

This chapter outlines the methods used to achieve the overall research objectives. First, the section below provides an introduction of the basic physiography of Gulf County, Florida. Second, Section 3.3 contains a brief description of each of the specific profile sites used for this study. Finally, the concluding sections outline the methodology used to obtain results.

3.2 Study Site

The field research for this dissertation was conducted in Gulf County, Florida along the Gulf of Mexico shoreline from approximately 26°54.8’N, 85°22.2’W to 29°40.7N, 85°14.4’W (Figure 3.1). The foredunes studied extend along St. Joseph Peninsula, a recurved spit approximately 24 kms in length, Cape San Blas (the southernmost point of the county), the south facing stretch of coast to the east of the cape, and along the mainland portion of the coast east of St. Joseph Peninsula (Figure 3.1). The northern half of St. Joseph Peninsula is in the T. H. Stone St. Joseph Peninsula Memorial Florida State Park and as a result has minimal anthropogenic impact altering natural vegetation growth. The study sites chosen on the Gulf County coast were relatively undeveloped compared to locales west of the County, which made Gulf County an ideal area to conduct natural beach-foredune research. The first beach nourishment project there was approved in 2007 and completed in 2009 (FDEP, 2012; Lush, 2013). The nourishment project extended 7.5 miles north from Cape San Blas, however no noticeable change to the foredunes resulted from this project.

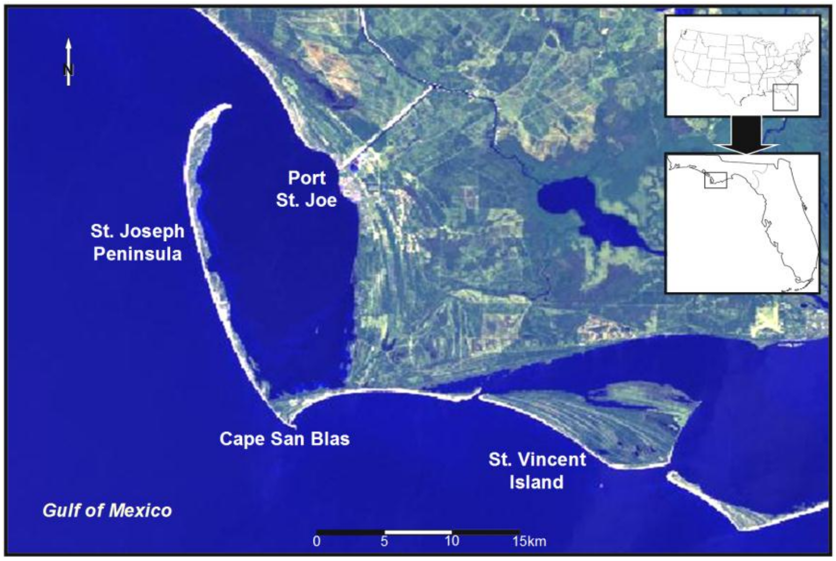


Figure 3.1 - Study region extending from the mainland north of St. Joseph Peninsula, the Peninsula, Cape San Blas and the eastern extension to Indian Pass.

3.2.1 Physiography of Gulf County

The prevailing coastal features in Gulf County are St. Joseph's Peninsula and the highly erosional Cape San Blas, which is the southernmost point of the former Pleistocene deltaic plain. Otvos (2005) used Optically Simulated Luminescence (OSL) methods to date the spit and the barrier running east from the Cape to be predominantly younger than 2.0 ka, with the oldest date at Richardson Hammock (2.9ka), 3 kilometers north of Cape San Blas. Otvos (2005) describes Richardson Hammock as having originally been an island from which the spit prograded northward.

Foster and Cheng (2001) estimate that the Gulf County mainland shoreline, north of the tip of the peninsula, is accreting between 0.6 to 1.5 m per year based on data from 1973 to 1997. The tip of the spit peninsula is accreting at rapid rates, yet the majority of the spit is slightly eroding for most of the peninsula from (0.0 to 0.65 m per year, and then a marked increase in erosion rates (beginning at FDEP Range Monument 90) to the Cape at 0.65 to 13.1 m/a (Foster and Cheng, 2001). The east-west shoreline stretching eastward from the cape is experiencing high rates of accretion near the cape (up to 9.1 m/a) to near very slight deposition (FDEP Range Monuments 136 to 155) through the remainder of the study area (Foster and Cheng, 2001).

Foredunes in Gulf County range in height from approximately 10 meters above MSL in the middle of St. Joseph Peninsula to no dunes located at the highly eroding cape (Rizk, 1991). The foredunes predominantly comprise stages 2-4 of the Hesp classification of established foredunes (Hesp, 1988b).

Thus far the region is undeveloped, especially in comparison to the highly developed tourist areas to the west. However, new development projects are being conducted in the eastern portions of Gulf County, which may increase human impacts to the coastline. The northern half of St. Joseph Peninsula has the T. H. Stone St. Joseph Peninsula Memorial State Park and therefore there has been minimal anthropogenic impact in this area.

3.2.2 Wave Climate

The study area is micro-tidal with a tidal range of .36 m) to .35 m) (Foster and Cheng, 2001). A wave rose is presented in Figure 3.2 for the region (USACE, 2012). Gorsline (1966) found average wave heights to be approximately .30 m between Indian Pass and Pensacola, Florida. Offshore mean significant wave heights (recorded at USACE WIS Station 37 from 1975 – 1997) were recorded at 19 m depth offshore of St. Joseph Peninsula and listed as .6 m (Foster and Cheng, 2001). The area was described by Tanner (1960) and Kwon (1969) as being a moderate energy coast with dominant easterly (and northerly along the peninsula) longshore currents. However, following Short and Hesp (1982), the Gulf County coast would be considered low energy (<1m). Stapor (1971) and Stone and Stapor (1996) reported multiple longshore sediment transport cells in the region, including southward transport near the tip of the

Cape, which supplies sediment to the Cape San Blas Shoal. Foster (1991) estimated that erosion has occurred at the Cape for at least the last 110 years and will continue for at least the next 90 years based on historic shoreline data modeling.

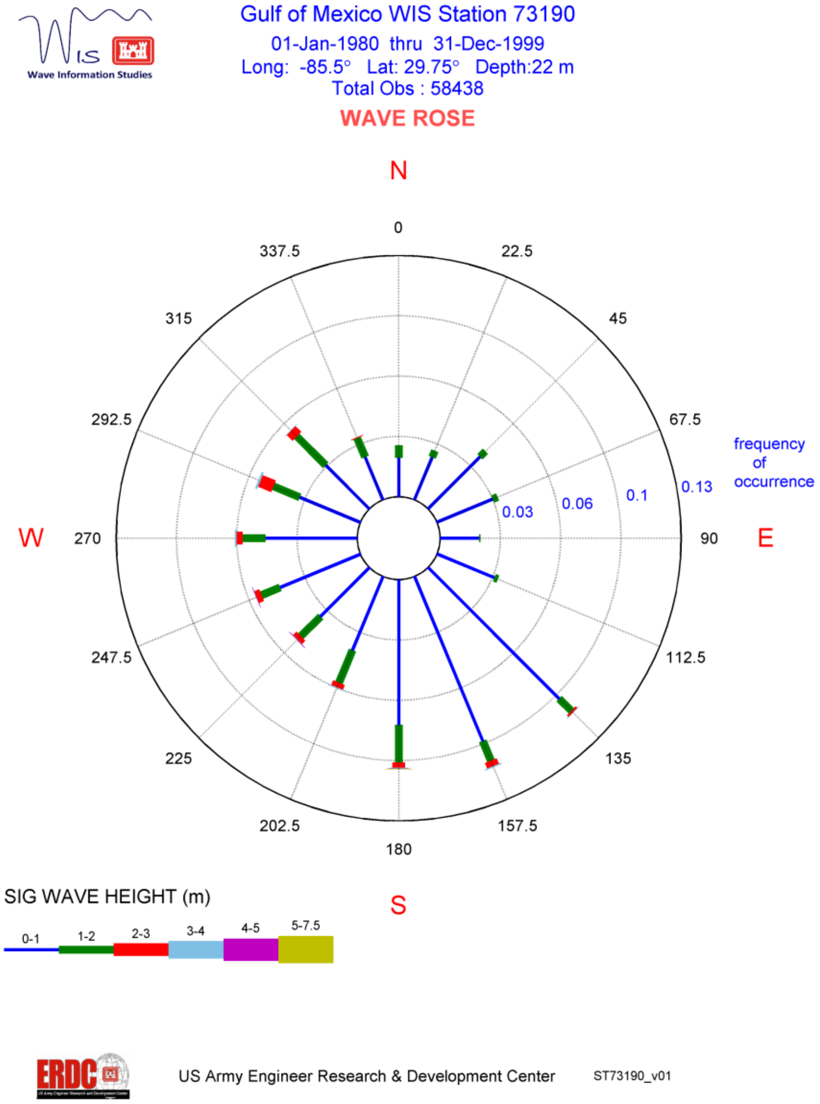


Figure 3.2 - Wave rose for station 73190 approximately 10 kms offshore from the center of Saint Joseph Peninsula (USACE, 2012).

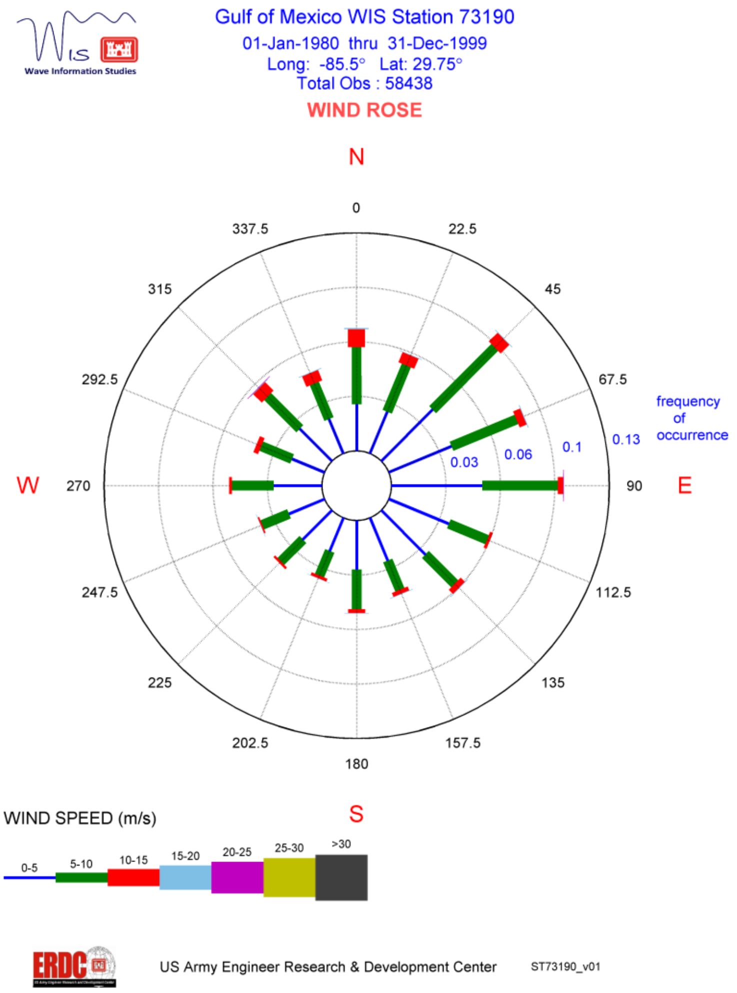


Figure 3.3 - Wind rose for station 73190 approximately 10 kms offshore from the center of Saint Joseph Peninsula (USACE, 2012).

3.2.3 Regional Wind Summary

Offshore Winds are dominated by easterly flow for this region as recorded at NDBC wave buoy 42039 and Tyndall tower SGOF1 (Figure 3.4). Resultant wind directions from both locations indicate dominant winds are from the east and north, however winds from Tyndall tower (the closest wind measurements to the Cape,) resultant wind direction is 67^{o}, or from the east-northeast. Nevertheless, there are winds throughout the year in all directions, just not as dominant from the south and west to which most of the study profiles point.

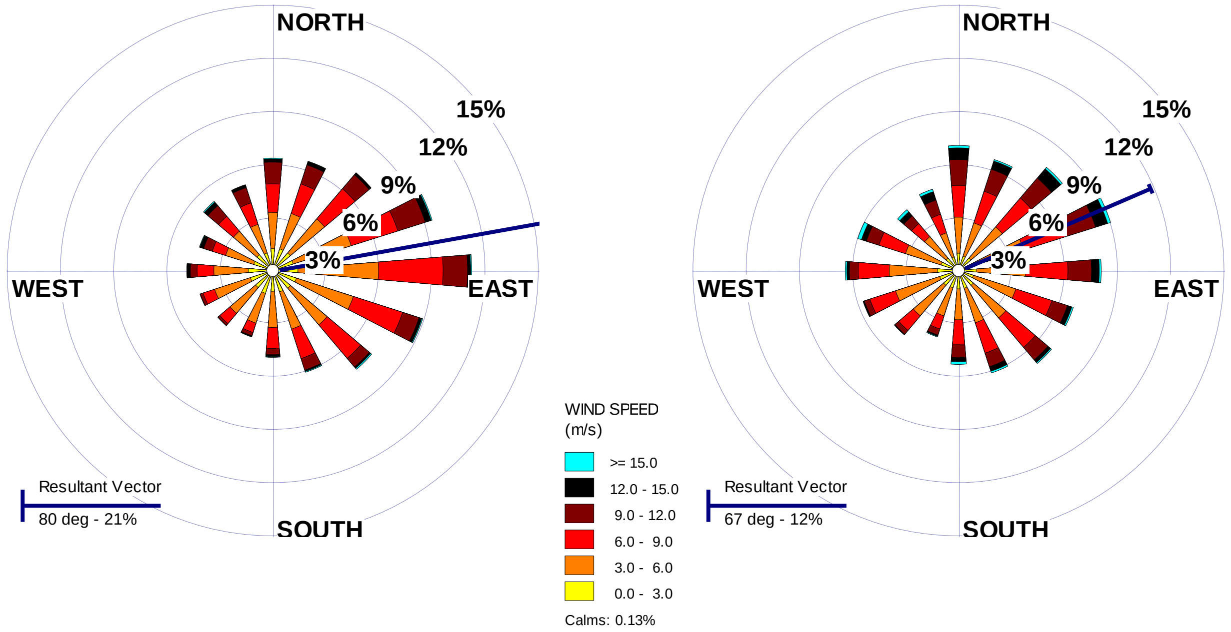


Figure 3.4 – 2003-2007 winds for NDBC wave buoy 42039 (left wind rose) and nearby NDBC tower SGOF1 (right wind rose). Wind roses created using WRPLOT.

3.2.4 Gulf County Hurricanes

Keim et al. (2007) and Spaziani (2010) examined hurricane return periods for the U.S. Gulf of Mexico and U.S. East Coast. For Gulf County, they found that all tropical storms and hurricanes had return periods of 4 years; hurricanes had a return period of 10 years overall, though hurricanes classified as Category 3 or stronger were calculated to have a return period of more than 105 years. Using the National Oceanic and Atmospheric Administration's (NOAA) National Hurricane Track website (Figure 3.5) 115 Tropical Storms (Tropical Storm through Saffir-Simpson Hurricane Category 5) have travelled within 160 kilometers of Cape San Blas since 1842 (NOAA, 2012). Of these, 10 storms (Figure 3.6) were major hurricanes (Saffir-Simpson Hurricane 3, 4, or 5) (NOAA, 2012).

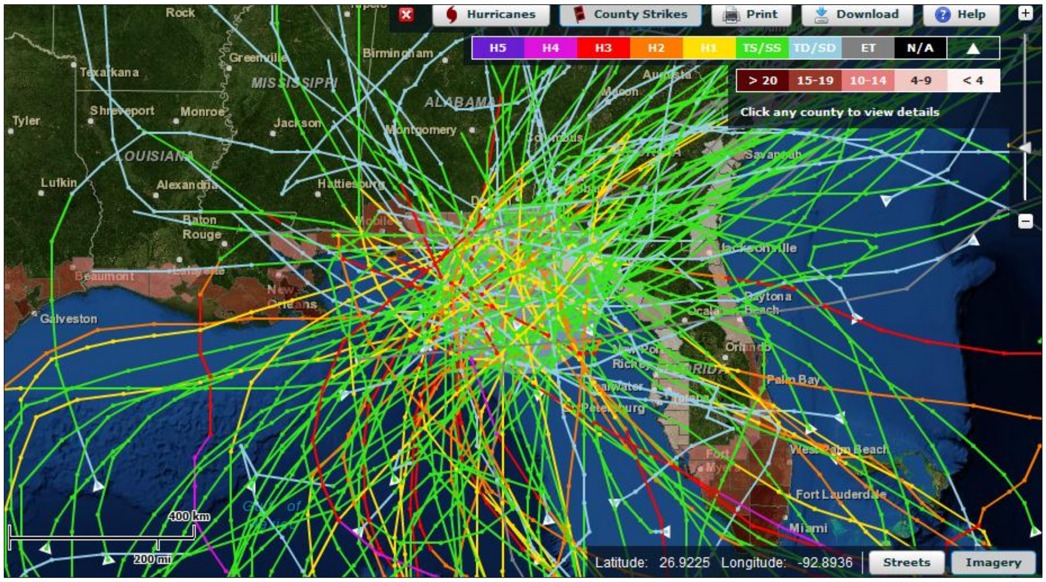


Figure 3.5 – Tropical Storms, Tropical Depressions and Hurricanes tracking within 160 kms of Cape San Blas (NOAA, 2012). 115 Storms were recorded since 1842.

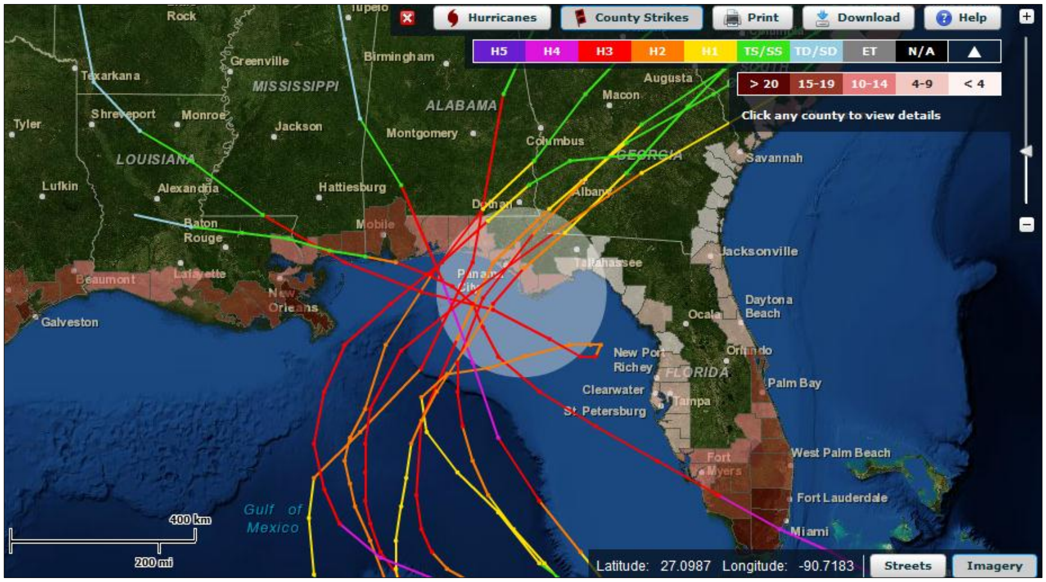


Figure 3.6 – Major Hurricanes (Saffir-Simpson H3-H5) within 160 kms Cape San Blas (NOAA, 2012).

Storms surge impacts from tropical storms on foredunes depend on the storm's track, and the extent and height of foredune development (Thieler and Young, 1991; Sallenger, 2000; Morton, 2002; Nott, 2006; Houser and Hamilton, 2009). Needham and Keim's (2011) archival research found there to be four significant hurricane storm surges within 40 km of Cape San Blas greater than 2 m over the past one hundred and thirty years (1880-2009), and a total of 18 storms with recorded significant surges during the stated time period and location. Any one of these storms may have played a role in shaping the coastal morphology.

3.2.4.1 Recent Highly Erosive Storms

Hurricane Ivan (2004), Hurricane Dennis (2005) and Hurricane Katrina (2005) were documented as having direct significant impact, causing erosion and overwash to the beach and foredunes in Gulf County, Florida (FDEP, 2005). Ivan storm surge values of 2-3 m were observed from Destin, Florida to St. Marks (Stewart, 2005). Dennis' storm surge was approximately 2 m above normal tide levels, which overwashed Santa Rosa Island and Navarre Beach, west of St. Joseph's Peninsula. A storm surge of 2-3 m above normal tide levels occurred in Apalachee Bay, Florida, which is east of Gulf County (Beven, 2005). St. George Island, east of Gulf County, recorded storm surges of 1.60 m for Hurricane Ivan and 2.45 m for Hurricane Dennis (Miller et al., 2010). While short and long-term changes to foredunes post-storm have been documented (e.g. Wang et al., 2006), long-term impacts on the overall geomorphology of spits and their incipient and established foredunes were not documented. Hurricane Katrina (2005) played a larger role in morphological change to St. Joseph Peninsula. Where the beach was narrower pre-storm, beach and foredune scarping occurred (Wang et al., 2006). However, the location with a wider beach on the peninsula lost beach sediment, but only very minimal scarping of the dune toe (Wang et al., 2006).

3.3 Study Profile Locations

The Florida Department of Environmental Protection (FDEP) has beach and beach-dune profile data for each of the 160 range monuments in Gulf County beginning in the early 1970s.

The FDEP also has documents that contain data providing variable long-term shoreline change rates, which can be used to estimate beach sediment supply changes.

Twelve specific study sites, or profile lines, were chosen to incorporate a range of wind and wave exposures, a range of foredune heights and beach erosion/accretion rates, and based on a lack of observable anthropogenic influence (Table 3.1; Figure 3.7).

Table 3.1 - Profile study sites situated along Florida Department of Environmental Protection (FDEP) Profile Lines.

FDEP Profile	Orientation (^{o})	Dune Height (m)	Beach Erosion- / Accretion+ (m/a) (Foster and Cheng, 2001)
R6	230	3.5	+1.07
R27	255	3.3	+1.22
R32	360	3.6	+2.13
R33	330	2.4	+2.74
R37	310	5.7	+3.51
R52	270	8.4	-0.46
R71	255	7.7	-0.46
R100	240	4.1	-3.35
R110	200	2.0	-8.71
R122	135	3.3	7.92
R143	180	3.2	0.30
R155	200	2.6	1.22

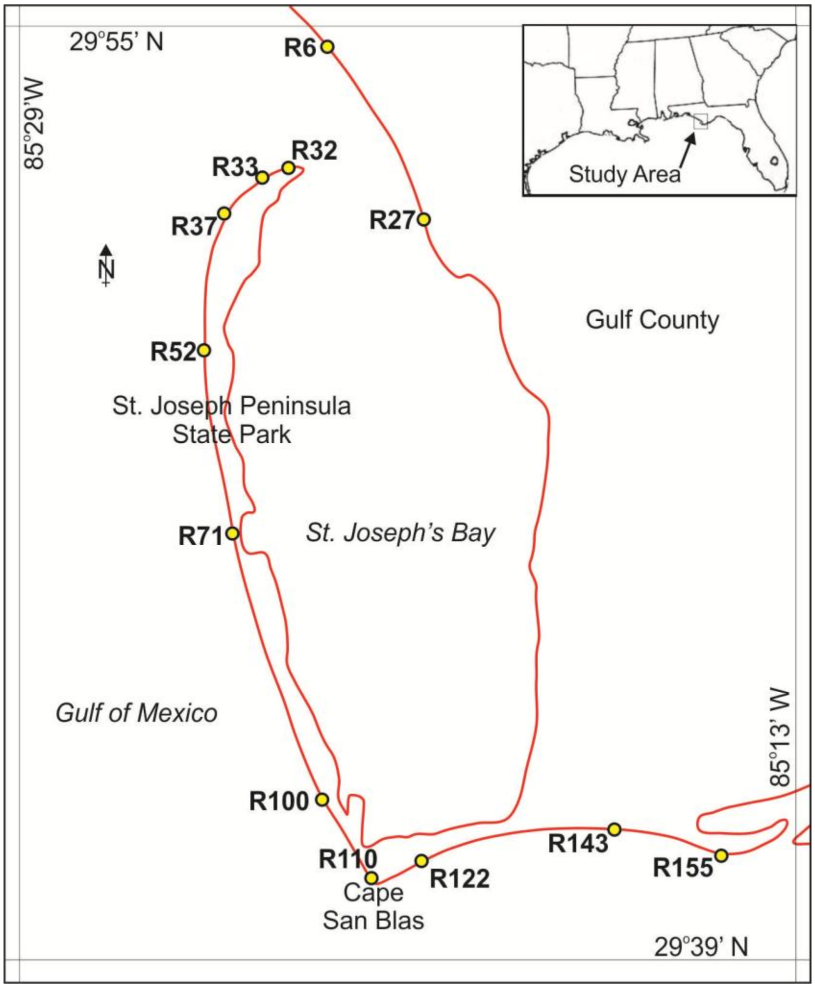


Figure 3.7 – Study profile locations within Gulf County, Florida. Each profile location used the Florida Department of Environmental Protection (FDEP) benchmarks and profile locations to have comparable historic data.

3.4 Methods

The following section will discuss methods employed to complete the research. In addition to the methods listed below, archival research was conducted at the Florida Department of Environmental Protection (FDEP) Beaches and Shore Division head office in Tallahassee Florida. At FDEP, data was acquired for beach and dune profiles, and available air photos were examined, and copies of aerial videography were made.

3.4.1 Topographic Profiles

FDEP data include 1973, 1983, 1993 and 1997 surveyed cross-sectional shore-normal profiles for each range monument in Gulf County as well as profiles extracted from a 2004 LiDAR dataset.

Approximately every six weeks (beginning June 2006) detailed topographic profiles were measured using a Sokkia Total Station to indicate short-term morphological change. Additional benchmarks were set along the profile as described by the FDEP, such that profiles were conducted along the same orientation for each survey. All dune heights are relative to the height above mean seal level (NAVD88). These profiles were established along the FDEP Range Monument profile lines listed in Table 3.1, to compare and contrast erosion and deposition, as well as rates of change between the short term (6-week) and decadal scales. Locations of vegetation occurrence and high tide swash lines were documented on each profile to use as

Table 3.2 – Project field study dates.

Dates	Topographic Surveys	Vegetation Surveys	Wave Study
May 29-June 4, 2006	Yes	Yes	
July 5-8, 2006	Yes		
August 16-20, 2006	Yes		
September 14-18, 2006	Yes		
November 2-5, 2006	Yes		
January 2-7, 2006	Yes	Yes	
February 17-19, 2007	Yes		
April 2-5, 2007	Yes		
May 20-24, 2007	Yes		
June 19-23, 2007	Yes	Yes	
August 7-12, 2007	Yes		
October 24-29, 2007	Yes	Yes	
May 28-June, 2008	Yes		Yes
August 2-6, 2009	Yes		

potential indicators for dividing beach versus dune segments, for calculating beach and dune volumes, and their rates of change.

If a tropical storm or hurricane were to impact the study area then the cross-sectional profiles before and after the storm would provide data that can be used to aid in hindcasting morphologic change during large erosion events.

3.4.2 Vegetation Profiles

Vegetation surveys were conducted along the topographically surveyed cross-sectional profiles of the first dune ridge. The vegetation surveys were conducted utilizing standard techniques (Gardiner and Dackombe, 1983); contiguous $1m^2$ quadrats were sampled for species presence or absence, and percent cover. Because species in a single quadrat can overlap, a greater than 100% total cover was possible. All vegetation surveys were carried out along the topographic survey line, from the landward edge of the foredune, over the foredune crest, and extended seaward to the point where no further vegetation was encountered. Vegetation Surveys were conducted in June 2006, September 2006, January 2007, June 2007, and October 2007, and were used to document seasonal variations in vegetation species and abundance as described by Martinez et al. (2001) and Miot da Silva et al. (2008). Pioneer versus climax species and functional plant groups (Garcia-Mora et al., 2000) was noted.

3.4.3 Wave Measurements

3.4.3.1 Visual Observations

During each topographic survey 10 minute visual observations of wave height were taken. This was completed while capturing submarine data points. Wave heights were observed against the survey prism rod, averaged, and recorded in field notes.

3.4.3.2 Measured Wave Heights

Pressure transducers were calibrated using a PVC pipe standing upright, leveled, and filled with water. Instrument output (mV) was measured at 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5 m depth. Measurements were taken in both ascending and descending order. No significant hysteresis was found. Linear regression was used to perform the calibrations and R^2 values were greater than 0.99 for the pressure transducers.

Wave data was collected at 4 hz for 10 minute bursts at each profile location at least 3 times for comparison with other sampled sites and modeled results. Data was processed using a MATLAB routine available from Urs Neumeier (2006), to correct the attenuation of pressure variations with depth using a Fast Fourier Transform algorithm using the widely accepted zero-crossing method. Significant and average wave heights were recorded.

3.4.3.3 Computer Simulated Wave Heights

The MIKE-21 spectral wave model, developed by the Danish Hydraulic Institute, was employed in this study because it has been applied successfully for off-shore wave simulations in the Gulf of Mexico (Jose and Stone, 2006; Jose et al., 2007). Long term wave and wind records available from the National Climate Data Center (NCDC) and the National Data Buoy Center (NDBC) C-MAN Station SGOF1 located offshore south of Cape San Blas, and NDBC Moored Buoys 42039 (located southwest) of the cape and 42036 (southeast of the cape,) were used to establish a wave and wind climate history for the region.

To develop a bathymetry for MIKE-21, offshore data sets were downloaded from NOAA National Geophysical Data Center (NGDC). To reduce computer processing time, the offshore bathymetry was created using 3 second grid spacing. However, a far more detailed bathymetry was required for the nearshore zone. The outer nearshore data from the NGDC was collected at

50 m spacing. For the immediate nearshore zone, 1m grid spacing was developed from 2007 LiDAR data files, and downloaded from NOAA's Coastal Service Center (CSC). These files were exported into a MATLAB routine to eliminate subaerial points, and then converted to x,y,z files and imported into ArcGIS 8.3 Geographic Information Software. The border of the LiDAR (Light Detection and Ranging) data was outlined, and then this area was subtracted from the NGDC coarse resolution data, such that the LiDAR data could take its place. This new bathymetry set was exported to MATLAB, then run through a smoothing routine, and finally imported into MIKE-21 to create the bathymetry for the Gulf of Mexico (Figure 3.8).

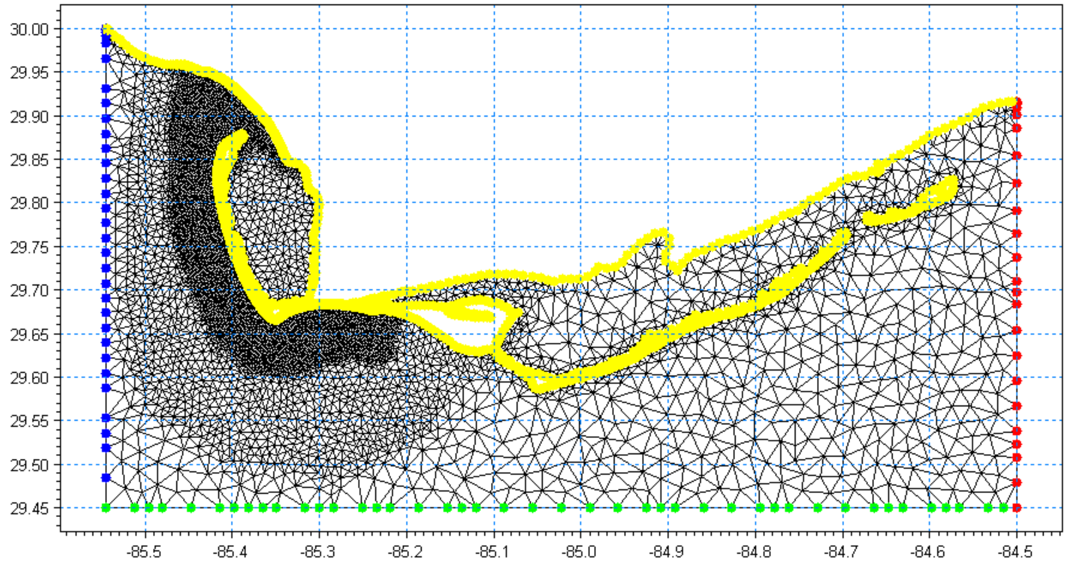


Figure 3.8 - MIKE-21 detailed mesh for developing local bathymetry from NGDC 3-second bathymetry and LiDAR data. Closer grid spacing was used in the nearshore portion of the study area. Offshore grid locations (indicated by colour coded dots) were used as landmarks for calculating wave parameters into the nearshore zone from the greater Gulf of Mexico parameters.

This study used MIKE-21 modeling software to create a first approximation of seasonal longshore sediment transport patterns under varying wave approach angles and energies. This was used to estimate longshore sediment supply rates for the peninsula. Sediment transport was calculated using the CERC equation:

$$Q_{lst} = \frac{pK\sqrt{g/\gamma_b}}{16(\rho_s - \rho)(1-a)} H_{s,b}^{2.5} \, sin(2\theta_b) \qquad \textbf{(1)}$$

Where Q_{1st} is the longshore transport rate in volume per unit time, K is an empirical coefficient, ρ is the density of water, ρ_s is the density of sand, g is the acceleration due to gravity, a is the porosity index (0.4), $H_{s,b}$ is the significant wave height at breaking, γ_b is the breaker index ($=H_b/h_b$), and θ_b is the wave angle at breaking (USACE, 1984).

Chapter 4
Cape San Blas – St. Joseph Peninsula Regional Wave Dynamics

4.1 Introduction

Examining wave energy and sediment transport in the study area is an important step in understanding changes to the coastal system including the morphodynamic changes to the beach, which ultimately can, or may affect foredune morphologies. This chapter identifies the variability in wave heights reaching the Gulf County coast, and models the sediment transport regimes along the shorelineto better ascertain the morphodynamic nature of these shorelines, to order them in terms of relative wave energy, and to understand the relationship of sediment transport and supply to beaches and to foredunes discussed in subsequent chapters. This chapter will examine visual observations and pressure transducer measurements of wave heights. This is followed by a validation of the MIKE-21 modeling to define wave parameters, based on comparison with NDBC buoy measurements and a comparison of field results, and the resulting wave heights and ultimately the sediment transport along Gulf County shorelines. The chapter will also examine seasonal variations and dominant wave directions in the region, and the subsequent influence on sediment transport. Subsequent dissertation chapters will examine correlations between foredune dynamics and morphologies and the results from this chapter.

4.2 Gulf County Wave Height Observations

4.2.1 Historical Data

Gorsline (1966) found average wave heights to be approximately 0.30 m between Indian Pass and Pensacola Florida. Offshore mean significant wave heights (recorded at USACE WIS Station 37 from 1975 – 1997) were recorded at 19 m depth offshore of St. Joseph Peninsula and listed as .6 m (Foster and Cheng, 2001). The area was described by Tanner (1960) and Kwon

(1969) as being a moderate energy coast with dominant easterly (and northerly along the peninsula) longshore currents. However, following Short and Hesp (1982) the Gulf County coast should be considered low energy (<1m).

4.2.2 Visual Observations

In testing models of surfzone-beach-foredune development and interactions, examining the wave height is an essential part of the model. Despite the entire area having average low wave heights, there is variability in wave heights along the Gulf County shores. To examine the variability of wave height and energy along this portion of coast, and test the Short and Hesp (1988) model and potentially propose an adaptation or a new model of foredune development for Gulf County, an understanding of the wave height variability is required.

The first step was to identify wave heights on each survey trip through visual observations. While the survey trips occurred in a regular (~ 6weeks) pattern, they did occur at random timings through all seasons, and the trip observations provide a good estimate of wave heights under different conditions and times for the study region.

In correlation with Gorsline's (1966) report of wave heights being less than 0.30 m, the average of all visual wave heights at all sites during the 2007-2009 study season was 0.30 m (Figure 4.1). The lowest wave heights were consistently recorded at the northern tip of St. Joseph Peninsula, with averages observed to be less than 15cm on the highly reflective spit tip. Wave heights increased from the spit tip toward the southern end of the peninsula, where an increase in wave heights was accompanied by a more intermediate beach state, exhibiting cusps and rhythmic bar forms. Where these cusps formed, there was a definite decrease in beach width, and thus a decrease in sediment available to be transported into the back beach and foredune system. The appearance of these cusps continued around the cape and along the east-west (sites R122-R-155) arm of the County's shorelines. However the cape itself rarely exhibited these cusp forms, but rather constantly displayed a decrease in beach width as the shoreline eroded throughout the study period.

4.2.3 Field Measurements

The visual observations corresponded well with the measured pressure transducer wave heights recorded in May 2009. The average of the pressure transducer measurements can be seen in Figure 4.1, with the average of all pressure transducer measurements being 0.24 m. The pressure transducer measurements were recorded over a 6-day period of relatively low wave heights in the region, and hence the possible lower value of average wave heights compared to the visual observations conducted throughout the year.

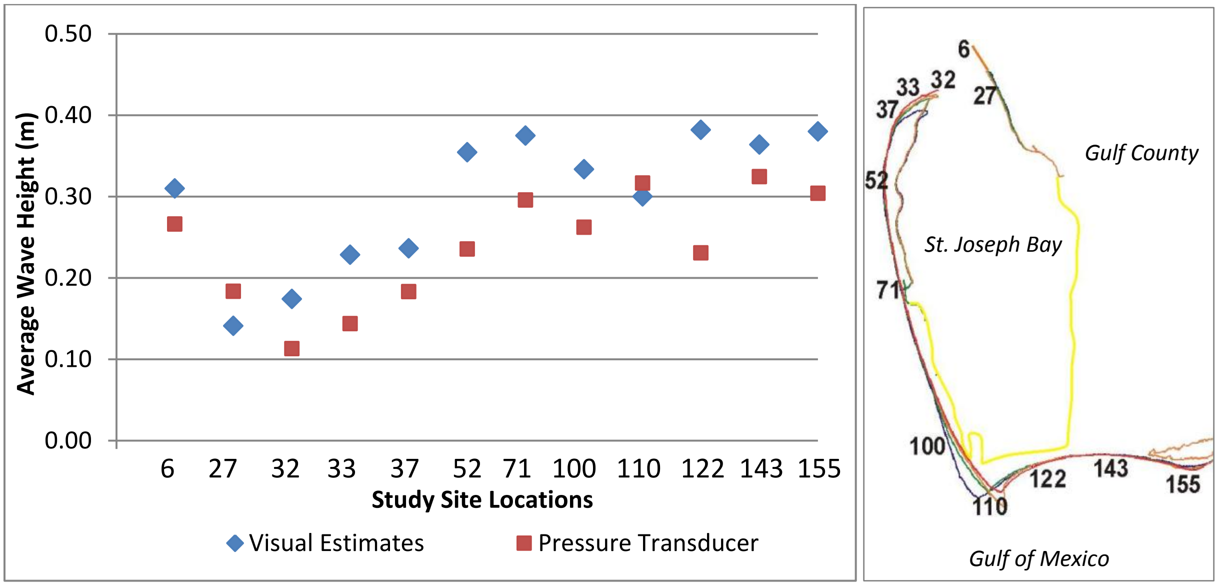


Figure 4.1 – Wave height averages for profile locations in Gulf County, Florida. The average for the visual estimates observed throughout the calendar year was 0.30 m, and the pressure transducer average wave height was 0.24 m for the study region. Profile locations refer to FDEP Range Monument Locations and are shown on the outline image to the right. The outline image displays retreating shorelines at the southern Cape, and the progradation of the spit tip.

4.3 MIKE-21 Model Development

The MIKE-21 spectral wave model, developed by the Danish Hydraulic Institute, was employed in this study as it has been applied successfully for Gulf of Mexico off shore wave simulations and in more detailed studies in the Gulf (Jose and Stone, 2006; Jose et al., 2007). The bathymetry for MIKE-21 was created using approximately 30 m (3-second arc length) spaced bathymetry for the offshore zone (Figure 4.2), and was replaced with NOAA acquired LiDAR 0.20 m horizontal spacing data for the nearshore zone, as described in the methodology section (Figure 4.2). To balance computer processing time with heightened detail, an unstructured mesh was created with three different levels of interpolation spacing; the nearshore

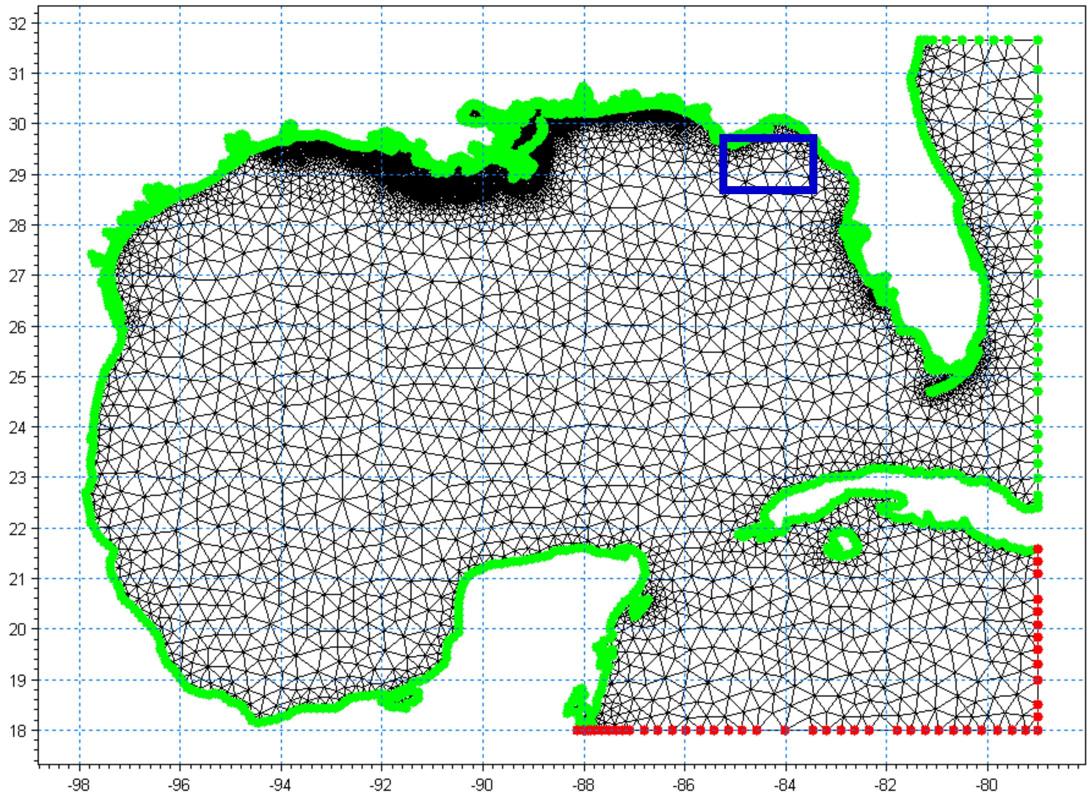


Figure 4.2 - Gulf of Mexico grid for developing bathymetry and calculating offshore wave parameters. The blue inset box highlights the study area used for nearshore wave parameter calculations.

zone, a middle zone, and the deeper water and eastern section of the interior zone were 5 m, 50 m, and 500 m respectively (Figure 4.3). The bathymetry for the nearshore modeling was then created based on the generated grid from the raw data within MIKE-21 (Figure 4.4).

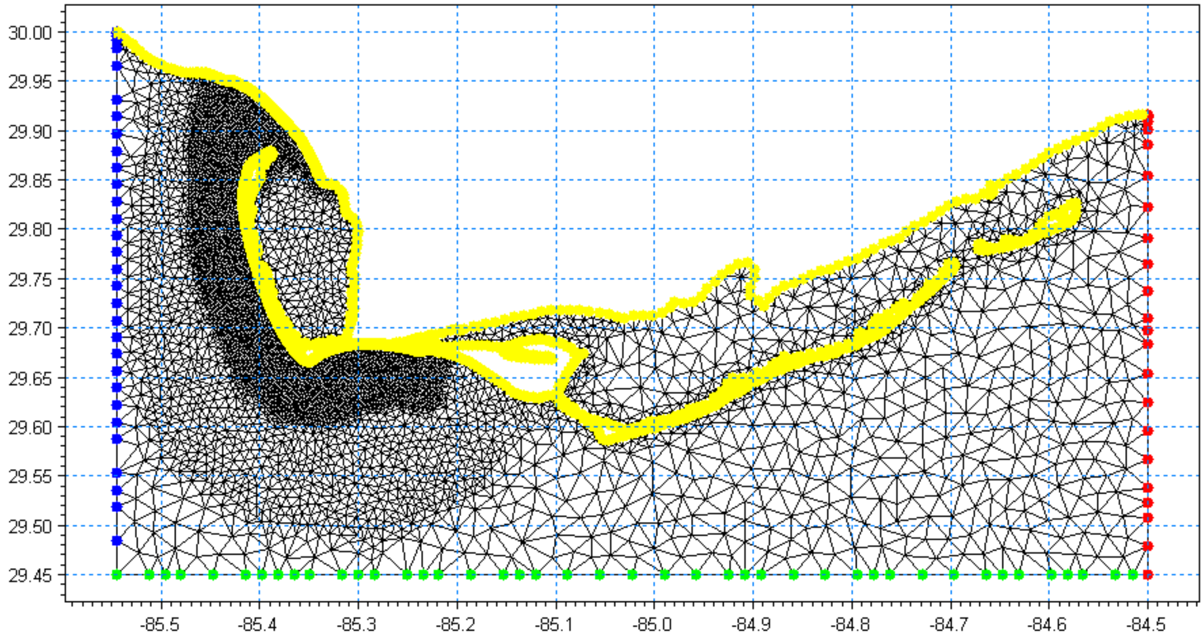


Figure 4.3 - MIKE-21 detailed mesh for developing local bathymetry from NGDC 3-second bathymetry and LiDAR data. Closer grid spacing was used in the nearshore portion of the study area. Offshore grid locations (indicated by colour coded dots) were used as landmarks for calculating wave parameters into the nearshore zone from the greater Gulf of Mexico parameters.

To utilize modeled results, it was first necessary to validate MIKE-21's competency to obtain adequate results; this was accomplished by applying the model and comparing its results to the known wave heights from the Gulf County offshore region. The first step for validating the output was to run the NCEP (National Centers for Environmental Prediction) NARR (North American Regional Reanalysis) wind generated file in MATLAB to simulate the offshore wave conditions to check if the model's simulations adequately reproduced the actual recorded wave heights. A period in January 2008, which included the passing of three winter cold fronts, was chosen to compare a period of large to very small waves from multiple directions. The modeled

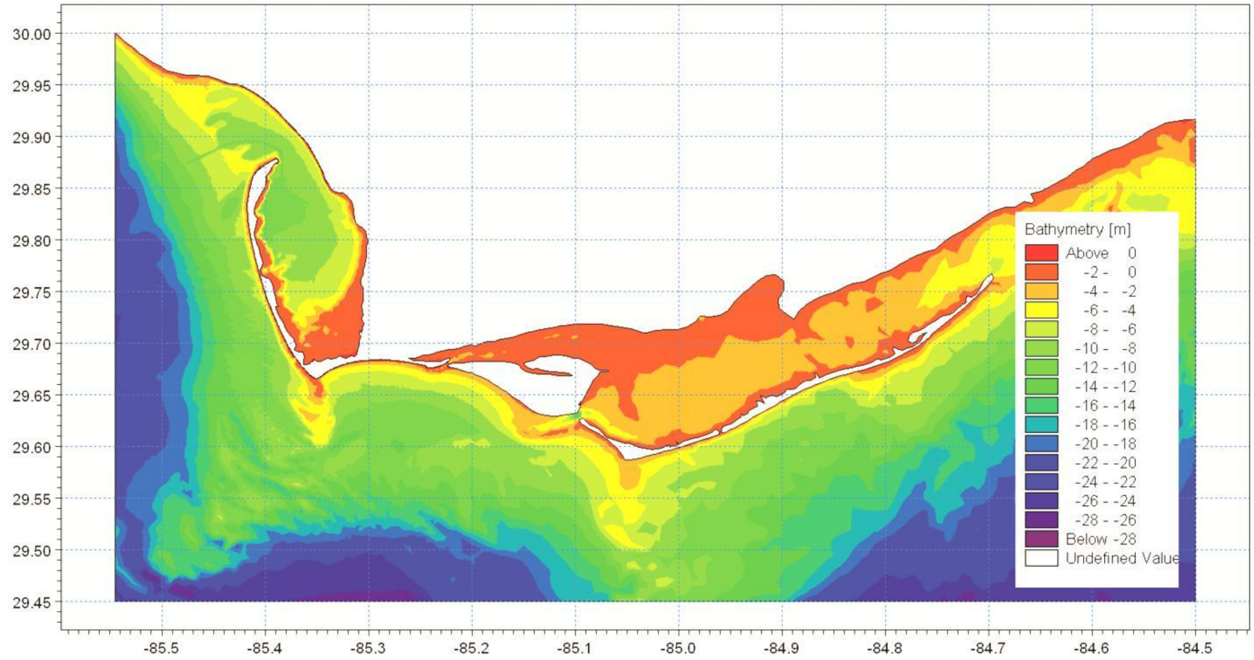


Figure 4.4 – Nearshore resultant bathymetry created in MIKE-21 for wave modeling. Note the large shoal extension stemming south from Cape San Blas.

waves were compared to the six offshore NDBC buoys, including the two closest buoys (NDBC buoys 42036, 42039), which recorded significant wave heights and wave periods (Figure 4.5).

Comparative plots (Figure 4.6, 4.7) display the relationship of the wave measurements generated by MIKE-21 from the NCEP-NARR wind field for the Gulf of Mexico, versus the actual waves recorded at the NDBC buoys. The significant wave heights developed by the model adequately traced the same peak periods for the wave heights recorded by the NDBC buoys. The regression coefficients for wave heights for each station are listed in Table 4.1. As shown in figure 4.6, the wave heights for NDBC buoy 42039 showed an 83% prediction in significant wave height for the largest waves. This was taken into consideration as a potential cause for an under-prediction of wave heights in the nearshore zone. However, the greatest

Figure 4.5 –NDBC Buoy locations for comparing actual wave parameters with MIKE-21 calculated wave parameters.   Image source: Modified from NOAA NDBC website (2010).

under-prediction occurred during a period of waves moving west across the Gulf, which has minimal impact on the predominantly south and westerly-facing shorelines. In addition, NDBC buoy 42039, which is located east of the study site where these storm waves arrive from, did not under-predict these waves. The regression coefficients were calculated for all MIKE-21 developed wave heights versus recorded NDBC buoy recorded wave heights for each seasonal wave sampling (Table 4.1). Wave periods and direction results were comparable to the accuracy of the wave height results.

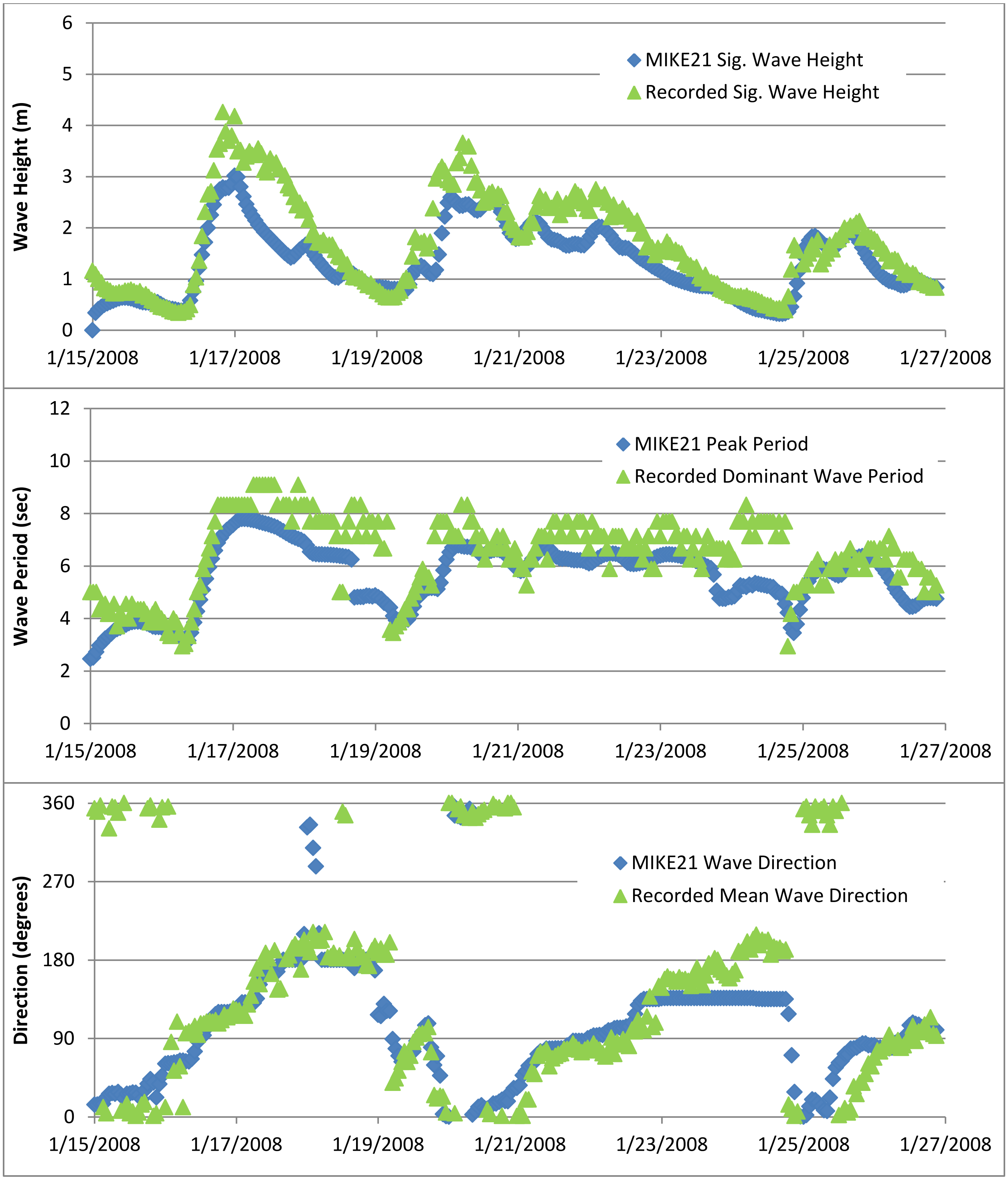


Figure 4.6 – Comparison of MIKE-21 wave parameters with in situ recorded wave parameters at NDBC buoy 42039, located 114 kms offshore in a water depth of 274 m. MIKE-21 under-predicted wave heights (~20%) at this location. The other Gulf locations, however, showed more accurate simulations of waves. This may be due in part to the exact location of the buoy relative to the passing of the first and second cold front.

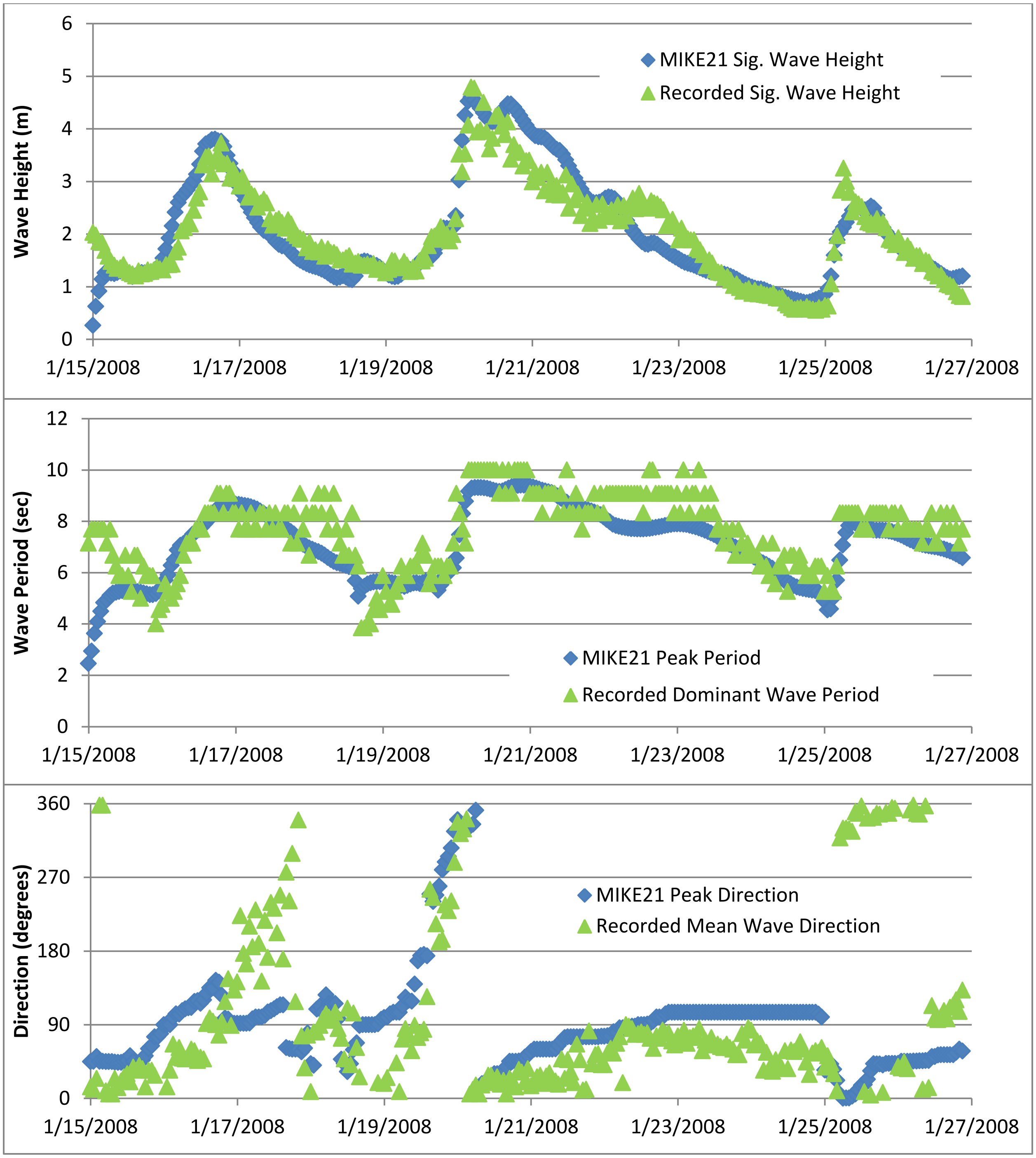


Figure 4.7 – Comparison of MIKE-21 wave parameters with in situ recorded wave parameters at NDBC buoy 42036, located 129 kms offshore in a water depth of 54 m. The MIKE-21 simulated waves correspond well with the actual parameters recorded at the buoy.

Table 4.1 – Regression coefficients for comparison of wave heights recorded at NDBC buoys 42001, 42003, 42036, 42039 and 42099, and MIKE-21 model simulations wave heights, for these locations. NDBC buoys 42036 and 42039 were the closest to study sites in Gulf County, Florida. Regression coefficients were much lower during the summer period relative to the very low wave height (< 0.50 m) simulations.

	42001	**42003**	**42036**	**42039**	**42099**
Spring 2007	0.81	0.80	0.84	0.86	0.79
Summer 2008	0.56	0.70	0.56	0.69	0.60
Winter 2008	0.87	0.77	0.85	0.85	0.79
Fall 2008	0.70	no data	0.78	0.72	0.80

The second method of validating MIKE-21's predictive capabilities was to skill assess the ability of the model to accurately predict wave parameters in the nearshore zone. The MIKE-21 simulation from summer 2008 was performed to correspond to a period in which wave heights were measured along topographic profile locations in the nearshore zone using *in situ* pressure transducer measurements (Figures 4.8 and 4.9). A summary of the wave heights for the

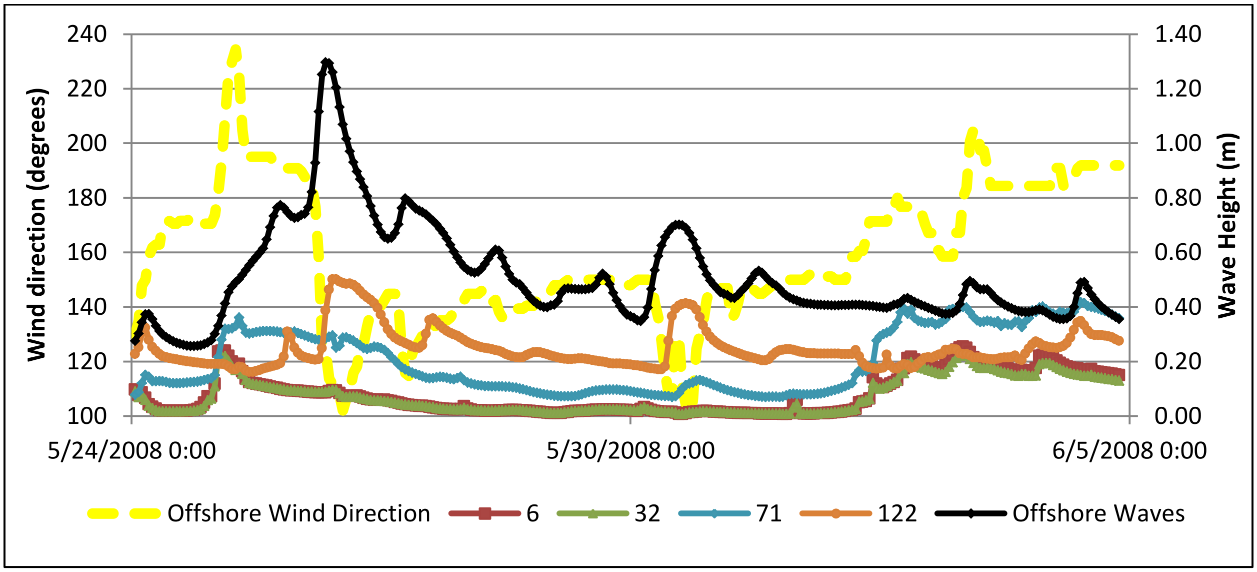


Figure 4.8 – Comparison of MIKE-21 modeled wave heights for 4 different profile locations as compared to offshore wave height (black) and wind direction (yellow). Pressure transducer measurements began May 31, 2008, during very calm offshore southeast winds and waves that progressively switched to the south-southwest with a change in wind direction.

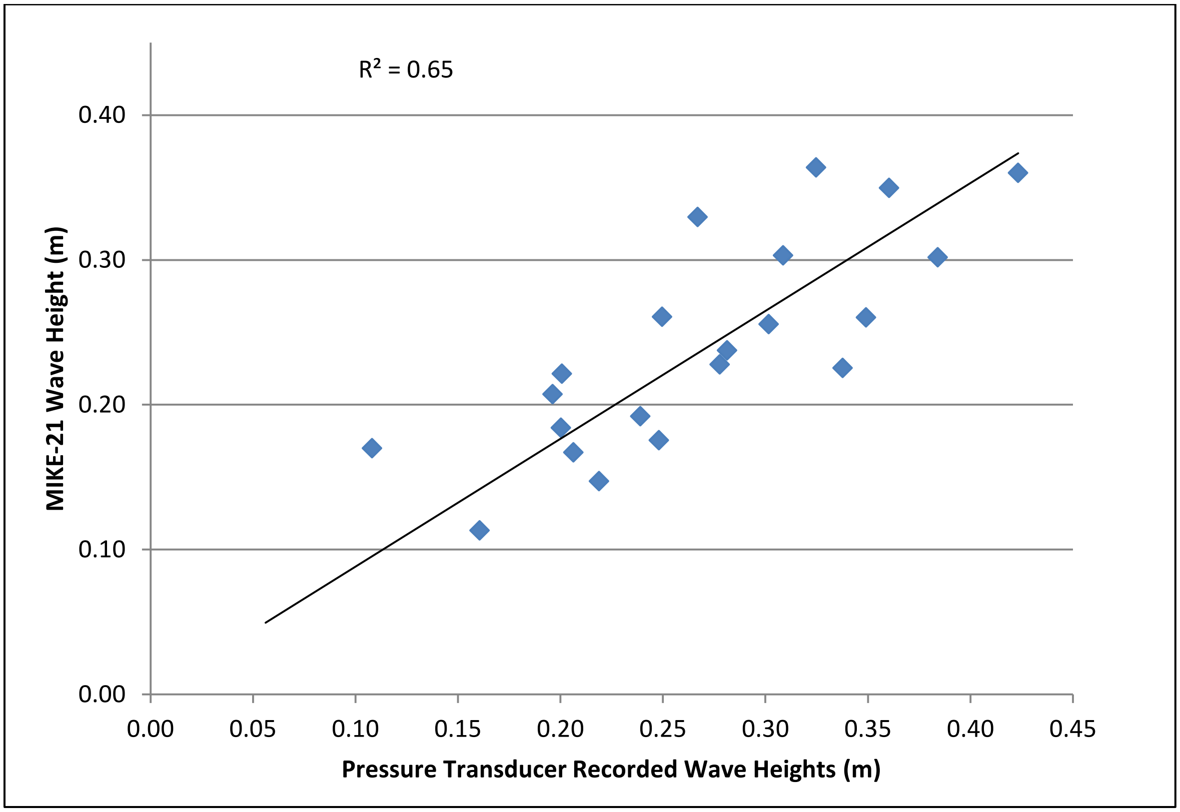


Figure 4.9 – Comparison of pressure transducer wave height measurements with MIKE-21 simulated wave measurements, excluding extremely calm conditions (wave height less than 0.10 m).

nearshore zone, the results of the variability between average wave heights recorded at the sites, and the model simulation for each of the times and locations are presented in figures 4.8 and 4.9.

Initial assessment showed that there was a high degree of variability between the MIKE-21 wave heights and pressure transducer recorded wave heights ($R^2 = 0.27$). However, when wave heights below 0.10 m are eliminated, a stronger relationship ($R^2 = 0.65$) exists between MIKE-21 and the pressure transducer recorded wave heights. Computer simulated wave heights underestimated the wave height by approximately 10% during this low wave energy study period. However, there is considerable agreement between the recorded wave heights and the wave height trends in the study area. Thus, use of the MIKE-21 software is appropriate for estimating nearshore wave heights in Gulf County, Florida.

4.4 Regional Wave Variability

The following section examines results from the MIKE-21 analysis for annual and four seasonal time periods. The reason for examining this was three-fold: 1) to determine if the modeled results within each season were valid, as differing wind regimes may affect the output wave heights, and 2) to gain a better understanding of the wave energy affecting the shores at each study location, and 3) to further examine the amount of sediment moving through each location and to estimate the amount of sediment available for transport to the backbeach and foredune. For evaluation purposes, periods of higher wave energy at offshore NDBC buoys 42036 and 42039 were utilized to capture the time periods with the greatest wave height variability to best assess the model's simulations of offshore wave conditions. For each time period, the waves were modeled into the nearshore zone to gain an idea of wave energy variability for the Gulf County coast. The goal of examining these data was to support the documented low energy conditions of Gulf County (Tanner, 1960; Gorsline, 1966; Kwon, 1969; Foster and Cheng, 2001) and the visually observed wave heights, including simulation of wave heights during frontal storm conditions. Figure 4.10 displays the average of visually observed wave heights from 13 different trips to the study region at varying times during the year, pressure transducer recorded wave heights at 1m water depth, and average significant wave heights estimated by MIKE-21 simulations at 1.5 m water depth. For each location and season, average wave heights are below 0.42 m, which equates well with the Gulf County average wave height of 0.30 m (Gorsline, 1966; Foster and Cheng, 2001).

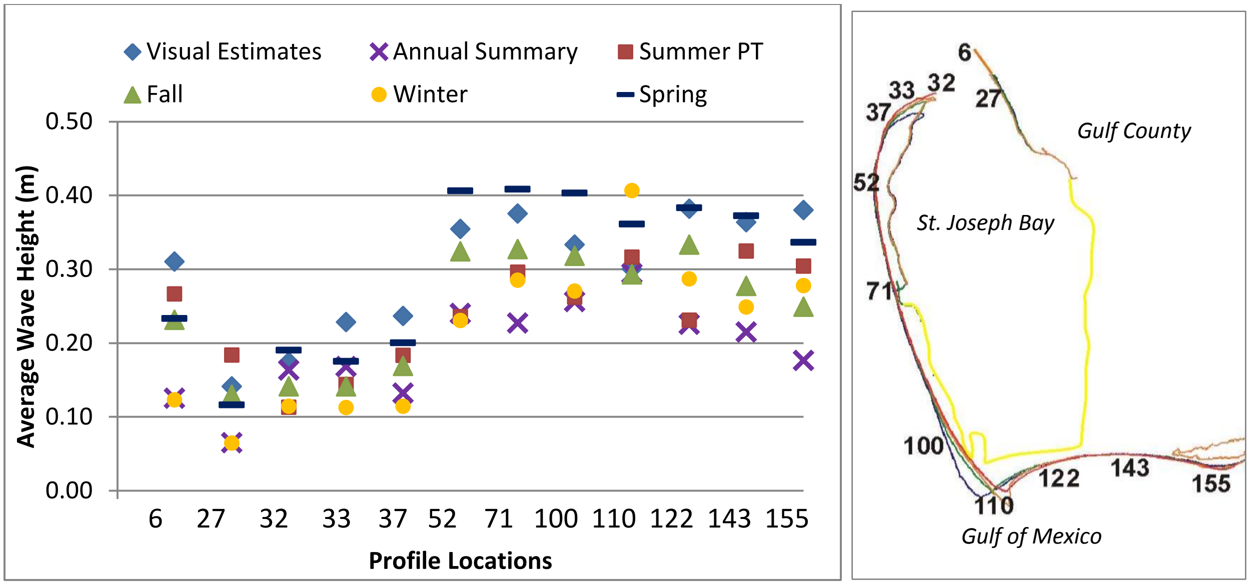


Figure 4.10 - Average Wave Heights for each profile location in Gulf County. Profile locations refer to FDEP Range Monument Locations and are shown on the outline image to the right. The outline image displays retreating shorelines at the southern cape and the progradation of the spit tip.

4.4.1 Wave Height Variability by Location

On the northern portion of the Gulf County mainland, wave heights on FDEP profile 6 are much higher than the wave heights just south on the mainland at profile 27. This can be directly attributable to profile 27’s sheltered location behind St. Joseph Peninsula, within St. Joseph Bay. Murali (1973) showed that before the peninsula had grown to its current length, higher wave energy reached this portion of the shoreline, and at this time a series of beach ridges were built. However, evidence from topographic profiles indicates three new ridges have been built at this location since 1973, despite being sheltered from the spit. Additionally, there is still enough wave energy to bring sediment south from the more open coast and into the Bay as the shore has been prograding 1.22 m/a (Foster and Cheng, 2001). The possible origin of these new ridges will be further discussed in a subsequent chapter.

Similar to the coastline in the bay, the tip of St. Joseph Peninsula has very low wave heights and reflective beach conditions when compared to the rest of the Gulf County coastline. Offshore Winds are dominated by easterly flow for this region as recorded at NDBC wave buoy 42039 and Tyndall tower SGOF1 (figure 4.11). The easterly winds reduce the fetch length and time for local wind generated waves to impact the east-facing sections of shoreline (profiles 6 and 27) and the north-facing coastline of the spit tip.

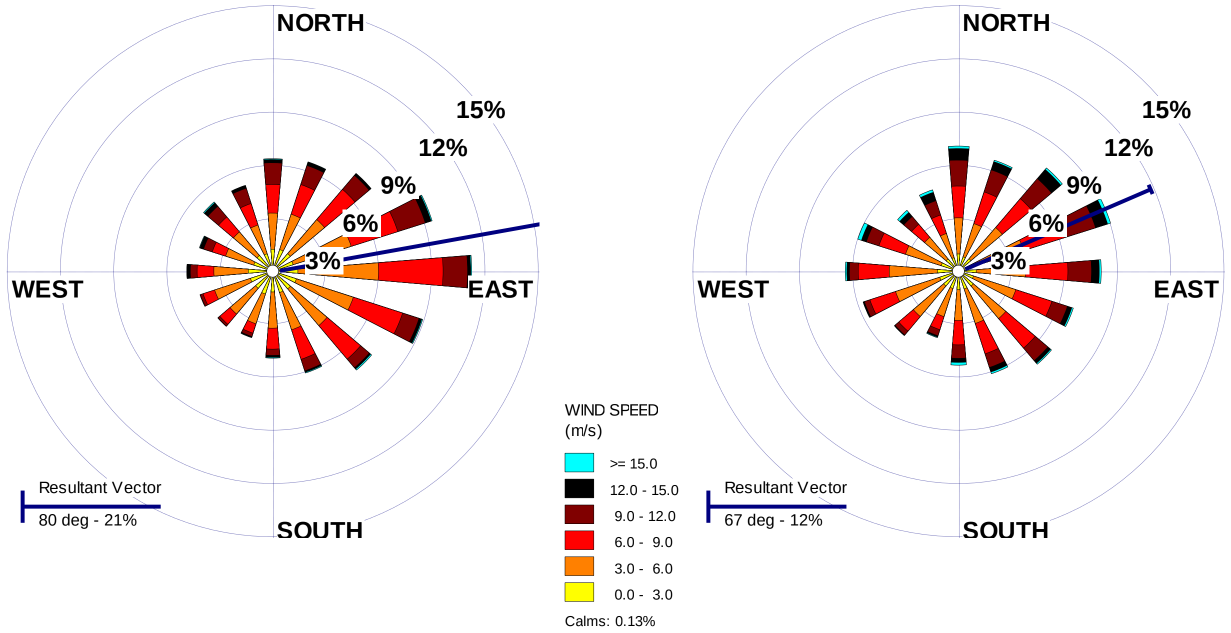


Figure 4.11 – 2003-2007 winds for NDBC wave buoy 42039 (left wind rose) and nearby NDBC tower SGOF1 (right wind rose). Wind roses created using WRPLOT.

Easterly and southeasterly waves dominate this part of the Gulf of Mexico as reported from SSMO (Summary for Synoptic Observations) for Apalachicola, located just east of Gulf County (Mossa, 1984). Mossa (1984) found SSMO data sources to be the best for most applications of wave data. Analysis of 2003-2007 wave components for offshore buoy 42039

Table 4.2 – Dominant offshore wave components for NDBC buoy 42039 during the years 2003-2007. Average wave components were separated by direction (8 cardinal directions), dominant wave period (3 second intervals), and wave heights (1.0 m intervals). This study used the first 65 components, which included 99.0% of all waves recorded during the study time frame. Any subsequent component occurred less than 0.06% of the time, or approximately 5 hours per year.

COMPONENT	DIRECTION	DOMINANT PERIOD	WAVE HEIGHT	FREQUENCY (%)
1	S	7.5	0.5	10.11%
2	SE	4.5	0.5	7.81%
3	S	4.5	0.5	7.61%
4	E	4.5	0.5	7.37%
5	S	7.5	1.5	4.99%
6	W	4.5	0.5	4.80%
7	SW	4.5	0.5	4.51%
8	NW	4.5	0.5	3.98%
9	SE	4.5	1.5	3.34%
10	E	4.5	1.5	3.30%
11	N	4.5	0.5	3.23%
12	NE	4.5	1.5	3.06%
13	SE	7.5	1.5	2.72%
14	E	7.5	1.5	2.36%
15	SW	7.5	0.5	2.26%
16	N	4.5	1.5	2.19%
17	S	4.5	1.5	2.15%
18	S	10.5	0.5	1.93%
19	NW	4.5	1.5	1.91%
20	NE	4.5	1.5	1.59%
21	E	7.5	2.5	1.57%
22	W	4.5	1.5	1.44%
23	SW	7.5	1.5	1.39%
24	W	7.5	1.5	1.07%
25	S	7.5	2.5	0.99%

showed that the five most dominant directions for waves ranged from the east to south as well (Table 4.2), and over 60% of waves were from the east, southeast and south for this study period. Table 4.2 displays the 25 most dominant components based on wave direction (8 cardinal directions), wave height (average within 1 meter intervals), and dominant wave period (average within 3 second intervals).

Profiles 33 and 37, located southwest of the tip, have north-northeast facing shores and also have very low wave heights compared to the spit tip profile 32, which faces due north. Waves at these locations are strongly refracted by all waves coming from the east through southwest (figure 4.12). Refraction is also noted when due west waves bend around the spit fulcrum, (or the change in shoreline orientation from north-south to southwest-northeast, and west-east.) These extremely low energy waves are causing very little erosion to the beach. Furthermore, as will be noted in a subsequent section, there is a large amount of sediment moving northward into this region, and therefore there is a high rate of deposition in this area. This deposition of sediment is continually increasing the beach width, thus creating a larger amount of beach sand available for transport to the foredune or embryo dunes.

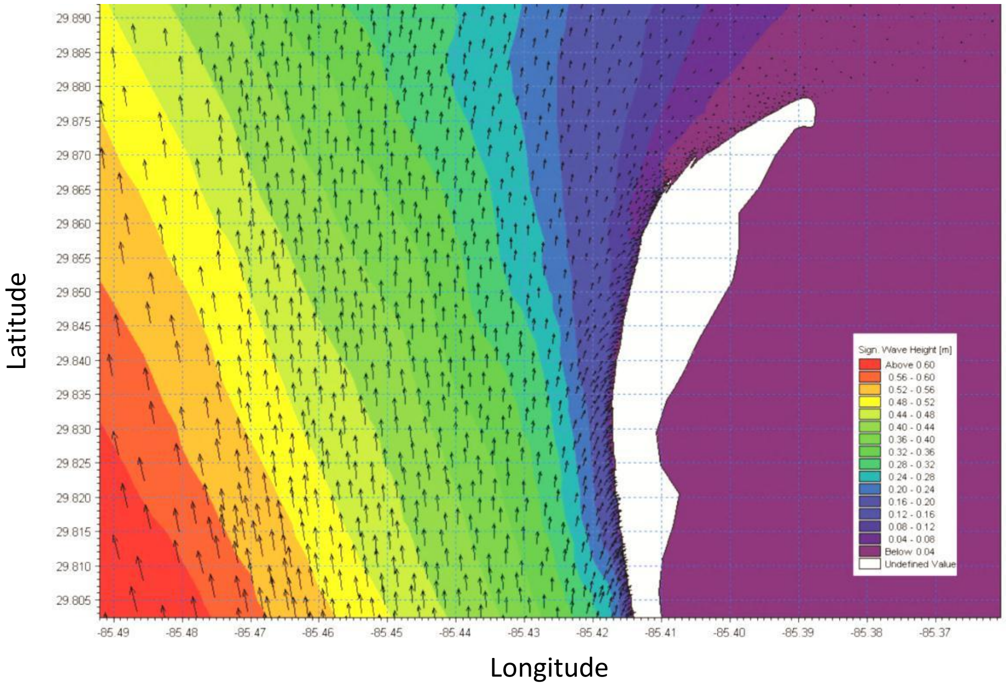


Figure 4.12 – MIKE-21 output presenting offshore southeast waves refracted around the spit tip, and a subsequent decrease in wave energy. Wave heights range from less than 0.06 m (purple) to greater than 0.60 m (red). Arrows indicate wave direction, and the arrow length is relative to the wave height. Note the extremely low waves (blue) in the nearshore zone around the northeast bend in the spit.

FDEP profile sites 52, 71, and 100 all have predominantly western-facing shorelines and higher wave energy approaching the shoreline as observed in MIKE-21 simulations, pressure transducer measurements, and visual observations when compared to the spit tip. This is attributable to the decreased amount of refraction of easterly through southwesterly wave approaches. Direct westerly waves have the highest energy reaching this stretch of shore due to minimal refraction. As a result, this stretch of the shore has increased erosion rates, which decreases the total beach sediment available for aeolian transport. Additionally, in contrast to the prograding spit tip, these locations all have eroding shorelines. The southernmost point on the Cape, profile 110, has the highest wave heights recorded and the highest rate of erosion (9.1 m/a) in Gulf County over the past 35 years. This can be attributed to a strong increase in energy reaching this headland feature as waves refract around the San Blas shoal (Stauble and Warnke, 1974; Foster, 1997) (Figure 4.13). There is a strong relationship ($R^2 = 0.97$) between the wave energy and shoreline loss for the eroding portion of the Gulf County coast (Figure 4.14). This indicates that where eroding coasts are occurring in Gulf County, the rate of erosion is directly related to the increasing wave heights for each location. Therefore, the higher wave height leads to a more elevated erosion rate, which in turn decreases the beach width, ultimately resulting in less sediment being available for transport to the back beach and foredunes.

Profile sites 122, 143 and 155 all have larger wave heights than the north and west-facing shoreline locations. Site 122, oriented to the south-southeast, has a tendency to have slightly larger waves than south-facing site 143, and even slightly larger waves than the south-southwest facing site 155. Whilst offshore waves predominantly come from the east, southeast and east (over 60% of waves during the 2003-2007 period), it is not surprising to find the largest waves

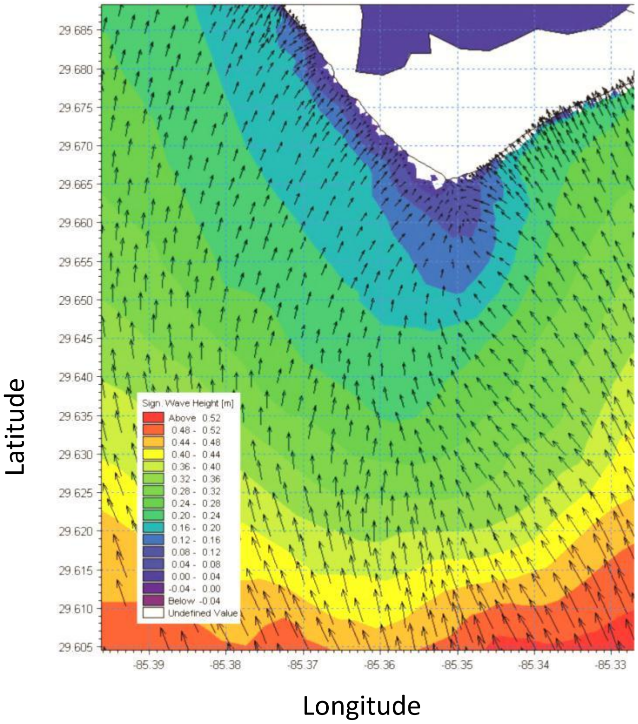


Figure 4.13 – MIKE-21 output presenting offshore south waves refracting around the Cape San Blas Shoal. Wave heights range from less than 0.50 m (red) to greater than 0.10 m (blue). Arrows indicate wave direction, and their length is relative to the wave height.

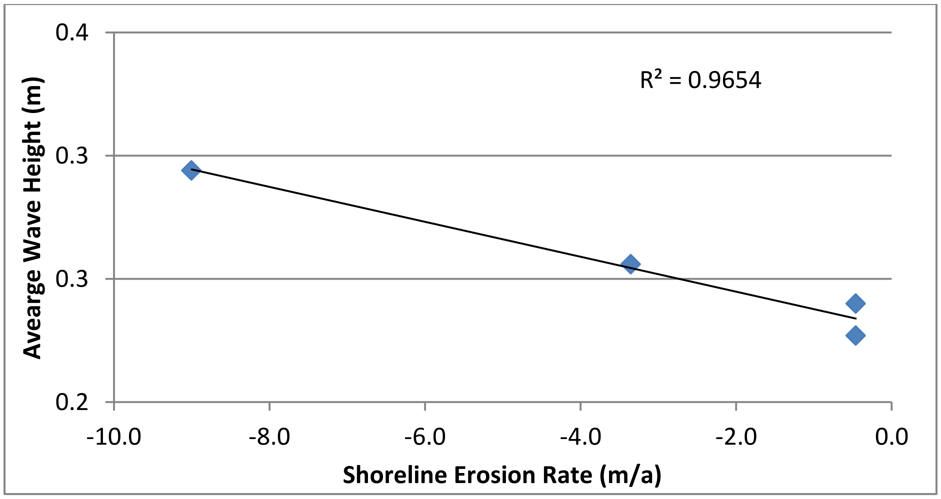


Figure 4.14 – Relationship between average wave height and erosion rate for the eroding portion of Gulf County coastline profiled herein.

on the south-facing shoreline. Figure 4.15 displays a MIKE-21 output for waves coming from the southeast. The highest wave heights (~0.30 m) can be seen reaching this south-facing shoreline. Strong refraction occurs around the Cape San Blas offshore shoal, which refracts wave energy into the Cape. Much smaller waves impact St. Joseph Peninsula as the energy decreases after refracting around the Cape. Under these easterly and southeasterly wave conditions, the wave energy at the spit tip is minimal. The same low energy conditions occur at the mainland profile sites, especially profile 27, located just within St. Joseph Bay. This was visually observed during several trips to Gulf County.

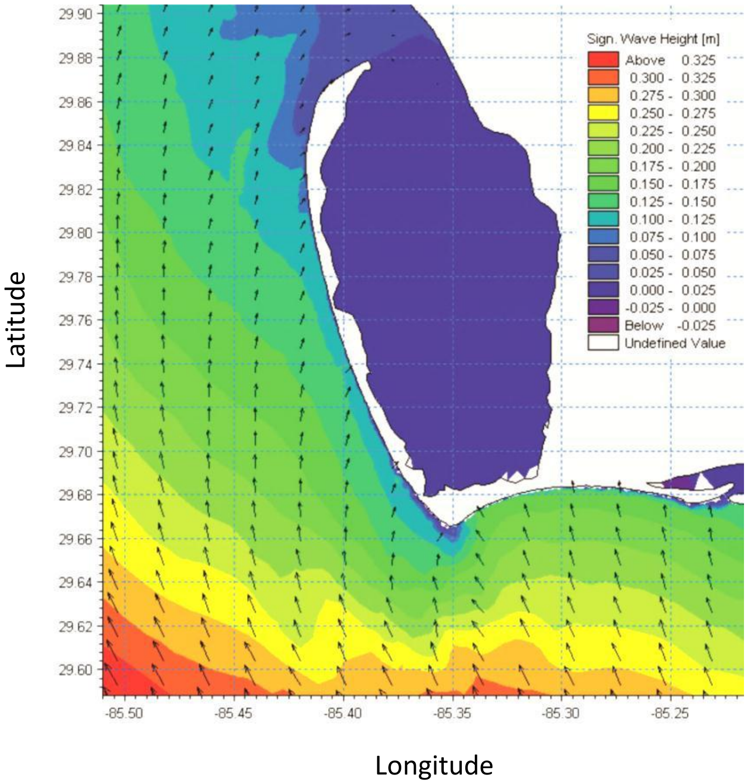


Figure 4.15 – MIKE-21 output displaying southeasterly offshore waves with wave heights of less than 1 meter and a wave period of 4.5 seconds. This wave component was the second most frequent, and the refraction patterns are a good representation of the dominant waves coming from the east, southeast, and south. Wave heights range from less than 0.10 m (blues) to greater than 0.30 m (red). Arrows indicate wave direction, and the arrow length is relative to the wave height.

4.4.2 Wave Height Variability by Season

Seasonal wave variability was compared using the MIKE-21 data computed from two-week periods of representative wind and wave data. The average wave heights at each of the topographic profile locations are displayed in figure 4.16 and show the variability between each site and the seasonal change in wave heights. The lowest wave heights at all locations occur during the summer season, averaging only 0.16 m. During the fall, wave energy increases due to an increase in stronger easterly and southerly waves. Additionally, passing fronts increase the wave energy of westerly waves. This is due to winds coming from the northwest through northeast during the passing of cold fronts in winter months (Kobashi et al., 2005). In the winter, wave energy tends to decrease slightly compared to the fall months. The average wave height in winter is 0.21 m, whereas in the fall the average wave height is 0.24 m. It is assumed that wave

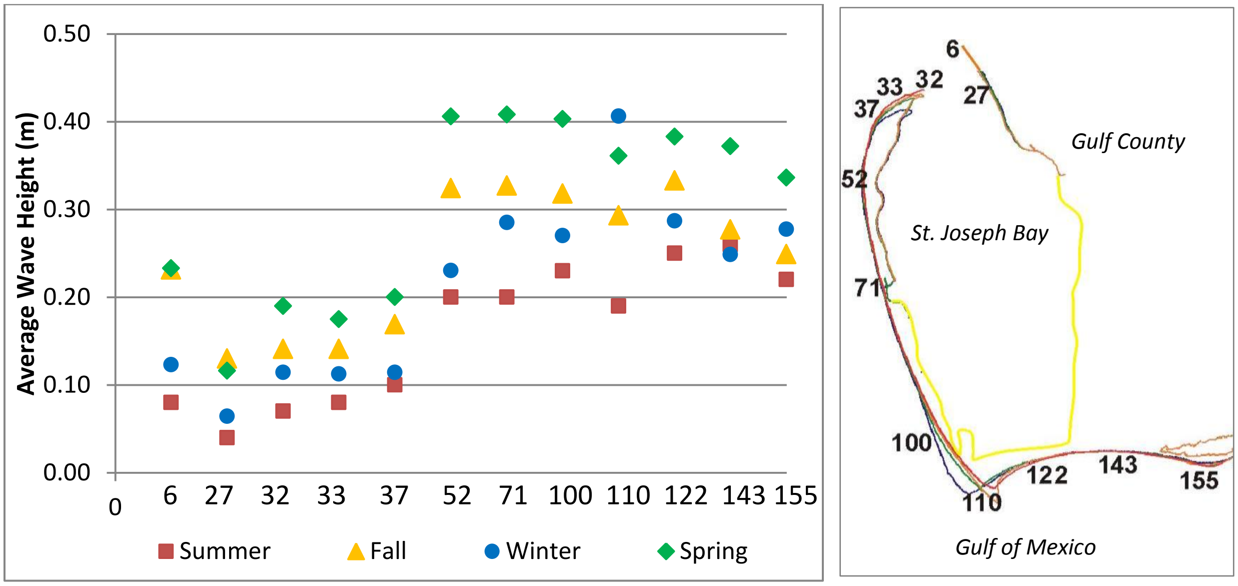


Figure 4.16 – MIKE-21 average wave weights at each profile location in Gulf County from sampled seasonal data. Profile locations refer to FDEP Range Monument Locations and are shown on the outline image to the right. The outline image displays retreating shorelines at the southern Cape and the progradation of the spit tip.

heights are not as high from these northerly approaches due to the limited fetch and the offshore winds reducing the swell wave energy reaching the nearshore.

The highest waves occur during the passing of frontal storms in the spring months, yet during this time the average wave height is only 0.30 m for all profile locations. The increased frequency of westerly winds and waves increase the energy on the west-facing shores, with waves averaging over 0.40 m at profiles 52, 71, and 100. The westerly waves associated with frontal systems produce the highest waves in all seasons except summer. In contrast, the winds and waves are dominated by east and southeast flow in the summer months. Hence, the highest waves during the summer are found on south-facing shores at profiles 122, 143, and 155. The lower waves along the west-facing coastline occur due to greater refraction around the cape from the southerly and easterly waves.

One reversal of these trends occurs at Cape San Blas, at profile 110. The summer waves are lower than adjacent sites 122 to the east and 100 to the north. This may be a result of the already low wave energy being dissipated as the wave travels across the large San Blas Shoal. In contrast, during winter months wave energy peaks at the cape. This is likely a result of the offshore shoal being located predominantly to the east of the profile location despite its trend southwest into the Gulf of Mexico (Stauble and Warnke, 1991). The north and northwest winter waves do not have to travel as far across the shoal before reaching profile 110. Therefore, higher wave energy may reach profile location 110. MIKE-21 computed wave heights corroborate the visually observed heights and confirm the high wave energy reaching this location on the Cape during strong storms.

4.5 Longshore Sediment Transport

It is clear from imagery of the St Joseph Peninsula region that as one approaches the western and northern terminus of the spit there is considerable nearshore transport taking place. Figure 4.17 clearly shows marked parabolic or curved bedforms in the outer shoreface, and long linear bars, or longshore sand waves as termed by Saunderson and Davidson-Arnott (1990), in the inner shoreface area indicating pronounced longshore transport.

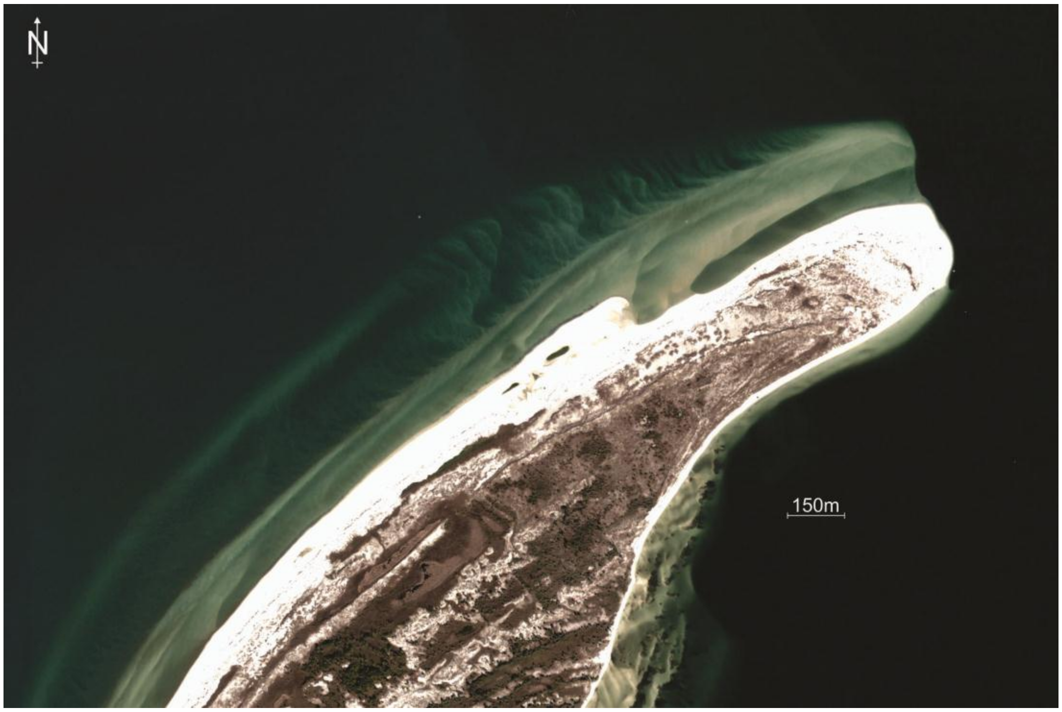


Figure 4.17 – Aerial photo of St. Joseph Peninsula Spit Tip, January 21, 2004 (Image Source: Google Earth). Sediment is being transported north along the peninsula, and northeast around the recurved spit tip.

To better understand the recent geomorphological changes in the nearshore zone, longshore sediment transport was calculated using the MIKE-21 nearshore data. Sediment transport was calculated using the CERC equation:

$$\boldsymbol{Q_{lst} = \frac{pK\sqrt{g/\gamma_b}}{16(\rho_s - \rho)(1-a)} H_{s,b}^{2.5} \sin(2\theta_b)} \tag{1}$$

Where Q_{1st} is the longshore transport rate in volume per unit time, K is an empirical coefficient, ρ is the density of water, ρ_s is the density of sand, g is the acceleration due to gravity, a is the porosity index (0.4), $H_{s,b}$ is the significant wave height at breaking, γ_b is the breaker index ($=H_b/h_b$), and θ_b is the wave angle at breaking (USACE, 1984). The CERC (USACE, 1984) formula has been widely used despite there being many concerns regarding its accuracy. For the purpose of this study, the general trends of sediment transport are more important than the precise volume of sediment transported. Additionally, estimating the wave height and water depths at breaking at multiple locations for over 65 different offshore wave parameters was beyond the scope of this project and cannot be done with total accuracy using the methodology presented. However, it will be shown in a later section that this formula performed well for estimating sediment transport at the peninsular tip. The one adjustment from the original CERC (USACE, 1984) formula was the use of the empirical coefficient K=0.39. Schoonees and Theron (1993, 1996; Bayram et al., 2007) compiled data from empirical field studies and found the value K= 0.20 to be more accurate, which was therefore used for this study.

4.5.1 Annual Longshore Sediment Transport

The annual sediment transport was calculated using the 65 most dominant offshore wave parameters based on direction, period and height (Table 4.2). These 65 components comprised 99.0% of all of offshore waves recorded at NDBC buoy 42039 from 2003 to 2007. The calculated longshore sediment transport is displayed in figure 4.18. Along the northernmost stretch of the county's mainland shoreline, sediment is moving south into St. Joseph Bay. This can be observed in recent profile data that show a measured progradation of the beach in the northernmost part of St. Joseph Bay at a rate of 1.07 m/a and 1.22 m/a at profile locations 6 and 27, respectively (Foster and Cheng, 2001).

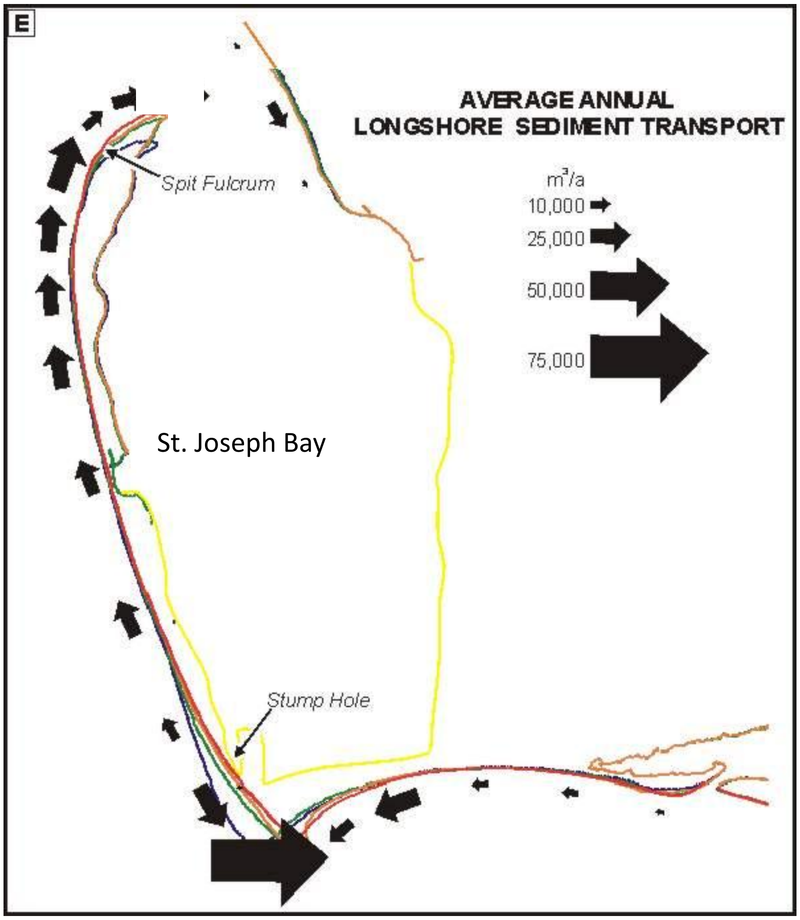


Figure 4.18 – Longshore Sediment Transport calculated using CERC (USACE, 1984) equation with MIKE-21 simulated wave data. Shoreline data dating to the 1870s (Morton et al., 2004) show the elongation of the peninsular tip and the erosion of Cape San Blas in the south.

Annual sediment transport on the peninsula is dominated by longshore currents driving sediment to the north (Figure 4.18). At the spit fulcrum, there is a decrease in sediment transport directly related to the higher degree of wave refraction, marked changes in wave approach angle, and decreased energy north of this point. The decrease in sediment transport rates at this northern extent allow for sediment accumulation at the spit tip.

A diversion of sediment transport paths exists close to Stump Hole near the southern end of the peninsula, a division that was thought to occur at the Cape itself (Tanner, 1974). South of

Stump Hole, where a directional switch from north to south occurs, sediment is feeding Cape San Blas and the San Blas Shoal. Since the Cape has been eroding over the past half century, according to Stapor (1971), there is a great amount of sediment moving offshore at this headland point, as opposed to migrating east. Stapor (1971) estimated that 17 x 10^6 m^3 of sand had been eroded over a 60-plus-year period just north of Cape San Blas, and most of this sediment was deposited on the San Blas Shoal. Stauble and Warnke (1974) estimated that the shoal sands were moving eastward, which would be in sync with the strong eastward currents. Sediment that is moving west along the east-west stretch of the Gulf County coast is nourishing the accreting beach and sandy ridges. The sediment transport path continues along the southernmost stretch of Gulf County coast directly to Cape San Blas.

4.5.2 Longshore Sediment Transport Supporting Data

A partial validation of the sediment transport was conducted by estimating the total sediment deposition at the distal end of St. Joseph peninsula in comparison to the longshore sediment transport rate at the spit tip, which was estimated to be 27,000 m^3/a. Air photos from 2004 and 2007 (figure 4.19) were compared to coarsely estimate the amount of sediment carried by longshore processes and deposited above mean sea level by wave processes. The spit tip was used for this estimation because rapid and significant accretion occurs at this point. Longshore sediment transport currents would decrease or cease beyond this point, and therefore sediment will be predominantly deposited in the nearshore zone where the currents cease (Meistrel, 1966). The subaerial coverage of the exposed spit tip was measured from the point in which the beach width no longer was constant between the two photos. The aerial section was drawn from this

Figure 4.19 – St. Joseph Peninsula distal end in 2004 (photo on left) and 2007 (photo on right). Shaded areas represent the surface area used to approximate total sediment deposition. Geo-referenced air photos acquired from FDEP (2010).

point, normal across the spit, and followed the shoreline as identified in the air photos. Neither the exact date nor the time of day was included in air photo metadata to estimate the shoreline position resulting from high or low tides. However, the micro-tidal regime would only make minor differences in the shoreline position at this resolution, assuming no surge is taking place. Additionally, the bay side of the spit, which undergoes only minor changes from minimal wave exposure, was depicted along the same line for each air photo independently. The 2004 subaerial beach was measured to be 40,100 m^2, and the 2007 beach was measured at 48,000 m^2 an increase 79,000 m^2.

To estimate the sediment deposited in the nearshore zone, the total depth of sediment needed to be calculated. An approximation of water depth above the emerging sand bars to mean sea level was averaged to be 0.50 m (figure 4.20), which was calculated from topographic profiles measured at the spit tip. The height of sediment above mean sea level at the spit tip was calculated to be approximately 1.0 m (figure 4.20). Therefore, where a new subaerial berm was present, there was estimated to be a total of 1.50 m of new sediment deposition in height, or 1.50

m^3/m^2. To estimate the total sediment deposited between the 2004 and 2007 air photos, the surface area was multiplied by the sediment depth and divided by the time period between air photos:

$$\textit{annual volume of sediment} = (\textit{depth} \times \textit{surface area}) / \textit{time} \qquad (2)$$

The 2004 photo was taken in February, but the date of the 2007 photo is unknown. Therefore, the potential time period between air photos was anywhere from 2.9 years to 3.9 years, thus giving a range of total sediment deposited at the spit tip to be 30,300 m^3/a to 40,800 m^3/a resulting from a change in the denominator in equation 2, above. The coarse estimation of total sediment deposited at the spit tip was averaged to be 35,500 m^3/a during this time period, a value higher than the estimated 27,000 m^3/a moving via longshore sediment transport. The variation, or the additional 24% of sediment added to the spit tip, may be related to: a) the MIKE-21 model's underestimation of the wave energy; b) the influence of cross-shore sediment transport in this extremely low energy environment carrying sediment onshore; c) the undocumented impact of hurricanes or d) human measurement approximation errors. Regardless, the sediment transport model is still within an order of magnitude of the sediment deposited at this location, which aids in validating the MIKE-21 outputs and sediment transport estimates.

4.5.3 Seasonal Longshore Sediment Transport

MIKE-21 simulations indicated that the wave energy and its directional properties varied significantly between seasons, ultimately depending on the passage of cold fronts during the fall-winter-spring season (Figure 4.21). Sediment is transported to the south along the northern mainland coast of Gulf County during all seasons except when a strong southerly wind and wave component push sediment northward out of the bay. However, sediment is predominantly

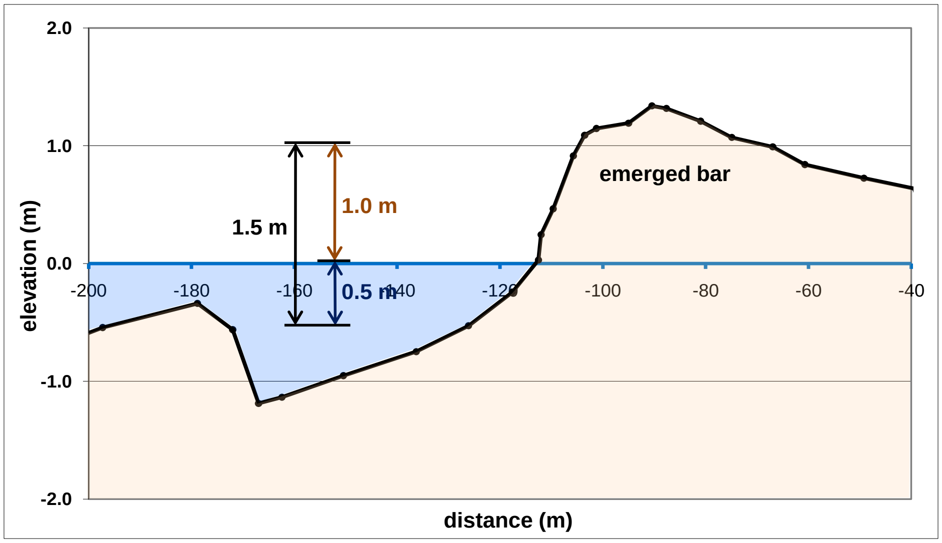


Figure 4.20 – Coarse estimates of subaerial and submarine sediment depths. Depths were approximated based on topographic profiles at the spit tip.

moving south into St. Joseph Bay, where accretion rates are greater than 1.0 m/a (Foster and Cheng, 2001), thus providing more beach sediment available to build adjacent foredunes.

While sediment predominantly transports northward along St. Joseph Peninsula, transport decreases in the northward direction due to frontal storms during winter. Strong northerly winds and waves can suppress the total northern sediment transport during winter, and as a result cause southward sediment transport. This strong reversal of wave energy was identified by Jose et al. (2007) off the south-central coast of Louisiana as well. Even in rare conditions in which sediment may be transported to the south at the spit tip, westerly waves still refract around the spit tip to drive the sediment to the northeast and east year-round, prograding the beach and available sediment for aeolian transport. Spring has a very strong northerly sediment transport component (transport rates over 250 m^3/a) on St. Joseph Peninsula, resulting from very strong winds and waves coming from the southwest through southeast. The lowest wave energy and lowest rates of northerly sediment transport on the spit occur during summer, resulting from a

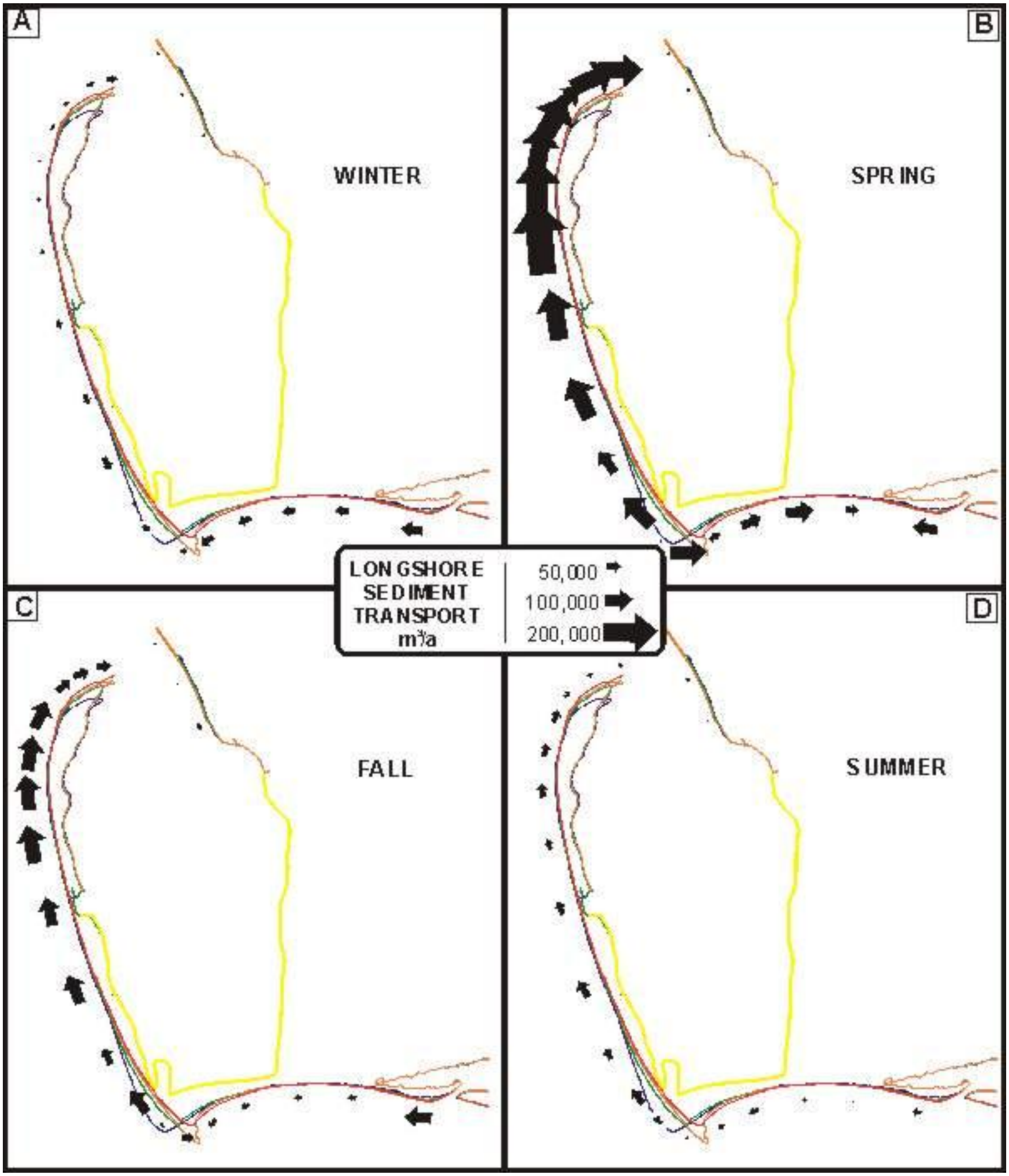


Figure 4.21 – Sampled seasonal longshore sediment transport calculated using CERC (USACE, 1984) equation with MIKE-21 simulated wave data. Shorelines downloaded from the USGS (Morton et al., 2004) show the elongation of the peninsular tip and the erosion of Cape San Blas in the south.

lack of frontal activity in the region and a general decrease in wind and wave energy. In fall, the sediment transport rates increase as stronger winds and frontal storms reappear in the region.

At the cape, sediment transport patterns switch with the passing of different wave trains as waves refract across the complex Cape San Blas shoal. Waves from multiple directions could be visually observed at the Cape simultaneously. Ultimately, the MIKE-21 nearshore simulations indicate there is a strong refraction into the Cape, and sediment is presumably transported offshore to the Cape San Blas shoal (Gorsline, 1966; Tanner, 1974, Stauble and Warnke, 1991), as indicated by the rapid erosion of the beach at this location.

Sediment transport to the west and east at rates over 75,000 m^3/a occur along the southern east-west coastline of Gulf County. The switching of currents is directly related to the direction of incoming waves; offshore waves from the north and west drive sediment to the east, and offshore waves from the south and east move sediment to the west. The dominant movement of sediment to the west can be responsible for the series of ridges building gulfward along this stretch of prograding beach.

4.5.4 Hurricane Waves

Keim et al. (2007) and Spaziani (2010) examined hurricane return periods for the US Gulf of Mexico and Eastern seaboard coastlines. For the Gulf County study region they found that all tropical storms and hurricanes had return periods of 4 years; hurricanes had a return period of 10 years overall, though hurricanes classified as Category 3 or stronger were calculated to have a return period of more than 105 years. Anecdotal evidence suggests Hurricane Ivan (2004) and Hurricane Dennis (2005) caused erosion and overwash to the beach and foredunes in Gulf County, Florida. Those anecdotes are supported by Florida DEP photographs and documents detailing these storms (Figure 4.22 and Figure 4.23). Ivan storm surge values of (2-3 m were observed from Destin, Florida eastward to St. Marks, which would encompass Gulf, County (Stewart, 2005).

Dennis' storm surge was (approximately 2 meters above normal tide levels, which overwashed Santa Rosa Island and Navarre Beach, west of St. Joseph's Peninsula. A storm surge of 2-3 m above normal tide levels occurred in Apalachee Bay, Florida, which is east of Gulf County (Beven, 2005). St. George Island, located just to the east, recorded storm surges of 1.60 m and 2.45 m for Hurricanes Ivan and Dennis respectively (Miller et al., 2010). Hurricane Katrina

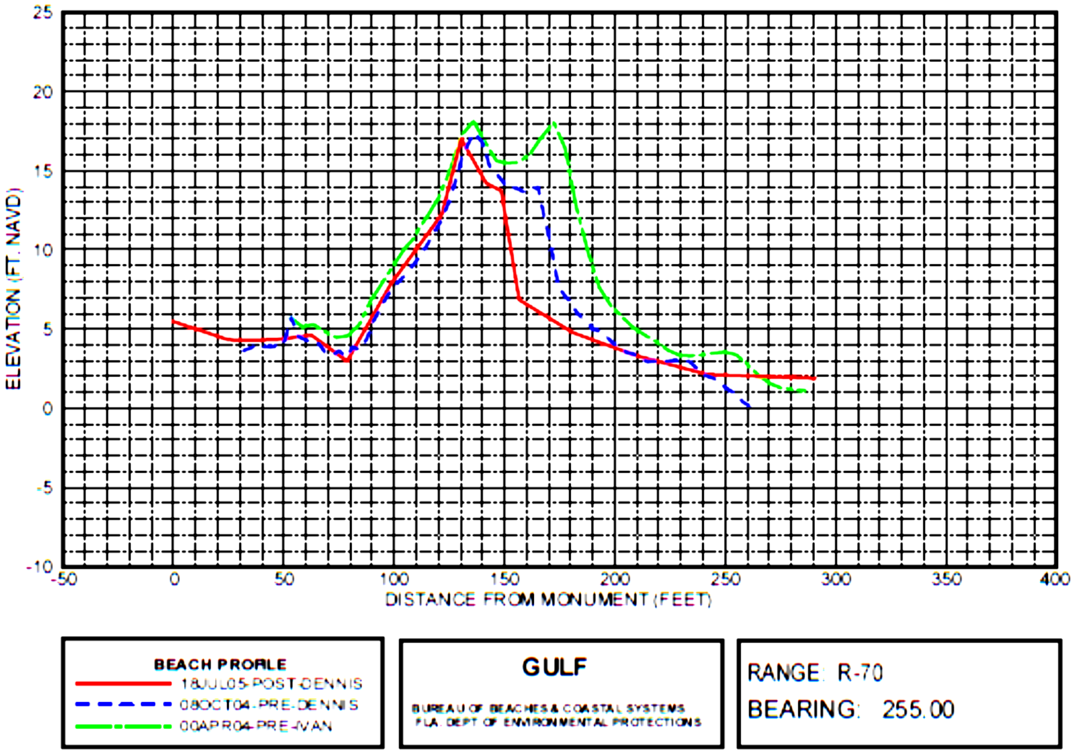


Figure 4.22 – Florida Department of Environmental Protection (FDEP) surveys of the foredune Pre-Hurricane Ivan (Green), Pre-hurricane Dennis (Blue) and Post-Hurricane Dennis (Red) on profile R70. Note the extensive foredune loss as a result of the hurricanes, indicative of major storm surge and wave erosion at this site on St. Joseph Peninsula. (FDEP, 2005)

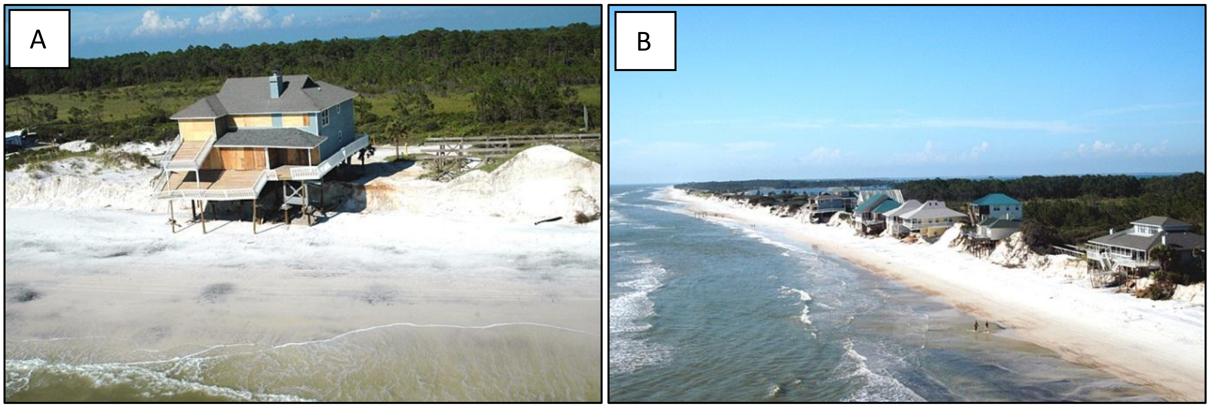


Figure 4.23 – St. Joseph Peninsula post-Hurricane Dennis. Both photos A and B highlight the storm's impact as the locations suffered beach and foredune loss, which exposed the properties pilings, and subjected the homes to infrastructure damage. (Photo source: FDEP, 2005)

(2005) played a larger role in morphological change to St. Joseph Peninsula. Where the beach was narrower pre-storm, beach and foredune scarping occurred (Wang et al., 2006). However, the location with a wider beach on the peninsula lost beach sediment, but only very minimal scarping of the dune toe (Wang et al., 2006). Storm inundation occurred during Katrina, Ivan and Dennis, and a more direct hit (Hurricane Katrina made landfall over 200 km to the west) would generate even larger wave heights and more erosion to the beach and dune system. During the study period, visual observations showed negligible change to the study area resulting from Tropical Storm Alberto (2006) and Tropical Storm Claudette (2009), aside from a potentially increased rate of erosion at Cape San Blas. This cannot be empirically validated because topographic profiles were not measured immediately pre- or post-storm.

MIKE-21 simulations of offshore hurricane waves drawn into the nearshore zone demonstrate there is a potential for significantly larger waves breaking near the shore. However, storm surge was not included in the modeling and the wave heights are based on the calm condition parameters, including bathymetry and shoreline position, and do not include the impact of the nearshore winds. Further investigation of these storm conditions would aid in validating the impact of storm surge and waves on the beach, dune system, and longshore sediment transport during hurricane events. Needham and Keim's (2011) archival research found there to be four hurricane storm surges greater than 2 m over the past one hundred and thirty years (1880-2009) within 40 km of Cape San Blas. However, further investigation with *in situ* verification of these storm surge heights and an examination of their impacts would benefit our understanding of storm surge levels and the resultant change to the beaches and foredunes in Gulf County. Further investigation with *in situ* verification would also add to our knowledge of the periodization and synchronization of dune and beach-building processes as proposed by Houser (2009) and how this may impact foredune development and characteristics.

4.6 Chapter Summary

Wave energy is very low in Gulf County, Florida, averaging less than 0.30 m. Visual observations, *in situ* measurements, and computed waves using the MIKE-21 Spectral Wave Model, all indicate that the largest wave energy occurs on the south-facing coasts and west-facing shores of St. Joseph Peninsula (Figure 4.24). These areas of larger waves are directly correlated to areas of increased erosion. The south-facing coasts have a dominant sediment transport moving from Indian Pass to the west, which is supplying new sediment to the system. This sediment transport then supplies new sediment to the beach, which can then be transported inland to the dunes. However, the highest energy waves occur at the Cape. The current absence of any dune form at the cape and the appearance of washover-like conditions on all surveys correspond with the extremely rapid erosion. The spit's direct western exposure to incoming waves has resulted in shoreline erosion, a smaller beach width, and a lack of foredune building, as the sediment supply available to the foredunes is reduced.

Although the tallest recorded foredunes for this study are located along the western facing shore of the spit, the dunes here have not increased in height or volume during the recent (2007-2010) study period. At the spit tip, wave energy decreases as waves have to further refract around the spit fulcrum. The mainland west-southwest facing shores experience low wave energy conditions as well, with the lowest wave energies experienced within the protected St. Joseph Bay. Subsequent chapters will correlate the wave energy and sediment transport rates with the foredune morphology at each study site within Gulf County.

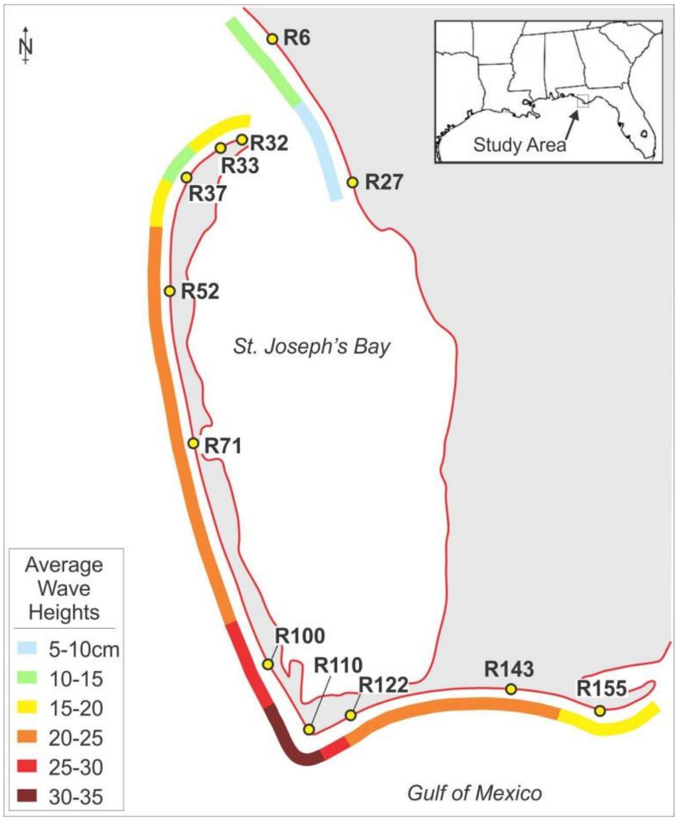


Figure 4.24 – Average wave heights in Gulf County, Florida. Average wave heights were calculate using MIKE-21, calculated using offshore dominant wind conditions documented in Table 4.2.

Chapter 5
Beach and Dune Profiles

5.1 Introduction

Examining beach and dune profiles is an important step in understanding temporal and spatial dynamics in the coastal system. This chapter examines beach and dune profile changes in the Cape San Blas - St Joseph's Peninsula region from 1973 to 2007. The first section will describe changes to the beach and foredune between 1973 and 2006. The second section will examine the short-term changes to the beach-foredune profiles measured approximately every six weeks from May 2006 to September 2007. The remaining sections will provide descriptions regarding the spatial and temporal variability of the profile volume changes.

5.2 Decadal Data

The following section includes descriptions of the 12 profile locations in Gulf County, Florida. The site names (e.g. R6) refer to the Florida Department of Environmental Protection (FDEP) Range Monuments profile locations (see Methodology chapter). Each of the sections includes a brief qualitative description of the study sites and the subsequent temporal changes. This will be followed by a description of beach and foredune volume changes. The profiles are plotted relative to North American Vertical Datum: Heights are relative to 0 meters, Mean Sea Level (Figure 5.1). Mean Higher-High Water Level (0.242 m) and Mean Lower-Low Water Level (-0.232 m) are plotted on Figure 5.1 but are not shown on subsequent profiles.

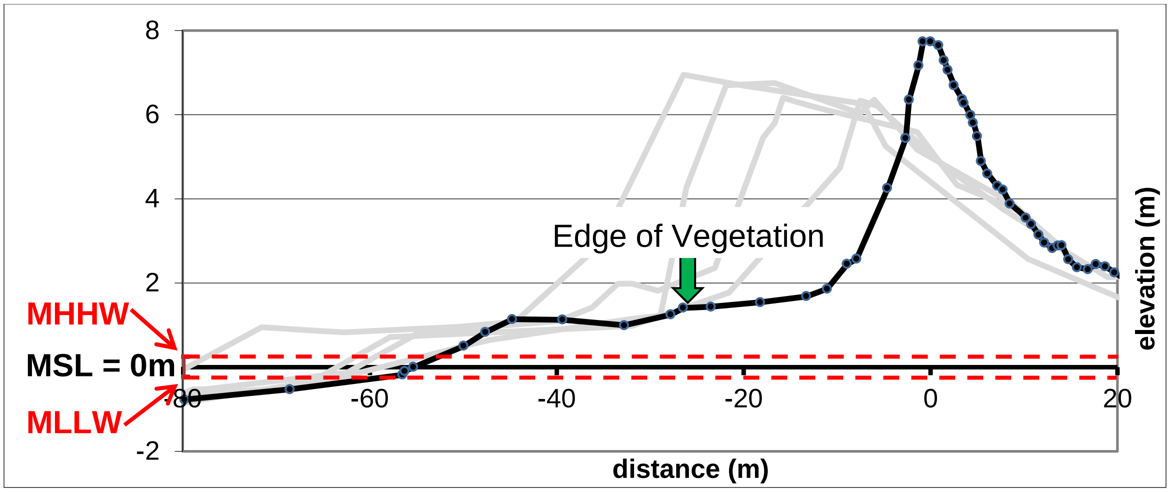


Figure 5.1 – Example beach-dune profile plot. Each profile will display multiple surveys, plotted relative to the NAVD (North American Vertical Datum) Mean Sea Level (MSL). This plot displays the Mean Higher-High Water level (MHHW) and the Mean Lower-Low Level (MLLW) relative to the NAVD MSL recorded at NOAA site St. Joseph Point, St. Joseph Bay, Florida (NOAA, 2008). The average edge of vegetation is indicated for the 2006-2007 profiles.

Figure 5.2 plots foredune heights versus the 30-year erosion/accretion rate. On accreting beaches in Gulf County, most foredunes are within 2-4 m in height, whereas foredune height varies much more on eroding beaches. To quantify the foredunes into groups for this study, a division of these dunes was created to qualify the dunes as low, medium or high dunes. The low dunes are from the *average dune height* (3.8 m above MSL) *to one standard deviation* (1.9 m) *below* the average for a range of 1.9 to 3.8 m above MSL. Any location with a max height below 1.9 m is considered "no dune" or washover conditions, and are only found at the highly eroding Cape San Blas (Range Monuments 116-120). Medium height dunes are located from the *average to one standard deviation above the average* (3.8 to 5.7 m above MSL). Anything above the *average plus one standard deviation* (> 5.7 m above MSL) were classified as high dunes.

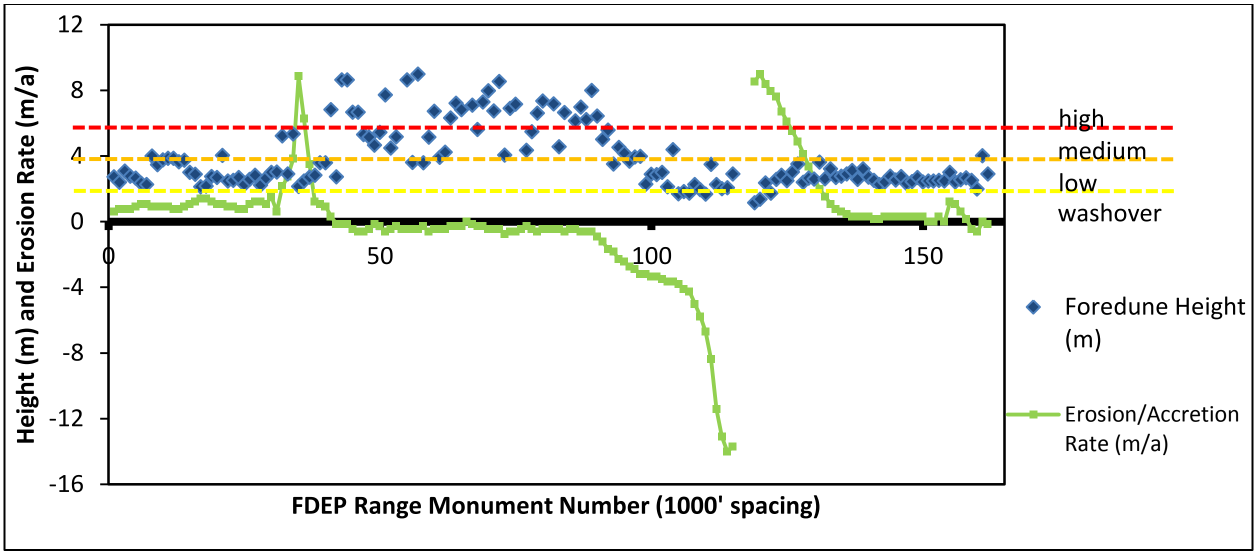


Figure 5.2 – Foredune heights (crest height above MSL) and 30 year erosion/accretion rate. Foredunes were classified as low dunes (1.9 - 3.8 m), medium (3.8 - 5.7 m), or high (> 5.7 m) based on the average foredune height and one standard deviation below, one standard deviation above, and greater than one standard deviation above the average foredune height respectively.

5.2.1 Profile R6

R6 is located in the northernmost section of the Gulf County mainland. The west-facing beach and low foredune is on a private undeveloped community beach between developed foredunes 200 m to the north and south of the profile line. The current foredune separates the beach from a low plain with small hummocky relic foredune ridges leading to Highway 98. In 1973 a foredune ridge was approximately 35 m behind the current foredune (Figure 5.1). Since 1973, two small ridges developed, but no longer existed by 1997. In 2004 the current foredune was 2.60 m above MSL. In 2006 the foredune height was 3.40 m, rising 0.48 m/a since 2004. The foredune grew in height again to 3.55 m, rising 0.11 m/a in 2007. Volumetrically, the ridge went from an incipient form that was 0.11 m^3/m in 2004, to a well-defined linear foredune ridge of 17.47 m^3/m in 2006, and continued to grow to 20.55 m^3/m in 2007 with increased sediment deposition. This contrasts with the relatively low amount of dune development during the first 30 years of the study period.

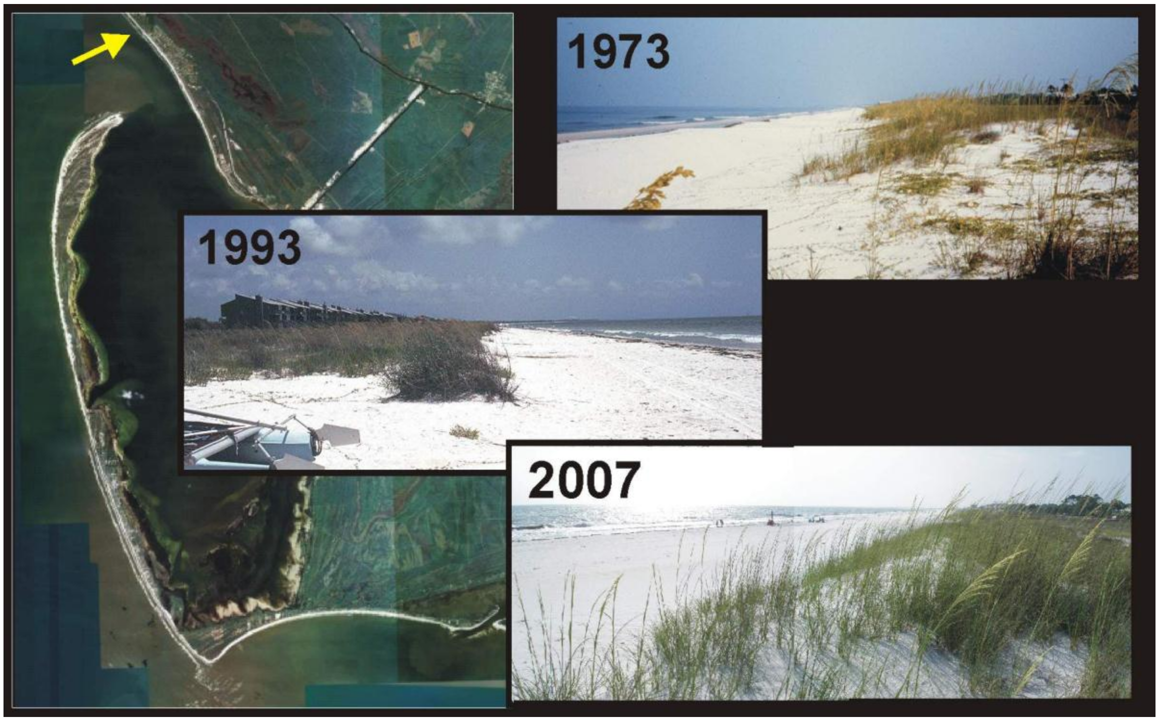


Figure 5.3 – Profile R6. The image on the left is a mosaic of 2004 air photos. The yellow arrow indicates the location of profile R6. The images on the right show the beach and low foredune in the year listed on each photo (1973 and 2007 looking north, 1993 looking south.)

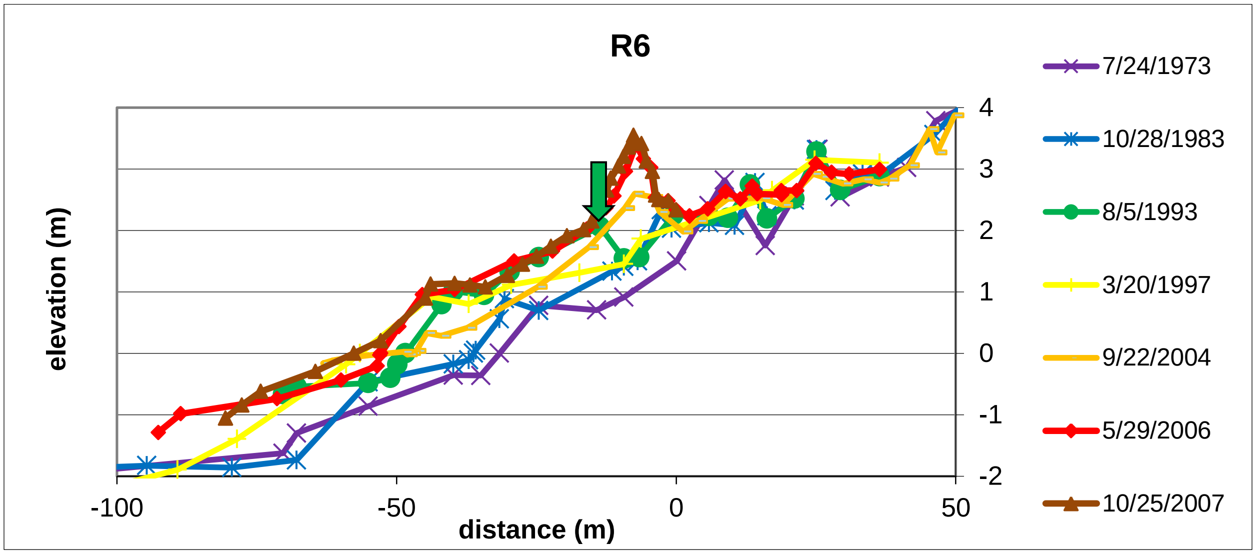


Figure 5.4 - Profile R6 cross-section. The current foredune is first detected in the 2004 profile. It grew over a meter in height by 2006 and 2007.

5.2.2 Profile R27

R27 is located on Gulf County's mainland, currently southeast of the tip of St. Joseph Peninsula, and appreciably protected from Gulf of Mexico swells. The beach swash zone is reflective and extremely steep with a narrow beach fronting the low foredune ridge. Two smaller ridges are landward of the foredune, followed by a taller more distinct ridge and a wide swale that leads to former Highway 98. The area between the Bay and the road appears to be uninfluenced by recent human disturbance.

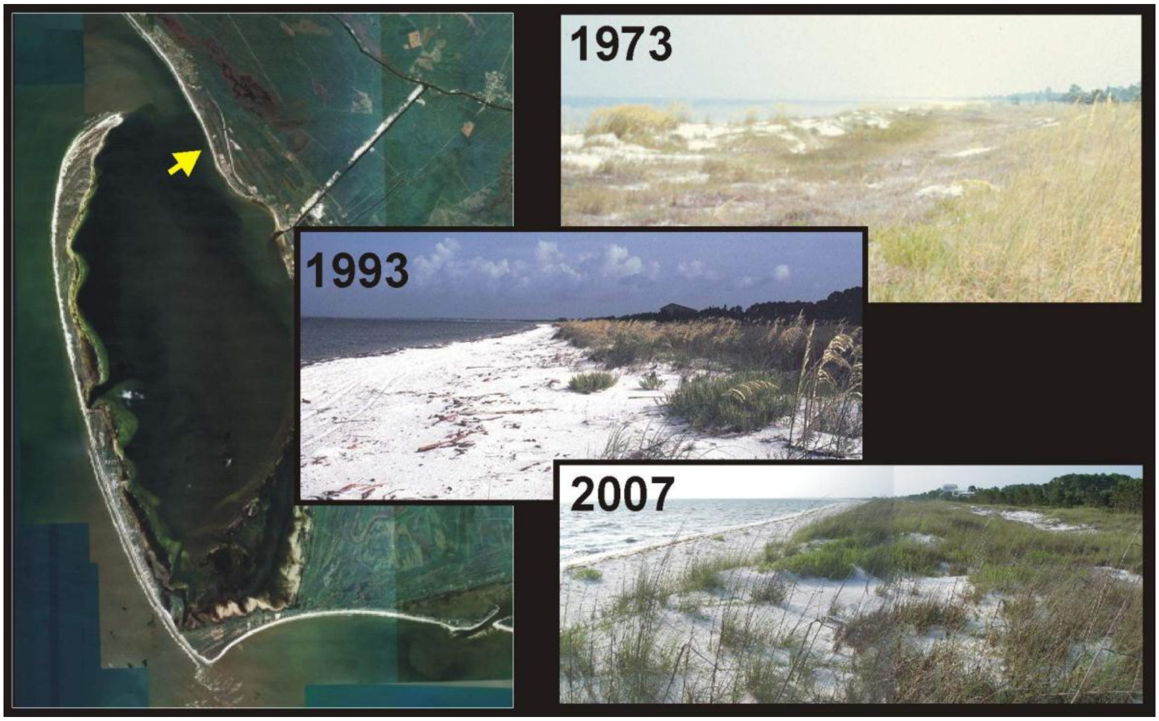


Figure 5.5 – Profile R27. The images on the right show the beach and foredune in the year listed on each photo.

In 1973 the shoreline was located where the present foredune exists. Since 1973 the beach has been slowly prograding at an average rate of 0.58 m/a, which was calculated based on average change per year (Figure 5.6). However, beach erosion (2.00 m/a) has been recorded since the 2004 profile was measured.

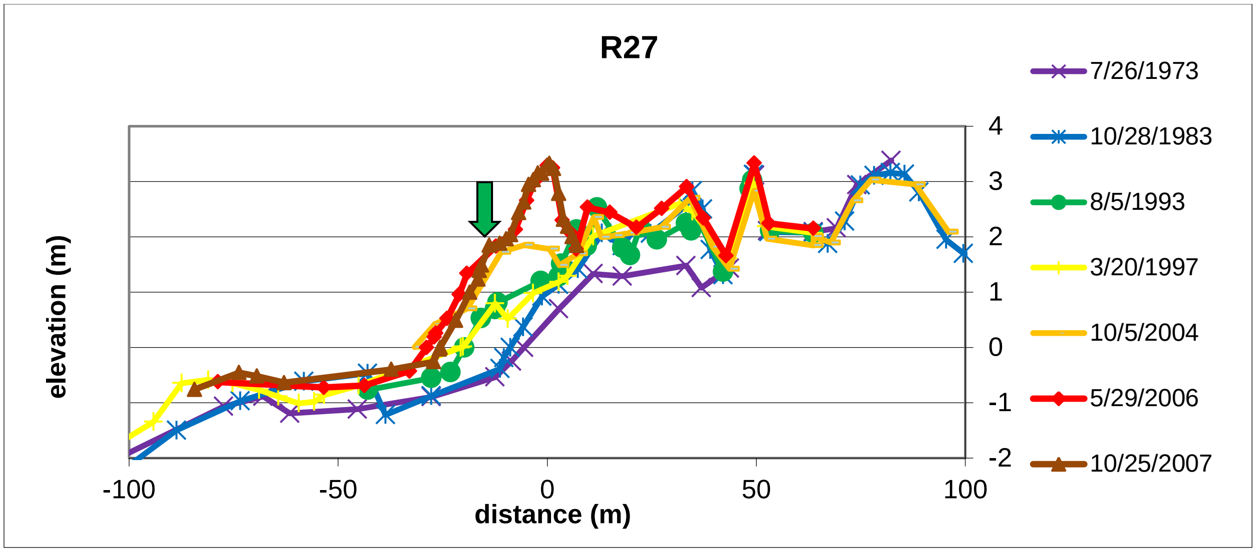


Figure 5.6 - Profile R27 cross-section. Similar to R6, the current low foredune was first detected in the 2004 profile, and subsequently grew in size in the 2006 to 2007 profiles.

Despite Tanner's (1973; and Otvos, 2005) reference to the ridges in this area being "beach ridge strandplains", there is no current evidence of ridges being built by waves and no large changes in sea level to suggest they are beach ridges (in the strict sense of Hesp, 2004). Rather, based on recent observations they appear to be a series of relic foredunes that develop as the coast progrades (Figure 5.7). In 1973 the foredune ridge was located 50 m landward of the current foredune location. Similar to profile R6, two new ridges have formed since 1973. However, the relict foredunes on profile R27 exhibit an upward building ridge and swale pattern. These relict foredunes did not develop as high as the present foredune, but have a greater landward-seaward width. There was no evidence of the current foredune forming until 2004, at which time the beach platform and a possible embryo dune was forming. The current foredune formed in less than 20 months and was measured at 3.29 m above MSL in 2004. The foredune volume was last recorded at 11.09 m^3/m in August 2007.

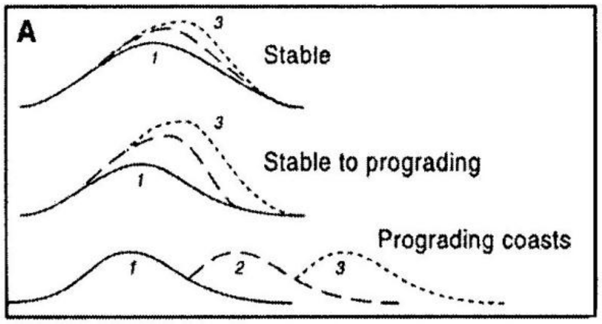


Figure 5.7 – Foredunes on stable to prograding coasts (from Hesp, 2002; 253). Both R6 and R27 show the same pattern of new foredune growth as the shoreline progrades, Between 1973 and 1993 the upper diagram of upward growth, and since 1993, new aeolian built ridges have been building as the coastline continued to prograde.

5.2.3 Profile R32

R32 is located at the northern tip of St. Joseph Peninsula, in the wilderness zone of St. Joseph Peninsula State Park. The historic FDEP R32 profile has a different orientation (320^{o}) than the profile dimensions that were measured from 2006 to 2007 (360^{o}).

Between 1973 and 1983 the 5.0 m high foredune remained stable, while the beach eroded 54.3 m (Figure 5.9). The subsequent profile (1993) exhibits 99.7 m of beach progradation and the development of two new ridges approximately 4.0 m and 3.7 m in height, the same number of well-developed new ridges found on the mainland at sites R6 and R27. From the profile data available it is unclear if these ridges developed as wave built beach ridges (Tanner, 1975; Otvos, 2005) or new foredunes formed by æolian deposition in vegetation. However, the heights of these ridges point toward their formation being initiated as either “beach ridges” or incipient aeolian foredunes, and subsequently they grew to their current heights through aeolian deposition. Assuming wave energy has remained relatively constant over the past 4 decades, the currently developing longshore sandwaves could not strictly build the 3+ m heights of the ridges on profile R32.

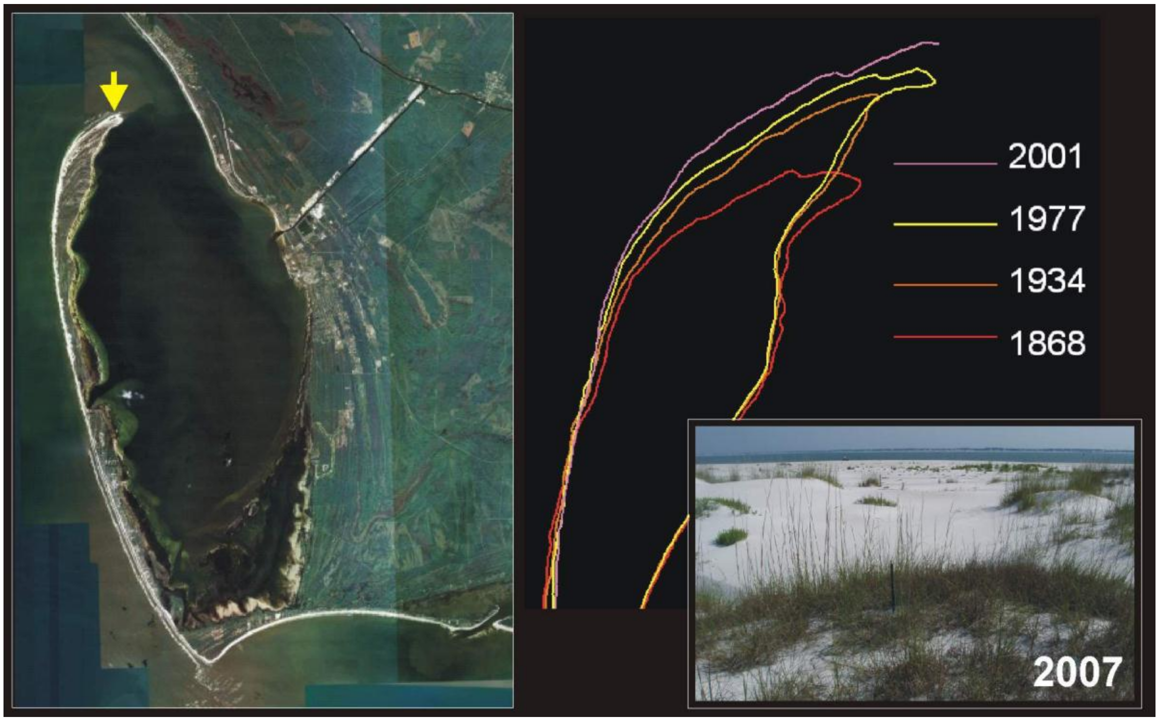


Figure 5.8 – Profile R32. The spit tip outlines (USGS, 2004) show the progradation of the tip. The 2007 photo shows a view from the foredune due north across the rapidly prograding beach. New aeolian built incipient dune lines have built around successive vegetation lines at this site since vegetation and topographic profiles were completed.

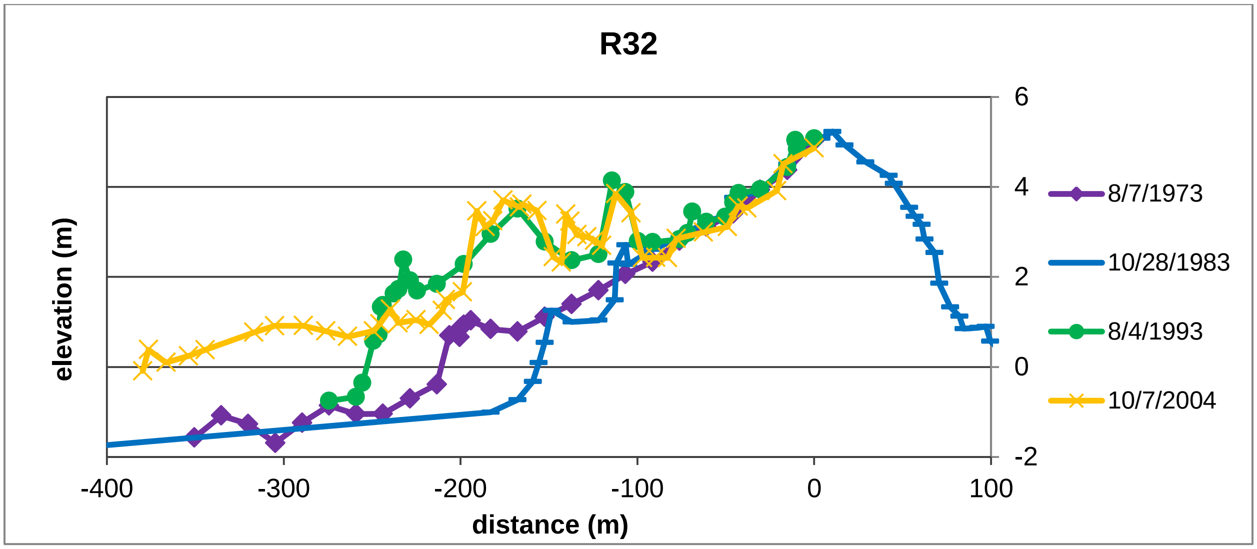


Figure 5.9 - Profile R32 cross-section. A larger, medium in height, foredune existed on the 1973 and 1983 profiles. The 1993 and 2004 profiles show the development of two and three new low ridges (respectively). Since topographic surveys ceased for this study, subsequent surveys have shown new aeolian built foredune ridges have formed to seawards.

5.2.4 Profile R33

R33 is located south of the tip of St. Joseph Peninsula. This is located in the area in which emerging bars attach and/or lengthen in incremental surges and have built these elongating emerged berms, recorded up to 1.6 m above MSL. The development of emerging beach berms or longshore sandwaves (as defined in 1990 by Saunders and Davidson-Arnott) appears to confirm the development of the spit berms and runnels described by Hine (1979). The 2006-2007 sandwaves on profile R33 are separated from St. Joseph Peninsula by a narrow 20 to 30 m lagoon (Figure 5.10).

The 1973 and 1983 profiles display a tall (4.5 m) and very steep face secondary dune, fronted by a large swale and a smaller foredune (Figure 5.11). The very steep face to this dune may indicate the dune was scarped by a large storm. However, given the location of emerging bars and the scarping north of the tip of these wide berms (Figures 5.11 and 5.12), this may have been a location in which this dune was scarped by average wave conditions, because it is common in this region for the foredune to be eroded in the immediate downdrift area of an emergent bar. In 1993 a new foredune emerged while the previous foredune grew in height, and by 2004 a new foredune emerged. In 2006 this new foredune had built 0.43 m taller but had been scarped on the stoss side (Figure 5.10), and hence the foredune volume remained relatively constant. This scarping may have been initiated by wave refraction combined with a cut-off of the longshore sediment transport due to an emerging longshore sandwave at this location (Figure 5.10: 2006A). This process was observed north of profile R33 during field investigations during the study period.

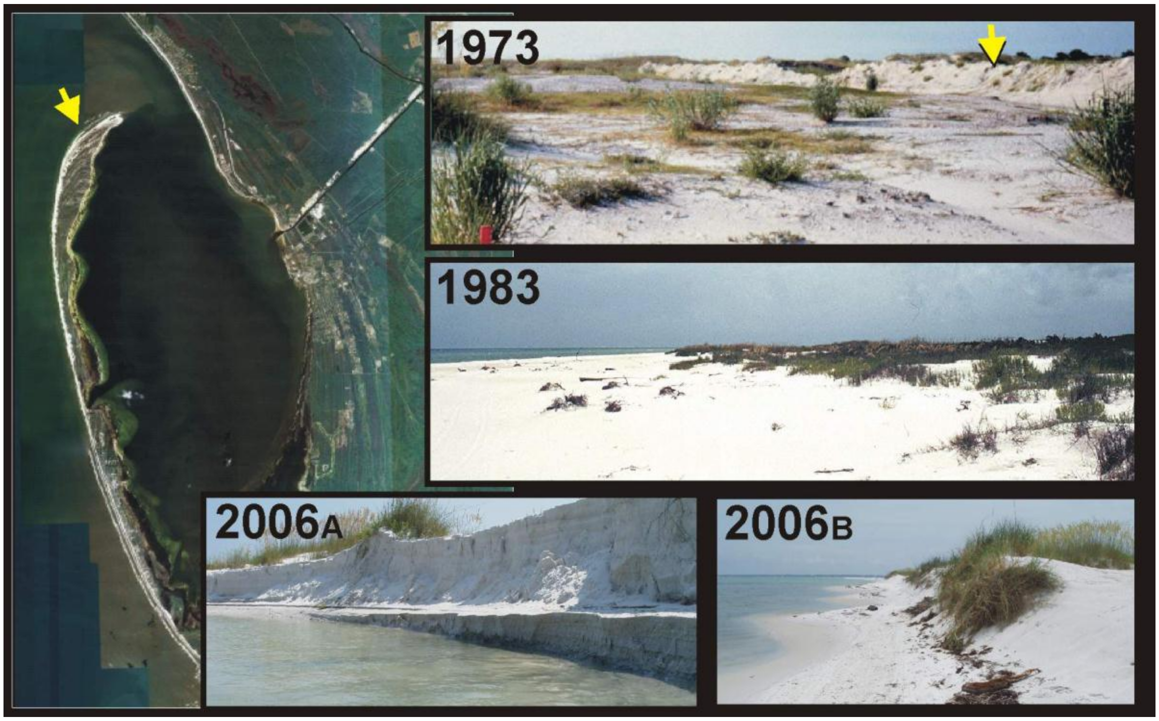


Figure 5.10 – Profile R33. The 1973 photo shows a scarped dune, which may be the large steep faced dune on the 1973 topographic profile (Figure (5.11). The photo 2006A, taken just north of the emerged bar, shows the scarping of the berm and foredune, which may have scarped the dune shown in the 1973 photo. 2006B is located on the profile line landward of the emerged bar.

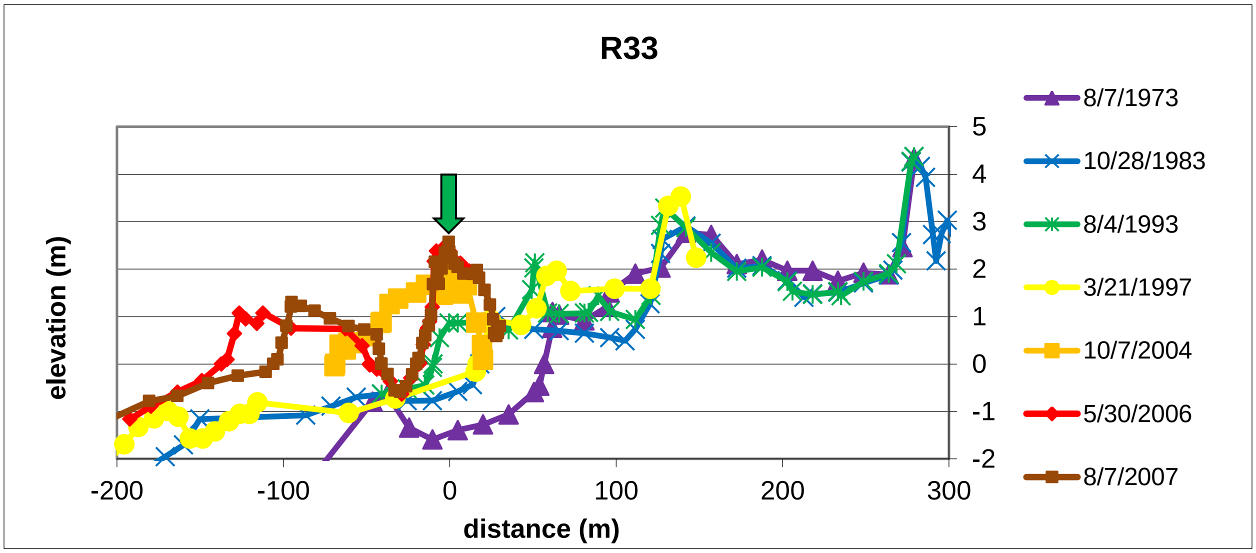


Figure 5.11 - Profile R33 cross-section. A series of new low ridges have formed as the beach has prograded seaward. The green arrow indicates the edge of vegetation. The 2006 and 2007 profiles display the longshore sandwave which has been migrating landward, and slowly infilling the lagoon situated between the accreting berm and foredune.

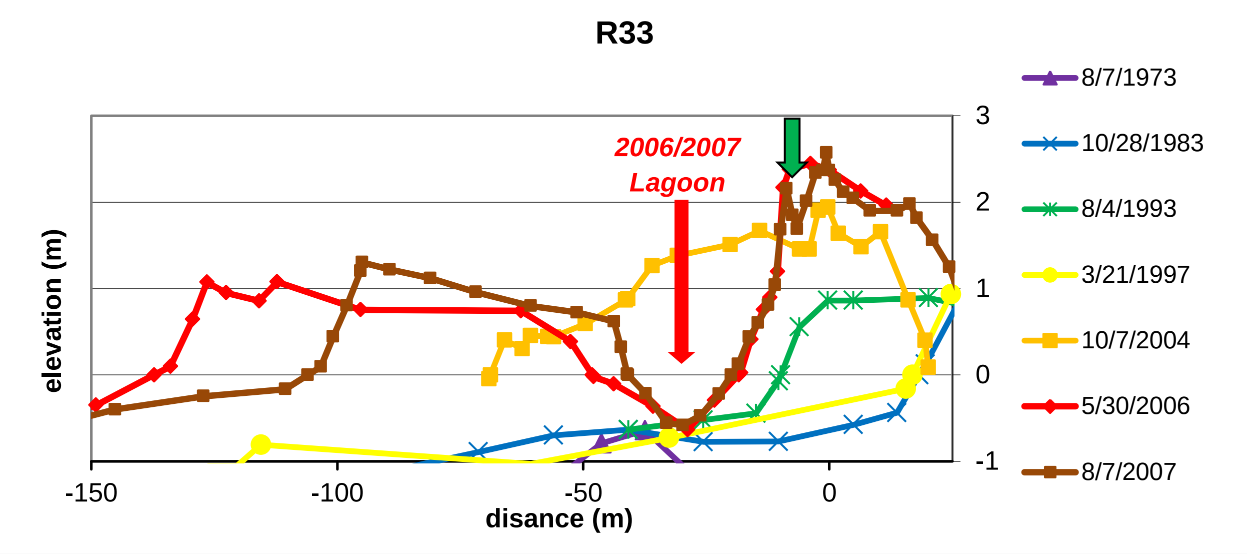


Figure 5.12 – Foredune and longshore sandwave on profile R33. The 2004 foredune has been scarped back to its current 2006/07 position. The longshore sandwave is present seaward (to the left on the graphic), but retreating. Due to the fronting lagoon, the beach has no new sediment available to rebuild the foredune. Therefore, the foredune continues to erode (decrease in height and volume,) as vegetation dies back.

Figure 5.13 – 1994 (left) and 2007 (right) aerial photos of emerging bars at St. Joseph Peninsula's distal end. The emerging bars located parallel to the coastline may coalesce with the shore to build wider beaches at the locations as occurred in 2007. A sample cross-sectional view of the emerging bar backed by a small lagoon can be seen in figures 5.11 and 5.12 on FDEP Profile R33. (Image source: Google Earth)

Figure 5.14 displays the relationship between beach volumes and widths and foredune heights and volumes. The beach width and volumes increased from 1973 (day 0) to 1983 (day 3721). While the foredune increased in height by 0.15 m, the foredune had been deflated or scarped during the 10-year period, as the volume had decreased (Figure 5.14). Over the next decade a new seaward ridge formed and, therefore, the relative beach volume and width had decreased due to the development of the new foredune. By 1997 (day 8845) the foredune volume continued to increase, despite there being a small decrease in beach width and volume. This corroborates the hypothesis that foredune volumes increase following small beach erosion conditions due to scarping of the stoss side of the foredune and translation of sediment over a new dune ramp and landwards (Psuty, 1988, Hesp, 2004). Again in 2004, a new foredune formed with slightly smaller dimensions, and by 2006 this same foredune volume decreased, yet the foredune height increased by the process described above. This brings in to question the meaning of Psuty's (1988, 2004) definition of maximum foredune development: foredune height or volume?

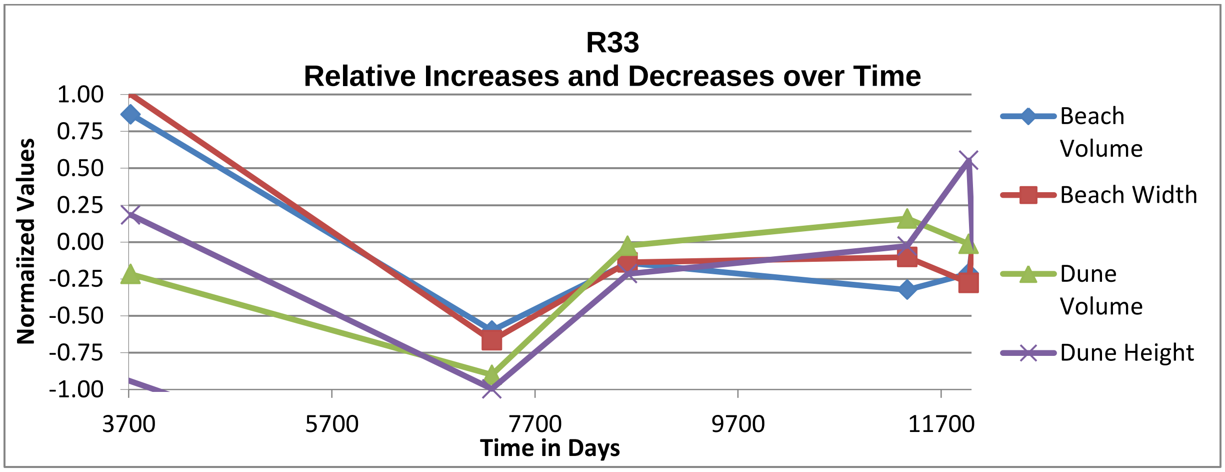


Figure 5.14 –Increases and decreases to the beach and foredune on profile R33. Y-axis values have been normalized to the maximum (positive or negative) amount of change for each beach and dune category. Negative values indicate decreases from the previous time, which is expressed in days since August, 1973.

5.2.5 Profile R37

R37 is located just south of the current longshore sandwave initiation point. From 1973 to 2007 the beach prograded 137 m, and a series of new ridges were built during that time period (Figure 5.16). Five new relatively low ridges formed between 1973 and 1983, all below 3 m, as the beach prograded 69 m. The 1983 foredune grew in height and an additional new embryo foredune formed in the next decade. Between 1993 and 1997 the beach eroded and the 1993 embryo foredune was eliminated and a new embryo dune formed 10 m landward. This embryo dune location was the site of a new established foredune reaching 3.64 m in 2004, and it continued to build in height to 5.51 m in 2006. These increases in height and volume were associated with the beach progradation and no fronting embryo or incipient dune forms; the expanding beach sediment supply was transported into the new foredune as opposed to initiating or adding sediment to an incipient dune.

The maximum foredune height occurred during the period in which the beach was prograding, and no apparent scarping of the foredune occurred. This is in opposition to the idea that maximum dune heights occur following periods of slight beach erosion (Psuty, 1992, 2004) if one assumes there is an immediate dune response to the erosion event that is maintained in the decadal record. However, following a decrease in beach width (76.9 m to 55.4 m), the 1997 foredune volume is at a maximum, which affirms the hypothesis of maximum foredune development, which is represented in the decadal data. While Psuty does not state the timeframe for the matrix (1992) or the morphological continuum (2004), this site demonstrates that the timeframe is important in determining dune types based on beach and dune sediment supply. The foredune volume was increasing between 1983 and 1993, a period in which the beach widened from 20.1 m to 76.9 m. The foredune volume was increasing again in 2006 when the beach width was 52.7 m. This indicates that conditions for foredune development occur when the beach width is between 20 and 80 m, with maximum foredune development occurring when beach widths are between 50 and 60 m for this location. Shorter beach widths, or smaller beach sediment supply, will not promote maximum foredune growth. If beach widths extend beyond 80 m, a new incipient and foredune may develop for this specific location.

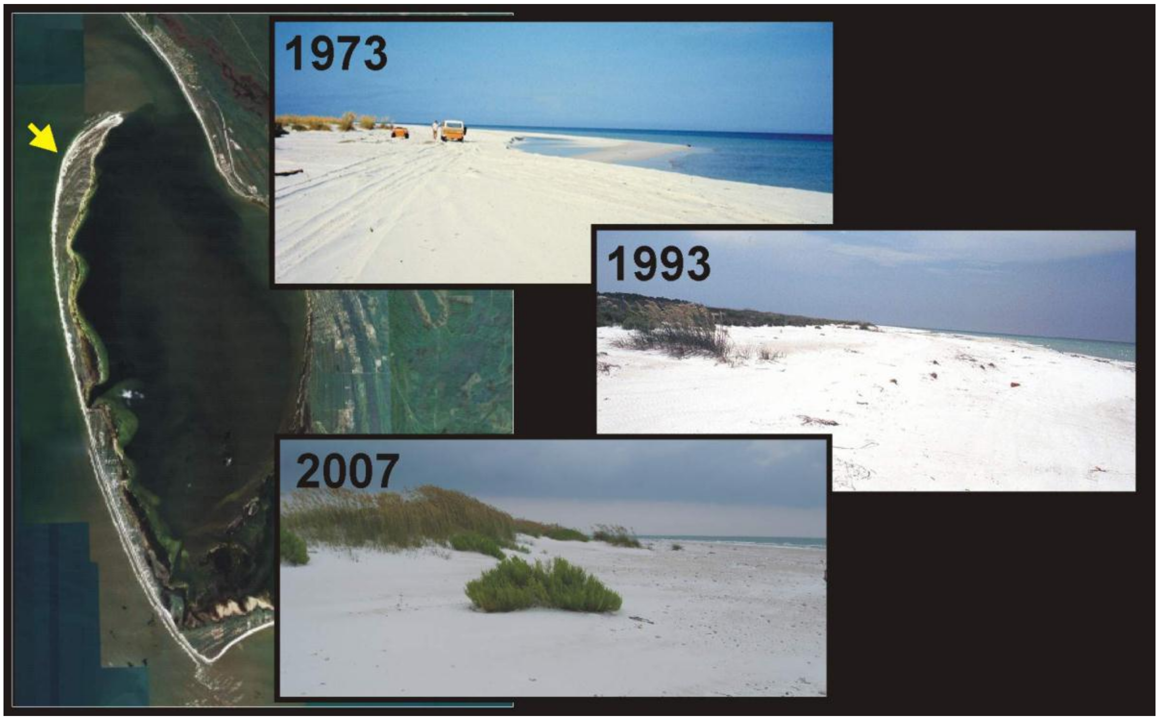


Figure 5.15 – Profile R37. The images on the right display a wide beach in each photo.

5.2.6 Profile R52

Profile R52 has the tallest foredunes recorded for this study, rising over 8 m above mean sea level. Profiles measured in this location show great variability between periods of beach and dune erosion (Figure 5.19). In contrast to the previously discussed profiles on prograding

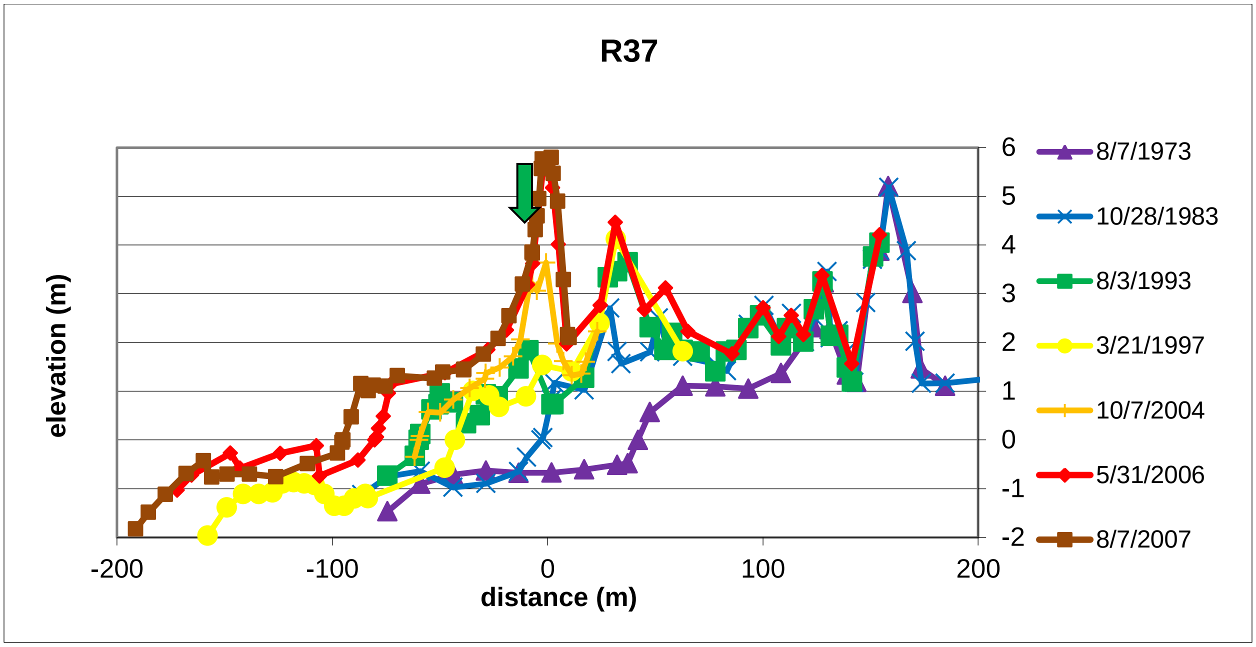


Figure 5.16 - Profile R37 cross-section. The beach prograded throughout the recorded history except during the period between 1993 and 1997. Multiple new ridges formed between 1973 and 1983, after which foredunes were predominantly building in volume and height.

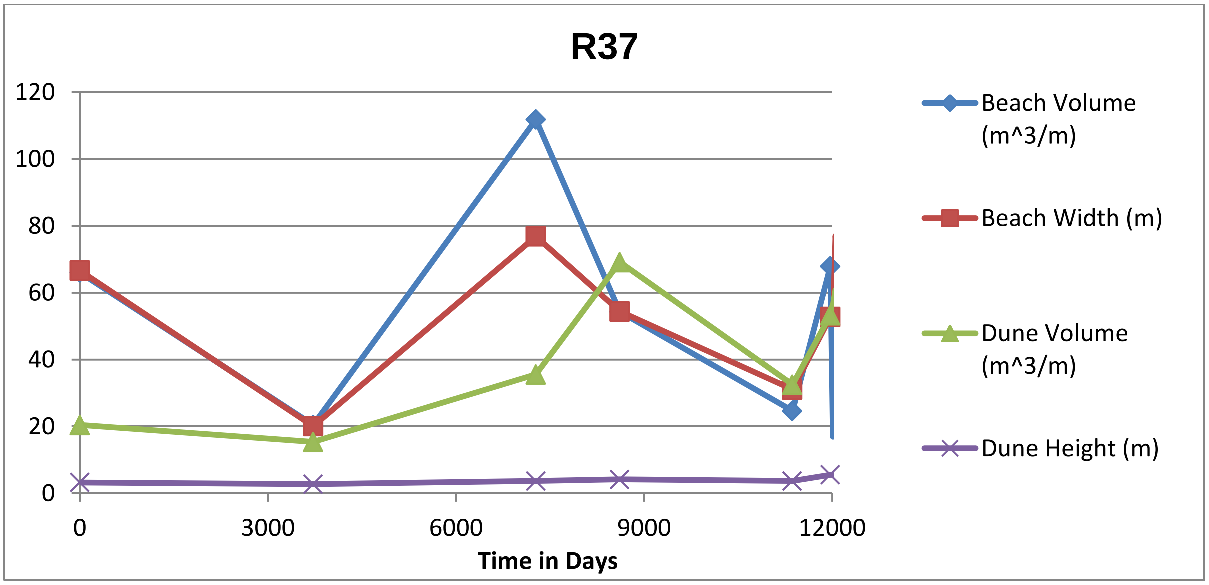


Figure 5.17 – Profile R37 beach and dune change. Foredune volumes increase during periods in which the beach width is between 31.0 m and 76.9 m. The maximum foredune volume occurred when the beach width was decreasing. However, maximum foredune heights occur at the end of the record when the beach is prograding and no new embryo or foredunes develop.

beaches, R52 displays one consistent foredune throughout the 33-year record. (The R52 2006-2007 profiles did not follow the exact same profile line as previous surveys but were conducted 92.2 m north, and therefore may not accurately represent changes to the foredune since 2004.

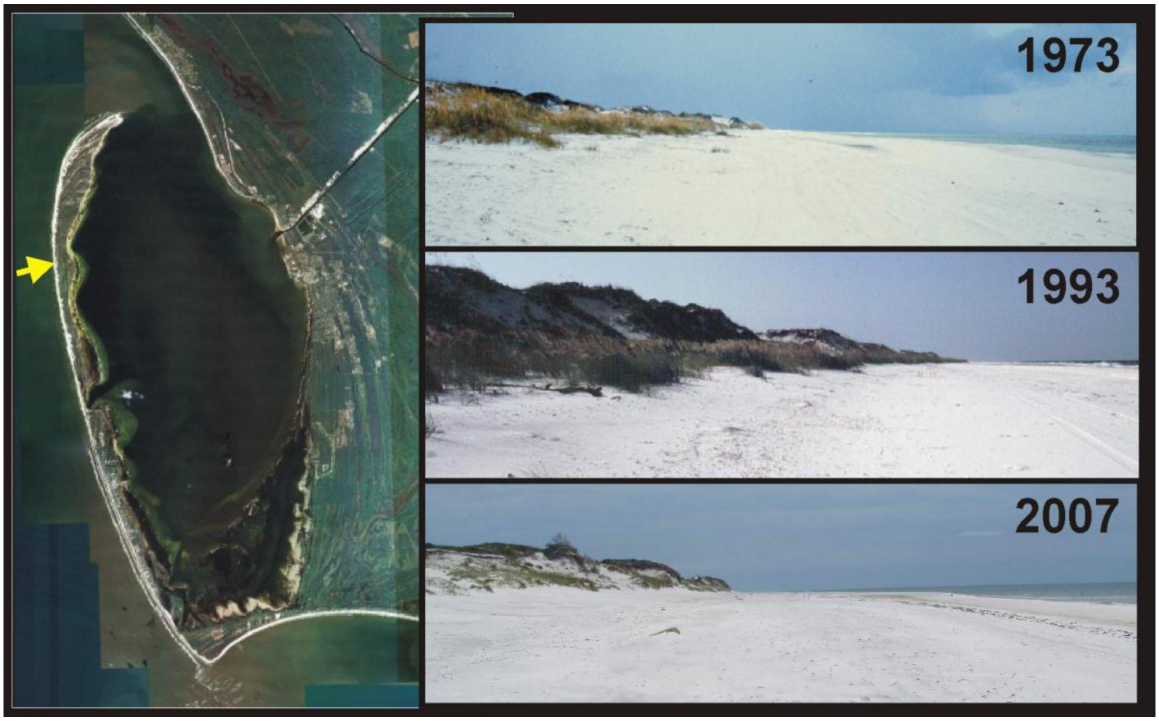


Figure 5.18 – Profile R52. Foredune and broad wide beach, looking south in all three years.

Between 1973 and 1983 the foredune grew from 4.8 m to 7.9 m in height. The foredune volume (including the main foredune and the fronting ridge) more than doubled from 91.6 m^3/m to 239.4 m^3/m, a period of large beach progradation. After 1983, the foredune dropped in volume from 239.4 m^3/m to 204.8 m^3/m in 1993. This large sediment loss may have resulted from foredune scarping during Hurricane Elena (1984) or Hurricane Kate (1985), both of which caused storm surges of approximately 3 m in the Apalachicola region (NOAA, 2007). The decrease in foredune volume can be attributed to losses to the stoss side of the foredune, which was probably scarped during storm events. The foredune very slightly increased in volume to

208.3 m^3/m in 1997 and was scarped again according to the 2004 profile to 197.4 m^3/m. Although it is not shown in the decadal profiles, the six-week profiles indicate that this beach changes very rapidly and often displays mega-cusp and horn embayments (up to 5 m cross-shore distance) features, which may aid in the foredune scarping events. Regardless, it is difficult to interpret influence and potential foredune scarping caused by these cusp features with the single profile data available (Figure 5.19).

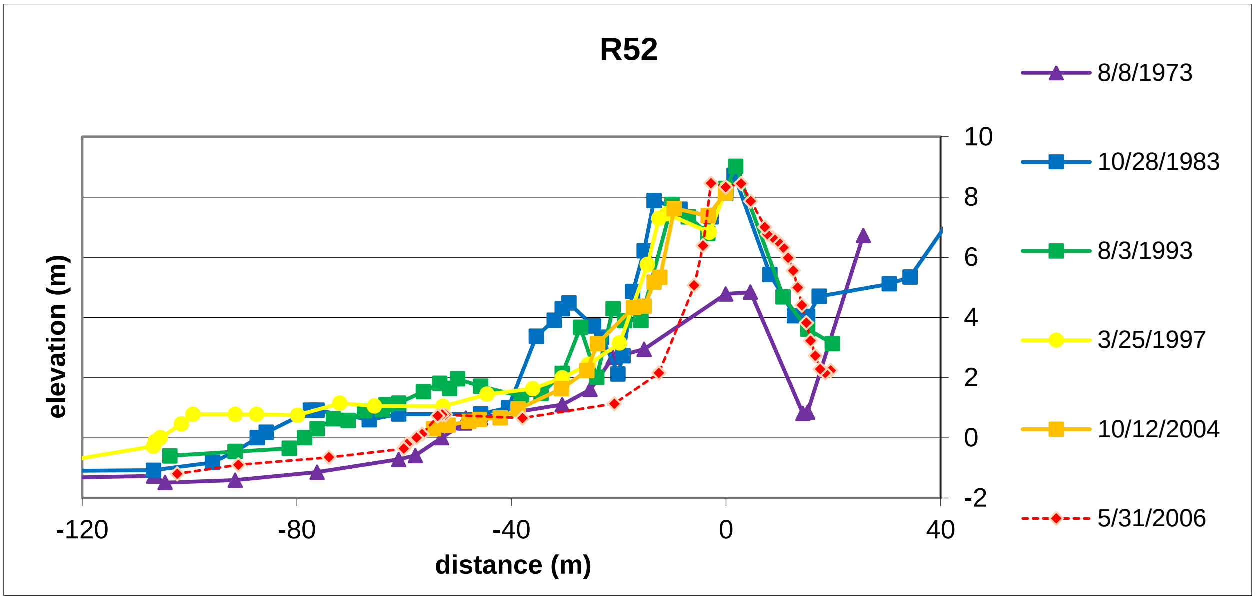


Figure 5.19– Profiles for R52 cross-section. The Profile for 2006 (red dashed line) was not on the exact profile line, but rather 10 m south on this linear continuous foredune. The high foredune developed to its large form between 1973 and 1983, but has experienced some erosion since 1983, and significant erosion following Hurricanes Ivan and Dennis.

5.2.7 Profile R71

Profile R71 has the second tallest foredunes recorded for this study, rising close to 8 m above mean sea level. However, R71 has lower volumes than the foredune on profile R52. In contrast to the highly variable beach widths on R52, R71 reveals less beach variability for the profile dates (Figure 5.22). (The R52 2006-2007 profiles did not follow the exact same profile

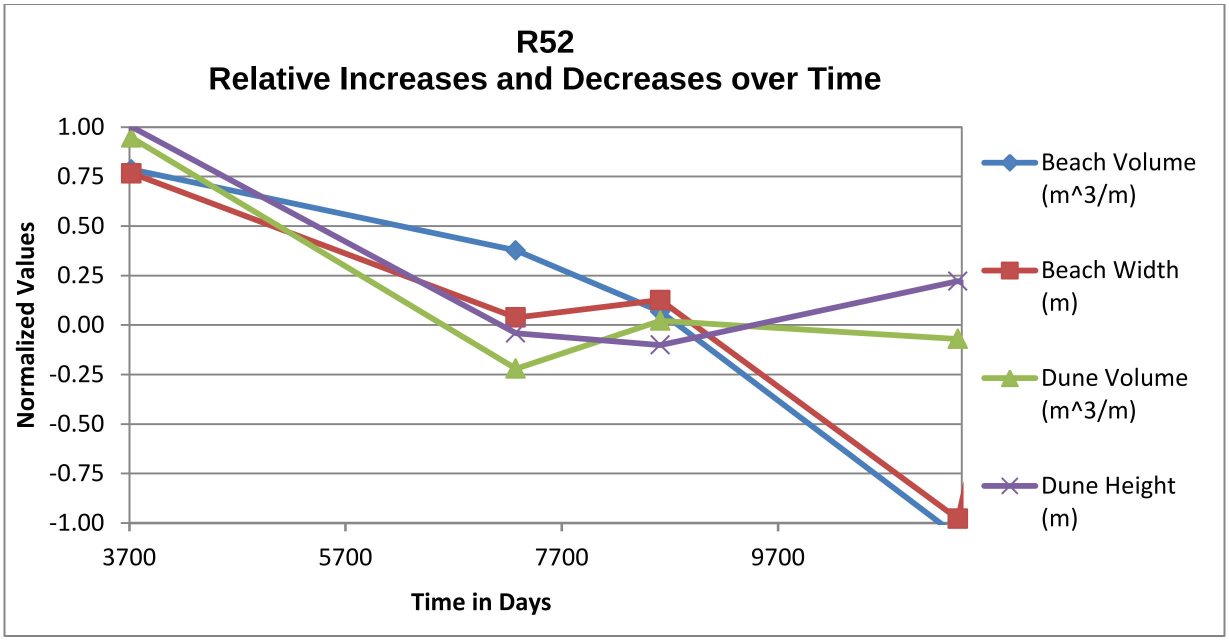


Figure 5.20 – Profile R52 beach and dune change. Foredune volume increase is at a maximum in 1983, then decreases slowly. Neither positive nor negative beach width and volume changes have any affect on the steady loss of foredune volume, although the decadal profile data may not provide representative beach conditions to conclude this.

line as previous surveys, but was 14.5 m south, and therefore may not accurately represent changes to the foredune since 2004. The foredune, however, is a continuous linear foredune with no visibly apparent variability as seen in figure 5.21.) The R71 foredune incrementally decreases in volume from 203.0 m^3/m to 83.4 m^3/m over the 34-year period of record. Foredune scarping on its stoss side is visibly apparent in the profiles. However, there is very little landward sediment transport over the crest of the foredune and minimal landward migration of the dune, thus leading to the decreasing dune volume. There are no reports of sediment on the road or in the parking lot landward of the single dune in this part of St. Joseph Peninsula State Park, and therefore the sediment must be transported offshore or further north with the longshore currents described in the previous chapter. Based on this data and sediment availability, if an erosion rate of 3.7 m^3/m/a (R^2 =0.97) continues, the R71 foredune will be gone in approximately 23 years (assuming no anthropogenic interference, the same erosion rate, and similar erosion events.) At this very narrow location of the spit, a washover event could divide the peninsula into a northern island and a southern spit still attached to the mainland. This contrasts with the foredune at R52, which has large amounts of sediment in landward dunes that may be cannibalized by the easterly retreating foredune. R71 has no available sediment or dunes landward to cannibalize or rework into the foredune as it retreats. While both R52 and R71 are the largest dunes in Gulf County, the profiles have different probable futures due to the sediment available for cannibalization as the foredune retreats. While it is often assumed that foredunes always migrate landward under beach erosion conditions (Figure 5.21 and 5.22), these foredunes have not been migrating landward in the short term (2004-2007), but maintaining their position, which may be best explained by the storm event dune scarping, sediment fill, and revegetation models (Giles and McCann, 1997; Hesp, 2002) as seen in Figure 5.23. However, in the longer term, both dunes are slowing translating landwards (Figure 5.23, 5.24, 5.25).

5.2.8 Profile R100

R100 has the second highest rates of shoreline erosion for this study, averaging 4.1 m/a over the period of 1973-1997. However, a much greater erosion rate was documented over recent years. The profiles measured in 2006 and 2007 were 10 m south of the FDEP profile line so as to not trespass through private landscaped property, and as such, these profiles are not a precise representation of the R100 profile (Figure 5.27). Additionally, it appeared anthropogenic activities helped build the foredune slightly seaward to protect the recreational vehicle parking space at this site. The lot has been undisturbed (and listed for sale) since the first field visit in 2006.

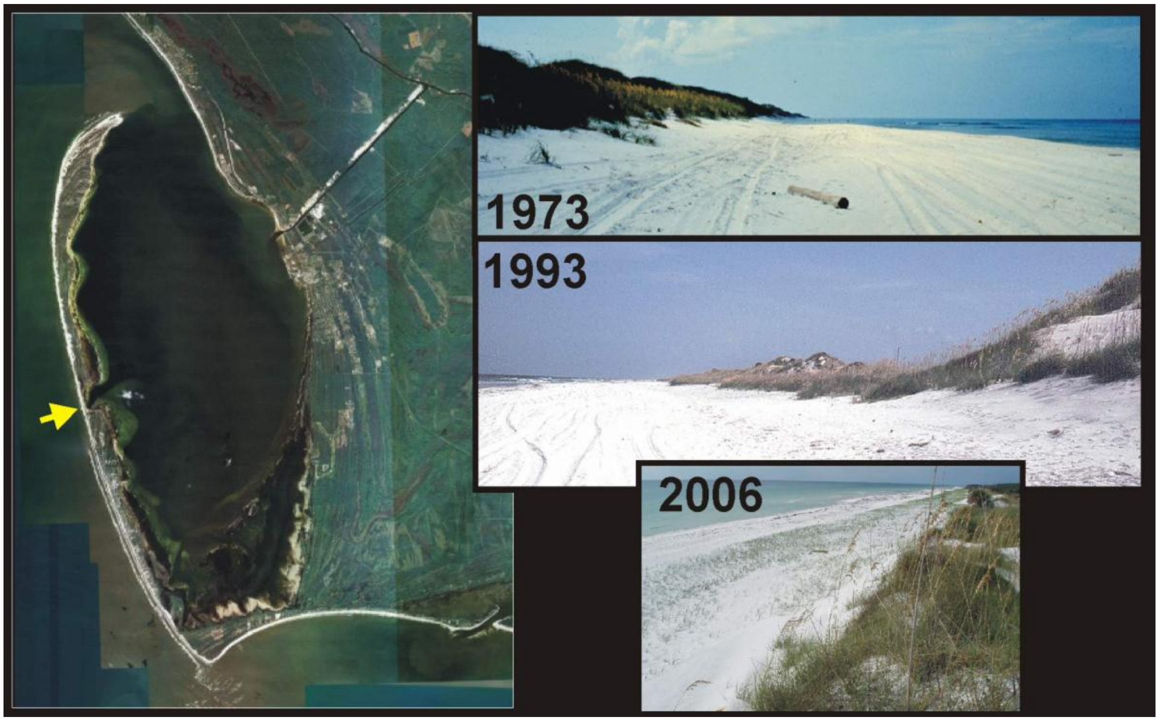


Figure 5.21 – Profile R71's high foredunes. New *Uniola sp.* were planted on the beach in 2006 to try to enhance foredune building, and increase protection to landward infrastructure.

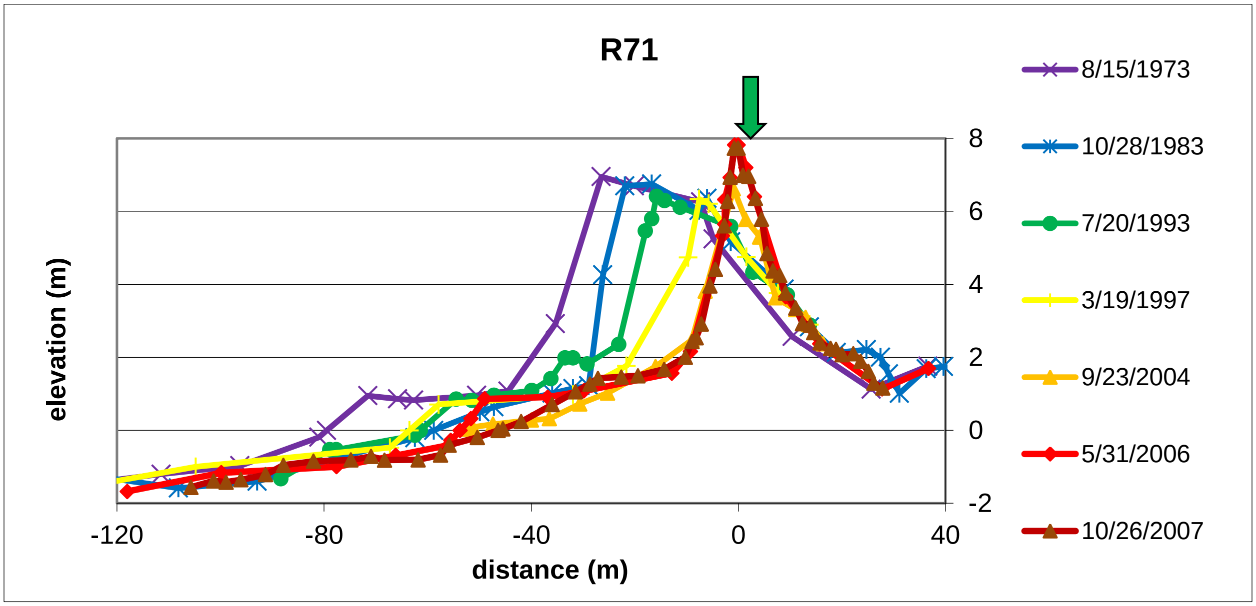


Figure 5.22 – Profile R71 cross-section. Foredune volumes decrease throughout the study period. The foredune progressively becomes more *arête-like* as sediment supply decreases.

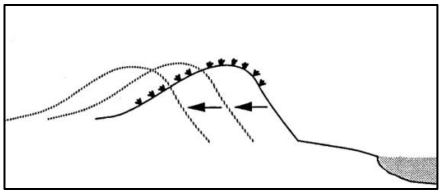


Figure 5.23 – Psuty's (1989; 303) model of foredune inland shifting due to beach erosion. Neither site R52 nor R71 exhibit the same degree of landward migration of the foredune as shown in the conceptual Psuty diagram, but certainly some landward lee slope development occurs over time. The dunes both decrease in height over the long term (particularly R71) but can remain relatively stable in height in the short term between major storms (e.g. R52, 2004-2007 period).

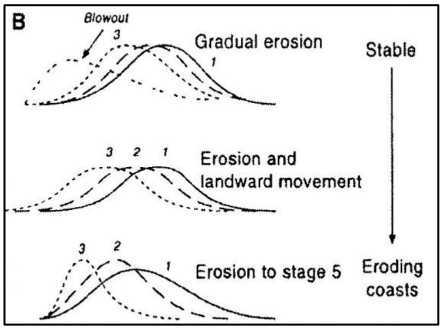


Figure 5.24 –Hesp's (2002; 253) amalgamated model of spatial-temporal foredune change depicts the foredune migrating landward on eroding coasts, seen in figures 5.17 and 5.20 of R52 or R71.

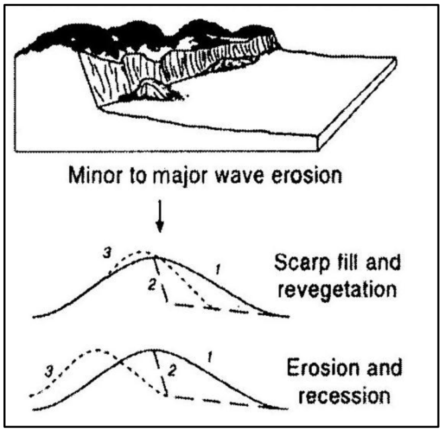


Figure 5.25 – The Hesp (2002; 253) model in which the upper diagram may provide a better explanation of the stable landward position of the foredune for sites R52 and R71 in the short term.scarp, fill and revegetation. Over longer time periods, the foredune may migrate landward while dense mature vegetation may hold the leeward portion of the foredune in position for a longer period. However, ultimately with each subsequent erosion event the foredune may retreat as shown in the lower time lapse diagram.

R100 foredune heights were at a maximum of 4.0 m, much lower than the heights found at the center of the peninsula (profiles R52 and R71 at 8.5 m and 7.8 m, respectively). The foredune crest has migrated landward with the shoreline with the crest being located 51.1 m (standard deviation = 3.8) behind the shoreline. This site's foredune is appearing to migrate landward as described in figure 5.27.

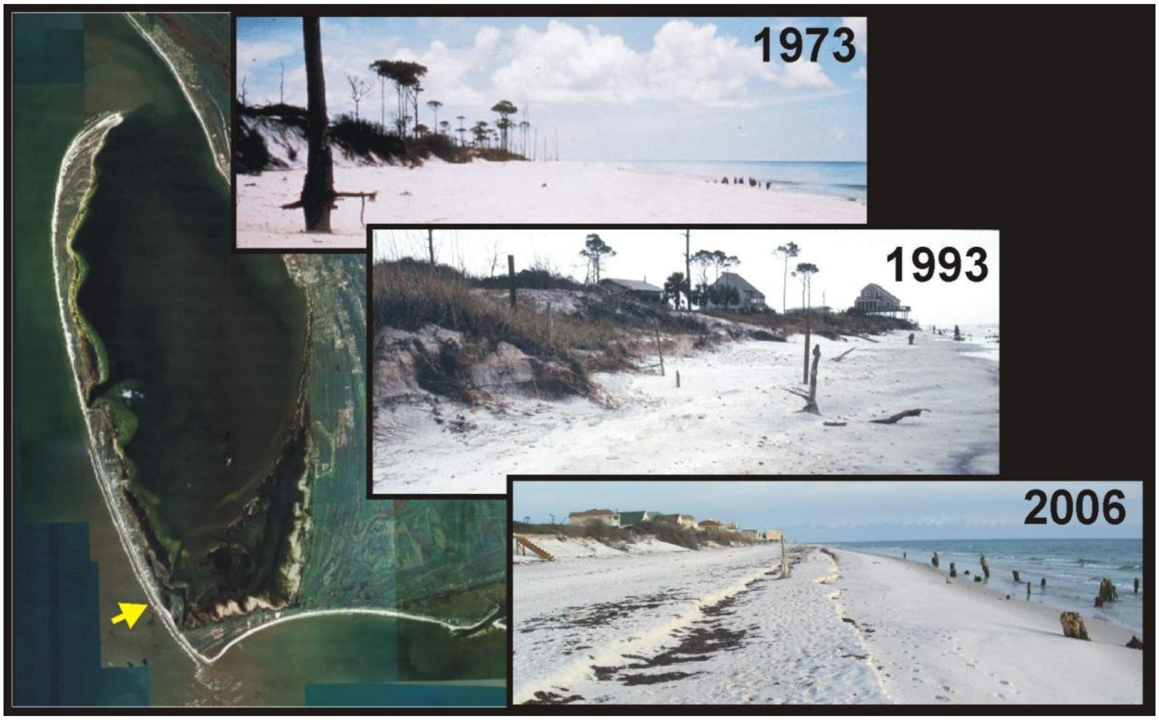


Figure 5.26 – Profile R100. Beach erosion as indicated by seaward tree stumps, has been accompanied by retreat and loss of the foredune.

5.2.9 Profile R110

Profile 110 is located at the highly eroding Cape San Blas (Figures 5.28 and 5.29), where the shoreline turns from a north-south alignment to an east-west alignment. Based on the 1973 to 1997 shoreline locations, profile R114 has the highest erosion rate in the county at 14.0 m/a (Foster and Cheng, 2001). Profile R110 has a very high erosion rate as well at 6.7 m/a (Foster

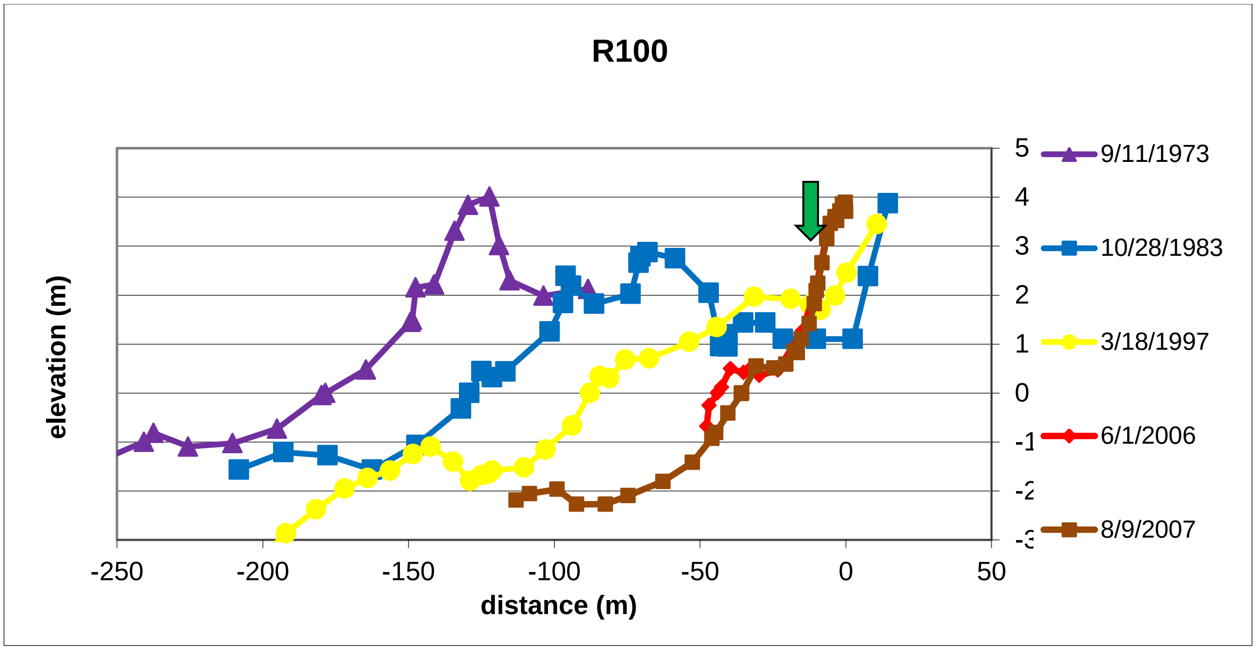


Figure 5.27 – Profile R100 cross-section. Constant beach erosion has been accompanied by retreat and total loss of the 1973 and 1983 foredune. The maximum width of the beach during the study period was 34.0 m. (1993 survey data not available from FDEP.)

and Cheng, 2001). The profile is located through an Elgin Air Force Base placement, which may be the reason for the flattened profile. Regardless, the rapid erosion has not provided a long enough time period for foredune development. A broad 2.8 m high foredune was present in the 1973 profile that had totally disappeared by the 1983 profile (Figure 5.30). A small embryo dune was present in the 2004 profile as well, but was no longer present in the 2006 profile due to ongoing beach erosion and/or severe erosion during Hurricane Ivan or Hurricane Dennis in 2005.

5.2.10 Profile R122

R122 is located close to Cape San Blas on the east-west arm of the Gulf County shoreline. Similar to R6 and R27, this area has been classified as a beach ridge strandplain by Tanner (1975) and Otvos (2005) and has a series of low ridges. Between 1973 and 1983 the

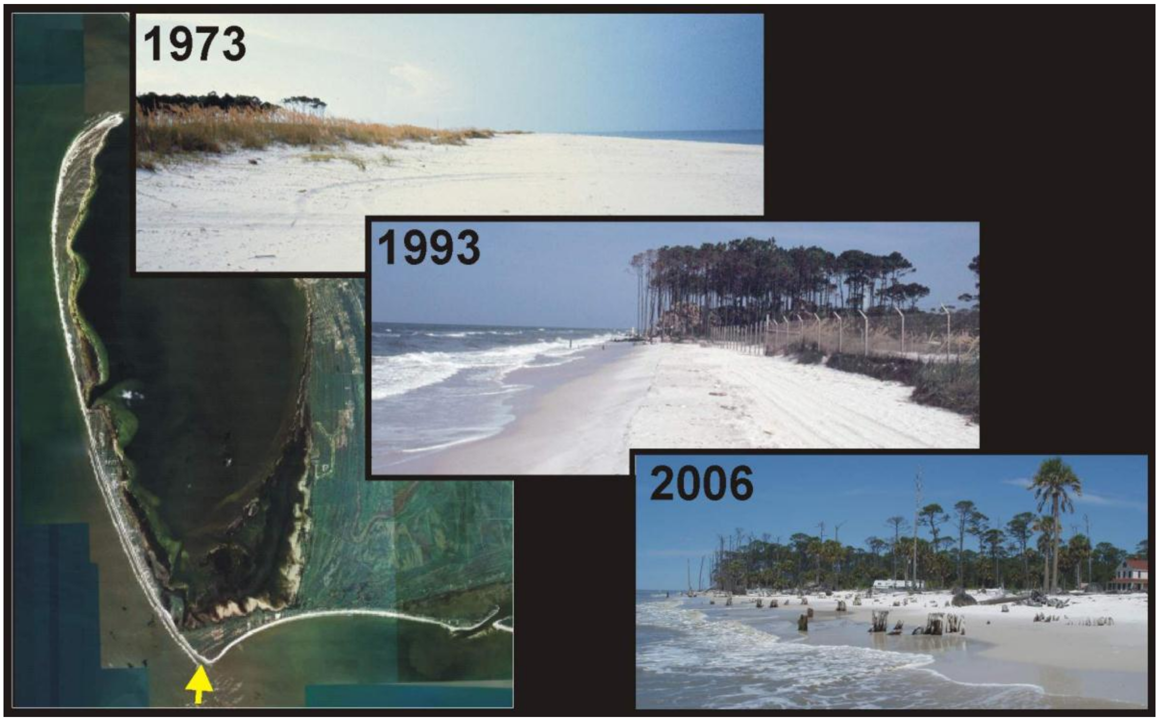


Figure 5.28 – Profile R110. The 1973 view (looking east) displays the wide beach and foredune present on the 1973 profile. Following extensive erosion, the 1993 (looking west from R112) and the 2006 (looking west) photo show no foredune and continued beach erosion.

beach prograded 87.6 m. During that time period, five new (sub-two meter) ridges formed (Figure 5.28). Subsequent time periods had a slower rate of beach progradation and fewer new small ridges formed. The 2004 profile displays a single new foredune, and an additional three new ridges were found on the 2006 profile (Figure 5.32). The 2004 foredune was no longer present in 2006, which resulted from sediment reworking and overwash during and post-Hurricane Dennis in 2005 (Figure 5.33). The beach progradation and recorded new ridge growth, although more rapid, is more comparable to profile R6 and R27 as was seen in figures 5.4 and 5.6.

Figure 5.34 shows the changes in beach and foredune dimensions. After the initial decrease in beach and foredune dimensions, the beach and foredune volumes changed inversely to each other from 1983 to 1993 (beach negative, dune positive), and 1993 to 1997 (beach

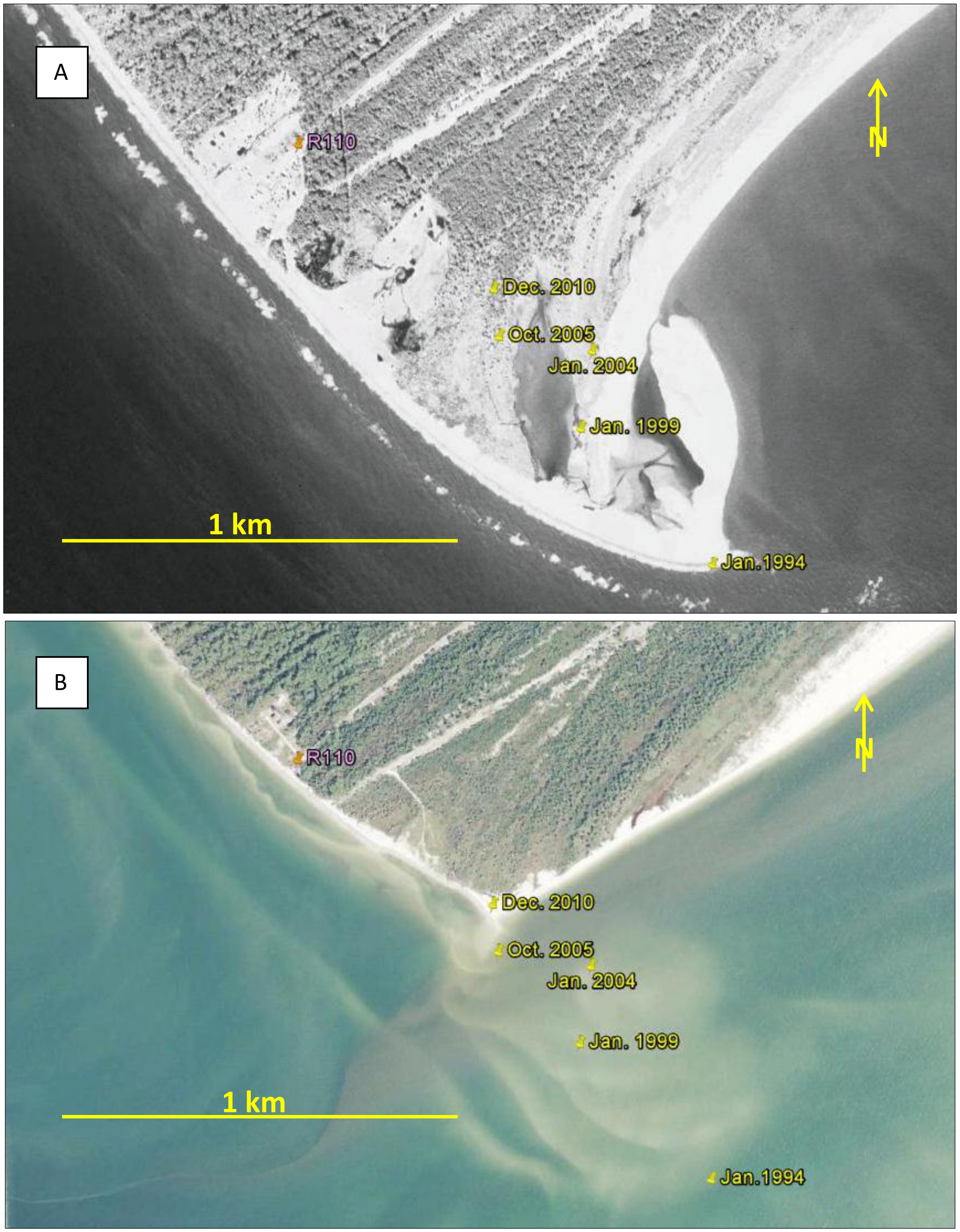


Figure 5.29 – Cape San Blas aerial photographs from January 1994 (A) and December 2010 (B). Great erosion occurred between 1994 and 1999 due to Hurricane Opal (1995) and steady erosion from relatively high energy refracted waves reaching the Cape.

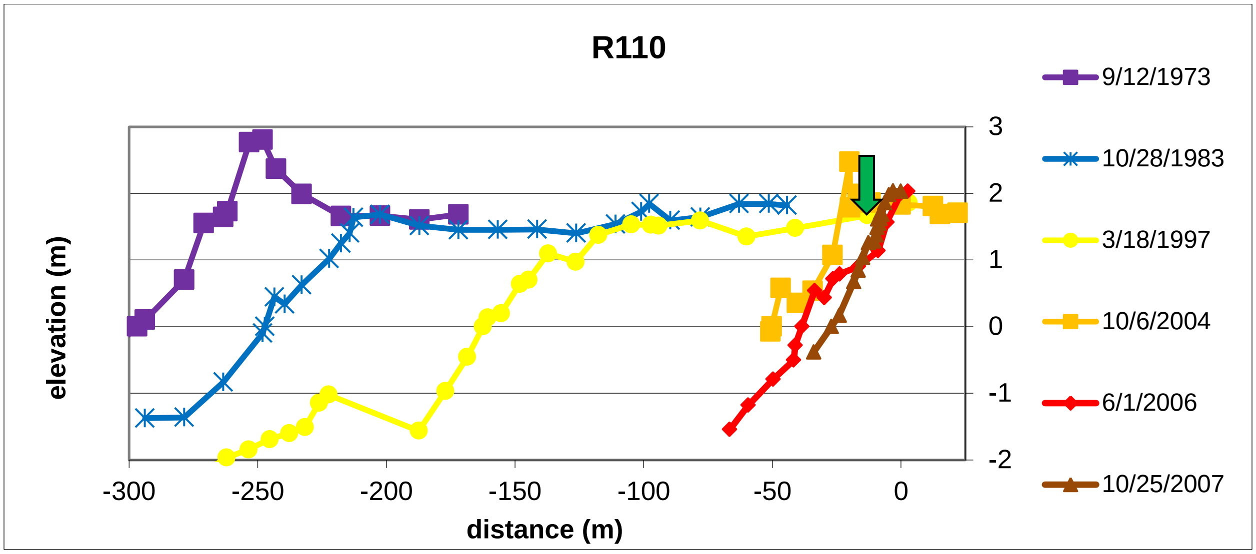


Figure 5.30 – Profile R110 cross-section. This site has an average erosion rate of 6.7 m/a, while the entire Cape has been eroding at a rate of 14m/a (Foster and Cheng, 2001). An established foredune was present in 1973. No new foredune was present until a small ridge formed between 1997 and 2004. However, this foredune was gone by 2006. (1993 data not available from FDEP.)

positive, dune negative). Between 1997 and 2004, the beach-foredune relationship remained constant until the beach and foredune dimensions increased from 2004 to 2006. This single profile location highlights the beach and foredune sediment supply variability, consequently making the Psuty (1998, 2004) sediment supply models difficult to apply to the highly dynamic nature of beach and dune change at this location.

5.2.11 Profile R143

Profile 143 is located in the center of the east-west arm of the Gulf County shoreline. During the period of record, the beach has remained relatively stable, with some beach erosion occurring between 1997 and October 2004 (Figure 5.36). This retreat of the shoreline might be related to sediment loss during Hurricane Dennis or Hurricane Ivan. However, the shoreline had returned to its previous position by 2006.

The 1973 foredune was at a maximum height in 1973. In 1983, two new ridges had formed seaward, but were no longer present in the 1993 profile. The new 1993 foredune ridge continued to build in 2004, but by 2006 this ridge had been scarped and/or migrated landward and built taller. The swales between the original 1973 ridges have been progressively filled with sediment since 1973. During periods of beach width and volume increase, the foredune volume decreased in size.

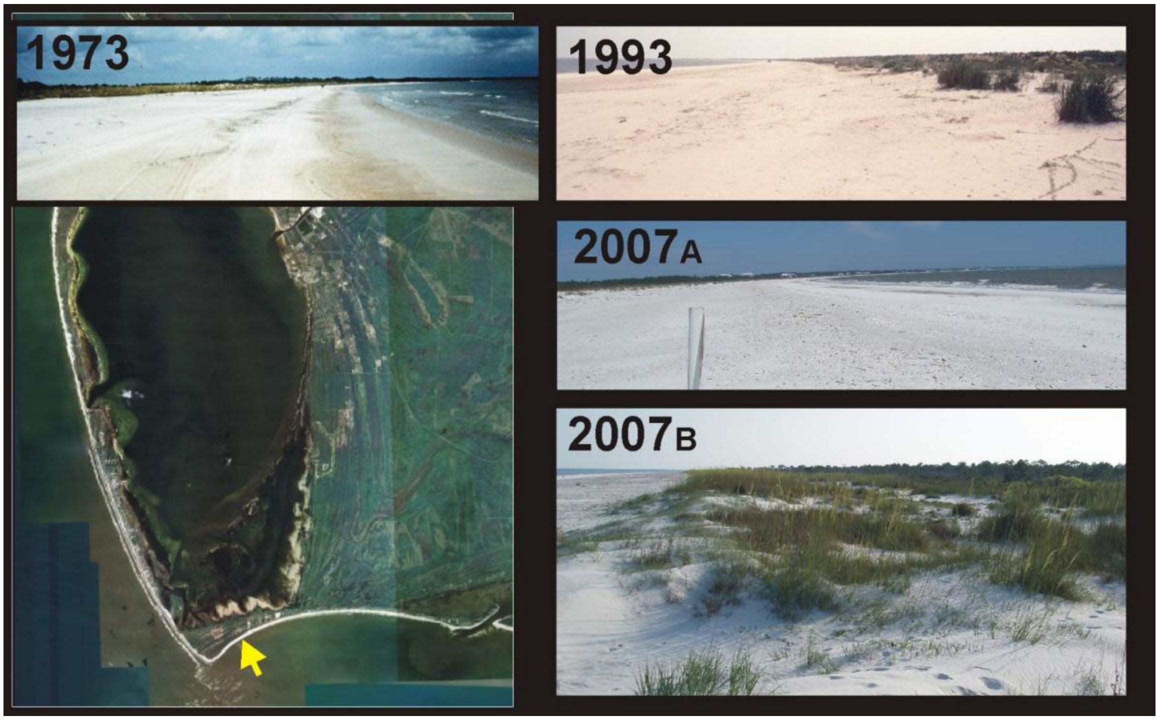


Figure 5.31 – Profile R122. The site consistently had a wide prograding beach with a series of low ridges since 1973. The 2007A photo shows the existing wide beach which may be sediment transport limited by the shell lag surface during this period. However, the foredune is still slowly building at this location.

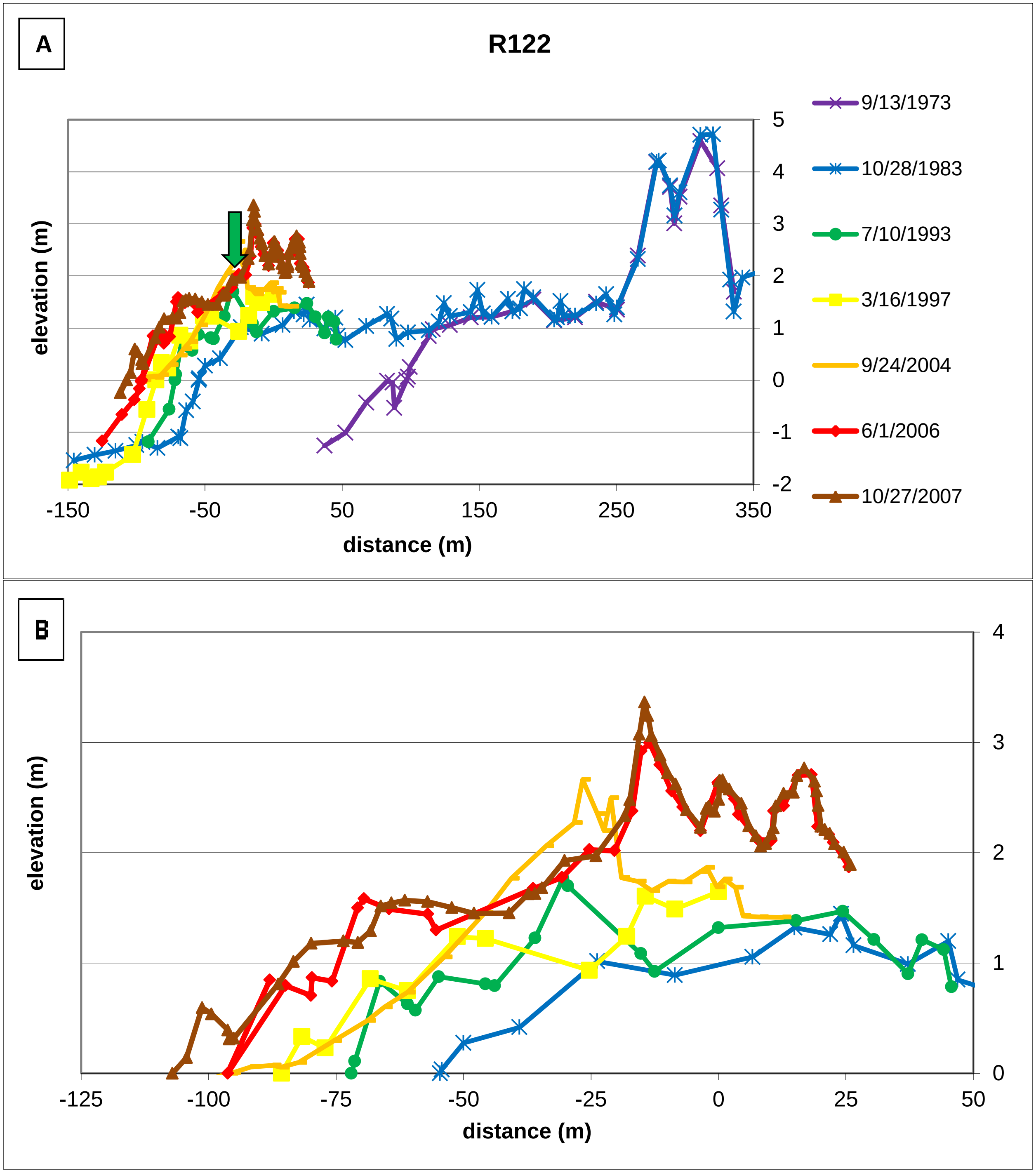


Figure 5.32 – Profile R122 cross-section. The top graph (A) illustrates the full profile from 1973 which displays large (4.2 m to 4.7 m high) relict foredunes behind a series of smaller ridges. The bottom graph (B) better displays the post-1993 profiles, including the three new ridges which developed between 2004 and 2006. It is speculated that the 2004 foredune was destroyed by storm surge and waves during Hurricane Dennis.

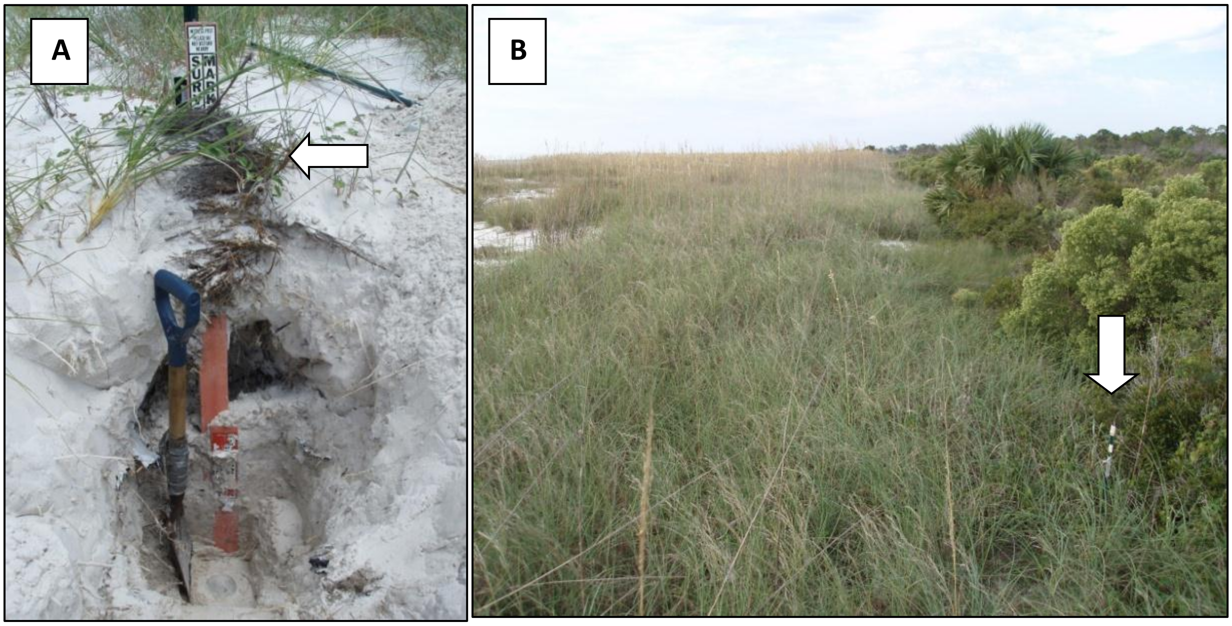


Figure 5.33 –The FDEP R122 benchmark buried over a meter deep (photo A). Vegetation wrapped around the survey marker indicates that washover conditions occurred at this location. The sediment has been deposited since September 24, 2004 indicating washover deposition during Hurricane Ivan (2004) and/or Hurricane Dennis (2005). The new deposition is dominated by pioneer grasses up to the end of the 2006 profile line (arrow in photo B) confirming recent deposition. The shrubline indicates the inland extent of washover deposits from the 2004 storms.

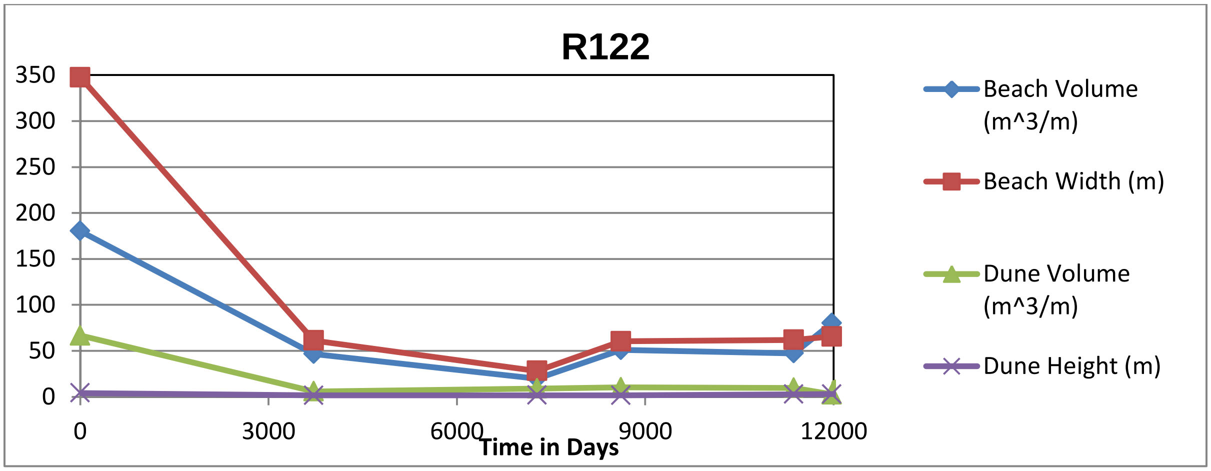


Figure 5.34 – Profile R122 beach and foredune changes. The 1973 (day 0) small ridges were included in the beach volume, and the foredune volume only included the large landward foredune on the profile.

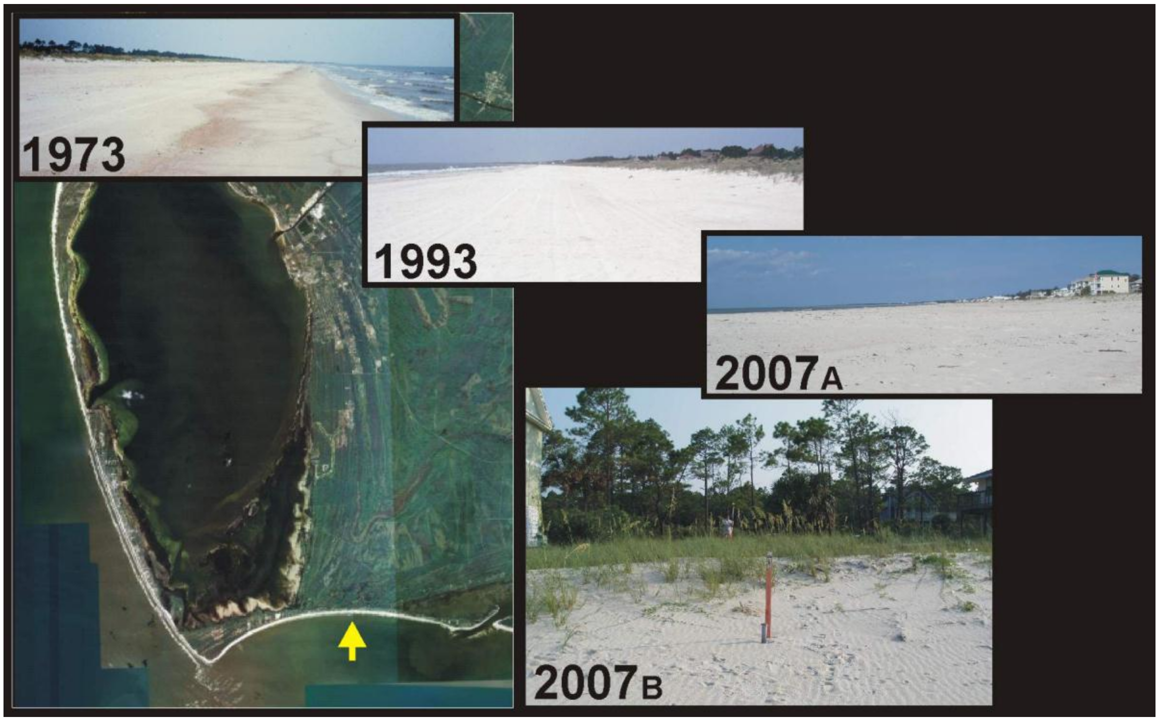


Figure 5.35 – Profile R122. The site maintained a consistently wide beach. New development near the edge of vegetation can be seen between the 1993 and 2007A photos. 2007B is one of the last lots still undeveloped on this stretch of Gulf County shoreline.

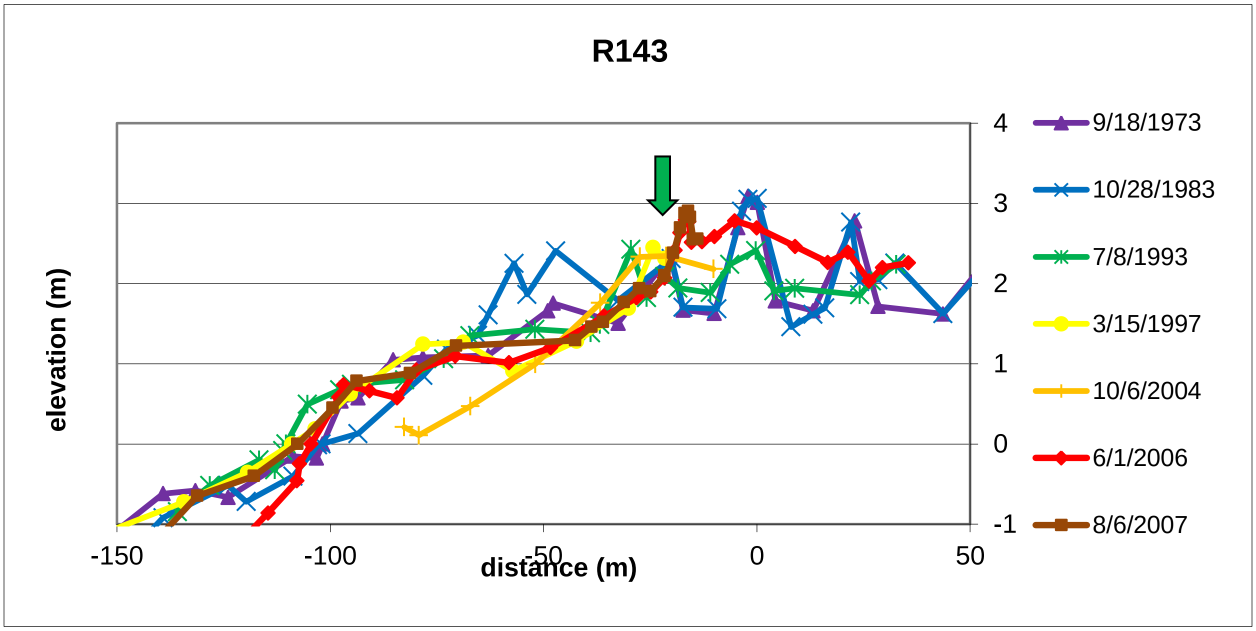


Figure 5.36 – Profile R143 cross-section. Shoreline position remained stable through the study period. The low foredune changed in height and location, however, it was never taller than 3.1 m.

While the beach and foredune locations change slightly, there is a consistent trend of an approximately 3 m high foredune located roughly 100 m from the shore. Beach width increases and decreases until the last part of the study period (2004-2006), when the beach volume and dune volume increases (Figure 5.37). Once again, this part of the Gulf County shoreline does not seem to maintain a consistent increase or decrease in dune or beach volume that could fit Psuty's (1988, 2004) models, despite the foredune not changing location or volume by large amounts. The growth in place of the foredune is better described by Hesp (2002) on a stable coast, which may go through a cycle of development followed by erosion and washover during hurricane events described by Cleary and Hosier (1979).

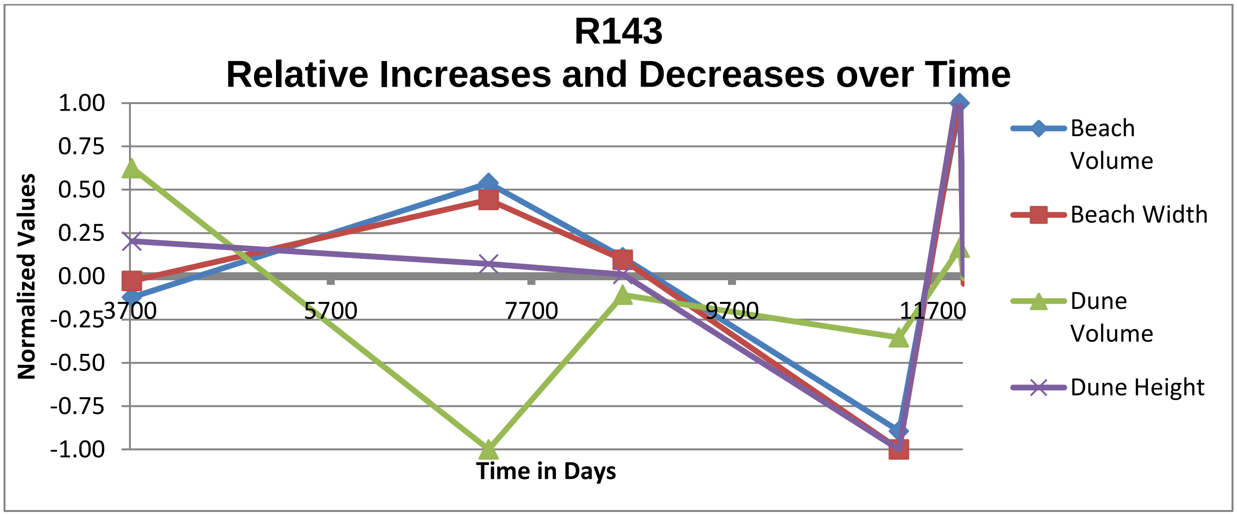


Figure 5.37 –Relative beach and dune change on profile R143. Foredune volume change is inverse to beach volume and width until 2004 when both are negative. By 2006 however, both beach and dune volume increased in volume.

5.2.12 Profile R155

Profile R155 is located at the eastern end of Gulf County's shoreline, near Indian Pass, where some of the Apalachicola River sediment discharges into the Gulf of Mexico (Kwon, 1969) (Figure 5.38). The beach rapidly prograded between 1973 and 1983, and a new 3.0 m high foredune was built during this time period (Figure 5.39). Between 1983 and 1993 the beach eroded and the 1983 foredune was no longer present. However, a series of new ridges evolved gulfward of the 1983 foredune. Between 1973 and 1983 the swale maintained its position but lost some of its depth, possibly by windblown sand filling in the bottom of the swale. Following 1993, the beach prograded and the ridges found in 1983 continued to build upwards. This foredune continued to build through 2006, and a new embryo dune-ridge was established and continued building through the 2007 study period.

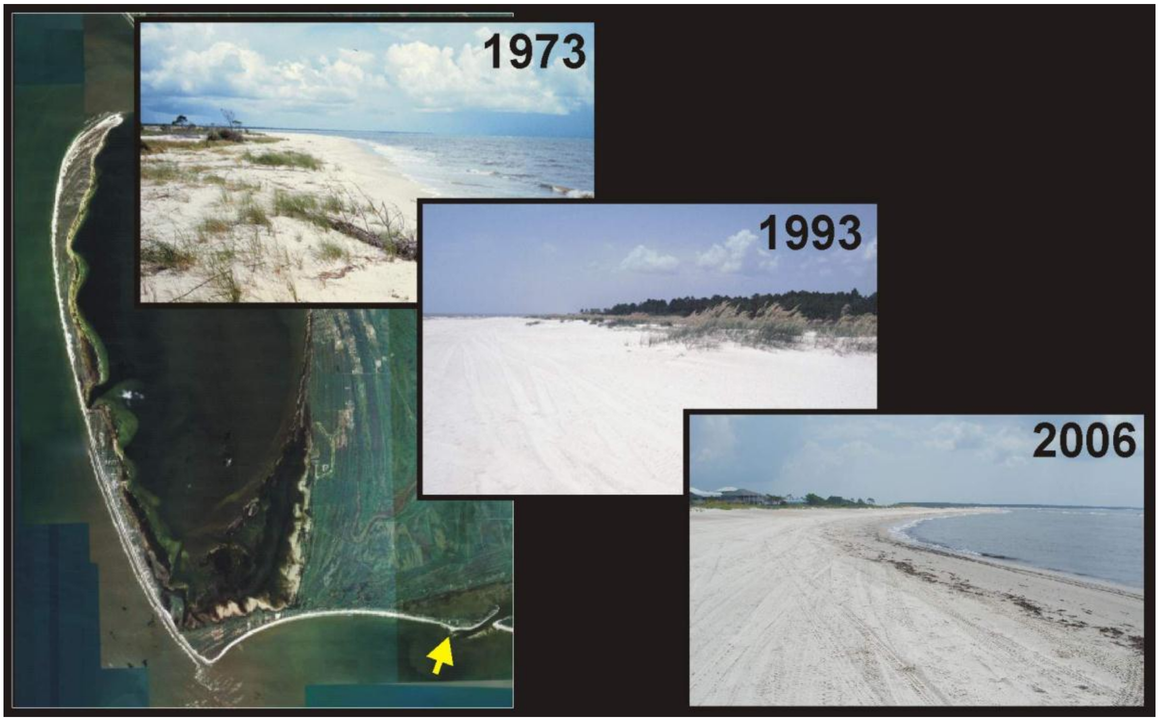


Figure 5.38 – Profile R122. The 1973 photo shows a vegetated ridge located near the shoreline, indicating a period of recent erosion. Subsequent photos display a wider beach.

Foredune volume and height increases coincided with beach progradation to 1983. The foredune volume evidently decreased in association with a decrease in beach width and volume (Figure 5.40). This resulted from a new foredune developing further seaward on the prograding beach, and as a result the new foredune was smaller and the adjacent beach was smaller in dimensions. The beach continued to prograde, while no new foredune developed until 2007.

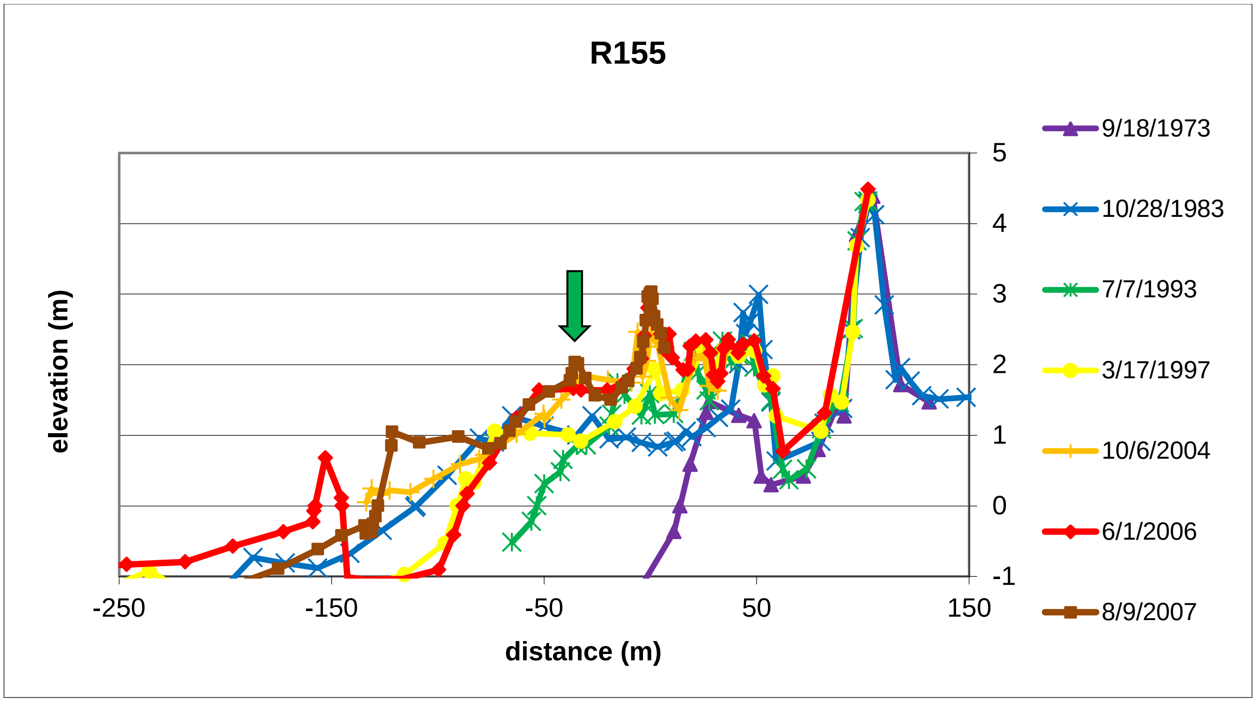


Figure 5.39 – Profile R155 cross-section. The beach steadily prograded with new ridges evolving over time. The current foredune has been building upwards in its current location, while a new embryo dune ridge is developing seaward.

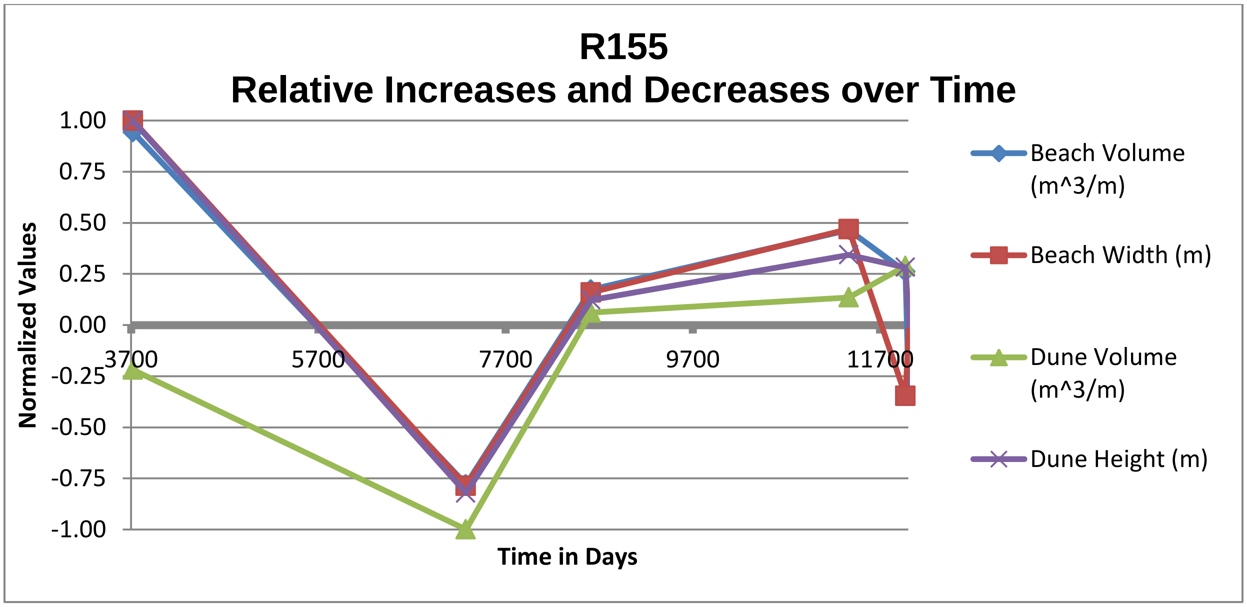


Figure 5.40 – Beach and dune changes on Profile R155. The foredune and beach dimensions operated in sync until 1997 when the beach increased while the foredune decreased. The foredune decrease in volume is a result of the initiation of a new foredune seaward of the previous dune.

5.3 Short-Term Data

The following section includes descriptions of the short-term changes to the profiles described in section 5.2. Each section includes a brief description of the study sites and the small changes to the foredune in the profile locations. These approximate 6 week profiles do not show the same dramatic change when compared to the decadal data presented in section 5.2. This may be related to no major tropical storm or hurricane impacting the study area from May 2006 through 2008 or no new event synchronization as decribed by Houser (2009).

5.3.1 Profile R6

The approximately 32 m wide beach on profile R6 migrated back and forth over a range of 10 m (standard deviation of 5.5 m) during the study period. This migration, however, did not alter the position or general shape of the low foredune (Figures 5.41 and 5.42).

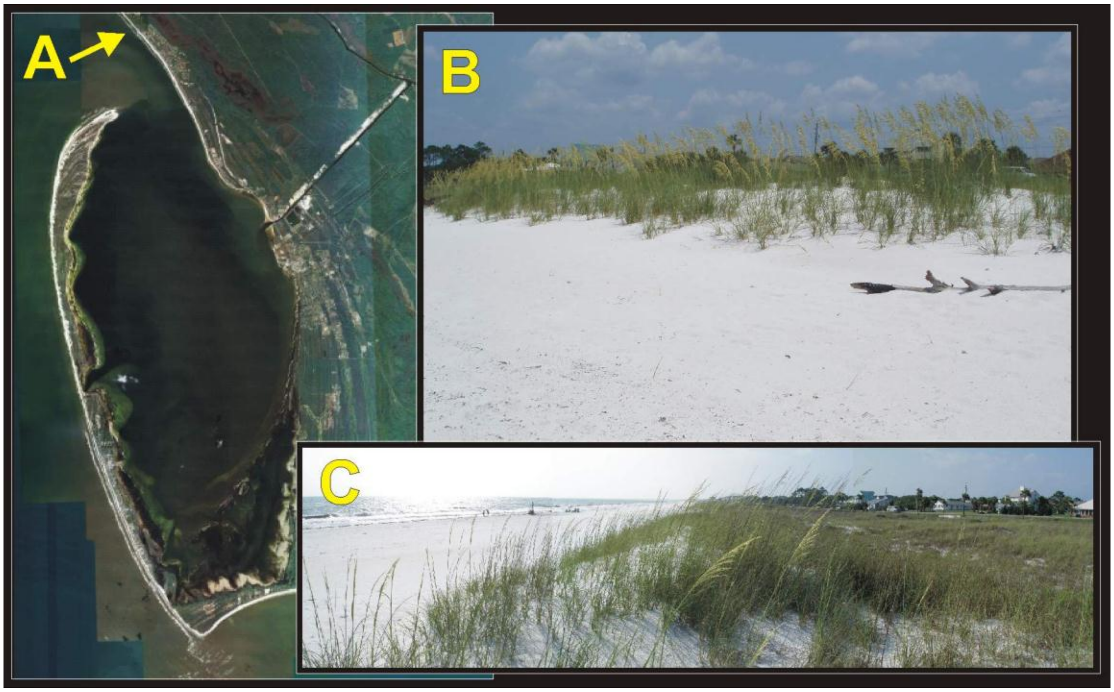


Figure 5.41 – Profile R6. Photo A marks the location of the profile in Gulf County, Florida; photo B shows the gulf-side of the foredune; and photo C displays the beach and foredune looking north.

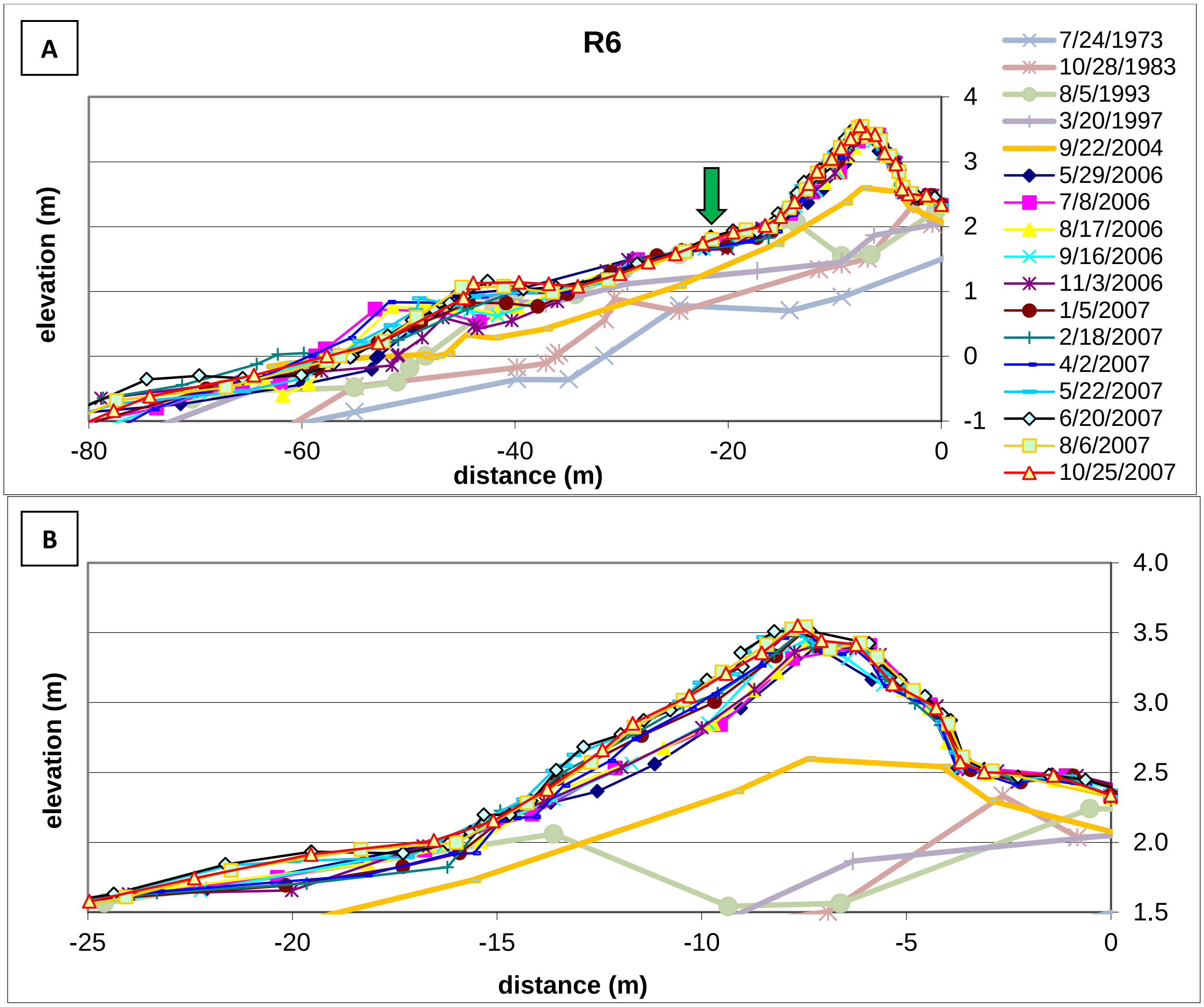


Figure 5.42 – 1973 to 2007 profile change data is shown in the top profile (A), including the recent 6-weekly surveys. The bottom profile (B) displays closer detail in the 2004 (orange line) and the 2006 to 2007 profiles. While the general morphology changed very little between 2006 and 2007, there was seaward building above the dune toe and a progressive increase in foredune volume.

The foredune progressively increased in volume from 17.47 m^3/m to 20.55 m^3/m during the 2006-2007 study period. This increase in volume can be attributed to sediment deposition on the seaward side of the foredune and only minimal sediment passing through the more densely vegetated foredune crest. The foredune grew in height approximately 0.15 m during the 513 day

(0.11 m/a) study period, which was a slow increase compared to the 0.80 m during the 2004 to 2006 (0.48 m/a) period.

5.3.2 Profile R27

In similarity to profile R6, the low foredune on profile R27 maintained its shape, with a slight increase in volume (1.40 m^3/m) and a minute change in height (approximately 2 cm - an increase that could be attributable to measurement error,) during the 2006-2007 study period (Figure 5.43 and 5.44). Additionally, a small incipient dune was present at the location in 2004 that became a foredune by 2006. In contrast, the foredune only grew in height approximately 0.02 m during the 2006-2007 study period, but the height was lost, possibly due to anthropogenic disturbance or during the topographic surveys. The limited increase in foredune volume and height is probably related to minimal sediment transport on the steep, short beach.

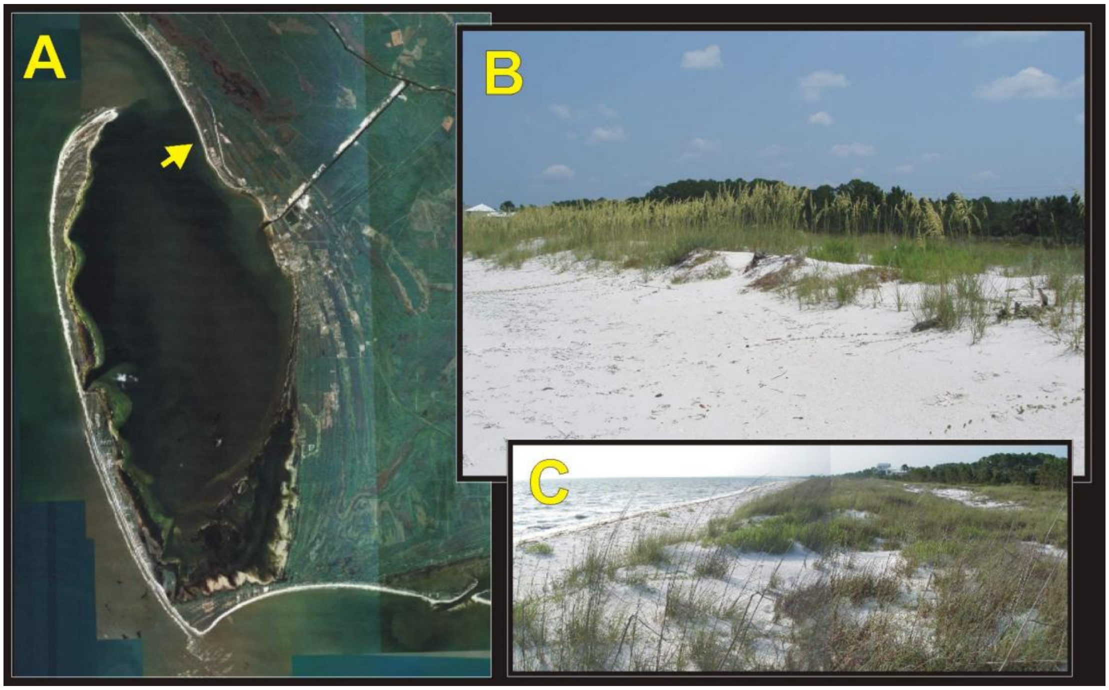


Figure 5.43 – Profile R27. Photo A marks the location of the profile in Gulf County, Florida; photo B shows the gulf-side of the foredune; and photo C displays the beach and foredune looking north.

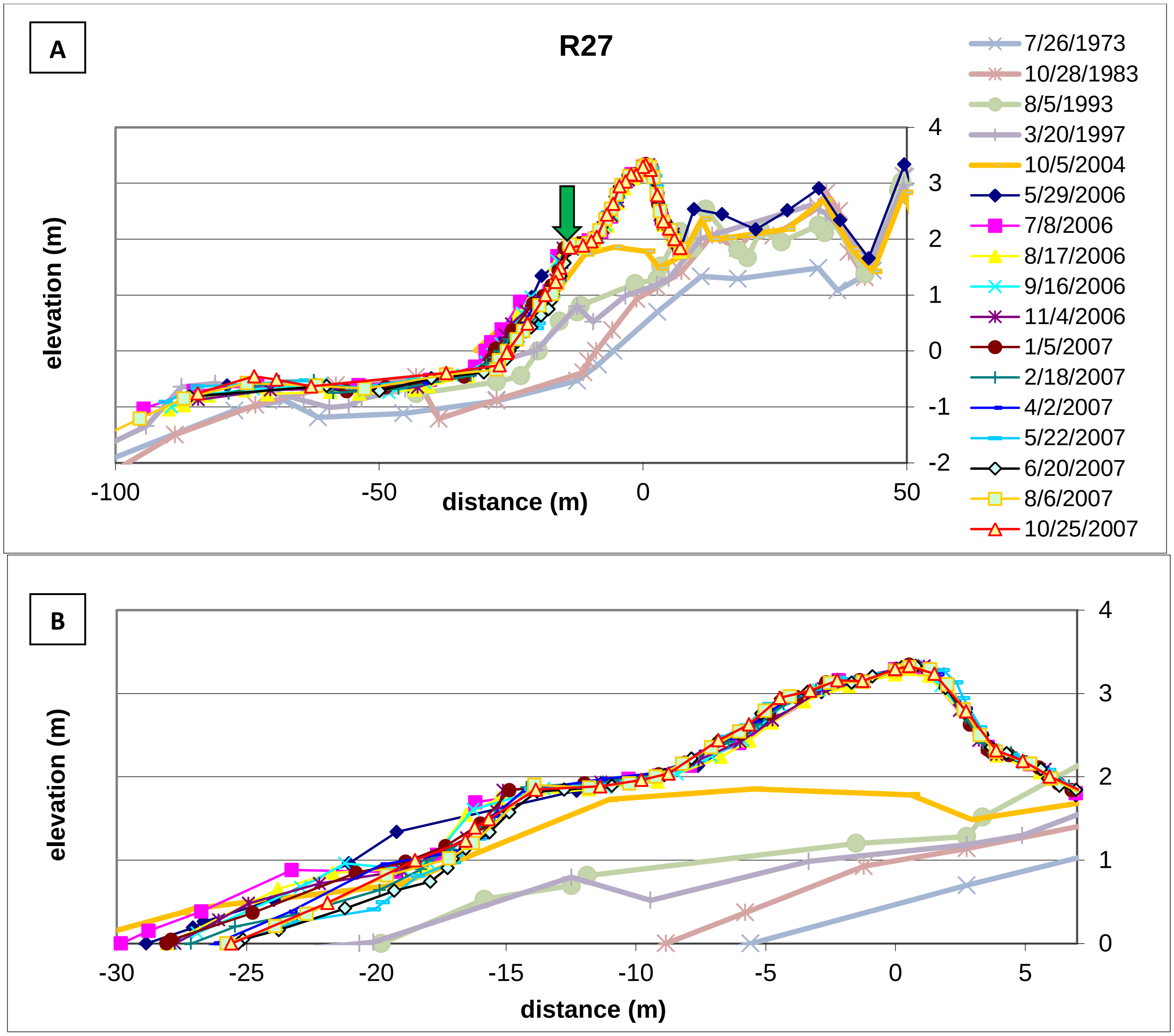


Figure 5.44 – R27 1973 to 2007 profile change data is shown in the top profile (A), including 6-weekly surveys. The beach eroded slightly between 2006 and 2007, yet the foredune showed no signs of scarping and increased 0.99 m^3/m in volume. The bottom profile (B) displays more detail in the 2004 (orange line) and the 2006 to 2007 profile. The general morphology changed very little between 2006 and 2007.

5.3.3 Profile R32

Profile R32 had two ridges that coalesced during the 2006-2007 study period (Figures 5.45 and 5.46). Sediment filled the small gap between the two ridges and as a result this became the new foredune that was used for foredune height and volume calculations. Prior to the formation of the merged foredune, both ridges were included in the volume calculations, thus the only major changes to foredune volumes occurred while the gap between ridges was filled.

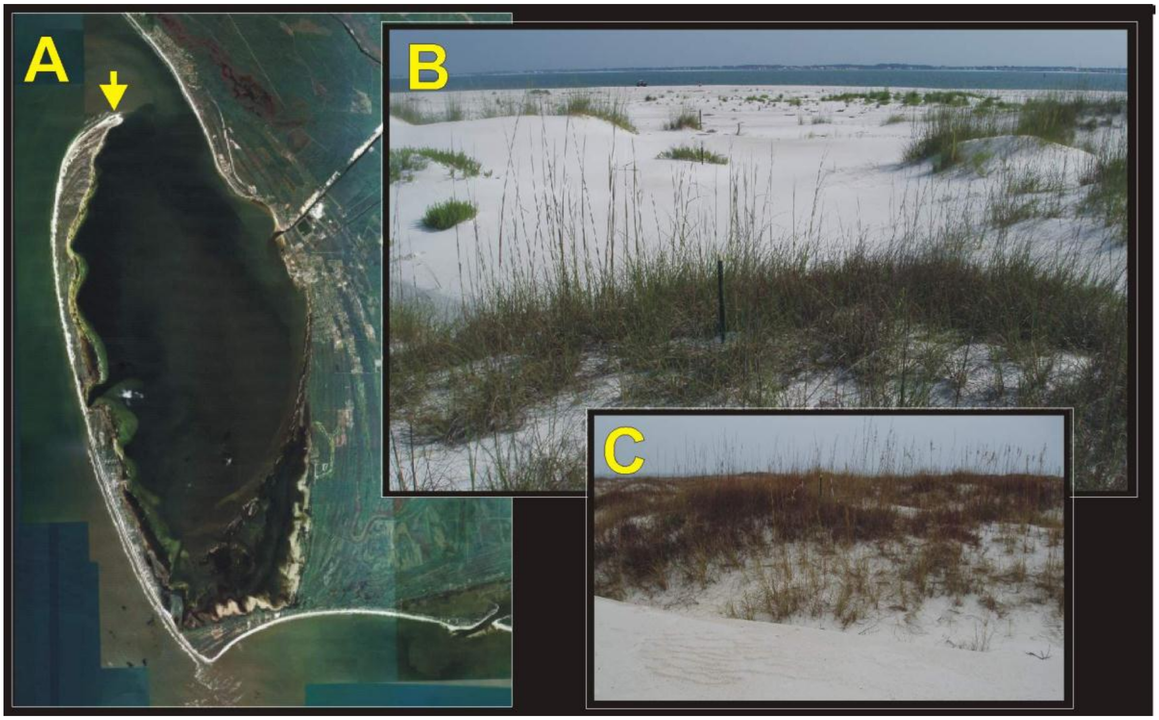


Figure 5.45 – Profile R32. Photo A marks the location of the profile in Gulf County, Florida. Photo B looks due north from the top of the foredune, with Mexico Beach visible on the horizon. Photo C looks south at the foredune crest. There is a slight gap between the more recently deposited sediment and the vegetated foredune. The gap was filled by February 2007.

Profile R32 had the fastest prograding beach in Gulf County during the 2006-2007 study period. Located at the tip of St. Joseph Peninsula, and in the approximate direction of maximum spit elongation, the beach prograded a total of 53.15 m (37.8 m/a). While this progradation occurred, a beach larger than 200 m was exposed to wind and potential sediment transport. However, there was a large increase in foredune volume only in the time period in which the gap between ridges filled-in. After the gap between the two ridges was filled, the foredune volume increased less than 1.0 m^3/m, and the foredune height decreased 0.05 m despite the massive amount of sediment available for transport. However, aeolian blown sediment was starting to develop minor incipient dune forms (less than 0.15 m) across the beach, but these incipient dunes were not included in foredune volume calculations for this study. This wide foredune terrace continued to develop small hummocks around vegetation clumps and cats-eye ponds in subsequent surveys. Additional visits since 2008 show the development of new incipient and highly vegetated foredune ridges across the beach.

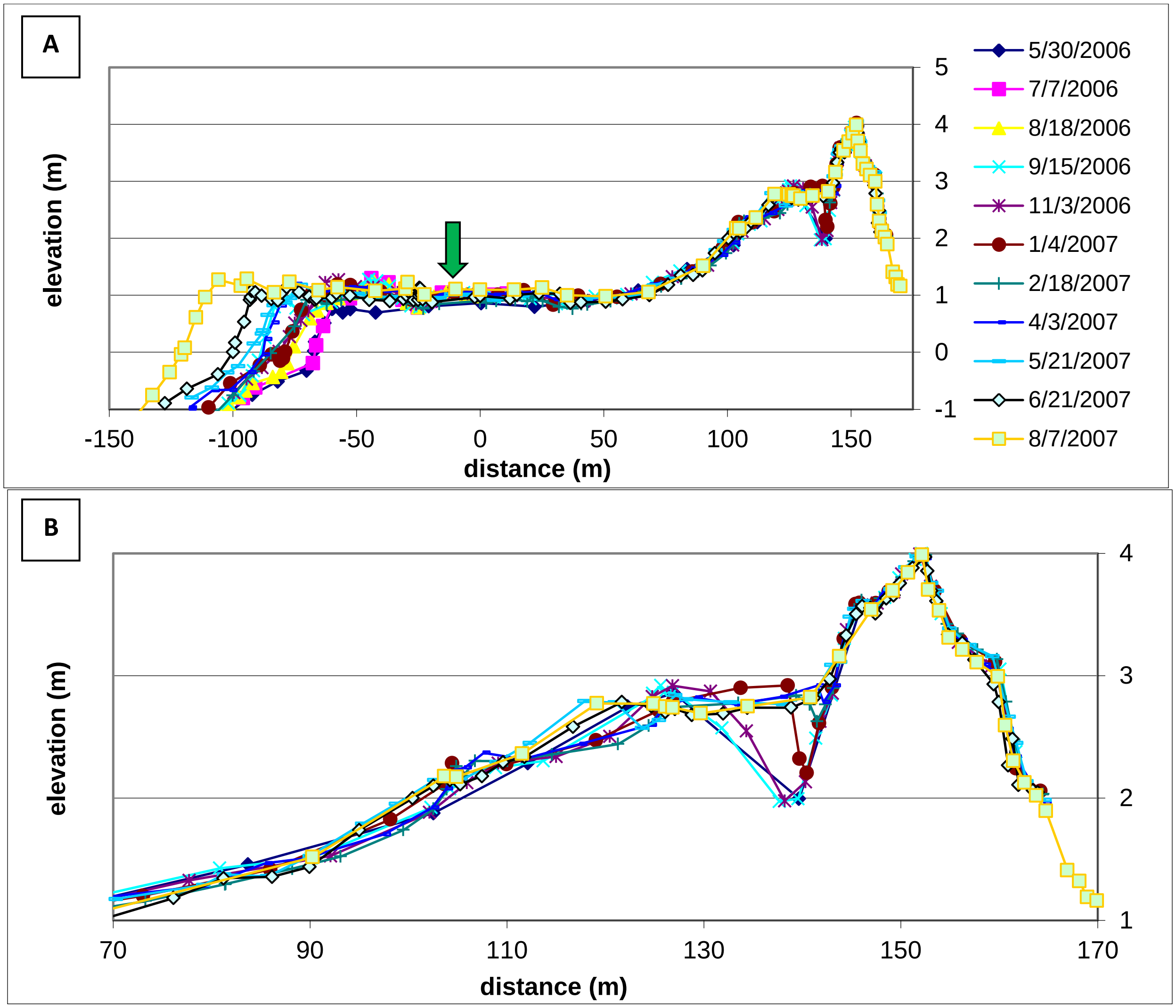


Figure 5.46 – R32 2006-2007 profile change. The top profile displays the extremely wide and rapidly prograding beach. During the study period no new foredunes had developed. The bottom profile displays a closer view of the foredune. The greatest increase in foredune volume occurred when sediment filled the gap between the two ridges of the foredune.

5.3.4 Profile R33

Profile R33 extends from a landward water-filled swale pool, over the foredune, into a lagoon, and across an elongating and emerging bar. The 2006-2007 emerged bar on profile R33 is separated from St. Joseph Peninsula by a narrow lagoon, which is slowly being filled (Figures 5.47 and 5.48).

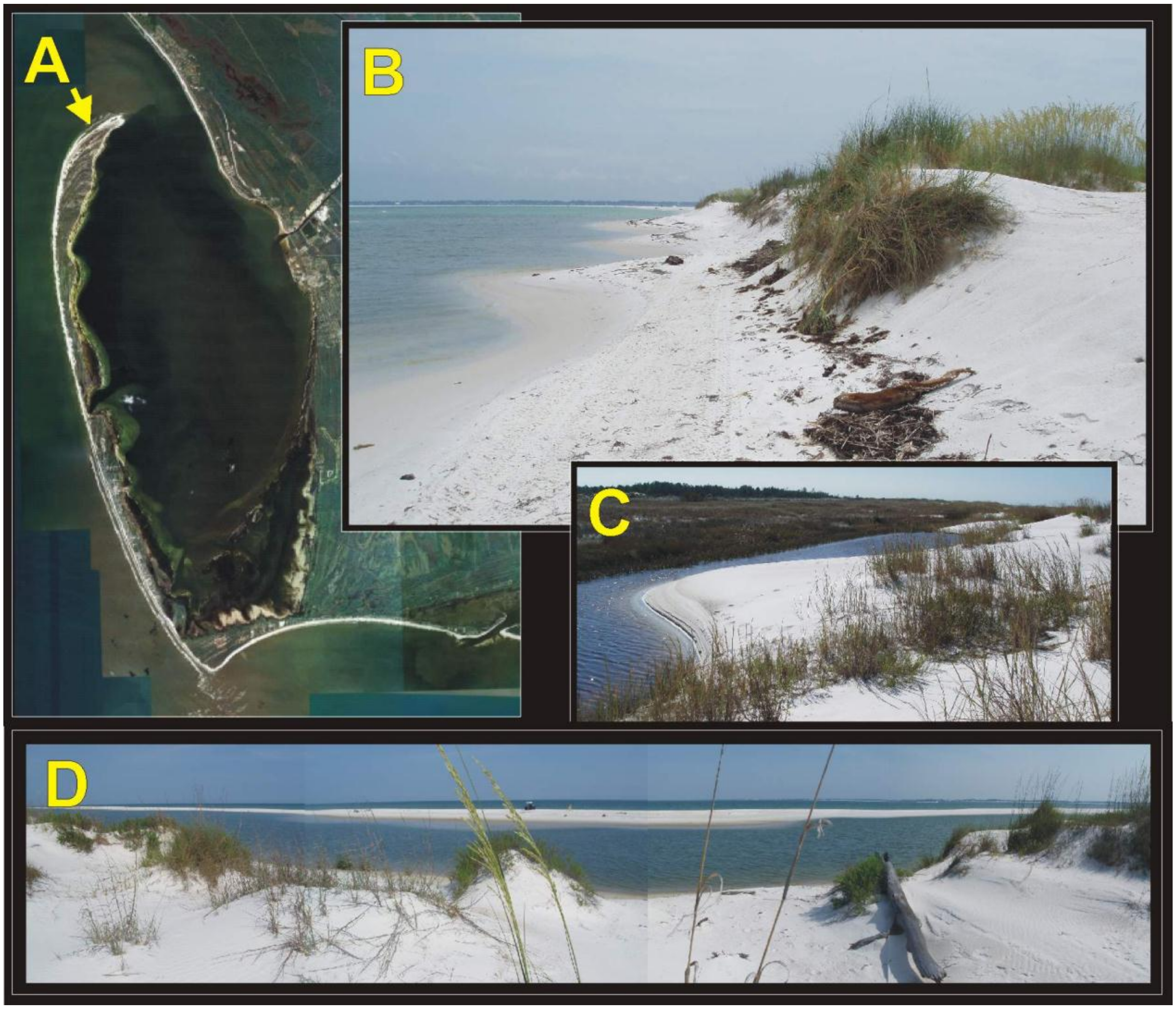


Figure 5.47 – Profile R33. Photo A marks the location of the profile in Gulf County, Florida. Photo B looks north along the beach and foredune. Photo C looks south leeward of the foredune crest. Sediment blowing through the scarped and eroding foredune is deposited landward into the adjacent swale pool. Photo D looks west across the foredune crest, across the lagoon and the emerged bar.

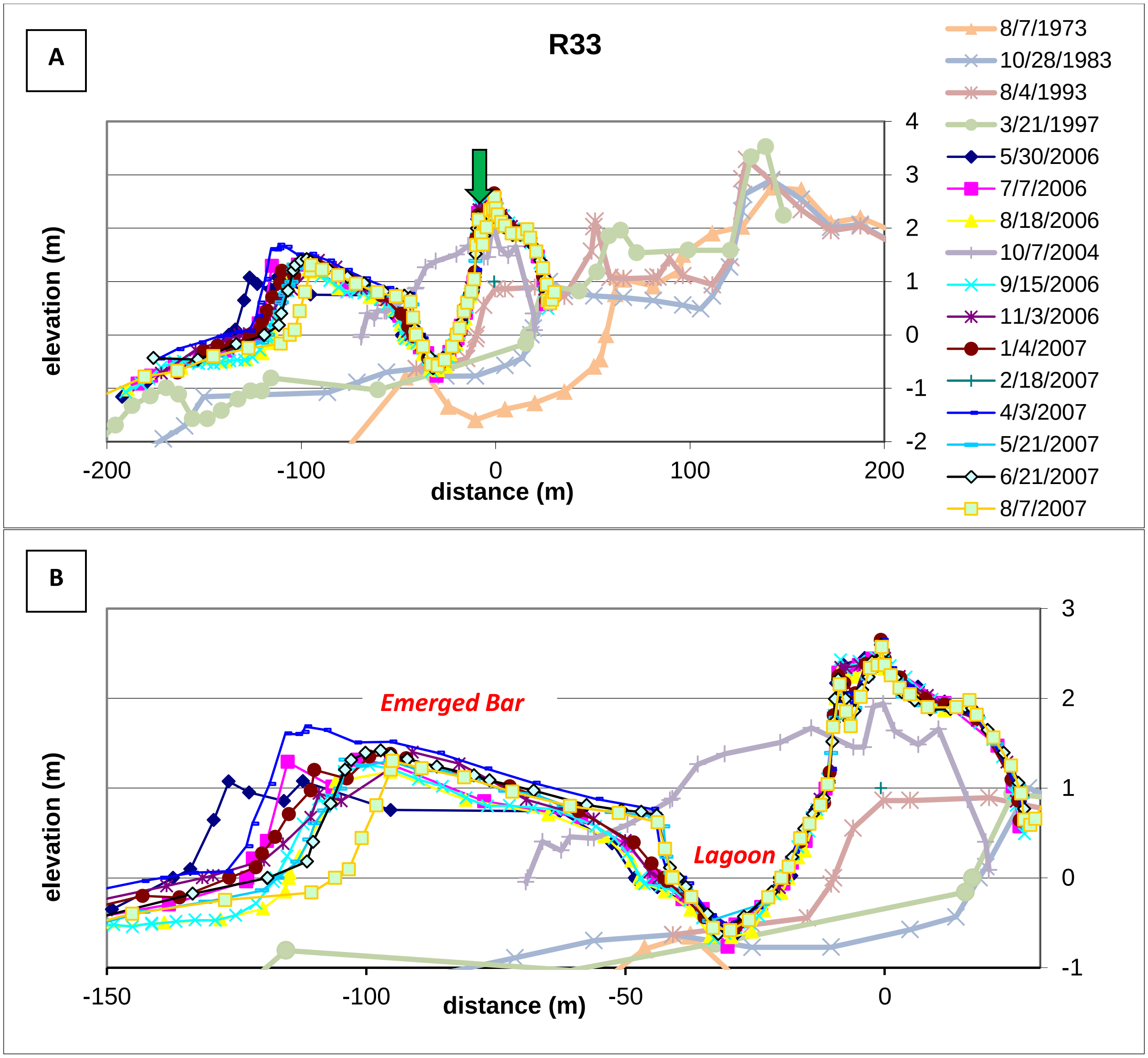


Figure 5.48 – R33 profile change. 1973 to 2007 profile change data is shown in the top profile (A), including 6-weekly surveys. During the study period the lagoon deepened, widened, and started filling (B). No new sediment was added to the beach, and hence no sediment was added to the foredune via aeolian activity.

The bar has been retreating landward, but building upwards, and some sediment has been filling the lagoon that divides the emerged bar from the peninsula. Just north of the tip of the bar the beach and foredune are being scarped. During this study period, as the bar elongated northward, the beach and foredune on the peninsula eroded at the tip's location, presumably as a result of wave refraction, increased wave energy and sediment bypassing this portion of the peninsula’s beach. This process explains the extremely short, steep beach and the scarped foredune on the profile line.

The foredune experienced aeolian erosion, which was made very noticeable by the lack of available beach sediment to replace the lost foredune sediment. Further scarping of the hummocky foredune ridge occurred due to the widening of a blowout toward the profile line. The sediment eroded from the front and side of the foredune and had been deposited on the backside of the foredune and was beginning to fill the landward swale. Profile R33 was the only location that experienced net erosion during the 2006-2007 study period losing 2.90 m^3/m.

Hine (1979) described the formation of similar berm and lagoon/runnel features in Massachusetts. Figure 5.49 is taken from Hine’s (1979; 348) model of berm-ridge and runnel development to create the multiple recurves of a spit. While the process described by Hine may help describe the process for the spit-tip (B-B’), the rest of the spit in his example was accreting, in contrast to St. Joseph Peninsula, which is eroding. Therefore, Hine’s description of spit development along A-A’ is not representative of most of St. Joseph Peninsula. Additionally, Hine’s model does not include reattachment of the emerged bars to the spit, which occurred at R33 during 2006 and appears to have happened many other times in locations along the peninsula based on the presence of cat-eye ponds. This will have implications for the sediment supply to the beach and subsequently the foredune morphodynamics.

Figure 5.50 shows a conceptual model outlining the changes that occur to the foredune as the emerged bar elongates with longshore sediment drift as seen on St. Joseph Peninsula. Not seen in the Hine model, foredune and beach berm scarping occurs in front of the elongating emerging bar/berm platform. On the diagram, cross-section A-A’ depicts the typical low

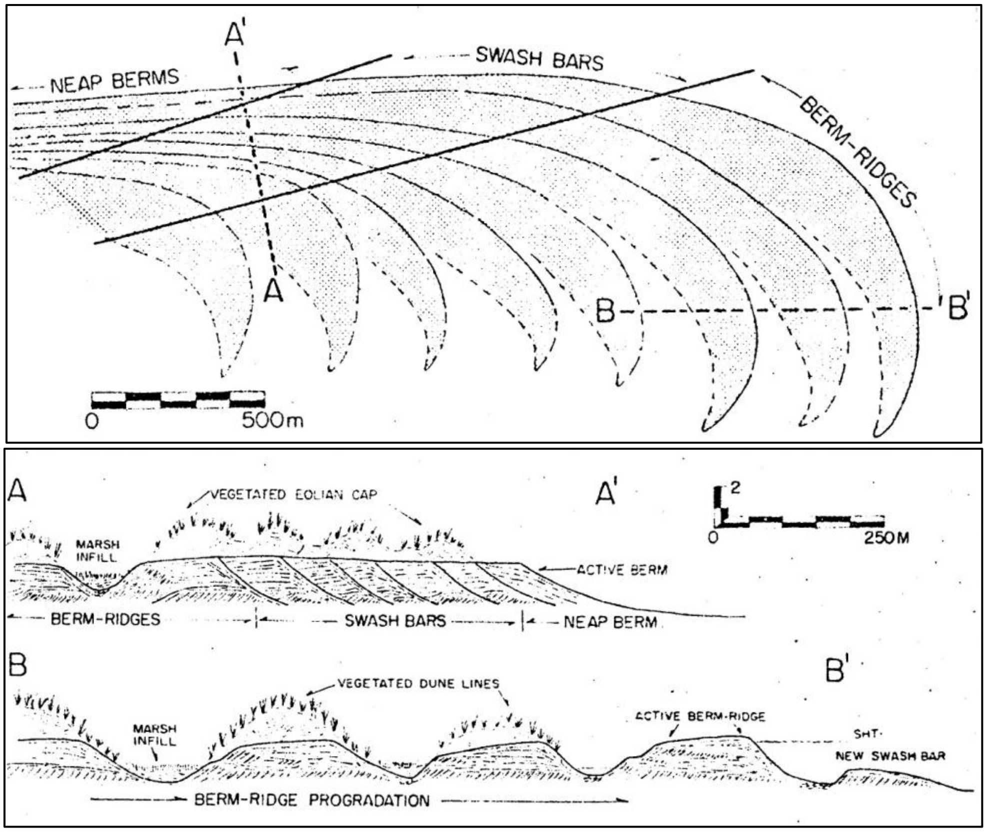


Figure 5.49 – Hine's (1979; 347, 348) model of spit tip development along cross-section B-B'. New berms develop vegetated dune lines. However, there must be an adequate sediment supply source to develop the dune before the sediment supply is cut-off by a new seaward emerging berm.

vegetated foredunes found in this area of the spit. As the emerged bar approaches cross-section B-B', wave refraction around the bar's distal end can enhance shoreline erosion and scarping of the foredune. Cross-section C-C' depicts the fully scarped foredune with a very short beach that lacks new longshore sediment supply, which in turn may reach a state of equilibrium with the fronting lagoon. Cross section D-D' shows the same short beach and scarped foredune behind the lagoon. The foredune may experience continued erosion and vegetation loss. If the emerged berm maintains sufficient width for vegetation growth, a new embryo dune may grow on the berm, thus creating a new foredune built through continued deposition in the vegetation.

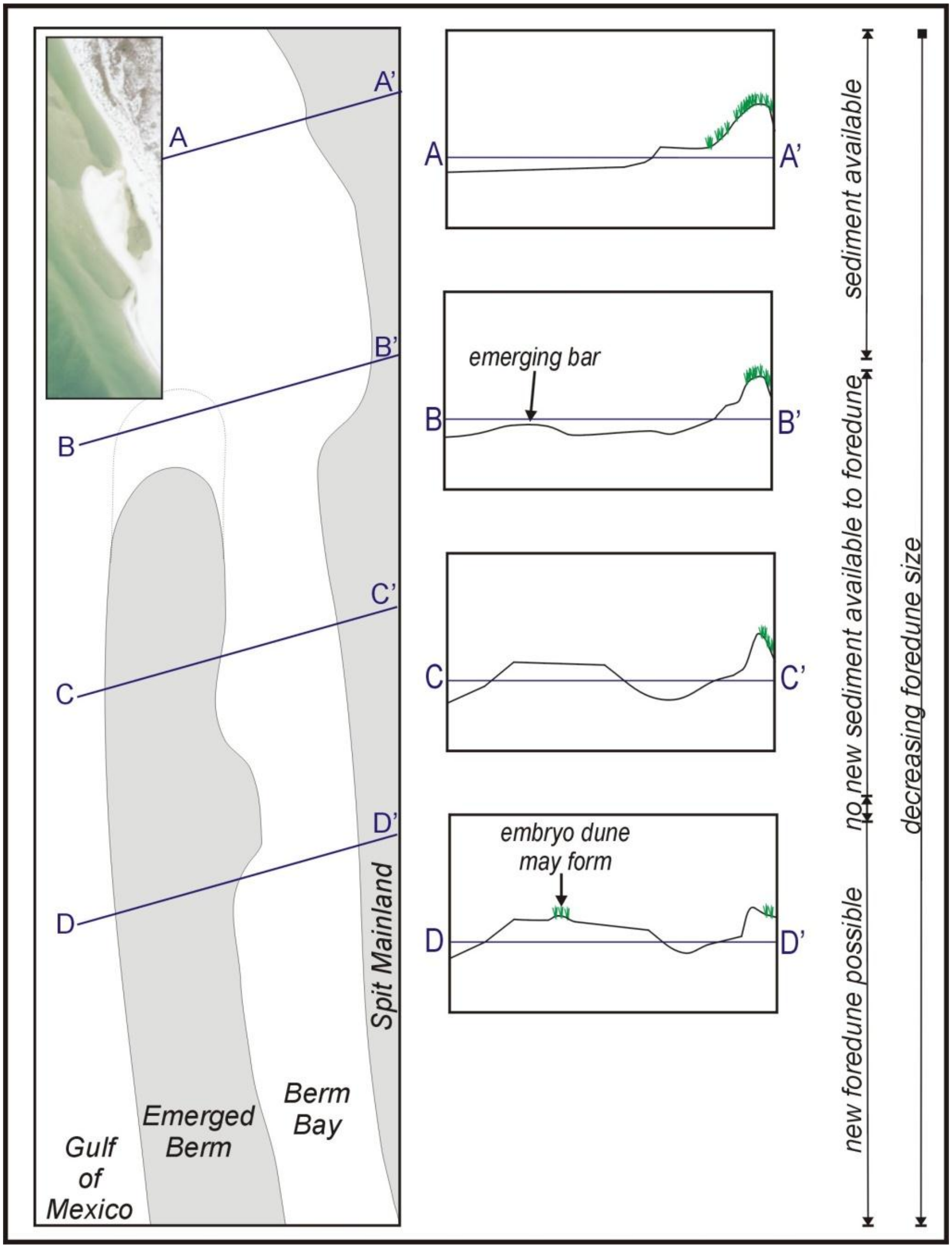


Figure 5.50 – Foredune change resulting from the elongation of an emerged bar separated by a small lagoon. (Inset photo from St. Joseph Peninsula where this process is occurring.) Erosion will occur to the down drift foredune as waves are focussed in that area, and afterwards as the beach sediment supply is cut-off. A new embryo dune or foredune may grow on the emerged berm.

5.3.5 Profile R37

Profile R37 is located south of St. Joseph Peninsula's fulcrum point, just before the beach orientation bends to the northeast and longshore sand waves appear to begin forming and disconnect from the peninsula. This location is characterized as having a very wide beach (53 to 63 m wide) during the 2006-2007 study period, the 4th largest foredune by volume, and 3rd largest by height measured during this study (Figure 5.51 and 5.52).

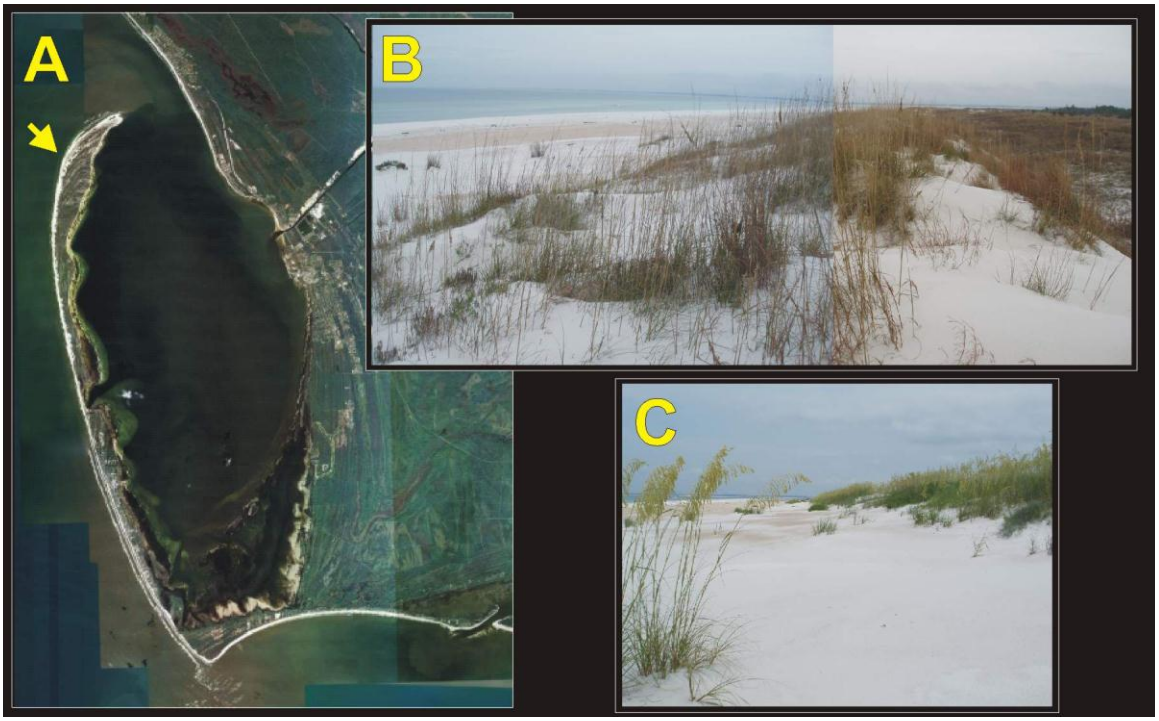


Figure 5.51 – Profile R37. Photo A marks the location of the profile in Gulf County, Florida. Photo B looks north along the foredune crest. New sediment is being deposited on the crest and landward. Photo C looks north along the foredune crest.

Similar to R6 and R27, the foredune at this location has been building since 2004. However, an established foredune was present in 2004, compared to just embryo forms at R6 and R27 in 2004. The foredune growth rate decreased from 12.5 m/a to 9.0 m/a when comparing the 2004-2006 to 2006-2007 data, despite the beach increasing in width and volume. The foredune increase of 10.7 m^3/m was the greatest volume change during the 2006-2007 study, yet the change occurred on the 4th widest beach available for aeolian transport. This foredune increase occurred on the prograding beach and the foredune showed no sign of recent scarping. This larger foredune development contrasts with Psuty's (1992, 2004) conditions for maximum foredune development, and the common hypothesis that maximum "foredune development" is associated with foredune scarping, followed by aeolian ramp building and maximum foredune aeolian sediment deposition (Hesp, 2002) as seen on profile R71.

5.3.6 Profile R52

Profile R52 is located near the center of St. Joseph Peninsula and is the last profile within the state park's wilderness zone. A large foredune blowout complex (Hesp, 1988) dominates this part of the coastline. The foredune exhibits a significantly scarped stoss slope.

The profile at R52 has the tallest foredune recorded during this study, ranging from 7.4 m to 8.5 m between 1983 and 2007. The range is only 8.4 m to 8.5 m for the 2006-2007 study (Figures 5.53 and 5.54). The foredune shape and volume changed very little during the 2006-2007 study period, ranging from 152.1 m^3/m to 153.9 m^3/m from start to study's end. Despite the historic trend of scarping, this did not occur during the 2006-2007 study. However, the potential for scarping was conceivable during periods in which a mega-cusp feature was located on the profile line. The beach width varied from 36.9 m to 13.3 m during the study period, with a trend towards an eroding beach (17.9 m/a, $R^2 = 0.81$). This rate, a much faster rate than the 0.5 m/a based on the previous 30 years of data (Foster and Cheng, 2001), suggests a strong potential for foredune scarping in the near future. However, a beach nourishment project to the south may

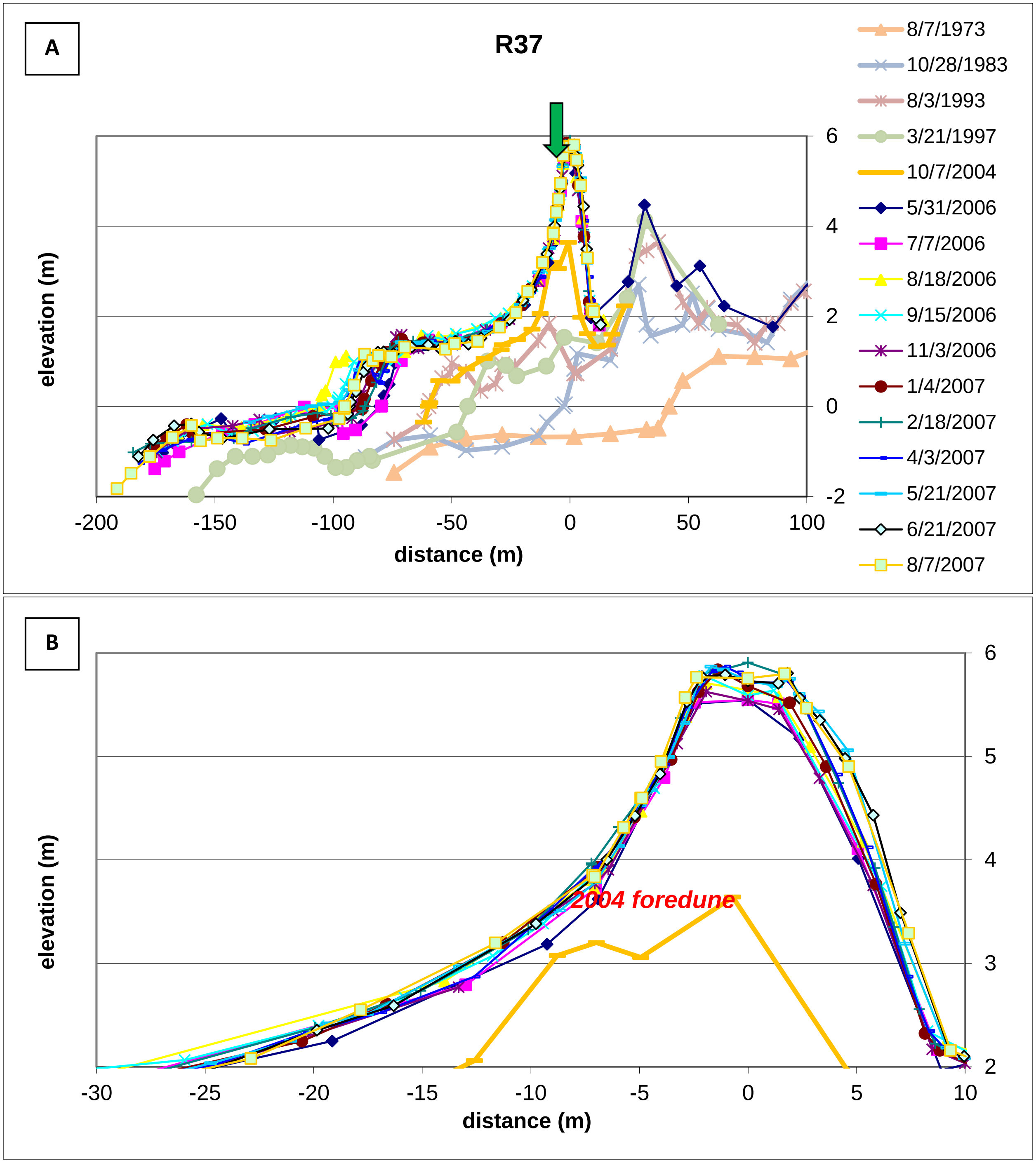


Figure 5.52 – R37 short-term profiles. The upper profile (A) displays profiles since 1973: Very little change is detected to the foredune between 2006 and 2007, compared to the changes over the previous 3 decades. Diagram B shows the foredune ramp is building slightly on the stoss side, and the foredune is building upwards and landwards, yet maintains its basic morphology. The 2004 profile (highlighted with the yellow line) shows the rapid foredune building between 2004 and 2008 in which no major beach erosion event occurred.

supply more sediment and delay foredune scarping events. While a foredune scarping event may be imminent, and we may achieve a new period of erosion event "synchronization" (Houser, 2009), the likelihood of total foredune loss is unlikely. This is due to the very large amount of sediment directly landward of the foredune and the ability of the foredune to cannibalize this sediment into a reformed foredune. The antecedent geomorphology located landward of the foredune provides a more than ample source of sediment available for the foredune to maintain or increase its total volume if the foredune migrates landward. It is not clearly evident in the descriptions published if this sediment is applicable to the Psuty (e.g. 1988) models.

5.3.7 Profile R71

Profile R71 is located within St. Joseph Peninsula State Park in the public access zone. The foredune (Figure 5.55) in this area is a linear continuous ridge with less dominant blowout features compared to the large blowout features found near profile R52. Similar to profile R52, the foredune on profile R71 has shown very little change to its arête-like shape, height (7.8 m to 7.7 m), and volume (83.3 m^3/m to 84.9 m^3/m). The negligible changes to the profile during the 2006-2007 study period do not represent the same large scarping of the foredune as shown in the decadal scale changes (Figure 5.56). The beach (width) at R71 did not have the same variability as found at R52, nor was there evidence at R71 of mega-beach cusps and horns during any of the 2006-2007 visits to the study site. The foredune volume increases during the 2006-2007 study contrasts with the overall long-term losses to the foredune at this location (post 1973 to present data). The lack of foredune change during this 16-month period is a result of no major storms eroding the beach and scarping the foredune. Of considerable note, however, is the fate of this foredune compared to the foredune on profile R52. The presence of landward dunes at R52 may

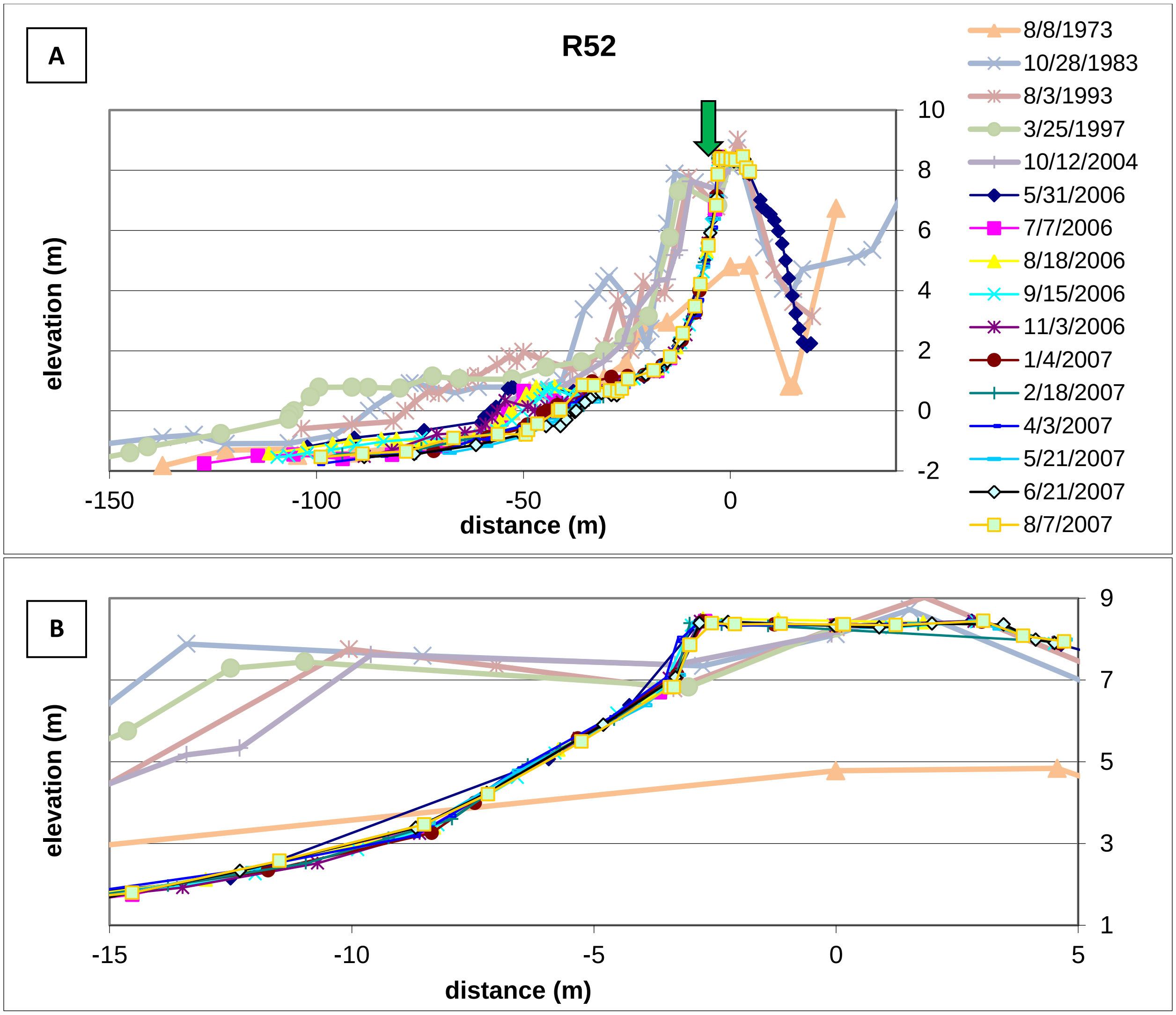


Figure 5.53 – R52 short-term profiles. The upper profile (A) displays profiles since 1973: There has been very little change between 2006 and 2007 compared to the previous decadal changes. When examining the 2006-2007 changes (B) there are no visibly apparent modifications to the foredune.

allow for an abundant supply of sediment for foredune growth at R52; in comparison to the peninsula's development at R71, there is no sediment surplus landward of the current foredune, which brings into question the fate of these foredunes. Despite their current similar height and volume, the role of the antecedent geomorphology will play a very important role in the future of these foredunes.

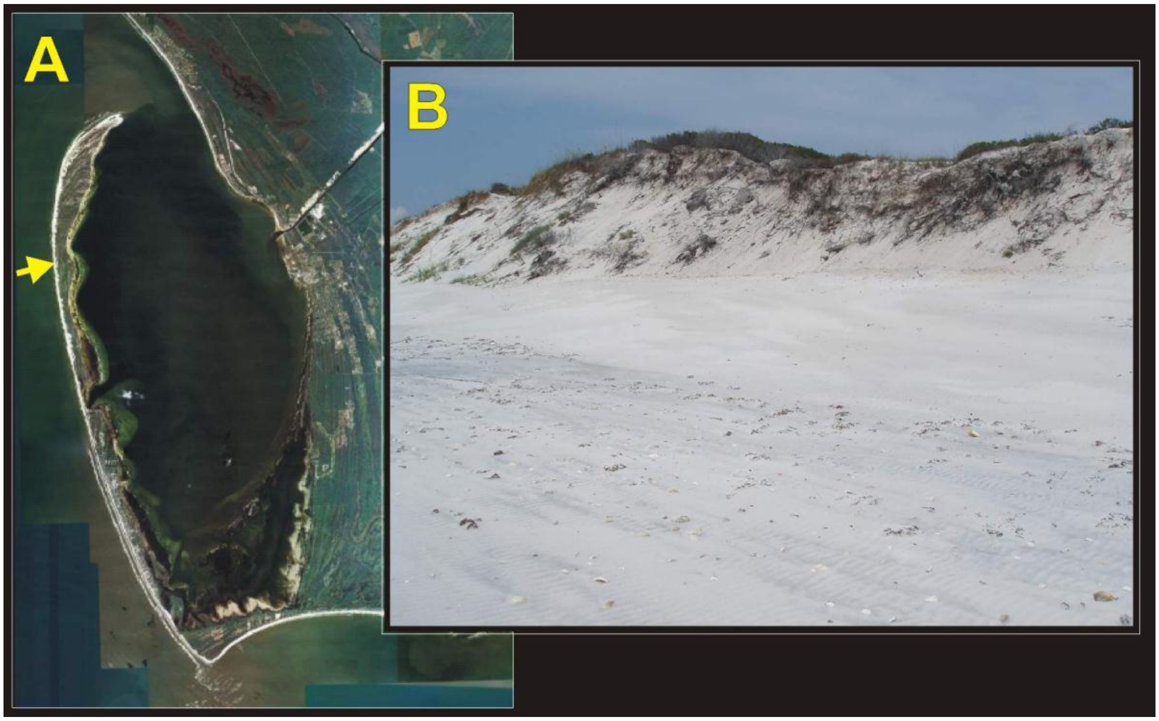


Figure 5.54 – Profile R52. Photo A marks the location of the profile in Gulf County, Florida. Photo B looks north-east along the foredune crest.

5.3.8 Profile R100

Profile R100 is located in another eroding portion of the St. Joseph Peninsula, which has homes located on scarped foredunes and evidence of structural undercutting near the profile line. The beach did show a large amount of change during the study, with an overall eroding trend averaging 15.2 m (standard deviation 4.6 m). Despite the long-term erosion of the beach and foredune, this site showed minimal change to the foredune (Figures 5.57 and 5.58). Similar to R52 and R71, the foredune morphologic changes on profile R100 were negligible compared to the long-term changes at this location. But of note, the increased erosion at this site and the role of the antecedent geology may play a critical role in the evolution of this foredune as well.

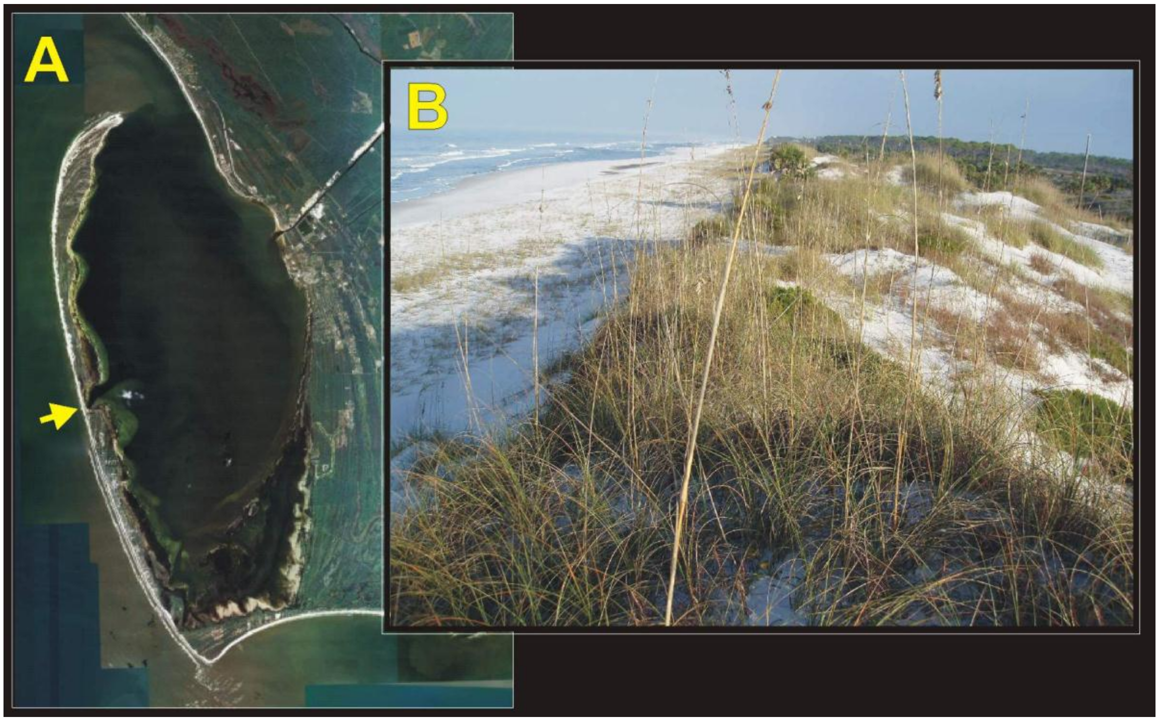


Figure 5.55 – Profile R71. Photo A marks the location of the profile in Gulf County, Florida. Photo B looks north along the foredune crest.

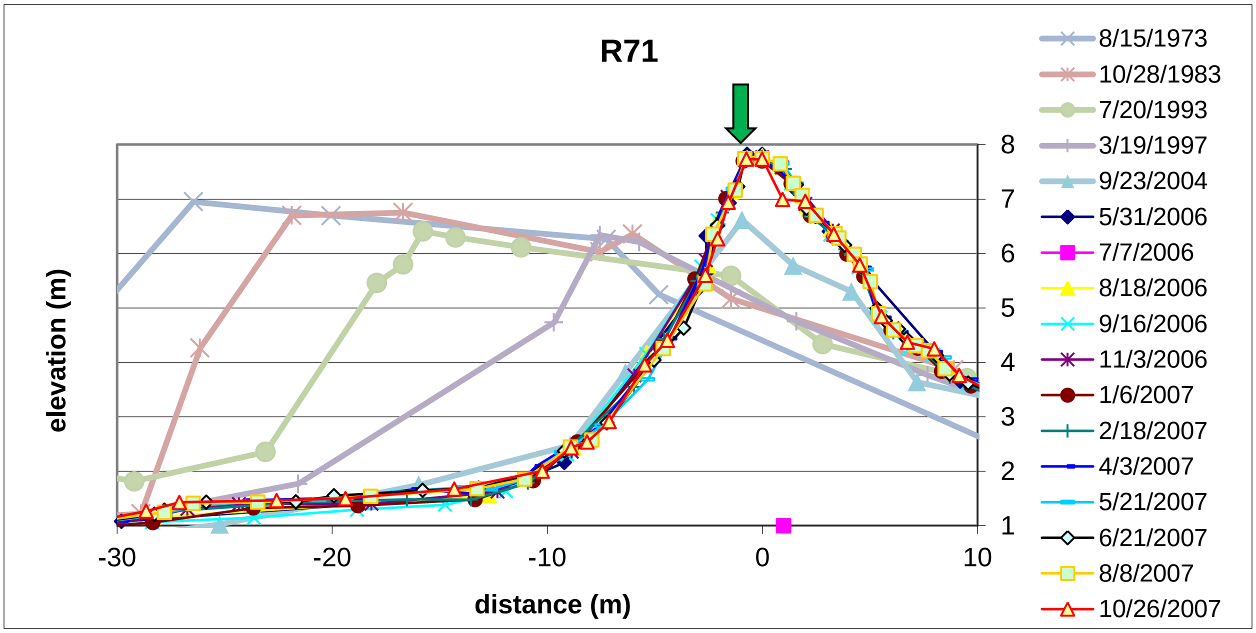


Figure 5.56 – Profile R71 cross-section. There was no visible change to the foredune shape or size during the 2006/2007 study period.

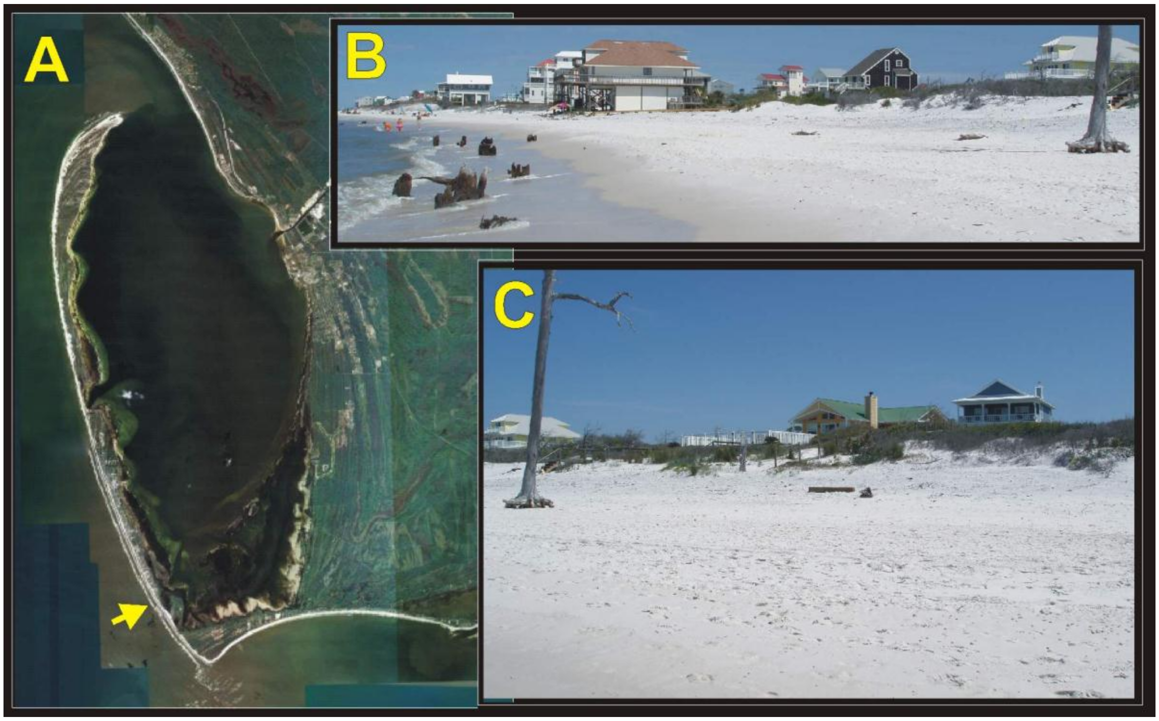


Figure 5.57 – Profile R100. Photo A marks the location of the profile in Gulf County, Florida. Photo B looks north along the eroding shoreline. Photo C displays the foredune and development landward of the foredune crest.

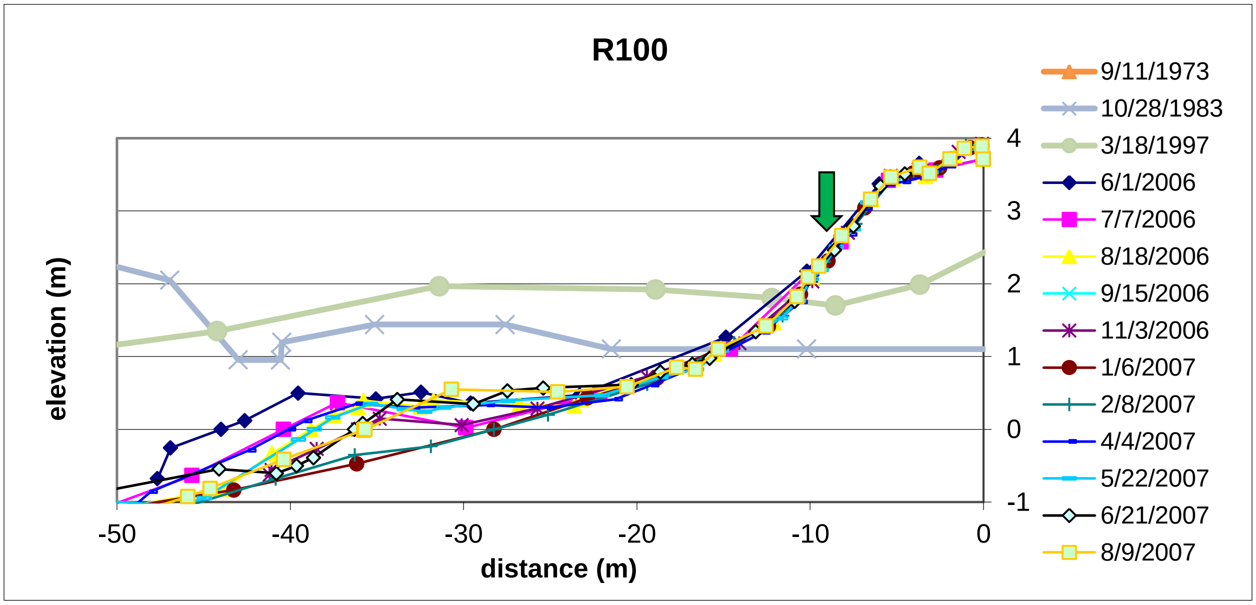


Figure 5.58 – Profile R100 cross-section. The foredune showed almost no change during the 2006-2007 study period, despite there being relatively large scale changes to the beach, ranging from 20.8 m to only 5.4 m in width.

5.3.9 Profile R110

Profile R110 is located at the highly eroding Cape and had no dunes present post-2004 (Figure 5.59). The sand approximately 1.5 m above MSL was far less compact than the further seaward sediment and was perceived as being reworked by aeolian processes. This region of aeolian deposition changed very little during the study period except for a period of seaward building at the start of the study. On the other hand, the beach profile underwent far more change (Figure 5.60). The beach width ranged from 21.5 m to 11.3 m during the study, undergoing a net loss of 6.7 m.

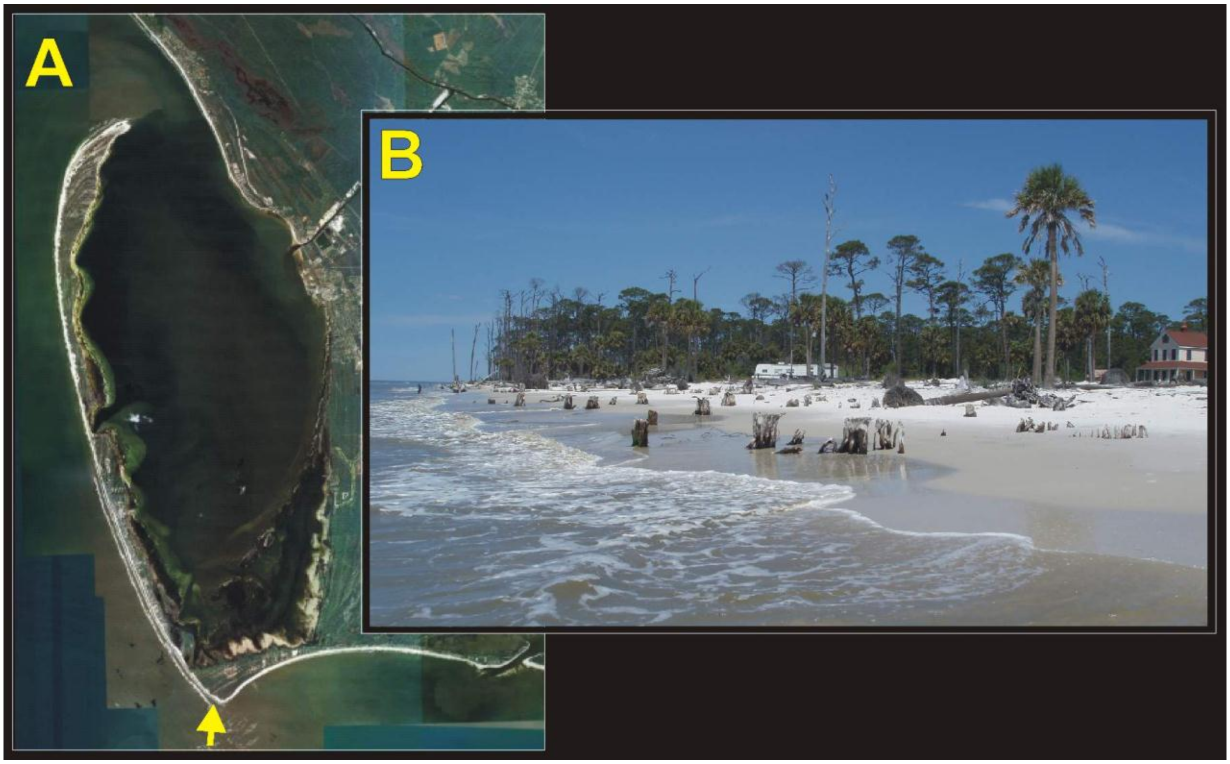


Figure 5.59 – Profile R110. Photo A marks the location of the profile in Gulf County, Florida. Photo B displays the site of former military buildings that have been destroyed and removed due to recent high erosion rates. Trees are visible adjacent to the water’s edge in the distance.

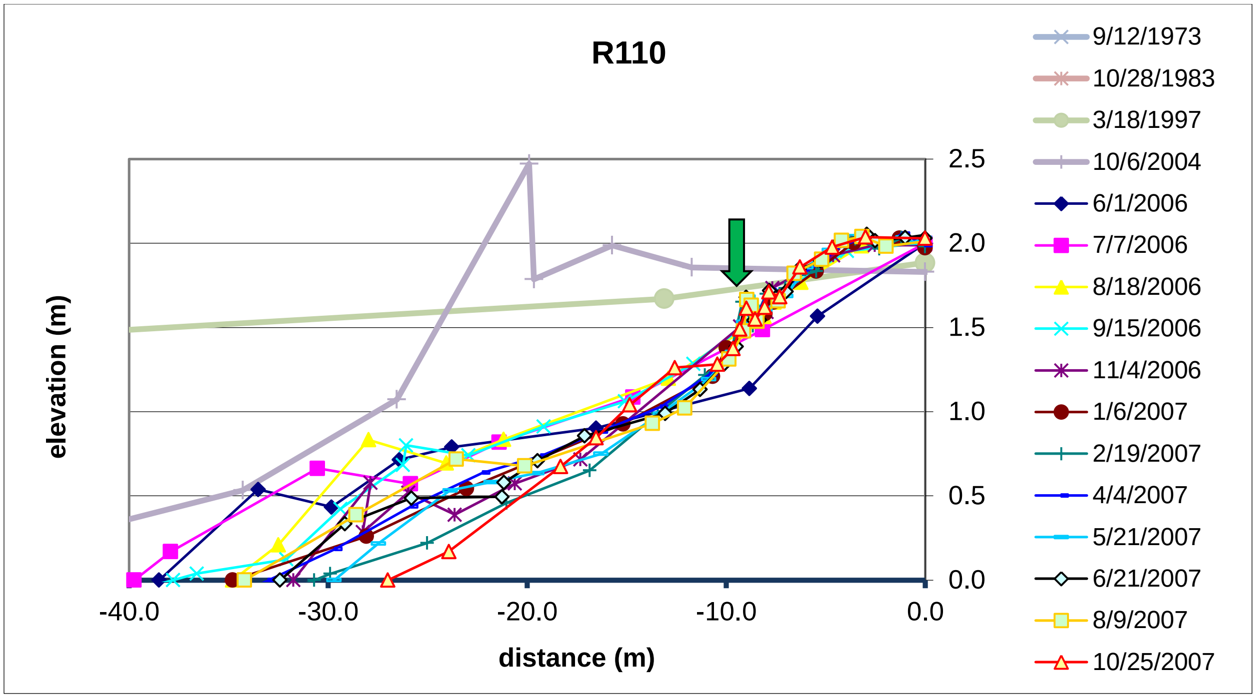


Figure 5.60 – Short-term changes to profile R110. The back beach exhibited minimal change during the study period. In contrast, the beach has been far more variable, presenting increased erosion after local storm events.

5.3.10 Profile R122

The decadal data have shown the development of a series of new ridges, including three new ridges on profile R122 since the 2004 profile was recorded. During this study, no new incipient form had developed, but the foredune was increasing in volume (Figure 5.62). The foredune has built laterally seaward and landward, and vertically from 3.0 to 3.4 m. The volume increased steadily from 4.3 m^3/m/a, then jumped in late September to early November by 2.1 m^3/m (or 15.9 m^3/m/a), and the rate slowed again to increasing 1.5 m^3/m/a. The overall growth was the second greatest amount of foredune deposition during the 2006-2007 study period for the twelve profiles measured.

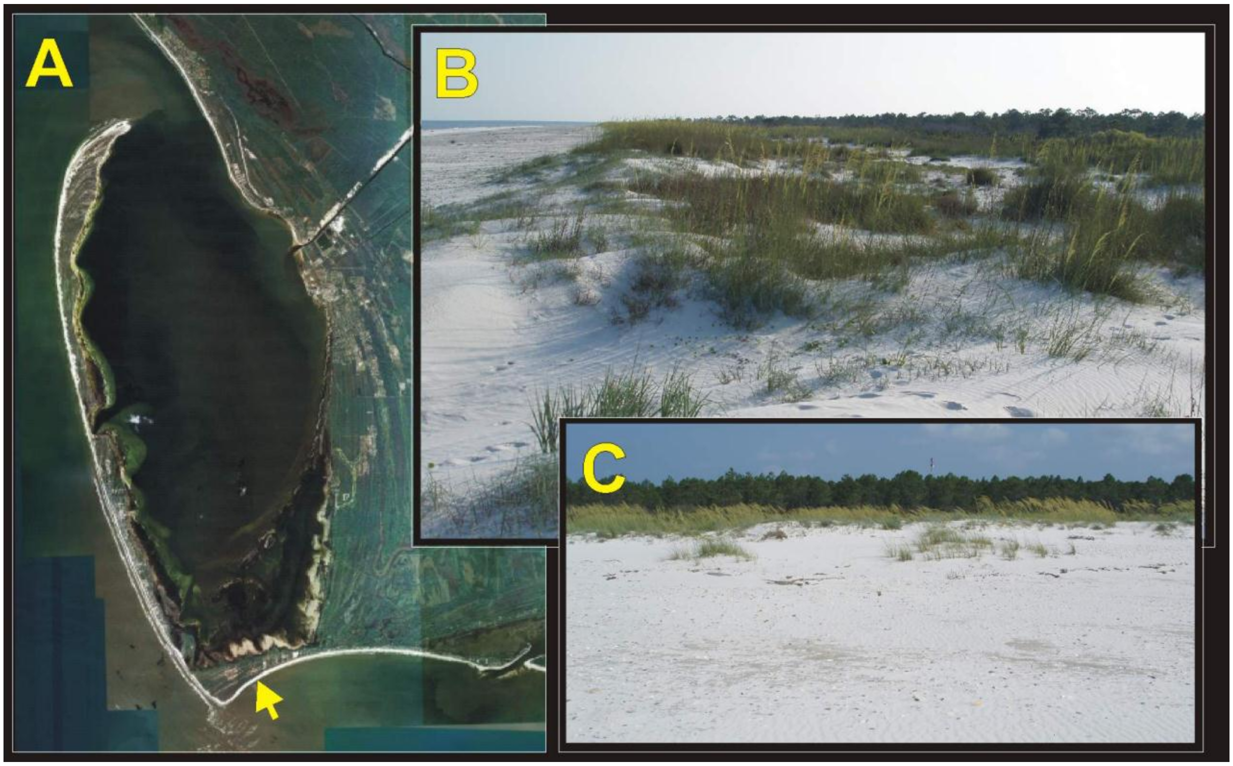


Figure 5.61 – Profile R122. Photo A marks the location of the profile in Gulf County, Florida. Photo B looks west across the foredune and hummocky landward ridges. Photo C looks landward at the foredune crest.

The three ridges developed since 2004 were spaced 15 m and 17 m apart. During the 2006-2007 study the beach steadily increased in width from 65.6 m to 73.4 m. This expansion may have widened the beach to a critical width to allow a new ridge to develop. Although no new distinct incipient form had developed, there was a small depositional rise 14.2 m seaward of the foredune in June 2007, a period when the beach was its widest point during the study. The small incipient foredune occurred around a small hummock located 45 m from the waterline. The beach, however, decreased in width after June 2007 and the potential new ridge was no longer present on the profile as the high tide line was visible up to the location of the former incipient dune.

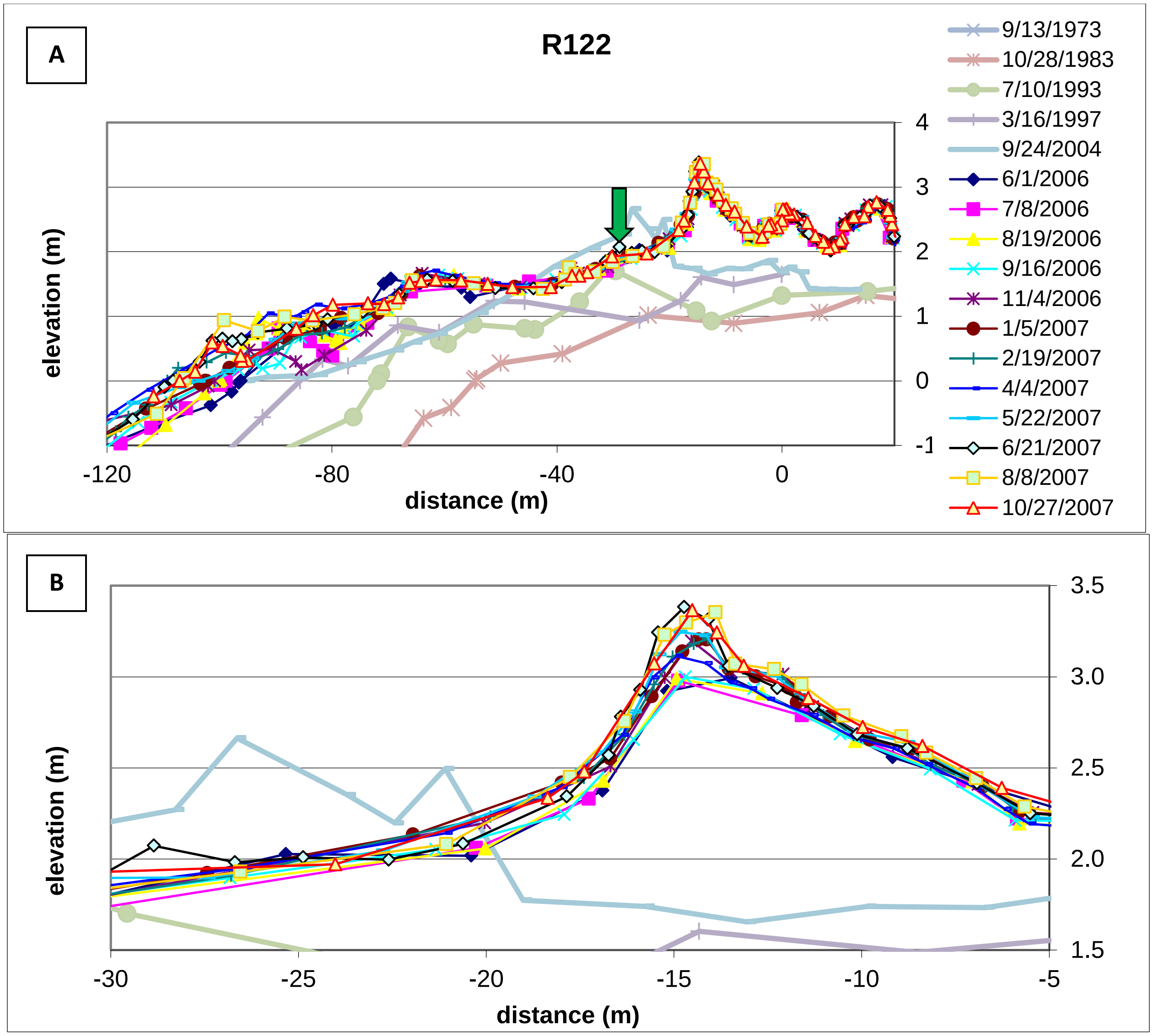


Figure 5.62 – Profile R122 cross-sections. The upper diagram (A) displays the three new ridges that formed since 2004. The new ridges display relatively little change compared to the decadal changes. The lower profiles (B) display the changes made to the foredune in which there was a jump in volume between the September and November 2006. The foredune expanded laterally and vertically, yet maintained its general morphology.

5.3.11 Profile R143

A new foredune had developed on profile R143 that was landward of previous foredunes, despite the beach remaining in a relatively neutral location (Figure 5.64). However, the 2004 profile did show a large retreat of the beach, and as a result a new foredune may develop seaward of the current foredune as the system reaches a new equilibrium state. The beach prograded slightly during the study, averaging 77.2 m in width. Despite having the third widest beach during the study, the foredune volume increased only 0.7 m^3/m. Of the 0.7 m^3/m change, 0.5 m^3/m occurred between September and November of 2006. At the same time there was a large increase in foredune volume on the adjacent foredune profile, at R122.

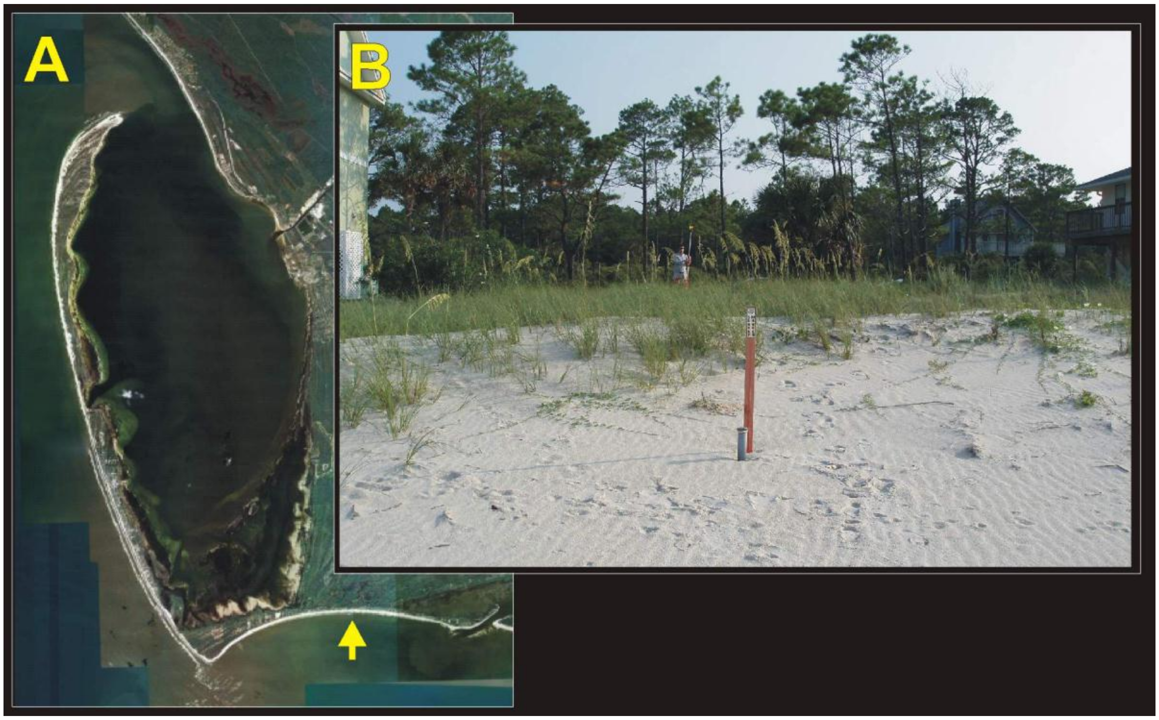


Figure 5.63 – Profile R143. Photo A marks the location of the profile in Gulf County, Florida. Photo B looks north at the small foredune.

5.3.12 Profile R155

Profile R155 is located at the eastern end of Gulf County near Indian Pass. The tidal outflow plays a role in developing dynamic beach adjustments on the profile line. At the start of the 2006-2007 study there was a small lagoon fronted by a mini-cuspate foreland, which can be detected on the profile (Figure 5.66). The foreland migrated landward, collapsing the ephemeral

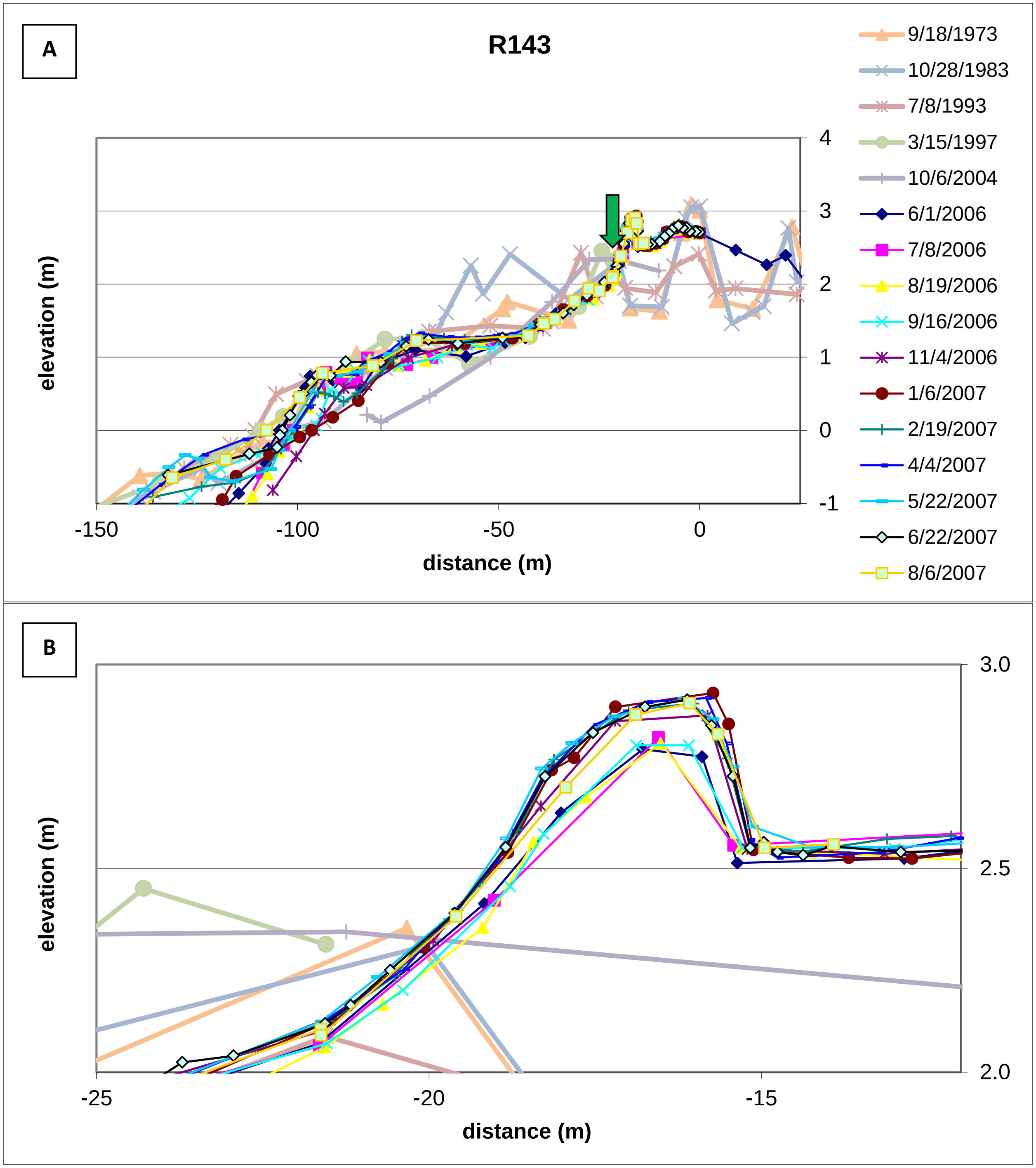


Figure 5.64 – Profile R143 cross-sections. The upper diagram (A) displays the new foredune that developed landward of previous foredunes. The new ridge displays relatively little change compared to the 30 year record. The bottom diagram (B) displays the changes made to the foredune between September and November 2006. The foredune increases in both height and volume.

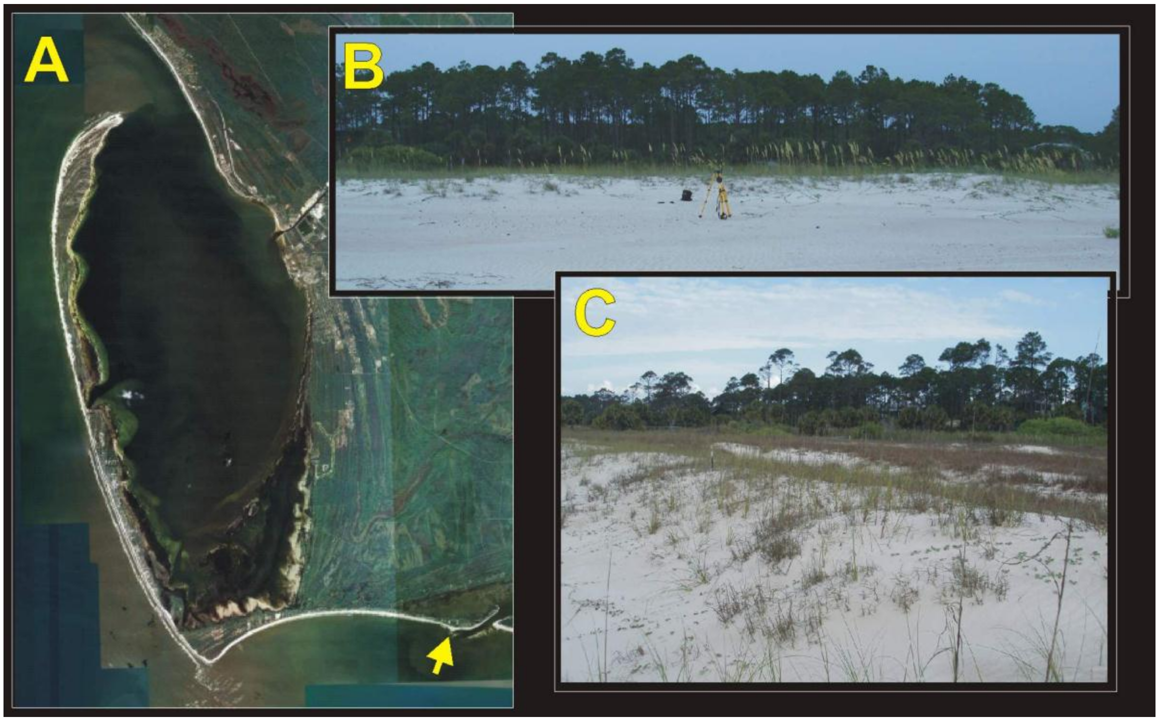


Figure 5.65 – Profile R155. Photo A marks the location of the profile in Gulf County, Florida. Photo B looks landward at the foredune crest. Photo C looks west across the foredune and landward ridges.

lagoon, and by January 2007 the lagoon had closed and the beach expanded from 77.1 m to 111.3 m due to the merging of the foreland sediment to the beach. At this time, a slight rise was detected on the beach approximately 35 m in front of the foredune. By April 2007, a distinct new incipient dune ridge was present in line with a small foredune to the east and west of the profile line. The original foredune increased in volume from 9.9 m^3/m up to 11.0 m^3/m. After the incipient started to capture sediment, the original foredune began decreasing in volume, and the incipient dune ridge increased in volume from 3.1 m^3/m to 3.8 m^3/m.

5.4 Profile Comparisons

Figures 5.67 and 5.68 (on the following pages) display time series of foredune and beach changes. When comparing the foredune volume changes between 1973 and 2006, it is apparent on the graphs that large changes occur to some of the foredunes (Figure 5.67). For example, the

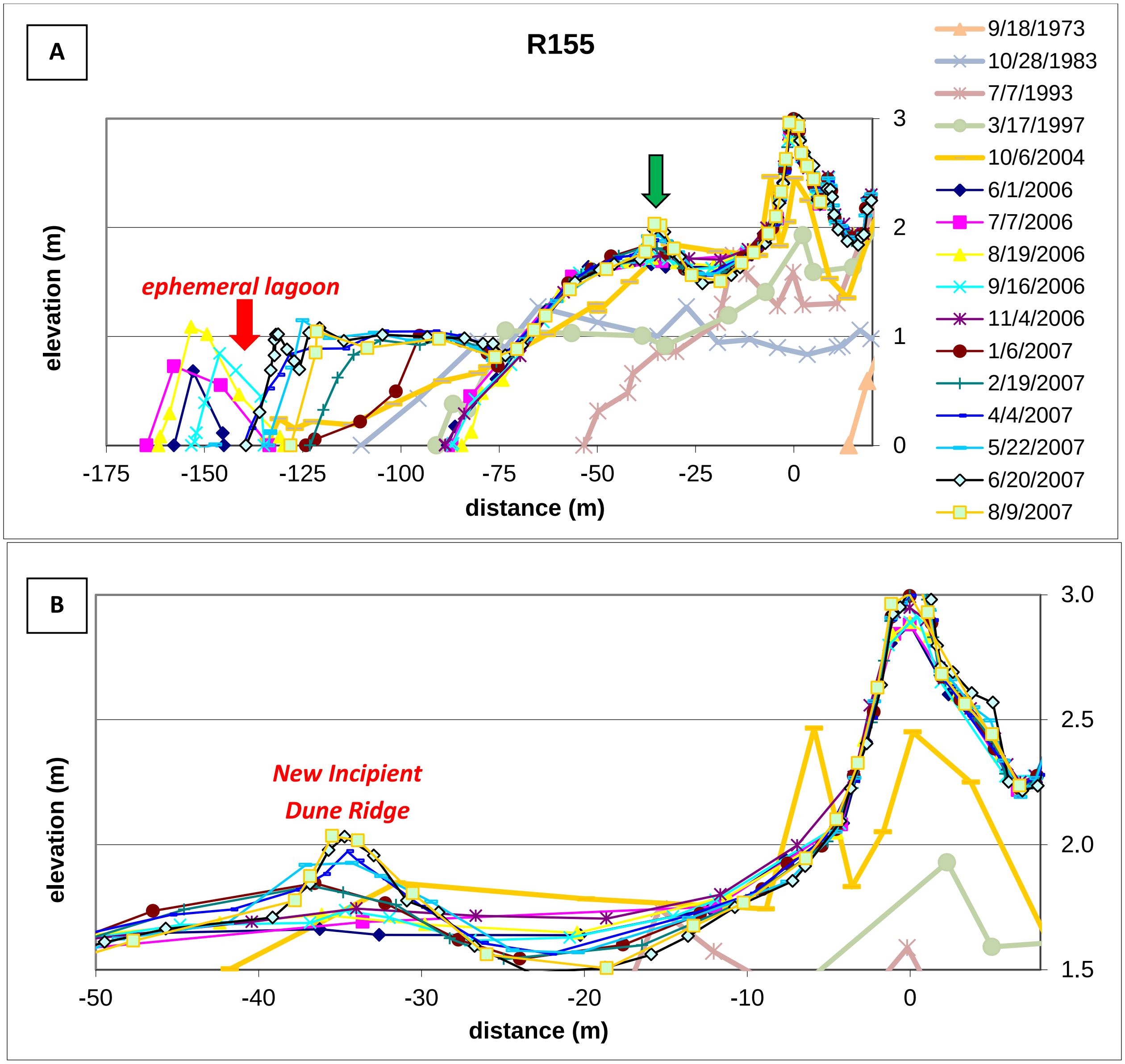
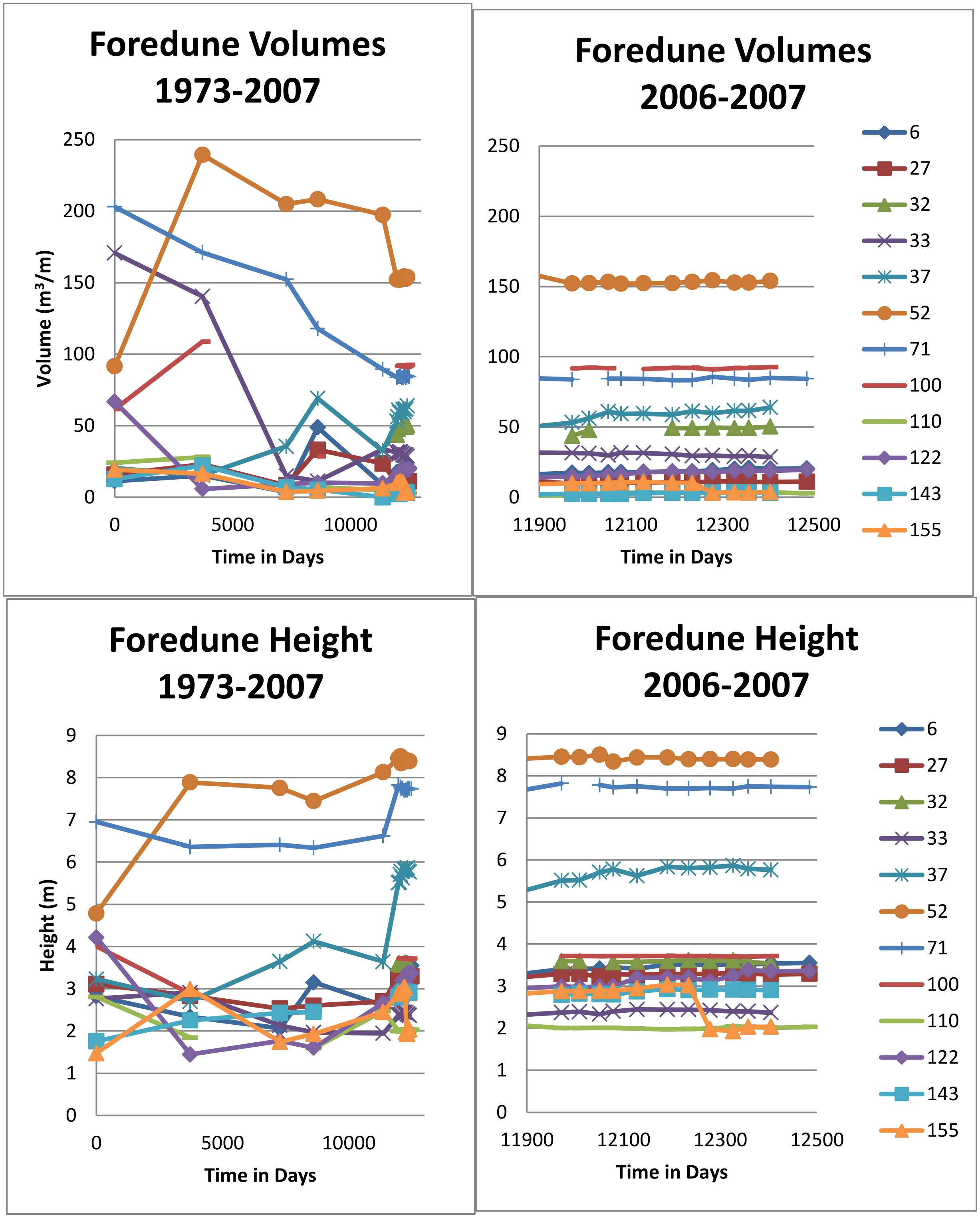


Figure 5.66 – Profile R155 cross-sections. The upper diagram displays the full profile including the ephemeral lagoon and fronting raised sandbar / cuspate foreland. The lagoon eventually filled as the sandbar migrated landward, and welded to the beach. The lower diagram displays the original foredune which grew in volume until a new embryo dune ridge started to build on the profile line.

R52 foredune had a huge increase in volume followed by a steady decrease; R71 and R33 had large decreases; and R27, R37 and R122 showed a large increase between 1993 and 1997, a period in which no major hurricanes impacted the study area. The 2006-2007 changes were negligible compared to the long term changes as seen in the upper diagrams of figure 5.63. During the 2006-2007 study period, the foredune volumes appear near linear with the exceptions of R37's increase in foredune volume and R155, in which a new incipient dune ridge formed. The average foredune volume change during this study period was 1.5 m^3/m/a, whereas the absolute foredune volume change for all previous years was approximately three times greater at 3.4 m^3/m/a, thus indicating a significant decrease in foredune volume change during this study period. The greatest variability in foredune volume change occurred along the westward-facing peninsula. Profile R6 is west-facing as well, which will be further discussed in the subsequent sections. The foredunes that showed the greatest change in the decadal data also contained the largest foredunes by volume. The 2006/2007 data did not show an equivalent relationship leading one to hypothesize that major events (such as hurricanes or sand bars that are emerging and coalescing to the beach) play the most critical role in foredune change on this low energy coast.

The foredune height change appears to be much greater over the three decade period. However, the changes in foredune height is similar when comparing annual averages for the 1973-2006 and the 2006/2007 study period at 0.081 m/a and 0.078 m/a respectively (Figure 5.63). Some of the decadal data variability is a result of new foredunes on the profile lines, while only one new foredune was established in the recent profiles, which accounts for the drop in profile volume on R155.

The decadal data shows greater beach volume and width variability when compared to the short term data (Figure 5.68), similar to the comparison between decadal versus short term foredune volumes and heights shown in figure 5.68. However, the short term data show greater


Foredune Volumes 1973-2007

Foredune Volumes 2006-2007

Foredune Height 1973-2007

Foredune Height 2006-2007

Figure 5.67 – Foredune volume and height change from 1973 through 2007. The upper diagrams display foredune volumes and the lower diagrams display foredune heights over time. The highly variable foredune volumes are highlighted in the upper left diagram. However, the foredune volumes changed very little during the 2006-2007 study period.

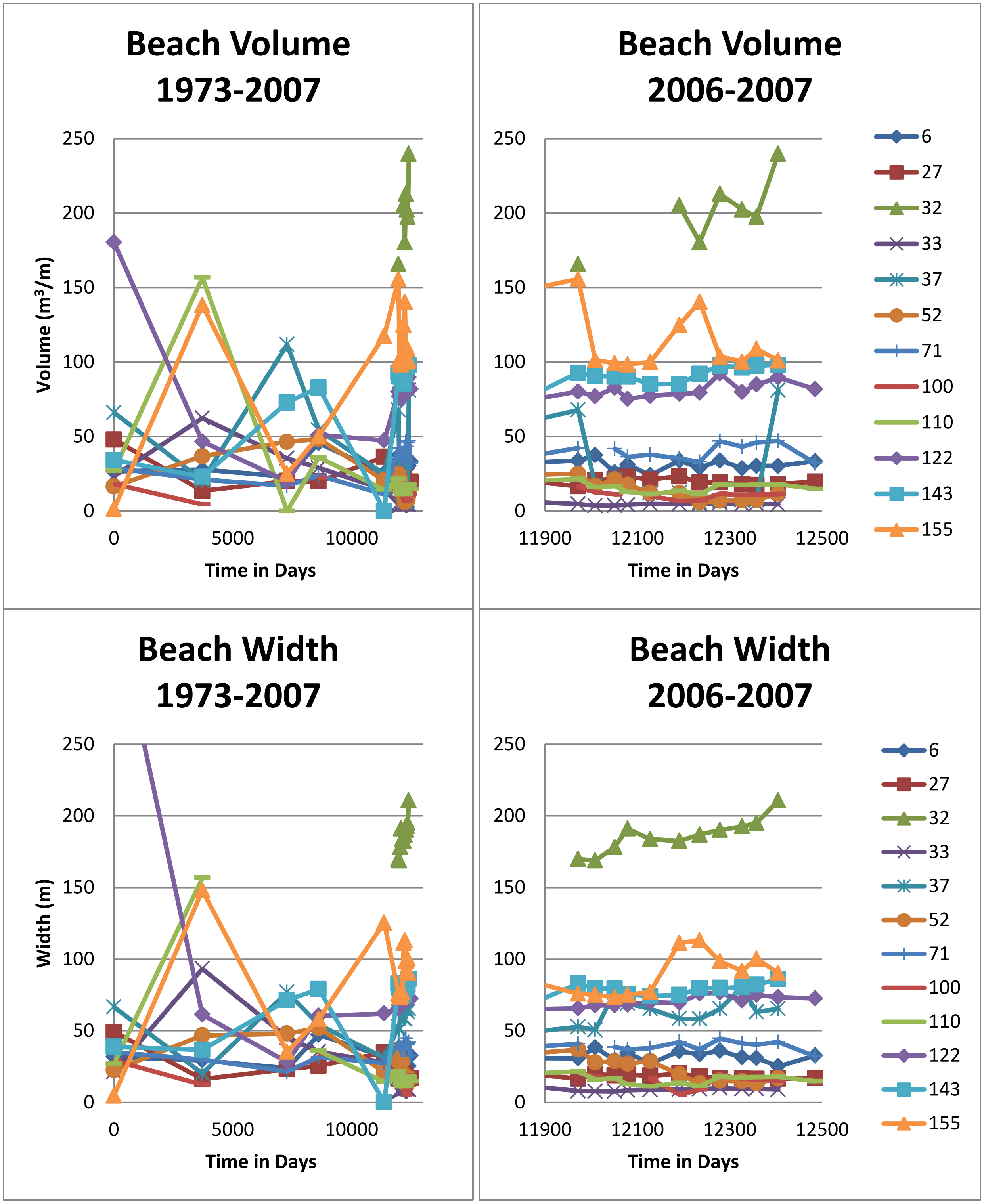


Figure 5.68 – Beach volume and width change from 1973-2007. The beach on profile R32 rapidly prograded during the 2006/2007 study period. Profiles R52, R110, R37, R52, R110, R143 and R155 had the most variability in beach width, primarily based on the location of new foredunes on the prograding beaches, and higher beach mobility on eroding beaches and emerging bars on R33.

variability for the beach compared to the dune measurements. The greatest variability was the rapid northward progradation of the beach at R32. The R52 beach also showed the most frequent cusp development and a higher potential for dune scarping (Short and Hesp, 1982). The process of cusp development and beach mobility adds to foredune variability and the consequent foredune-blowout development found in this region of St. Joseph's Peninsula.

Table 5.1 summarizes the foredune volume height and beach width data. The ordinal rankings from maximum values (1) to minimum values (12) are indicated in brackets. The ordinal rankings demonstrate that there is little relationship between the foredune volumes or height and beach width during the 2006/2007 study period. For example, Profile R37 had the largest beach width but only the 5th largest foredune (by volume) and the 4th largest increase in volume. By comparison, profile R155 had the second largest beach width but only the 11th largest foredune and only the 10th highest rate of foredune increase in volume. In contrast, the 11th widest beach on profile R100 had the 2nd largest foredune by volume. The largest foredune volume increase was found on profile R37, which had only the 5th largest beach width. The R37 foredune grew in volume more than double the next fastest growing foredune during this study, R122. While it has been postulated that beach width is a critical element in foredune development (Nickling and Davidson-Arnott, 1990; Bauer and Davidson-Arnott, 2002), it appears not to be a controlling factor in Gulf County. Nor does the potential sediment supply associated with beach width have a direct relationship with foredune sediment supply. Of note, some beaches have large shell lag deposits, which may play a critical role in reducing sediment transport (Carter, 1988; Nickling and McKenna Neuman, 1995; Davidson-Arnott et al., 1997). However, R122 had one of the greatest development of shell lags, and yet this foredune had the 2nd greatest foredune volume increase. Of most noticeable contrast to the Psuty models of foredune development are that within the recent study period, the four sites with the greatest increase in foredune volume are all on prograding beaches.

Table 5.1 – Foredune and beach averages for the 2006-2007 study period. Values in brackets indicate their ranking from 1 to 12 (highest to lowest) for the twelve sites. There was no statistical relationship between the ordinal rankings. (Profile R110 is highlighted because virtually no dune existed at this highly erosional site.)

		Foredune Volume (m^3/m)	Foredune Volume Increase (m^3/m)	Foredune Height (m)	Mean Beach Width (m)	Beach Orientation
Mainland	**6**	20.55 (7)	3.08 (3)	3.55 (6)	30.95 (7)	230
	27	11.09 (8)	1.40 (6)	3.29 (8)	17.88 (9)	245
Peninsula	**32**	50.33 (5)	2.46 (4)	3.57 (5)	186.34 (1)	360
	33	28.66 (6)	-2.90 (12)	2.37 (11)	8.73 (12)	320
	37	63.96 (4)	10.71 (1)	5.77 (3)	64.16 (5)	310
	52	153.93 (1)	1.79 (5)	8.39 (1)	22.00 (8)	265
	71	84.26 (3)	1.08 (7)	7.73 (2)	39.43 (6)	255
	100	92.56 (2)	0.82 (8)	3.71 (4)	15.20 (11)	240
	110	2.85 (12)	-0.22 (11)	2.03 (12)	15.72 (10)	230
East-West Arm	**122**	19.61 (8)	4.30 (2)	3.36 (7)	71.08 (4)	135
	143	3.33 (10)	0.72 (9)	2.91 (10)	87.47 (3)	180
	155	11.03 (11)	0.66 (10)	3.04 (9)	89.25 (2)	200

5.4.1 Application of the Psuty model to Gulf County

Gulf County beaches and foredunes cannot readily be applied to the Psuty sediment supply matrices (1986, 1988, 1992, 1994). Figure 5.70 displays empirical data from Gulf County as it compares to the positive and negative beach and foredune quadrants in the Psuty (1988) matrix. Results from Gulf County data show a disordered collection of values about the intersection of beach and foredune positive and negative changes. This cluster of values does not resemble the Psuty idealized asymmetric "distribution" line, nor are the data points comparable for individual

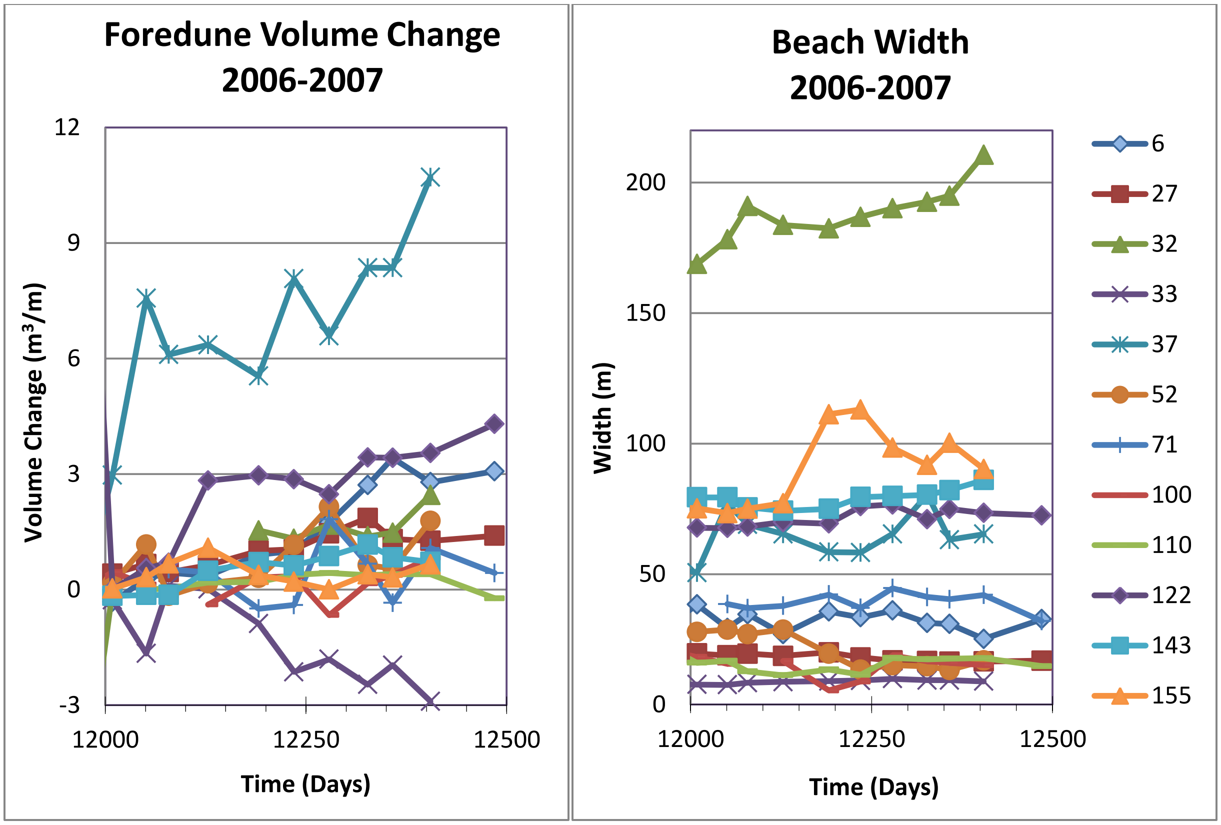


Figure 5.69 – Short-term foredune volume change and beach width. The foredune volume chart on the left displays the change in volume from the first survey conducted in 2006. Only R33, the site in which the beach had been cut-off form longshore sediment transport by a lagoon and sandwave, had a net foredune volume loss during the study period.

sites. For example, site R52, which has the largest foredune, has data points within 3 out of the 4 quadrants, including both negative dune quadrants and the beach positive / dune positive. This is in opposition to Psuty's placement of maximum foredune development in the beach negative / dune positive quadrant, the one location where the Gulf County empirical data does not have a value. A second example of the Psuty conceptual model's inability to apply to this study region is that within the sediment supply matrix, beach ridge topography occurs in the dune negative and beach positive quadrant. However, multi-ridge forms in the empirical data set have values in all four quadrants.

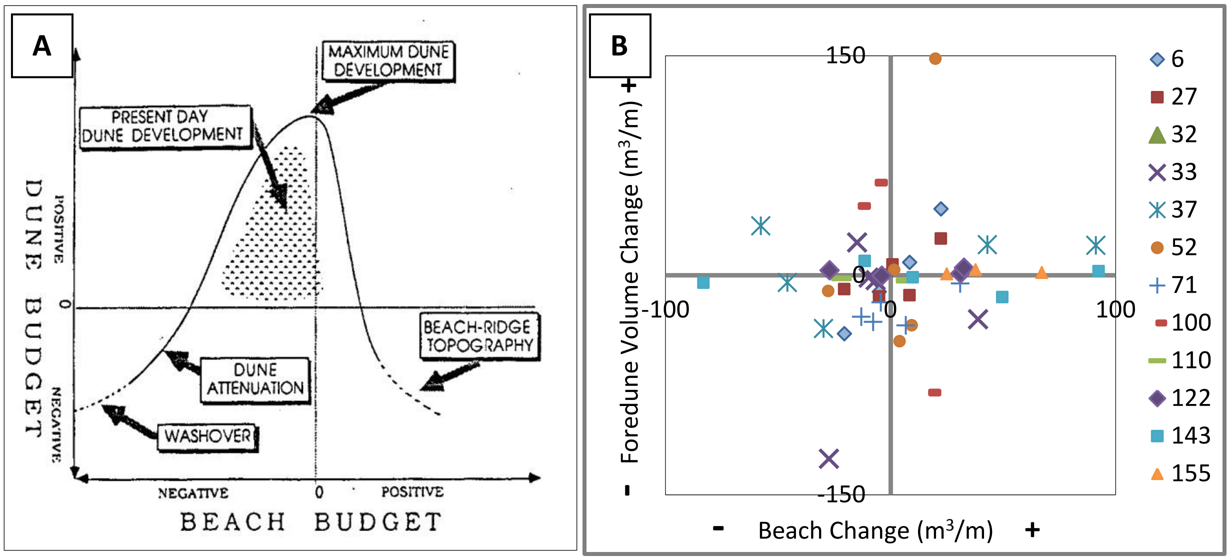


Figure 5.70 – Comparison of the Psuty 1988 sediment supply conceptual model with Gulf County, Florida beach and dune empirical data. Diagram A displays the original Psuty (1988; 4) model. Diagram B displays a chart using the 4 quadrants of the Psuty model with Gulf County data. The data shows the change in foredune volume from one profile to the next surveyed profile. For example, if the 1973 foredune volume was subtracted from the 1983 volume for foredune X, then a positive volume could result, indicating an increase in foredune volume, and this would be plotted on the y-axis. The same would be done for the beach volume. Values were plotted for each subsequent profile. This resultant data plot does not show a close correlation with Psuty's conceptual plot for positive and negative foredune and beach budgets.

To decrease the data scatter and develop a longer-term (35 year) representation, average beach and dune volume change per year was calculated for each of the study sites and are plotted in figure 5.71. The change was calculated by the change in volume, divided by the number of days of change, and multiplied by 365 days. The average of the sequential annual changes was averaged for each profile location. In contrast to the Psuty (1988) matrix, the maximum foredune development, (and in this interpretation, the foredune that increased the most both in volume (m^3/m), and height (m)), occurs under positive beach sediment supply conditions (R37). This is followed by time periods in which beach neutral conditions and positive dune budgets are found at sites R37 and R100. Where Psuty describes washover conditions to occur under negative beach and dune sediment supply, Gulf County data demonstrates that multiple dune ridges exist. In addition, the highly eroding Cape does not have a strong negative dune budget as it is remaining a neutral, or zero budget. In actual fact it is entirely a misnomer to say high negative dune budget because under such conditions because no dune exists. Thus, it is practically impossible to have a “dune budget”. Rather, site R110 at the cape has a near neutral sediment budget as the low dune to washover morphologies migrate landward with the shoreline. Of the Gulf County sites that do have multiple ridge forms, only one site (R155) occurs in the beach highly positive and dune negative quadrant. R143 and R71, both with single foredunes, are also listed in the same quadrant that Psuty states as having “beach-ridge” topography.

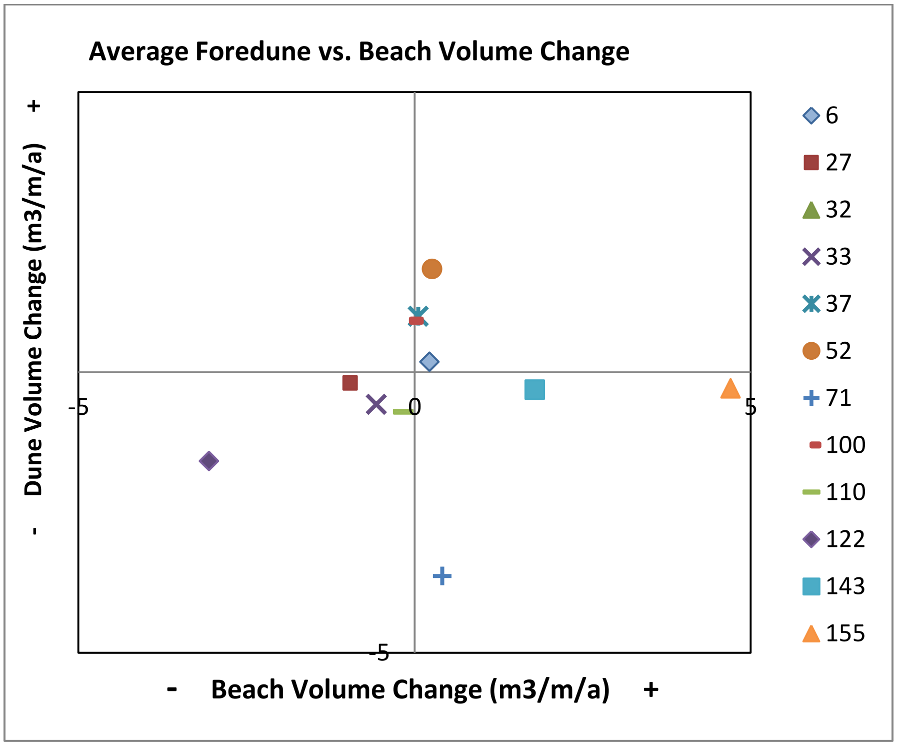


Figure 5.71 – Comparison of average foredune volume change versus average beach volume change for the study period 2006-2007. The values were calculated in order tocompare with the Psuty matrix. However, the Gulf County data does not fall within the Psuty morphological expressions for each quadrant of beach and dune volume change.

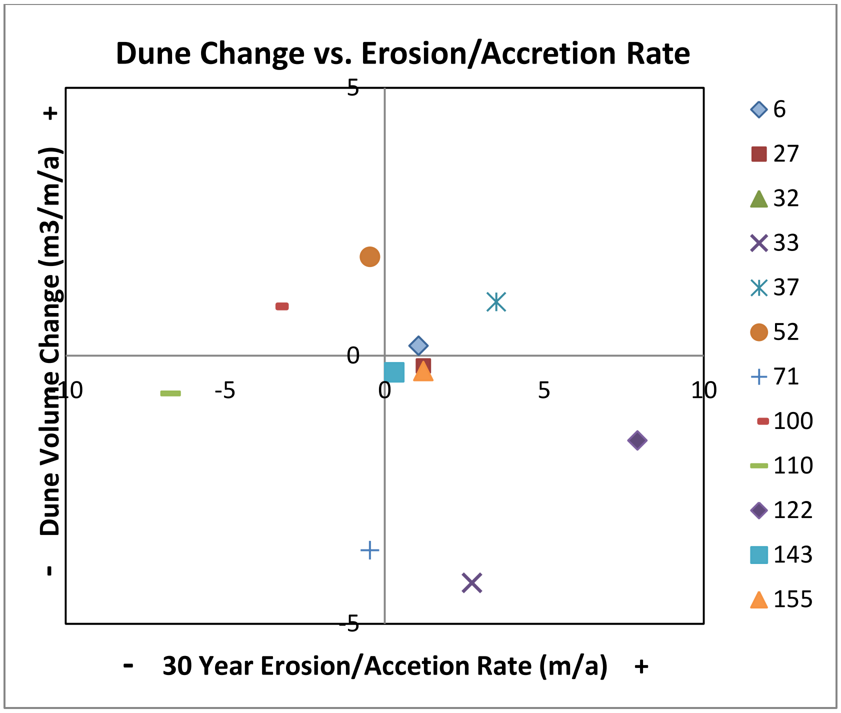


Figure 5.72 – Comparison of average foredune volume change with the 30-year erosion/accretion record. Using the erosion/accretion rate as a proxy for beach sediment supply provides a better comparison between the Psuty matrix and Gulf County data.

To find a better proxy for Psuty's axis of positive and negative sediment supply, the same values for dune volume change were plotted with the 30-year erosion rate (Foster and Cheng, 2001). This new axis effectively changes the beach sediment supply conditions from being a relative distance between shoreline and dune toe, to now including the long-term beach change (Figure 5.72 and 5.73). Plotting the Gulf County data with dune morphologies displays some comparable data to the Psuty plot: 1) The maximum foredune development occurs in the beach slightly negative quadrant, or low erosion rate region; 2) washover conditions exist at the most extreme erosion conditions; 3) multiple ridges are found in the beach positive – dune positive quadrant. However, there are discrepancies with the Psuty matrix. For example, site R71 has the same beach erosion rate as R52, yet the two sites have highly eroding foredunes, and are not growing in height or volume. R52 only display maximum development because the 1973 foredune had been essentially eliminated, and the landward larger dune had become the new foredune. Another discrepancy occurs with R143, which has a slightly accreting to neutral beach, yet has only one single low ridge – a condition not accounted for in the Psuty model. Additionally, multiple ridge forms are not just found in the beach positive and dune negative quadrants, as Psuty's matrix predicts, but multiple ridges exist in the beach positive and dune positive quadrants as well. These plots are indicators that there are other variables that must be incorporated into a conceptual model of foredune development to describe Gulf County dunes.

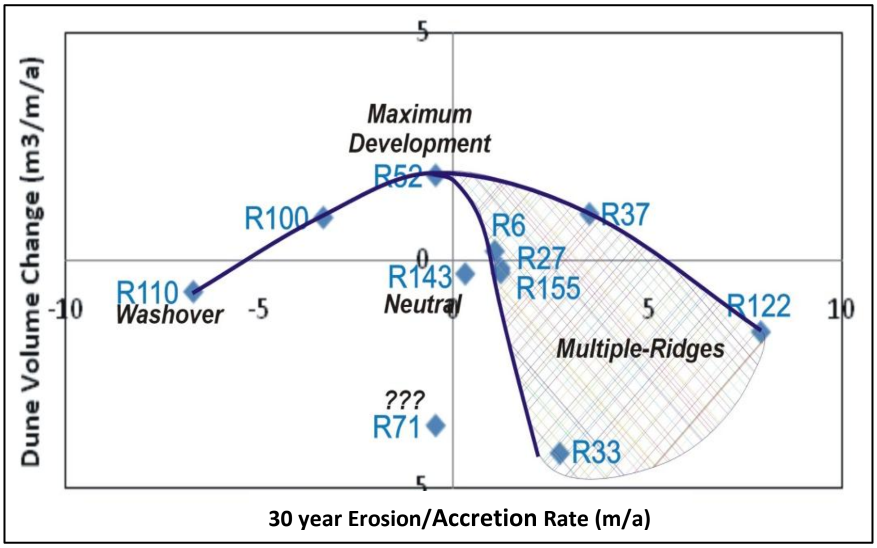


Figure 5.73 - Comparison of average foredune volume change with the 30-year erosion/accretion record. The foredune on profile R52 increased in volume as a new landward and canibalized dune became the foredune. In contrast, there are no landward dunes for the foredune on profile R71 to canibalize. Foredune morphologies have been added, some of which contrast with Psuty's (1988) results.

A new plot with foredune volume and the 30-year erosion/accretion rate was used to explore beach and dune morphodynamics relationship. Figure 5.74 charts all foredune volumes during the 1973 to 2004 time period as well as the first and last data points from 2006 and 2007. Using absolute foredune volume as a proxy for positive and negative foredune sediment supply change, the new chart displays conditions that more closely resemble the negative beach conditions of the Psuty matrix. The largest foredune volumes (R52 and R71) are found in slightly eroding beach conditions. Further erosion leads to a decrease in foredune volume (R100) and washover (R110). Under positive beach conditions, multiple dune ridges exist across the full span of beach accretion rates. The smallest foredunes are found at either end of the range of accretion rates for Gulf County, while some of the largest foredunes on prograding beaches have been found in locations within the mid-range of the spectrum of accretion rates (i.e. R33 and R37).

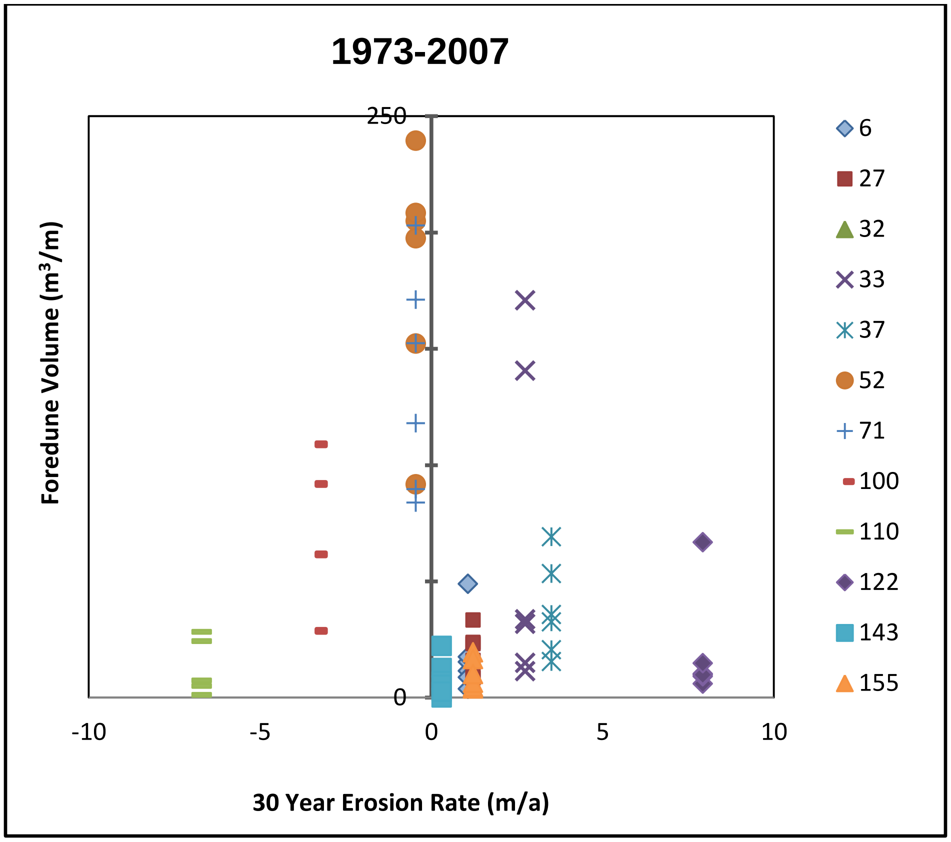


Figure 5.74 – Foredune volumes and the 30 year erosion/accretion rate. Visually, the model is closer to matching the Psuty (1988) matrix, but with the alternate axes described in the text.

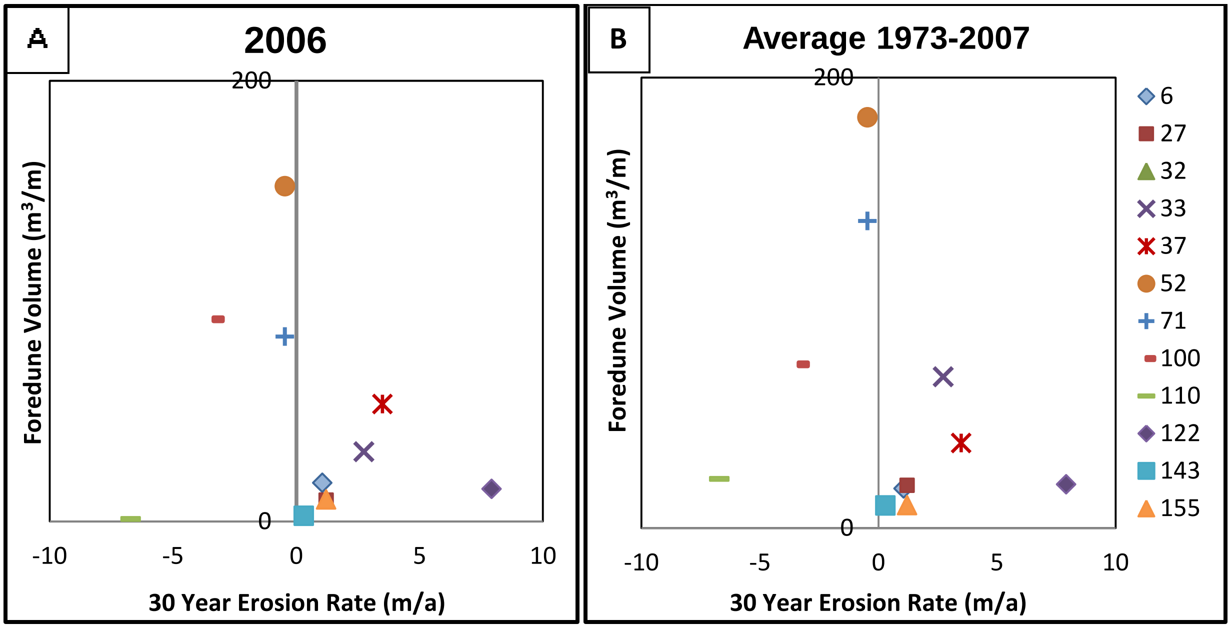


Figure 5.75 - Foredune volume and the 30 year erosion/accretion rate. Figure A plots a single survey sample of 2006 data. Figure 5.71B displays the average for the 1973-2007 data. Both show a very similar pattern indicating that the foredune volumes in 2006 are typical of the period between 1973-2007.

Figure 5.76 displays Psuty's 2004 morphological continuum and comparative plots of foredunes in Donano National Park, Spain (Vallejo *et al*., 2006), and plots for the recent 1-year period and the 34-year period for Gulf County, Florida. The recent (2006-2007) Gulf County data plot mirrors the Vallejo *et al*. plot, with *maximum foredune development* occurring along the prograding portion of the beach plot line. On this plot the foredune loss occurs after the beach sediment supply drops below zero, and beach and foredune erosion occurs. This contrasts with Psuty's model, which has maximum development occurring in dune negative sediment supply conditions. On either side of the maximum foredune development exists multiple ridges with slower rates of foredune development. The 2006-2007 Gulf County data presents washover features occurring as the beach erosion rate increases, a continuum extension beyond what was plotted by Vallejo *et al*. (2006).

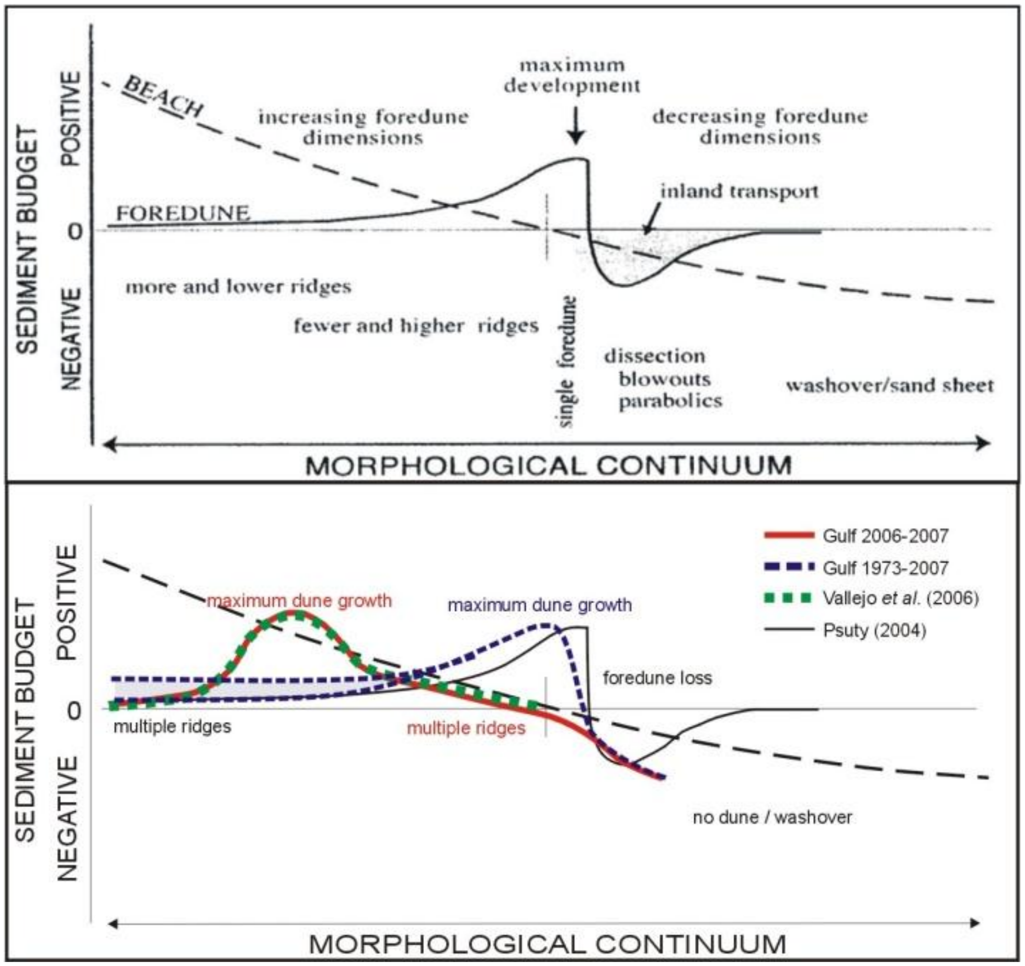


Figure 5.76 – A comparison of Psuty's (2004) conceptual morphological continuum with Donano National Park dunes in Spain (Vallejo et al., 2006), and Gulf County, Florida foredunes. For Gulf County data, Maximum dune growth was defined by the actual dune volume increase (m^3/m).

While the 2006-2007 Gulf County morphologic continuum representation (red line) in figure 5.76 closely resembles the Vallejo et al., (2006) plot, a different Gulf County plot occurs when looking at the longer-term data set for Gulf County (blue-dashed line). On this plot, the maximum foredune development is arguably more prevalent on profile R52, a location with a slightly eroding shoreline, which coincides with the Psuty (2004) plot. However, the foredune loss is undoubtedly not as drastic as the Psuty continuum suggests. Rather, foredune volumes decrease more gradually as the beach erosion rate increases. As the beach erosion rate increases, the foredune decreases in height and volume until only washover forms are present, as seen at

R110. On prograding beaches in Gulf County, foredunes may have a range of heights and volumes along the beach sediment supply continuum, and hence are displayed as a range of volumes, though always relatively small. These plots highlight that there are discrepancies when comparing quantitative data sets to the Psuty conceptual model, or morphologic continuum (2004). These discrepancies may be a result of misinterpretation of Psuty's (2004) qualitative descriptions, or there are additional factors that play a role in foredune development as found in the two sites used to test the model, (Gulf County, Florida, USA; Donano National Park, Spain).

5.4.2 Beach Dune Volume Index

To create an empirical relationship between beach and dune interactions looking solely at their volumes and sizes, a relationship was identified between the beach volume (m^3/m) divided by dune volume (m^3/m), herein listed as the Beach Dune Volume Index (BDVI). BDVI values less than zero indicate the dune volume is much larger than the beach volume, and are situated in areas with large foredunes, such as sites R52 and R71. Sites that have BDVI values greater than zero are indicative of wide beaches with a small dune volume, such as site R32. Comparing the dune height with the BDVI, a reasonable relationship is found (R^2 is 0.54 for the long-term record). The relationship improves when plotting BDVI against dune volume. R^2 is 0.92 for the long-term record and 0.80 for the 2006-2007 study period. (Figure 5.77). Spatially, an empirical pattern emerges, with the smallest BDVI values (i.e. large dunes, small beach) found along St. Joseph Peninsula. A range of values just above zero (i.e. slightly larger beach volume than dune volume) exists at the spit tip and the northernmost part of the Gulf County mainland. And the highest BDVI values (i.e. large beach, small foredune) are located from Cape San Blas to the eastern end of the county.

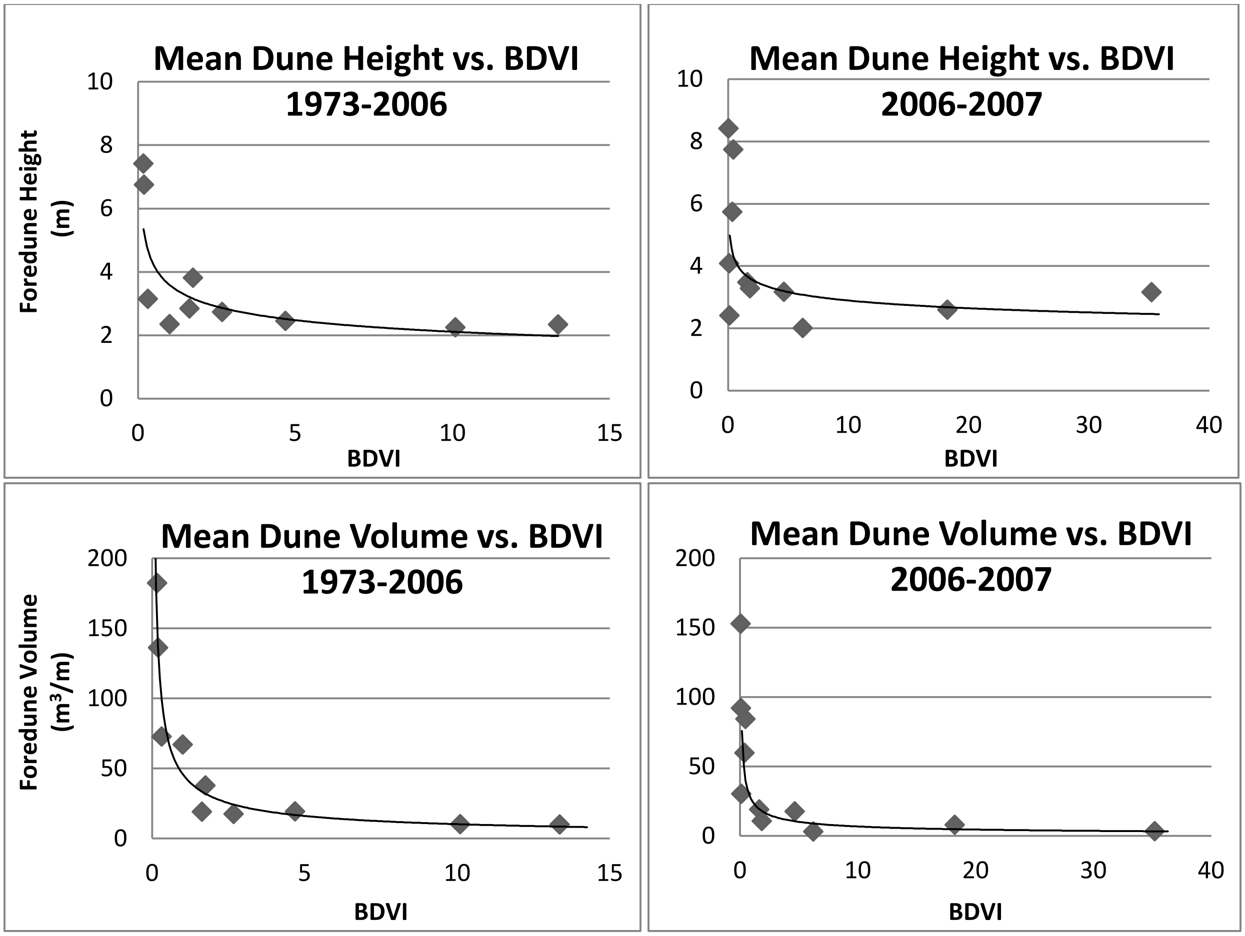


Figure 5.77 – Relationship between average foredune heights and volumes versus BDVI (BDVI=beach volume / dune volume) values. An R^2 value of 0.92 exists on a negative exponential regression for the long-term data. The short-term R^2 value is lower at 0.80, but reflects a period of less consistency for the study site when data is utilized over a shorter time period, (as opposed to the 30+ year average.)

The variance (an indicator of BDVI variability, or beach-dune morphodynamic change) between the sites is highest where the beach is either highly eroding or is situated in the area (R33) in which emerged bars may exist and disappear, causing the beach sediment supply to vary from rapid erosion to rapid progradation as these emerging bars attach to the peninsula. The variance values are listed in brackets adjacent to BDVI values in figure 5.78. The long-term BDVI (1.01) and short-term BDVI (.15) records for R33 are distinctly different. This indicates that the beach-dune volume relationship may be out of its most common state. The variance (1.12), which is the highest variance in Gulf County, explains that this site does experience a large amount of change over decadal scales. This is presumably due to the presence or absence of longshore emergent bars that can accelerate beach erosion and eliminate the potential foredune sediment supply, or large storms may have great impact on the area – factors which may be essential to creating a new foredune development model.

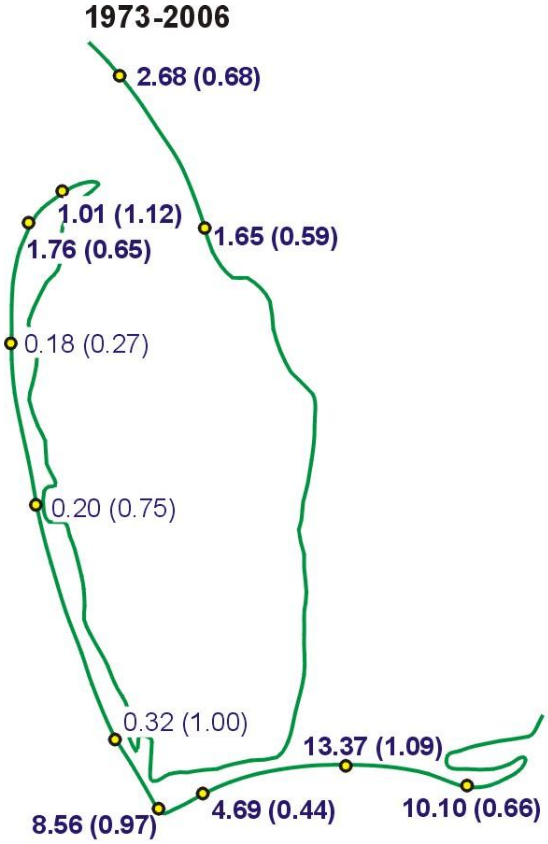


Figure 5.78 – Spatial distribution of average Beach Dune Volume Index (BDVI = Beach Volume / Dune Volume) values for 1973-2006 and 2006-2007. Values in bold type indicate values above zero, or locations in which the beach volume exceeds the foredune volume. The larger smaller BDVI values exist along St. Joseph's Peninsula except the proximal and distal ends. The 2006-2007 show smaller BDVI values near the distal end. Values in brackets indicate the BDVI variance, or the degree of variability for each site. Generally, the highest variability occurs in locations with high erosion rates, or in the dynamic zones north of the spit fulcrum where longshore sandwaves affect the beach-dune sediment supply rates.

5.5 Chapter Summary

Foredune profiles measured during the recent topographic surveys (2006-2007) have shown minimal change compared to the historical record for Gulf County, Florida. The foredunes have slightly grown in size (with the exception of R33 behind the newly emerged longshore sandwave), but these changes are small compared to the changes observed on the longer temporal scale, especially foredune losses that are recorded in the profile data between 1973 and 2004. The Psuty models (1988, 2004) do not accurately describe all foredune morphologies in Gulf County, but the models do provide a starting point for identifying the important variables (beach and dune sediment supplies) for predicting foredune morphology and behavior within the study area. The Psuty continuum model was, however, a closer approximation of Gulf County conditions on a longer temporal scale than was the Vallejo et al. (2007) model, which applied more directly to the most recent short-term study. For Gulf County, current models do not accurately describe the profiles and their changes over the time scales presented. Therefore, (i) the models do not adequately describe or model beach-foredune interactions, or, (ii) there must be other factors that are important in describing the dynamics and evolution of foredunes in Gulf County, Florida.

The BDVI created for the study region provides a small degree of explanation for the beach-dune relationships and may be a useful empirical tool to be tested in additional locations or to describe variations from natural trends in Gulf County. The average BDVI values (Figure 5.78) can be used to determine natural beach-dune volume ratios when systems may be out of equilibrium due to storms or anthropogenic impacts.

While understanding the variability in sediment supply may be an initial tool for determining foredune processes and morphology in Gulf County, other variables will aid in understanding beach-dune interactions and foredune morphologies in Gulf County.Those variables may perhaps include storm frequency, event "synchronization" (Houser, 2009) of large storms, vegetation, and relic dunes (or "antecedent geomorphology"). Additionally, the temporal scale of events is an important factor in determining the evolutionary states (and changes thereto) for foredune model development as described by deVries et al. (2010). Those temporal scale events can also be observed in the Gulf County data.

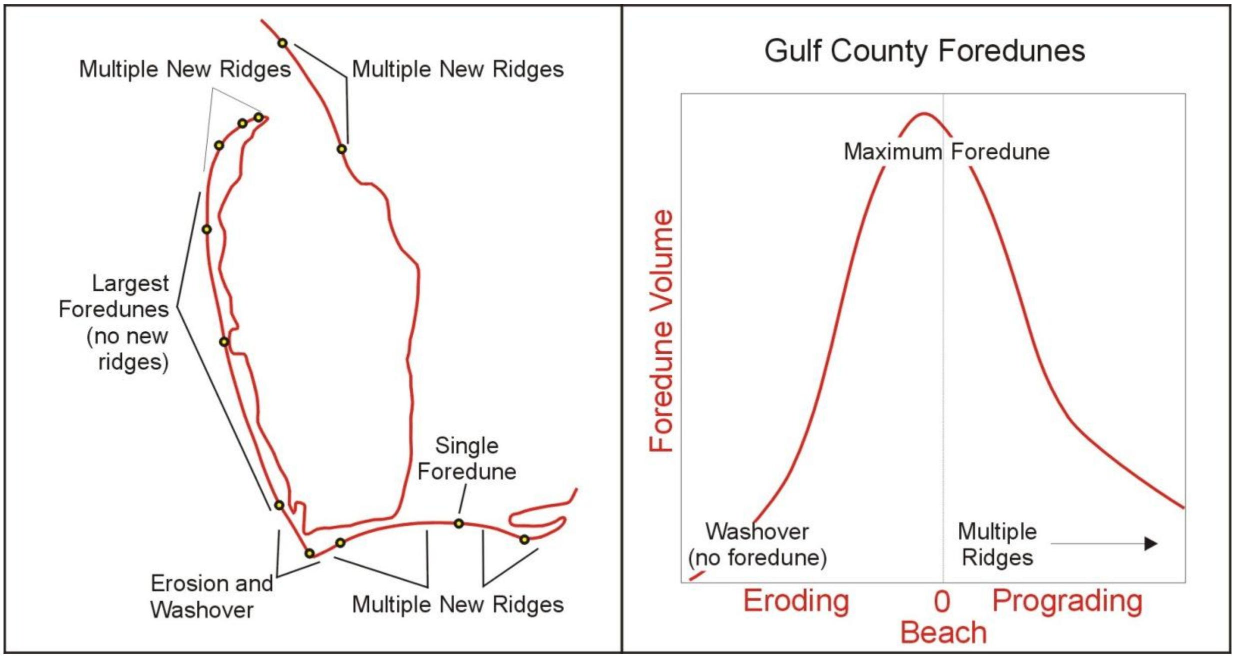


Figure 5.79 – Summary data of foredune types and volumes spatially and conceptually plotted against beach erosion rates. Larger foredunes dominate a majority of the Peninsula, while multiple lower ridges are found on the Gulf County mainland, the prograding spit tip, and along the south-facing east-west coast. Washover morphologies are located at the eroding Cape. The foredune volume data and 30-year beach erosion rate were used to derive the conceptual plot of foredune types for the study region. The Psuty sediment supply models (e.g. 1988) do not accurately describe the foredune morphologies in Gulf County.

Chapter 6
Foredune Vegetation

6.1 Introduction

Vegetation in coastal settings is critical to initiate incipient or embryo dune development on beaches, which may further develop into foredunes. Vegetation presence/absence, species growth habitat and morphology, species richness and diversity, cover, and the vegetation zonation are all critical factors affecting coastal foredune development, among others (e.g. van der Valk, 1974; Pye, 1983; Hesp, 1988, 2002; Arens, 1996; Giles and McCann, 1997; Hesp et al., 2005; Pye, 1983; Hesp, 1988, 1991, 2002; Arens *et al*., 1995; Giles and McCann, 1997; Hesp *et al.*, 2005; Miot da Silva et al., 2008; Hesp and Walker, in press). Sediment supply, beach-surfzone morphodynamic state (dissipative to reflective), and beach state (erosional, stable, accretional) are additional factors that may strongly influence foredune evolution and morphology (e.g. Short and Hesp, 1982; Davidson-Arnott and Law, 1990,1996; Davidson-Arnott, 2010). While there are many studies that examine coastal vegetation in various countries (e.g. van der Maarel (editor), 1993; Garcia Novo et al., 2004), there are few studies that examine the relationships between foredune and dune vegetation associations and shoreline state (eroding to stable to accreting). Gulf County, Florida, has a wide range of beach states from highly erosional to highly progradational, which make it an ideal location to study such relationships. Additionally, apart from the study by Hesp (1988) that examined foredune morpho-ecological types, vegetation associations, and the two fundamental drivers (salt spray and sediment delivery rates) of vegetation zonation, vegetation has yet to be included in any of the dominant conceptual models of foredune development (for example, Short and Hesp, 1982; Psuty, 1988, 2004; Sherman and Bauer, 1993; Houser, 2009). Also, coastal sediment transport models rarely consider the effect of vegetation in calculating sediment transport rates generally, and onto foredunes specifically.

Coastal plant species tolerate high salinity, high temperatures, wind abrasion, and extreme soil moisture conditions to various degrees (Hesp, 1991; Craig, 1991). The most critical factors in coastal dune vegetation zonation are salt-spray (Oosting and Billings, 1942; Sykes and Wilson, 1991) and sand burial (Van der Valk, 1974; Moreno-Casasola, 1986; Dech and Maun, 2005; Maun, 2009). However, swash inundation and ponding, dryness, light intensity, high temperatures, sand salinity, and nutrient deficiency are all stress factors in which coastal vegetation must have specific adaptations to survive (Hesp, 1991; Martinez *et al*., 2001). We know little, however, about how coastal plant associations and species respond to varying moderate to long-term levels of beach and dune erosion and accretion (Hesp and Martinez, 2007).

This chapter will examine the nature of vegetation presence/absence, diversity and richness on the foredune profile lines discussed in Chapter 5. Three vegetation surveys were conducted in 2006 and 2007. The first section will discuss the species presence and dominance on each profile. The following sections will examine the relationships and differences between each of the profiles.

6.2 Foredune Vegetation

Thirty species of vegetation were found on the twelve foredune profiles surveyed in Gulf County, Florida. The primary species, *Uniola paniculata,* is the most widespread grass on the Gulf of Mexico coastal dunes (Craig, 1991) and was the most common species found on the foredunes surveyed. However, profiles surveyed in locations with eroding shorelines versus prograding shorelines were comprised of different species. For example, *Quercus spp*. were only found where the coastline was eroding and foredune loss had occurred.

The following section includes descriptions of the vegetation found on each profile and the relative importance to each profile. Each profile will be examined sequentially from the northernmost location (R6) to the furthest east location (R155) in Gulf County.

6.2.1 Profile R6

Located in the northernmost portion of Gulf County, profile R6 has a slowly prograding shoreline. The less than 10-year old foredune was dominated by pioneer grass species *Uniola paniculata* and *Andropogon sp*., both of which promote sand accumulation by decreasing air flow through the grass (Figure 6.1). However, the *Uniola paniculata* will reduce in height and total biomass during winter, which may decrease the ability to promote sand acccumulation (Craig, 1991). The lower plant canopies of *Hydrocotyle bonariensis*., *Ipomoea imperati*, and *Sesuvium sp*. will promote lower sand dune growth by reducing air flow through the vegetation (Davies, 1980; Hesp, 1989, 2002). However, these species play a smaller role in sediment accumulation due to their minimal cover.

6.2.2 Profile R27

Located south of R6, profile R27 is located within St. Joseph’s Bay, which has typically much lower wave heights (described in chapter 4.) Thus, the potential reduction in salt spray and wave run-up allows for vegetation to grow closer to the waterline as seen in figures 6.3 and 6.4. This includes the low canopied *Hydrocotyle bonariensis* and the runners of *Ipomoea imperati,* which extended to the high tide line. Similar to R6, the vegetation in this profile is dominated by the pioneer grasses *Uniola paniculata* and *Andopogon sp.* on this less than 10-year old foredune.

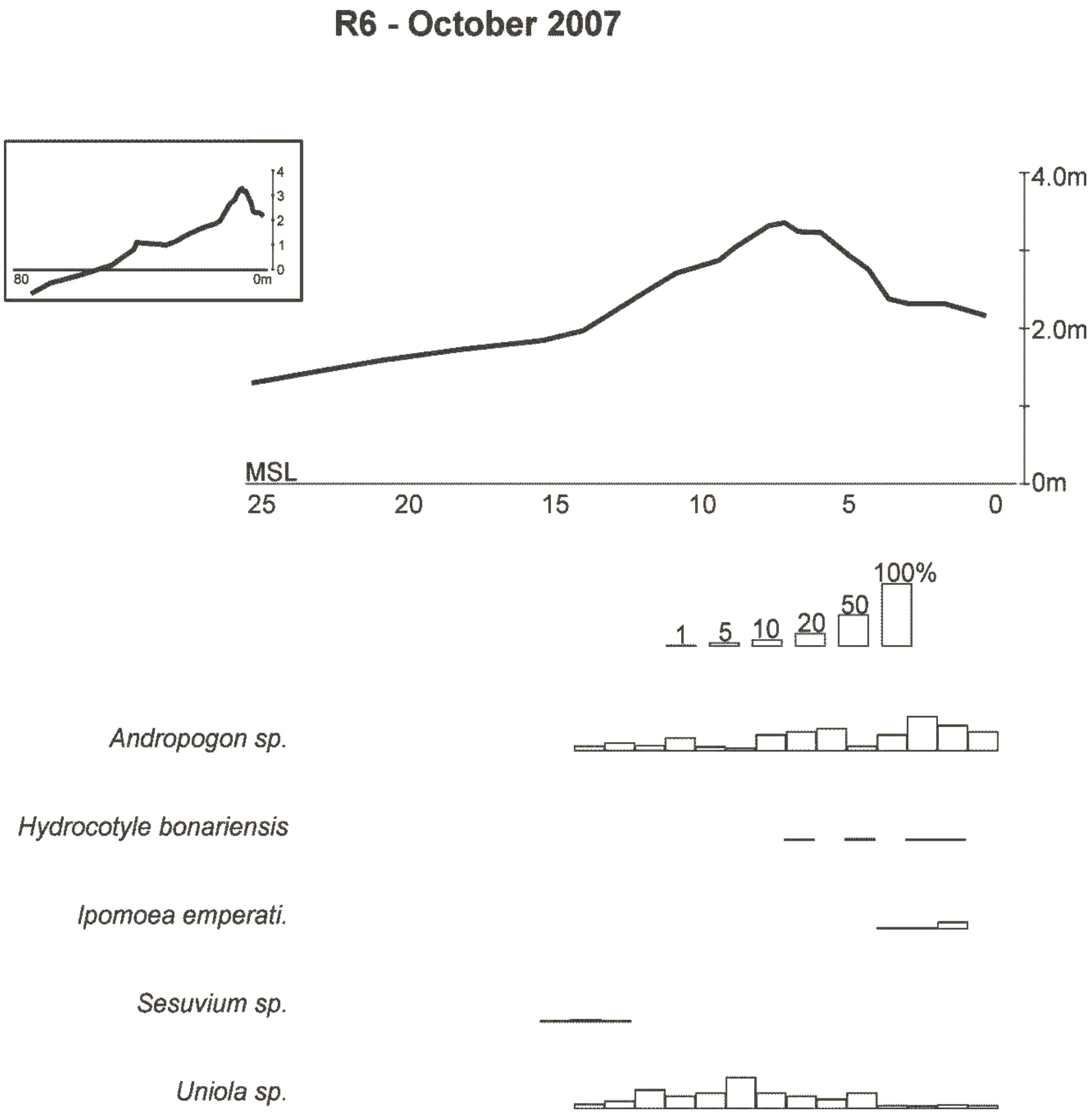


Figure 6.1 - Vegetation survey for east facing FDEP Profile R6 which is accreting at an average rate of 1.1 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance (percent cover within the quadrat measured) are shown graphically below the topographic profile.

Figure 6.2 – Profile R6 foredune looking east from the beach. *Uniola Paniculata* dominate the seaward side of the dune.

Figure 6.3 - Profile R27 vegetation. Dominant *Uniola paniculata* on the foredune with *Ipomoea imperati* runners approaching the waterline (October, 2007).

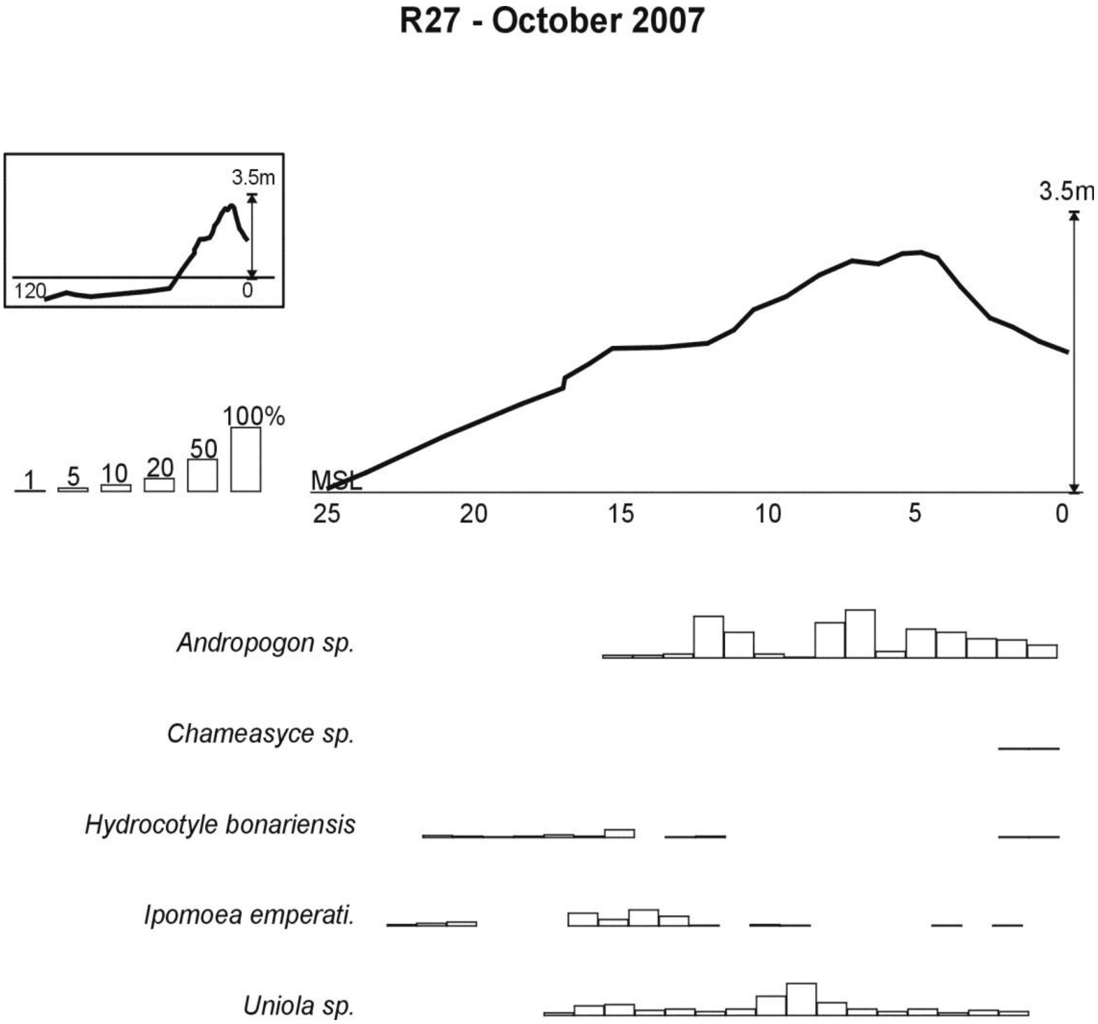


Figure 6.4 – Vegetation survey for east facing FDEP Profile R27 which is accreting at an average rate of 1.2 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

6.2.3 Profile R32

Profile R32 is located at the northern tip of the rapidly elongating St. Joseph Peninsula. The very wide, flat beach has grown so fast that new vegetation growth across the beach has not matched the rate of beach progradation. Since the initial vegetation survey in 2006, the beach has slowly had small clumps of *Uniola paniculata* appear on the profile line. However, the new vegetation is so sparse that no new embryo dunes had started to form by the end of the survey period.

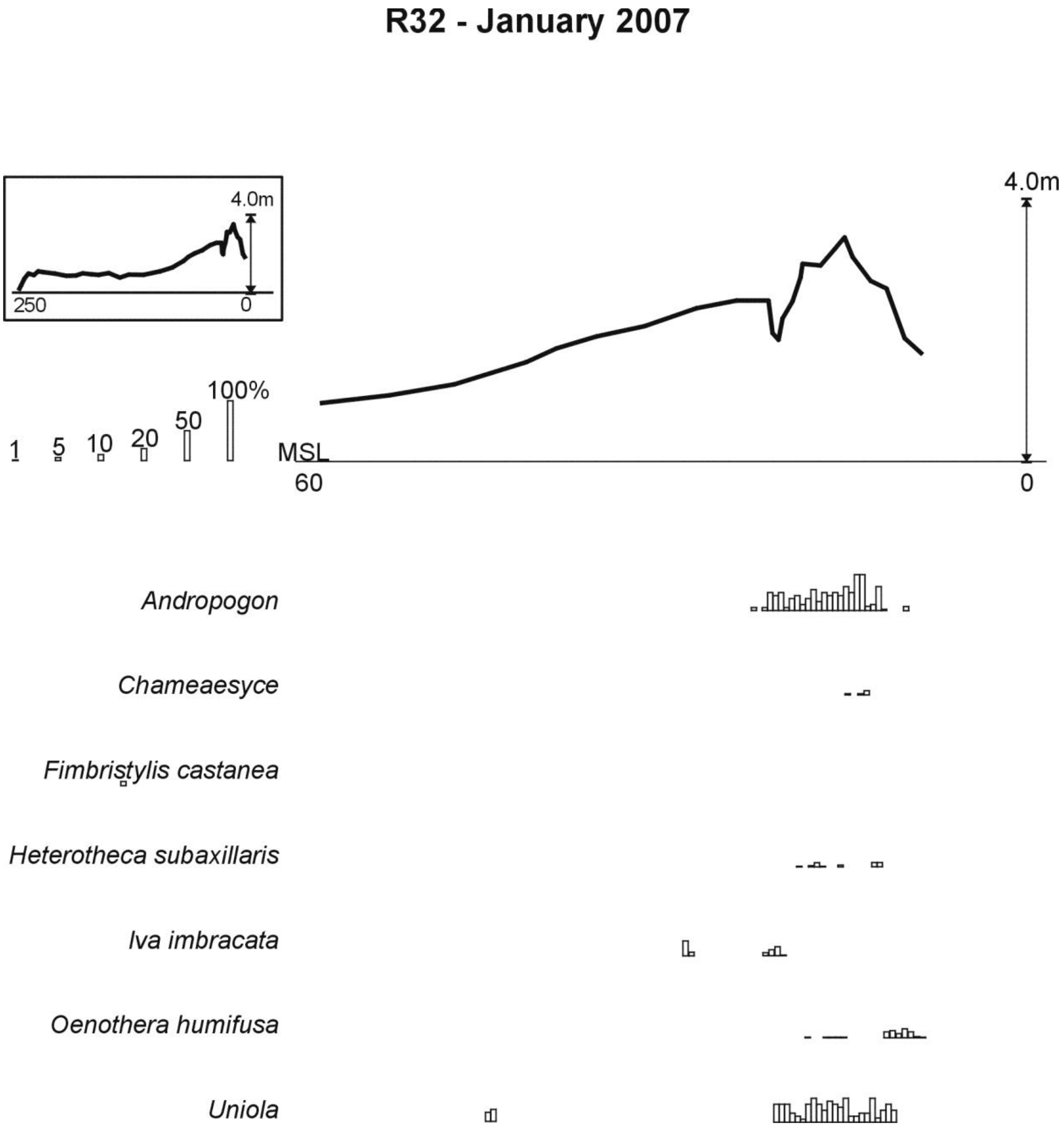


Figure 6.5 – Vegetation survey for north facing FDEP Profile R32 which is accreting at an average rate of 13.1 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

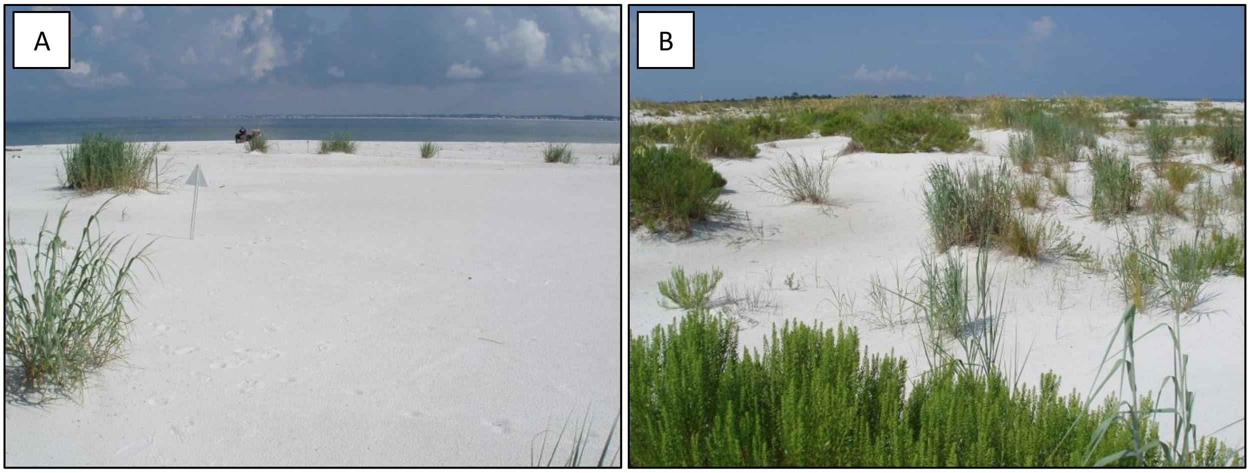


Figure 6.6 – Profile R32 vegetation change. Photo A (left) displays the wide beach along profile R32 with minimal vegetation taken in 2007. Photo B (right) shows the same site with increased vegetation clumps in late 2009, which became incipient foredunes.

The foredune itself is dominated by *Uniola paniculata* and *Andropogon sp.* (Figure 6.5). Five other low-lying plants make up a small percentage of the vegetation cover of the foredune. Two of these species, *Oenothera humifusa* and *Heterotheca subaxillaris* rarely grow on the seaward facing side of the foredune in Gulf County. However, these plants are located over 150 m from the shoreline, and thus probably have not been influenced by salt spray at the spit's northern tip.

6.2.4 Profile R33

The vegetation profile for site R33 only included the foredune landward of the emergent longshore sand bar. During the course of this study, vegetation had yet to grow on the emerged bar, so only the landward foredune was included in the vegetation survey. Once again, the dominant vegetation on this stretch of prograding shoreline was dominated by *Uniola paniculata* and *Andropogon sp.* (Figure 6.6). The emerged bar and swale protected the foredune from high wave energy and salt-spray, and therefore the vegetation was very close to the waterline. However, unlike Profile R27 in St. Joseph Bay in which vegetation was growing toward the waterline, the scarped foredune vegetation, rhizome, and roots were probably already located in their current positions.

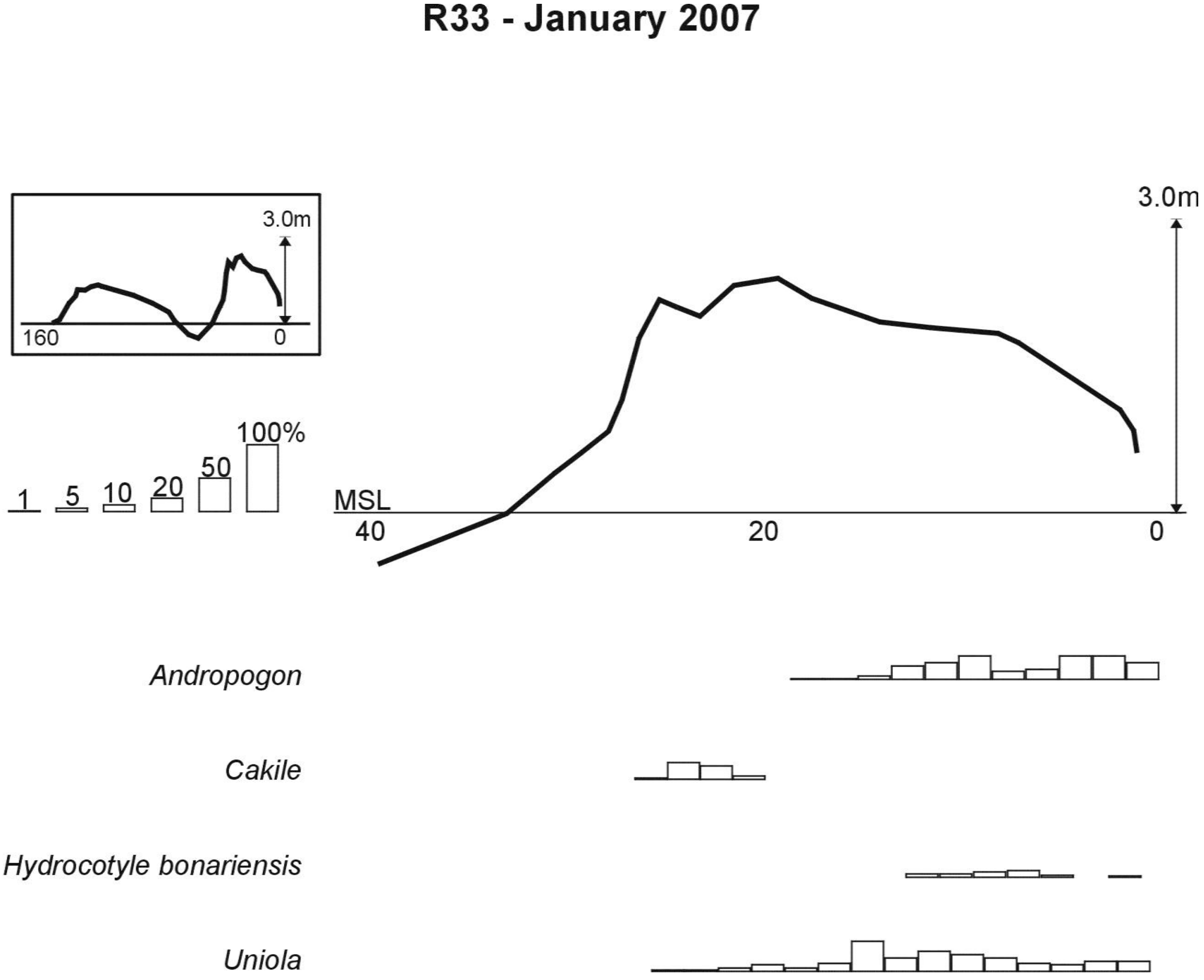


Figure 6.7 – Vegetation survey for north-east facing FDEP Profile R33 which is accreting at an average rate of 2.7 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

Figure 6.8 – Profile R33 looking north showing the cut back vegetation on the foredune. In the background is the emerging bar discussed in the previous section. No new vegetation established here during the survey period.

6.2.5 Profile R37

The vegetation on profile 37 is dominated by *Uniola paniculata* and *Andropogon sp.*, similar to the aforementioned four profiles, which occur on prograding coasts (Figure 6.9). The vegetation is densest on the crest and the landward side of the foredune. Despite the beach being extremely wide, new vegetation had not appeared further seaward on the foredune or the beach by the end of the study period.

6.2.6 Profile R52

The vegetation on profile R52 is distinctly different compared to the previously discussed vegetation surveys. *Uniola paniculata* was not initially present on the foredune crest. However, after a disturbance occurred during topographic surveying, *Uniola paniculata* was found in the

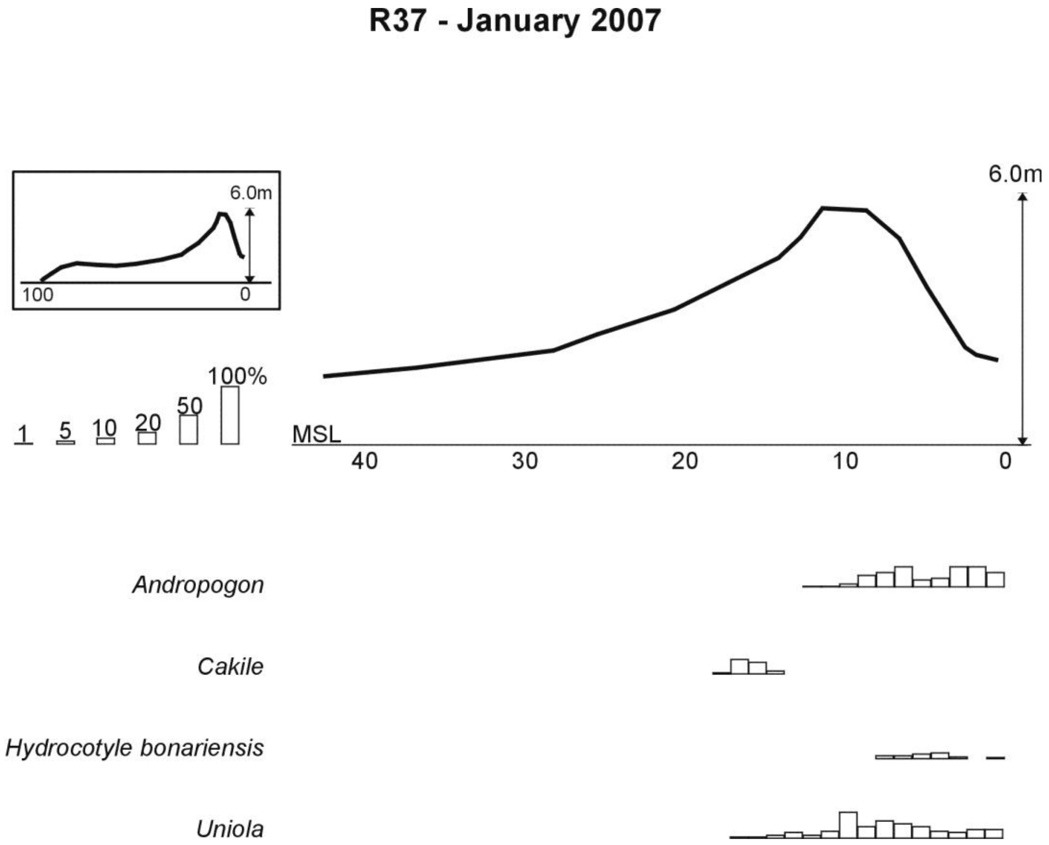


Figure 6.9 – Vegetation survey for east facing FDEP Profile R37 which is accreting at an average rate of 3.5 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

clearing. All species landward of the foredune crest were densely populated mature species, dominated by shrubs and trees, including three different *Quercus sp.* and *Pinus sp.* (Figure 6.11 and 6.12). These climax species are not found on young foredunes, but rather are only on older dunes as a result of shoreline and dune erosion. Removal and/or landward translation of the foredune results in them having a more seaward position.

Figure 6.10 – Dense *Uniola paniculata* cover on the foredune at profile R37. This vegetation is reducing flow and aiding in the largest amount of sediment accumulation measured.

Figure 6.11 - Profile R52 vegetation. Almost no vegetation is present seaward of the foredune crest. In contrast, landward of the crest has densely populated mature species.

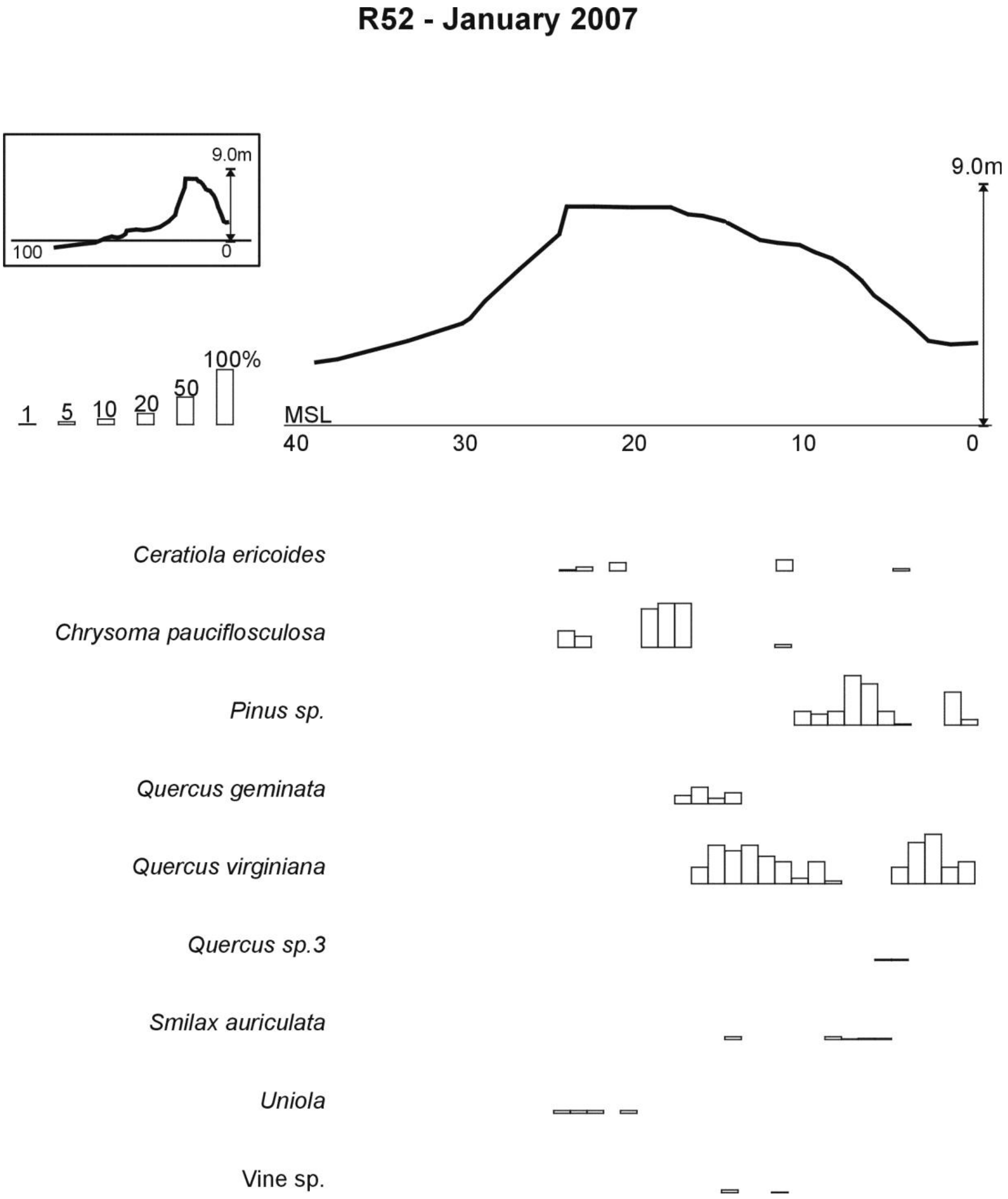


Figure 6.12 – Vegetation survey for east facing FDEP Profile R52 which is eroding at an average rate of 0.5 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

6.2.7 Profile R71

Profile R71 has many similar species as profile R52, and both profiles have similar long-term erosion rates. At the start of the study period, *Uniola paniculata* was not present on the beach or dune toe (Figure 6.13). However, in July 2006, park managers permitted the planting of *Uniola paniculata* to promote dune development in the southern end of the park, which included profile R71. Landward of the foredune crest, the shrub *Ceratiola ericoides* is the most abundant species (Figure 6.13 and 6.14). Johnston (1997) found this species to exist only as a third successive band on prograding dunes in neighboring Bay County, Florida. This confirms that the current foredune on Profile R71 had additional foredunes seawards at a previous point in time, or that the foredune has slowly translated landwards over time – which is true for at least the Florida DEP survey period (see Figure 5.20). Johnston (1997) found that *Ceratiola ericoides* occurs only on ridges protected from the shoreline from 53 to 117 years, which is supported by the historic profiles.

6.2.8 Profile R100

Profile R100, the third beach/foredune eroding site, has a thick patch of a *Quercus sp.* The presence of this mature species suggests a great loss of the foredune seaward portion, which is supported by the historic profiles for this location. During the study, the *Quercus sp.* maintained its presence; however, the shrub was rapidly dying, possibly due to its increased exposure to salt spray (Oostings and Billings, 1942; Hesp, 1990) on this eroding stretch of shoreline, or sand burial (van der Valk, 1974; Lee and Ignaciuk, 1985). This site's level of development landward of the foredune crest may have contributed to the types of vegetation found, and the relative lack thereof. Therefore, only the foredune crest and seaward was surveyed (Figure 6.16).

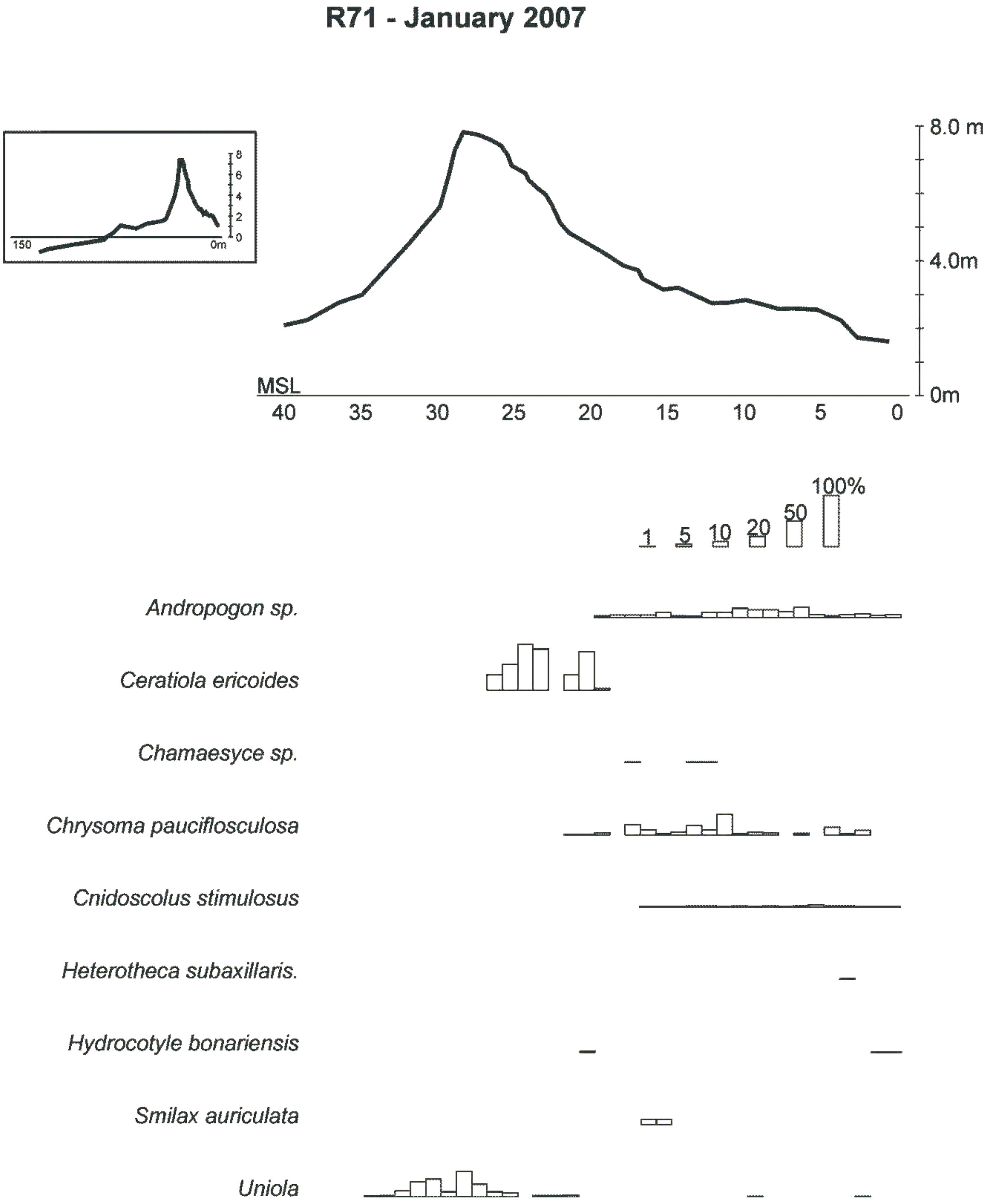


Figure 6.13 – Vegetation survey for east facing FDEP Profile R71, which is eroding at an average rate of 0.5 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

Figure 6.14 – New sediment on the foredune ramp on Profile R71 has not been colonized by plants. The vegetation clumps appear to be a result of vegetation/sediment slumping from the foredune crest. Picture taken before *Uniola paniculata* plantings.

Figure 6.15 – New *Uniola paniculata* planted on the beach and up to the dune toe on Profile R71 taken in June 2007. An incipient foredune was forming but a storm event overwashed the vegetation and incipient dune on the profile line. However, this originally anthropogenic protective measure is naturally rebuilding a new foredune where the overwash occurred.

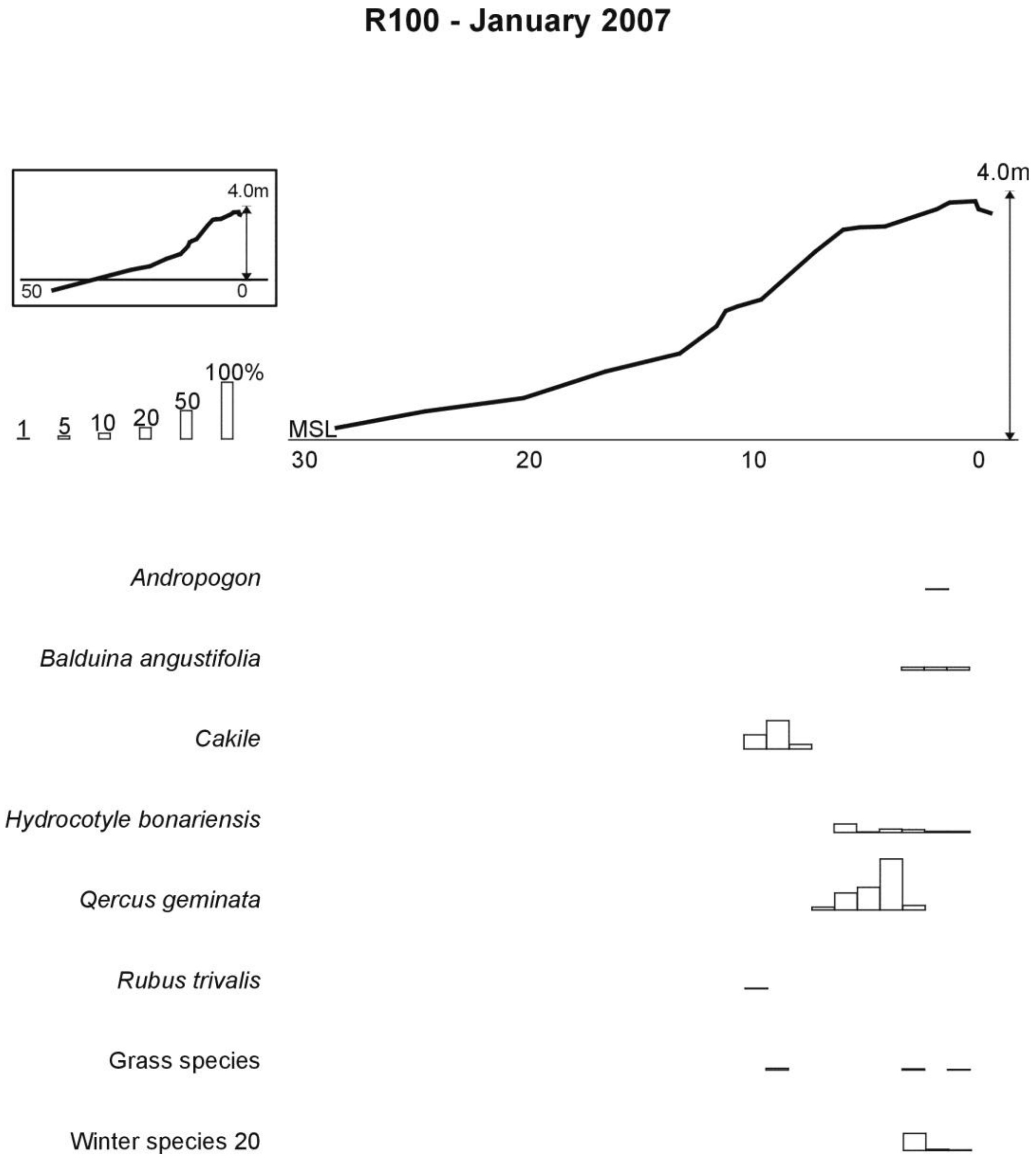


Figure 6.16 – Vegetation survey for south-east facing FDEP Profile R100, which is eroding at an average rate of 3.4 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

6.2.9 Profile R110

Profile R110 has limited to no aeolian depositional forms, but rather a flat beach backed by a clearing, which is part of a former military establishment. The low-lying species *Ipomoea* *imperati* and *Chamaesyce sp.* dominated this area, and did not promote the establishment or growth of any new aeolian forms during the study period (Figure 6.17). Looking either east or west from this location, trees are present adjacent to the waterline, which is evidence of the rapid erosion at the Cape over the past 30+ years (Figure 6.18).

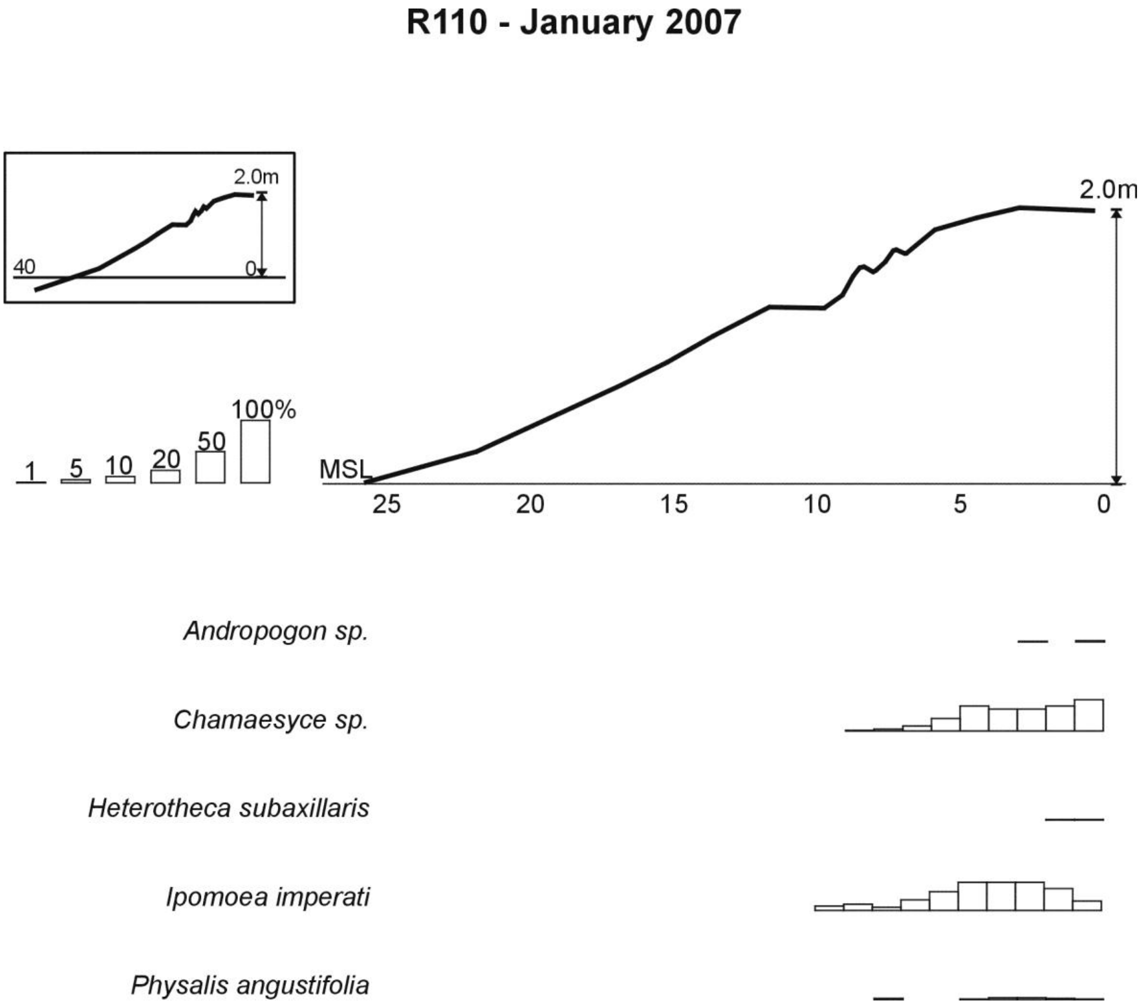


Figure 6.17 – Vegetation survey for south facing FDEP Profile R110, which is eroding at an average rate of 6.7 m/a. No evidence of any new aeolian deposition was documented during the study period, despite relatively high vegetation densities at times. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

Figure 6.18 – Just west of the profile line R110 take in June 2007, trees are located adjacent to the waterline, which is evidence of the extremely rapid erosion at Cape San Blas.

6.2.10 Profile R122

The vegetation on Profile R122 is similar to the species present on the prograding beaches to the north, with the dominance of *Andopogon sp.* and *Uniola paniculata* (Figure 6.19). This very young foredune is dominated by tall grasses that promote sand accumulation (Hesp, 1999). Seaward of the foredune exists a small clump of *Uniola paniculata*, which later became the site for the development of an incipient dune. This profile line's three new foredune ridge crests, which are all younger than five years old, are spaced approximately 20 meters apart--the same distance to the new clump of vegetation. The young low-hummocky back dunes are suggestive of Hesp's (1999) description of Type 1 incipient dunes, which develop into undulating ridges following lateral accretion. Small clumps of *Uniola paniculata* currently spread laterally (Figure 6.20) along the beach and may develop into these same incipient forms and later develop into a more hummocky aeolian-deposited ridge feature.

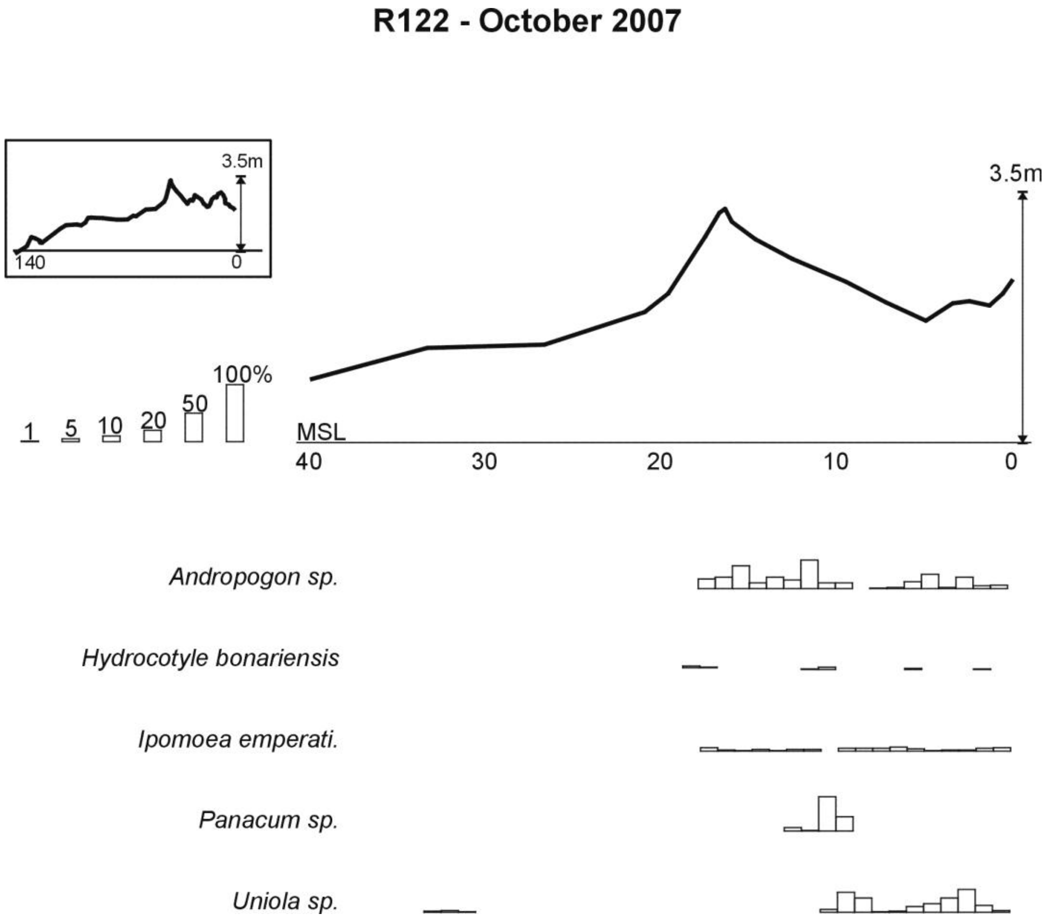


Figure 6.19 – Vegetation survey for east facing FDEP Profile R122, which is accreting at an average rate of 7.9 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

6.2.11 Profile R143

Profile R143 vegetation is dominated by *Uniola paniculata* on the foredune crest with small clumps of *Andropogon sp*. (Figure 6.21). *Ipomoea imperati* runners were extending seaward from the foredune and may start to develop a low incipient dune terrace (Hesp, 1989), unless the grasses (*Uniola paniculata* and *Andropogon sp.)* transfer seaward and develop discrete sediment accumulation zones and a more hummocky morphology.

Figure 6.20 – Profile R122 new *Uniola paniculata* clumps with *Ipomoea imperati* which may create a hummocky incipient terrain, which will lead to a new incipient foredune ridge (June, 2007).

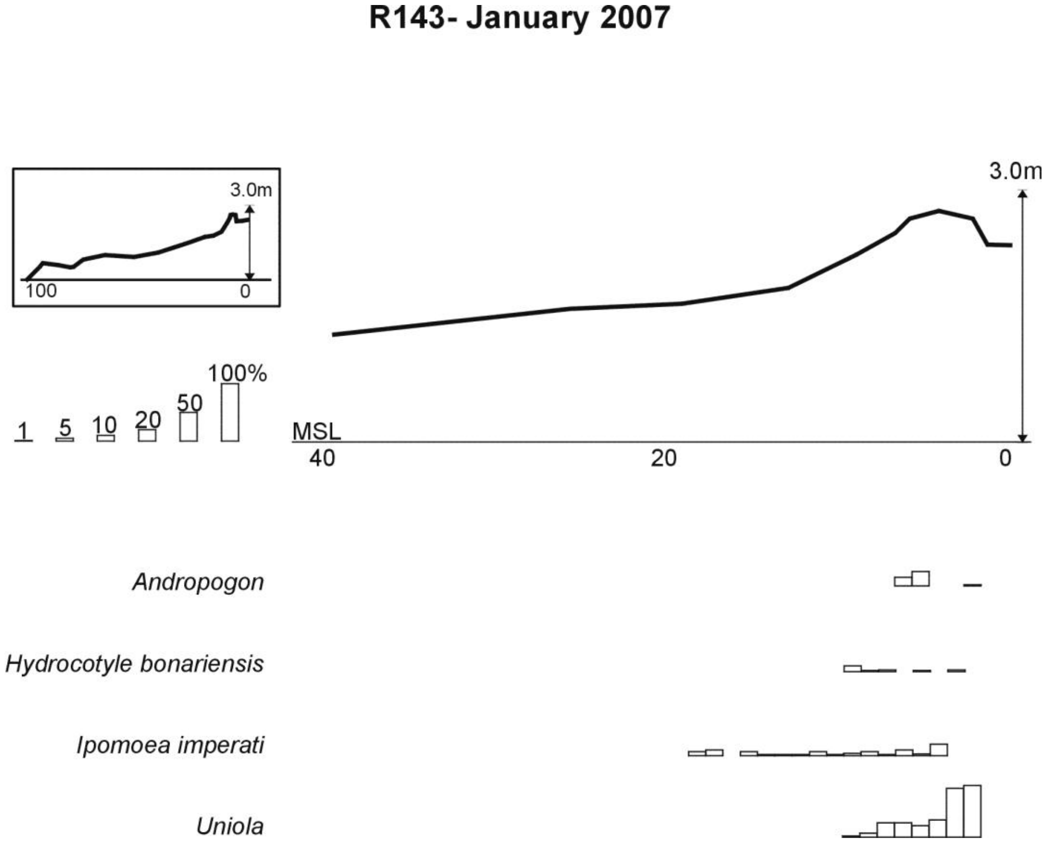


Figure 6.21 – Vegetation survey for east facing FDEP Profile R143, which is accreting at an average rate of 0.3 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

6.2.12 Profile R155

Profile R155, another prograding shoreline location, is dominated by *Uniola paniculata* and *Andropogon sp.* (Figure 6.22). Similar to profiles R27 and R143, *Ipomoea imperati* runners are extending seaward from the foredune crest. The presence of a secondary species, *Oenothera humifusa,* suggests that this foredune may have been situated in this location for a longer time period or the beach was much wider at this location at a previous point in time. Johnson (1997) found *Oenothera humifusa* appearing on dunes in Bay County, Florida that are older than 6 or more years. This closely tracks the profile history at this location, with the first incipient form showing up in the profile 15 years earlier, in 1993, and a more distinct foredune appearing on the profile in 1997.

Figure 6.22 – Profile R155 new *Uniola paniculata* clumps with *Ipomoea imperati* creating a hummocky incipient terrain with aeolian sediment supplied from the wide beach (August, 2009).

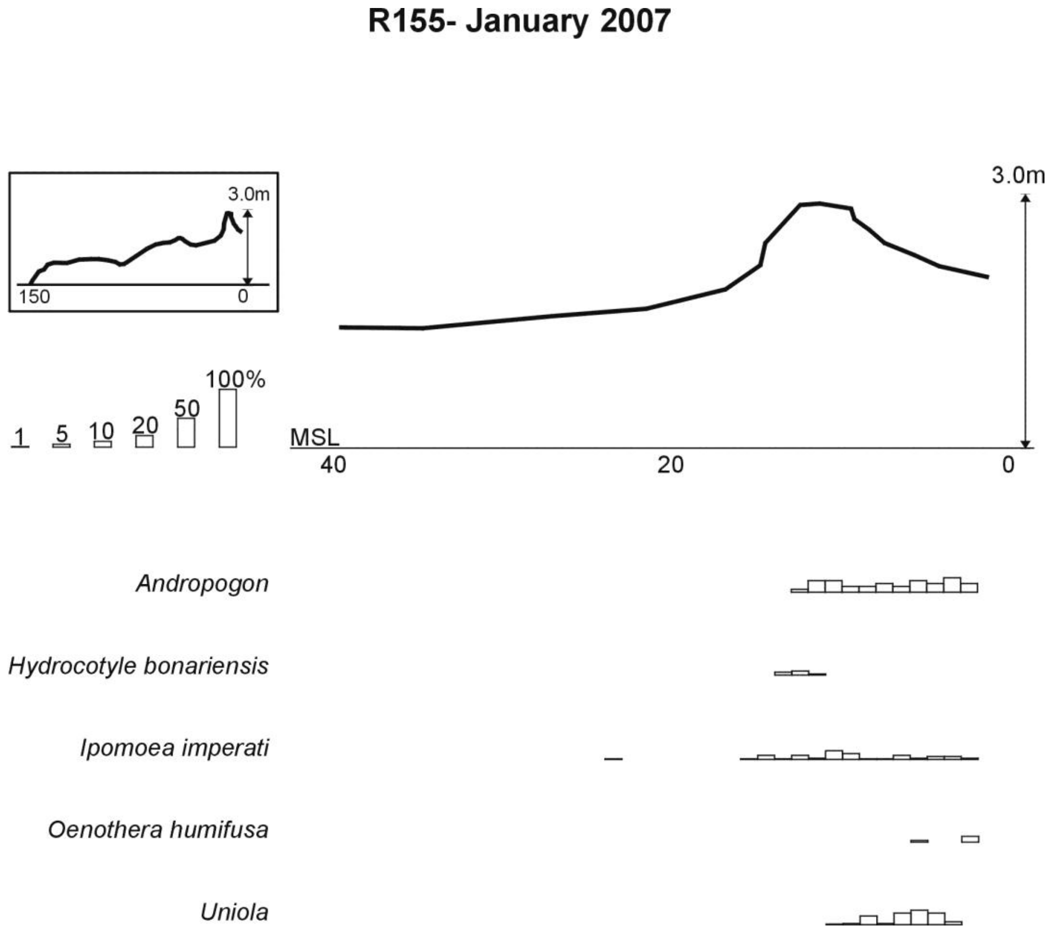


Figure 6.23 – Vegetation survey for east facing FDEP Profile R155, which is accreting at an average rate of 1.2 m/a. The vertical axis displays the height above mean sea level (NAVD88). The inset diagram shows a vertically exaggerated full profile from the leeward dune toe to the seaward extent of the topographic survey. Species presence and abundance are shown graphically below the topographic profile.

6.3 Similarity and Diversity Indices

In order to statistically compare the profile lines, the Sørensen Similarity Index (Sørensen, 1948) and the Shannon-Wiener Diversity Index (Shannon, 1948) were calculated (see Methods section). Additionally, relative importance (Krebs, 1986; Miot da Silva et al., 2008) charts and a hierarchical dendrogram display comparative results between the surveyed profiles.

The following sections will compare the various vegetation surveys, profile to profile and year to year.

6.3.1 Vegetation Similarity

The Sørensen Index (1948) was used for comparing the incidence of species on two vegetation profiles. The Sørensen index indicates sensitivity to heterogeneous data sets. Values above 0.5 are indicative of relatively stronger relationships (McCune and Bruce, 2002) and are listed in (Table 6.1).

Table 6.1 - Sørensen Similarity Index for January 2007 vegetation survey for 12 profiles in Gulf County, Florida. Highlighted values indicate stronger relationships.

	6	**27**	**32**	**33**	**37**	**52**	**71**	**100**	**110**	**122**	**143**	**155**	
6	**X**	0.55	0.36	0.57	0.60	0.29	0.46	0.46	0.25	0.60	0.43	0.44	**6**
27	0.55	**X**	0.57	0.60	0.62	0.24	0.38	0.25	0.18	0.62	0.47	0.67	**27**
32	0.36	0.57	**X**	0.60	0.62	0.24	0.38	0.13	0.36	0.46	0.47	0.50	**32**
33	0.57	0.60	0.60	**X**	0.38	0.24	0.25	0.13	0.00	0.31	0.24	0.33	**33**
37	0.60	0.62	0.62	0.38	**X**	0.25	0.53	0.27	0.00	0.67	0.63	0.55	**37**
52	0.29	0.24	0.24	0.24	0.25	**X**	0.42	0.21	0.00	0.25	0.30	0.27	**52**
71	0.46	0.38	0.38	0.25	0.53	0.42	**X**	0.22	0.00	0.53	0.53	0.43	**71**
100	0.46	0.25	0.13	0.13	0.27	0.21	0.22	**X**	0.15	0.27	0.32	0.29	**100**
110	0.25	0.18	0.36	0.00	0.00	0.00	0.00	0.15	**X**	0.20	0.29	0.44	**110**
122	0.60	0.62	0.46	0.31	0.67	0.25	0.53	0.27	0.20	**X**	0.63	0.63	**122**
143	0.43	0.47	0.47	0.24	0.63	0.30	0.53	0.32	0.29	0.63	**X**	0.67	**143**
155	0.44	0.67	0.50	0.33	0.55	0.27	0.43	0.29	0.44	0.55	0.67	**X**	**155**
	6	**27**	**32**	**33**	**37**	**52**	**71**	**100**	**110**	**122**	**143**	**155**	

The three profiles on the south-facing prograding beaches (R122, R143, and R155) have the strongest similarity relationships, with values of 0.55 to 0.67. The prograding profile R37 also has strong similarity values to all three of these profiles. The northernmost profiles (R6, R27, and R32) also have strong similarities, and all are located on prograding beaches. The statistical relationship probably stems from the presence and dominance of the pioneer species, *Uniola paniculata and Andropogon sp.*, on each of these foredune profiles. Table 6.2 displays the same values, but the profiles are ordered based on Foster and Cheng's (2001) erosion/accretion rates. This table highlights the relationship between the Sørensen values and erosion-accretion rate. The long-term eroding sites have very poor Sørensen Similarity Index relationships. The means of the Sørensen Index values for all the eroding sites (110, 100, 71, 52) and all the accreting/stable sites (143, 6, 27, 155, 33, 37,122, 32) were determined (Table 6.2), and a *T-test* was calculated to assess if there was a significant difference between the two groups. The *T-test* results indicate *P* values less than 1 %, with a confidence interval of 95%, indicating that there is indeed, a significant difference between the two groups; i.e. there is significant statistical vegetation species dissimilarity between the foredunes that are eroding and those that are ~stable to accreting. However, R71 does hold the closest Sørensen similarity relationship to the prograding coast profiles. The neighboring profiles R52 and R71 show the strongest relationship, weighted by the similar presence of *Ceratiola ericoides, Chrysoma pauciflosculosa* *, Hydrocotyle bonariensis,* and *Uniola paniculata.* However, the abundant tree and shrub species that were not found on profile R52 decreases the similarity of the two profiles. Profiles R100 and R110, despite being located near each other, have almost no similarity. The absence of a distinct dune form on Profile R110 makes it not surprising that there are very limited vegetative similarities with other profile locations.

The variability in foredune volumes/heights and accretion or erosion rates provide a wide range of vegetative settings. However, when comparing the total number of species to foredune height and volumes (Figure 6.24), strong relationships exist (R^2 = 0.84 and R^2 = 0.89 respectively). The consistent 3 to 4 m high dunes on the prograding coasts present similar new environments for pioneer vegetation species to dominate. Comparable relationships were found for each of the surveys conducted, but summer surveys showed even stronger relationships between sites R122, R143, and R155 (approximately 0.80).

Table 6.2 – The survey lines ranging from most erosional to most accretional and their associated Sørensen Index values, comparing vegetation species on profiles surveyed, January, 2007. Higher values indicate more common species presence between two sites and similarity, and are consistently found on prograding sites. Means of the Sørensen Index for each site are listed in the right hand column. A *t-test* was calculated for the eroding and prograding means to establish a statistically significant difference (with 95% confidence) in Sørensen values.

profile	**110**	**100**	**52**	**71**	**143**	**6**	**27**	**155**	**33**	**37**	**122**	**32**	
shoreline change (m/a)	-13	-3.3	-0.5	-0.5	0.3	1.1	1.2	1.2	2.8	3.5	8	14	
dune height (m)	2	4.1	8.4	7.7	3.2	3.5	3.3	2.6	2.4	5.7	3.2	3.6	**mean**
110	**X**	0.15	0	0	0.29	0.25	0.18	0.44	0	0	0.2	0.36	0.05
100	0.15	**X**	0.21	0.22	0.32	0.46	0.25	0.29	0.13	0.27	0.27	0.13	0.19
52	0	0.21	**X**	0.42	0.3	0.29	0.24	0.27	0.24	0.25	0.25	0.24	0.21
71	0	0.22	0.42	**X**	0.53	0.46	0.38	0.43	0.25	0.53	0.53	0.38	0.21
143	0.29	0.32	0.3	0.53	**X**	0.43	0.47	0.67	0.24	0.63	0.63	0.47	0.51
6	0.25	0.46	0.29	0.46	0.43	**X**	0.55	0.44	0.57	0.6	0.6	0.36	0.51
27	0.18	0.25	0.24	0.38	0.47	0.55	**X**	0.67	0.6	0.62	0.62	0.57	0.59
155	0.44	0.29	0.27	0.43	0.67	0.44	0.67	**X**	0.33	0.55	0.55	0.5	0.53
33	0	0.13	0.24	0.25	0.24	0.57	0.6	0.33	**X**	0.38	0.31	0.6	0.43
37	0	0.27	0.25	0.53	0.63	0.6	0.62	0.55	0.38	**X**	0.67	0.62	0.58
122	0.2	0.27	0.25	0.53	0.63	0.6	0.62	0.63	0.31	0.67	**X**	0.46	0.56
32	0.36	0.13	0.24	0.38	0.47	0.36	0.57	0.5	0.6	0.62	0.46	**X**	0.51

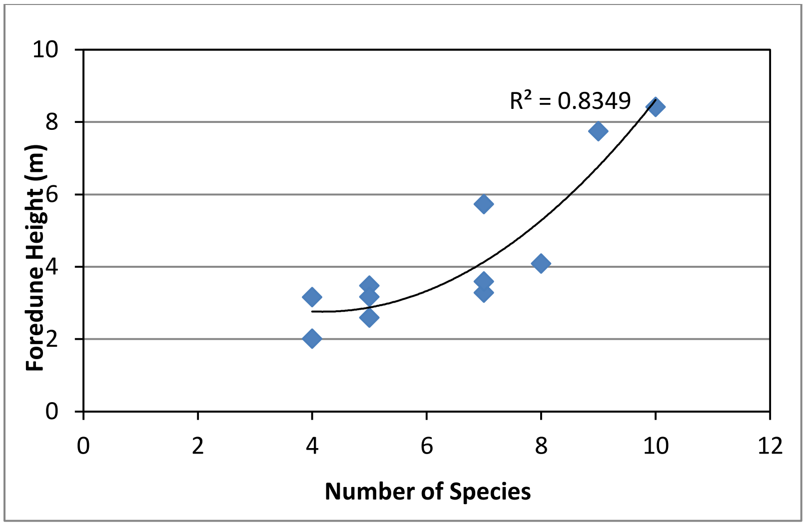


Figure 6.24 – Foredune height and Vegetation Diversity for the twelve surveyed profiles. Diversity increases on average with an increase in foredune height.

Figure 6.25 displays the Sørensen values comparing the summer and winter surveys for the study area. Values of 1.0 indicate that the exact same species were found on the profile during each of the summer and winter surveys. Profile R33, for example, had the same five species present throughout the study period. Values decrease as variability between the seasons increases. For example, the emergence of *Uniola paniculata* on profile R52 decreased the Sørensen index by a small fraction (from 1.00 to 0.95) when comparing the June 2006 and January 2007 surveys. However, between January 2007 and June 2006 no species were added or lost on the profile line, and therefore a Sørensen value of 1.0 was calculated.

The greatest change was found on Profile R27. This is because in winter a few plants of *Iva imbracata* and an unidentified grass species were present that were not present in summer. In addition, during summer, *Cakile sp.* and *Oenothera humifusa* were present. Despite there being only a few individual plants of the four aforementioned species, their presence created enough variability to change the Sorensen index more than any other profile. However, the seasonal change Sorensen variability is much smaller than the inter-profile variability, as this profile still retained five similar species between seasons. The variability for Profile R6 was due to the presence of perennial *Sesuvium portulacastrum* in summer, but not in winter. There were only a few plants on the profile that may have been trampled or died during winter, and therefore were no longer present.

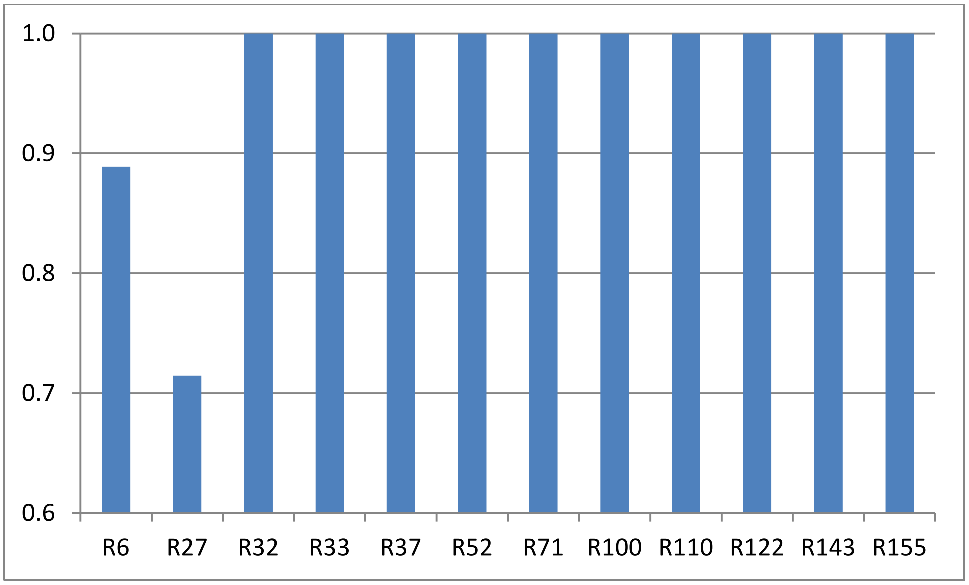


Figure 6.25 – Sørensen Similarity Index comparison between January 2007 and June 2007 vegetation surveys. Values of 1.0 indicate that the same species were present in both surveys. Very little seasonal variation in species presence or absence was noted.

6.3.1 Vegetation Diversity

The Shannon-Wiener (Shannon, 1948) diversity index (*H'*) was calculated to compare variations in vegetation cover using percentage cover for each 1 meter x 1 meter grid on the surveyed profiles after Martinez et al. (2001), and Miot da Silva et al. (2008). In contrast to the Sørensen Similarity Index, which examines species' presence or absence, the Shannon-Wiener Diversity Index looks at vegetation percent cover and variation in distribution on each profile. High *H'* values indicate greater "species richness" (number of species) and "evenness" (how equally abundant the species are (Miot da Silva, 2008; 1564). For the surveyed profiles, the highest *H'* values were found on the largest eroding dunes, profiles R52, R71, and R100 (Figure 6.26). These sites had the greatest number of species. However, the vegetation on these profiles was not distributed evenly. For example, the shrubs and trees were in distinct clumps, as opposed to prograding profiles, which may have an even distribution of plant *Andropogon sp*.

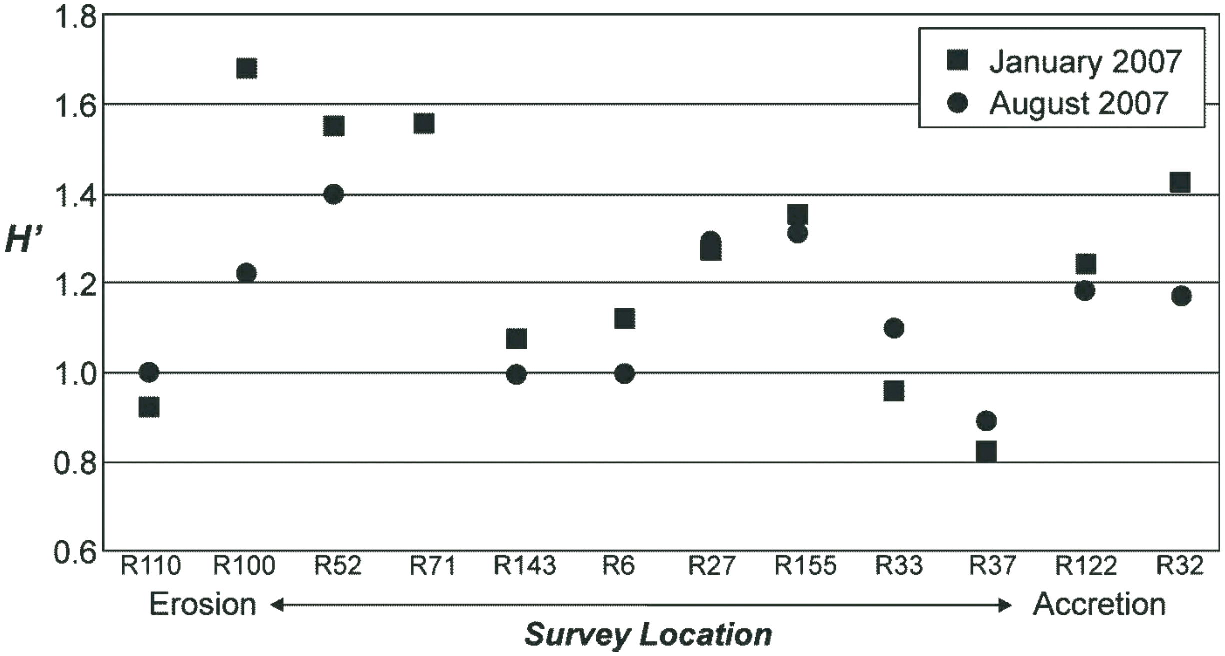


Figure 6.26 – Variation of the Shannon-Wiener Diversity Index (H') relative to each profile for two survey periods. R6 to R37 and R122 to R155 are on prograding profiles, R52 to R110 on eroding profiles.

Prograding beach profiles R6 and R27 have similar orientations facing east. However, R27 is located in St. Joseph Bay, which is more sheltered from wave energy. Hesp (1988) found that lower energy environments with fewer breaking waves would have lower amounts of salt spray. The very close proximity of vegetation to the waterline at R27 indicates perhaps the low level of salt spray aerosols at this site, which is supported by the low wave energy data presented in Chapter 5. R27 also had more species than R6, possibly due to the decreased salt spray, but perhaps also to the lower rate of accretion at R27 compared to R6. *Iva imbricata* and *Cakile* *endentula* are both salt tolerant plants, but are rarely found so close to the water's edge. Additionally, *Oenothera humifusa*, which is not considered a very salt tolerant plant, was found on Profile R27. Profile R32 had even lower *H'* values due to its extremely long vegetation profile length on this stretch of rapidly prograding beach, and therefore had a low distribution evenness due to largely unvegetated gaps between incipient dune clumps. The *H'* decreased from January 2007 to June 2007 because the vegetation survey had extended further seaward, thus decreasing the distribution evenness.

In contrast to a rapidly lengthening R32 profile at the spit's tip, profile R33 did not change its seaward extent. However, by that summer new patches of the already present *Uniola paniculata* had grown landward of the foredune crest, thus increasing its distribution evenness. Diversity continues to decrease moving southward from the spit tip to profile R37, where single patches of *Iva imbricata, Balduina angustifolia* and *Heterotheca subaxillaris* occurred only landward of the foredune crest.

Profile R52 and R71 had the highest vegetation species richness, and hence the *H'* values for these profiles was high relative to the other profiles surveyed in the study area. In addition, during winter the sparse vegetation at the dune toe had died from burial (Hesp, 1990; Maun 2004) and/or wave erosion. This created a shorter vegetation profile length with relatively even distribution. During summer however, the *Cakile edentula* and *Hydrocotyle bonariensis* had initiated new growth further seaward, thus making the profile's vegetation distribution less even. These three profiles also had a relatively high beach mobility, which could add to the higher *H'* values (Miot da Silva et al., 2008).

Figure 6.27 displays the relationship between foredune height and Shannon-Wiener diversity values. The figure displays foredune height on the y-axis for visualization purposes. However, the diversity is considered dependent on the foredune height. While the relationship is not strong ($R^2 = 0.33$), there is an increase in diversity as dunes become higher. [Removing the 6m above (NAVD88) sea level R37 outlier produces an R^2 value of 0.64.] In this region, the highest foredunes are the oldest and have had considerably more time to establish 'climax' or more diverse plant assemblages. They are also the most erosional, and so in many cases the pioneer and next successional stages are missing, thus giving the foredune a cover of later successional stage species, which are usually in higher numbers and in greater abundance. In addition, many of the erosional foredunes are slowly translating landwards and cannibalizing older landward dunes and their vegetation (often shrub and tree species).

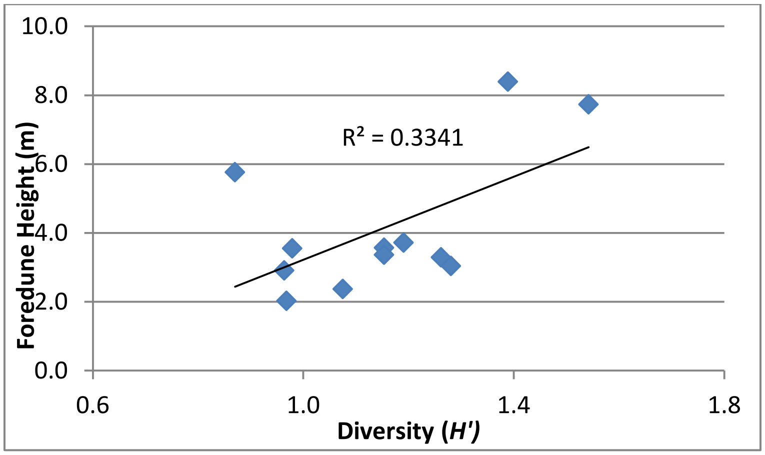


Figure 6.27 – Foredune Height and Vegetation Diversity for the twelve surveyed profiles. Diversity increases on average with an increase in foredune height.

6.4 Relative Importance

Relative importance is the ratio between the relative frequency of the species on the profile and the relative cover (proportion of percent cover of all species across the profile)

(Stephens and Krebs, 1986; Miot da Silva et al., 2008). Figures 6.28 and 6.29 display the calculated relative importance value for each species on each profile. Steeper slopes on each individual profile-curve highlight the importance of one species to the next most important species on the curve. For example, on profile R6, *Uniola paniculata* and *Andropogon sp.* are the most dominant species (higher relative importance values), and are clearly separated from the other species by a steep slope, or large gap, in relative importance values. On prograding coasts, pioneering species such as *Uniola paniculata* and *Andropogon sp.*, are the most important species. Upon germination, these plants initiate the colonization of beach and dune sands and can initiate foredune development by reducing air flow in and around the plant (Hesp, 1988). In addition to *Uniola paniculata* and *Andropogon sp.*, *Ipomoea imperati* is an important pioneer species on profiles R27, R143. R155. *Ipomoea imperati's* low canopy aids in producing the shorter slope on the lee side of these foredunes (Hesp, 2002).

In contrast to the prograding beaches and their vegetation species, the eroding beaches have different species types, which include *Quercus spp*., *Pinus sp*., and *Ceratiola ericoides.* Steep faced dunes can be found on profiles R52, R71, and R100, which have dense, tall species and have much longer and gradual lee side slopes. The reason for these longer lee slopes is twofold: 1) high erosion can scarp the foredune during cyclonic and tropical storm events, yet leave the lee side unaffected; and 2) the species presence of the dense and tall climax species found on these dunes. These taller trees and shrubs reduce air flow rapidly, which in turn promotes sediment deposition at the leading edge of the dune (Hesp, 1989; Jacobs et al., 1995), in contrast to the shorter steep sided lee faces found on the prograding beach foredunes with shorter, less dense plant canopies.

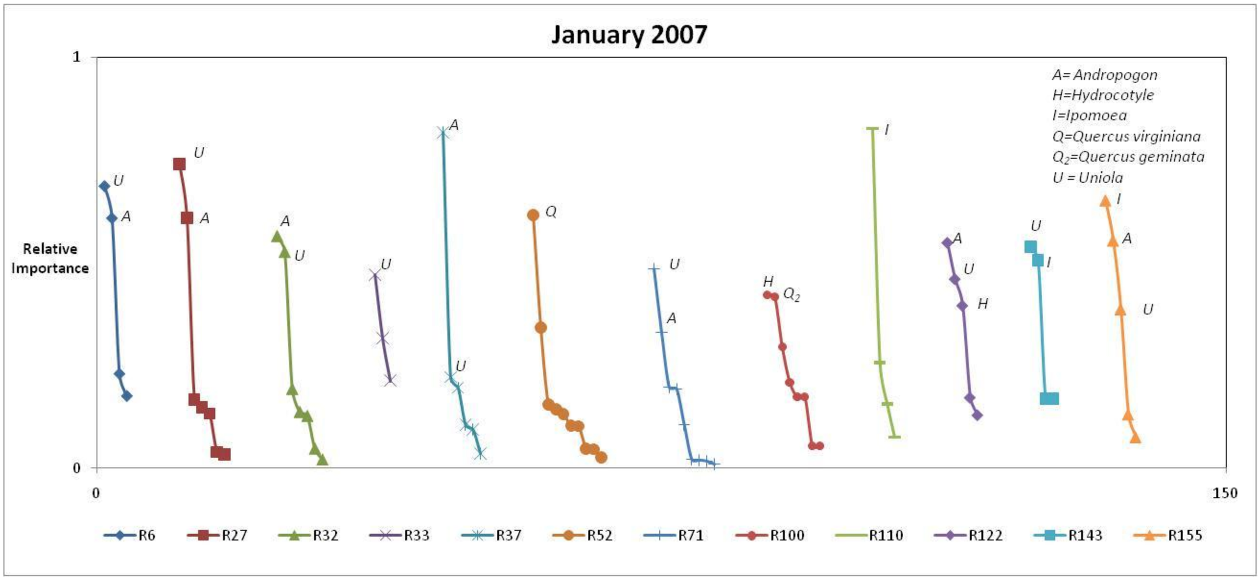


Figure 6.28 - Relative Importance of vegetation species along foredune profiles, January 2007. *Uniola paniculata* and *Andropogon sp.* dominate many of the profiles. *Quercus sp*. may dominate eroding foredunes.

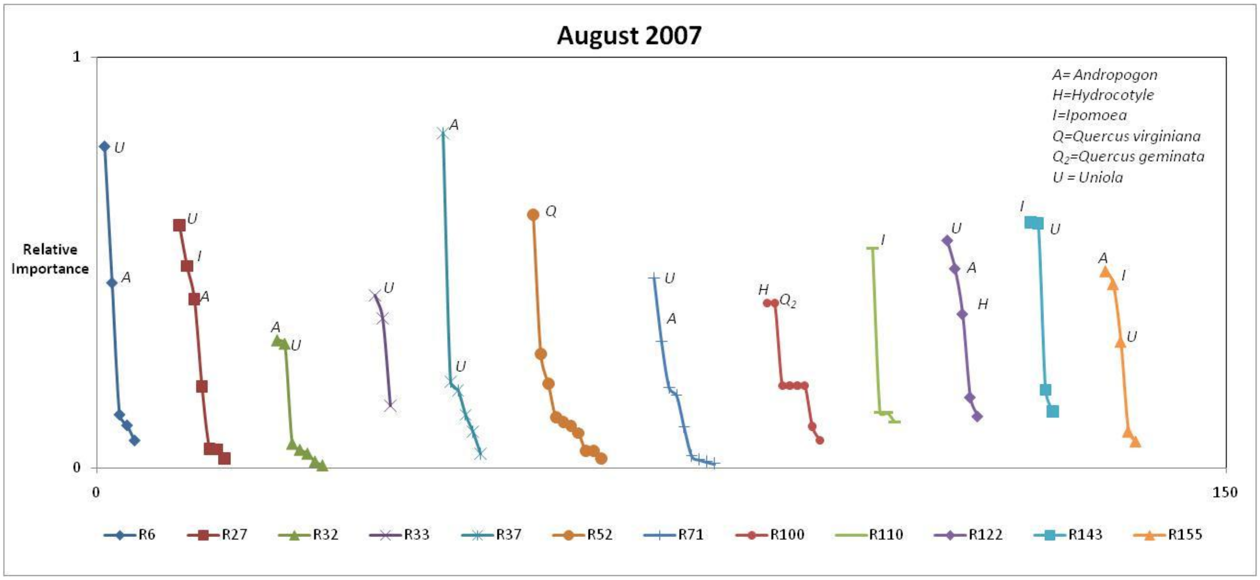


Figure 6.29 - Relative Importance of vegetation species along foredune profiles, August 2007. Relative Importance patterns are similar to the winter profiles (Figure 6.28).

Seasonal variations in vegetation importance are very minimal in Gulf County, Florida. However, the relative importance of *Uniola paniculata* decreases slightly on all profiles during winter (average relative importance for winter and summer are .41 and .46 respectively). This is due to the growth of tall stems which climax in late summer, followed by die back during winter. However, the stalks still remain in place through winter and spring, thus keeping *Uniola paniculata* the dominant species on most foredunes in this study area. Oertel and Larsen (1983) found the same dominance of *Uniola paniculata* on Georgia foredunes.

6.5 Vegetation Clusters

An agglomerative hierarchical cluster analysis was calculated to determine unbiased natural groupings based on the presence or absence of species on the vegetation profiles. The resulting SPSS output dendrogram is presented in figure 6.30.

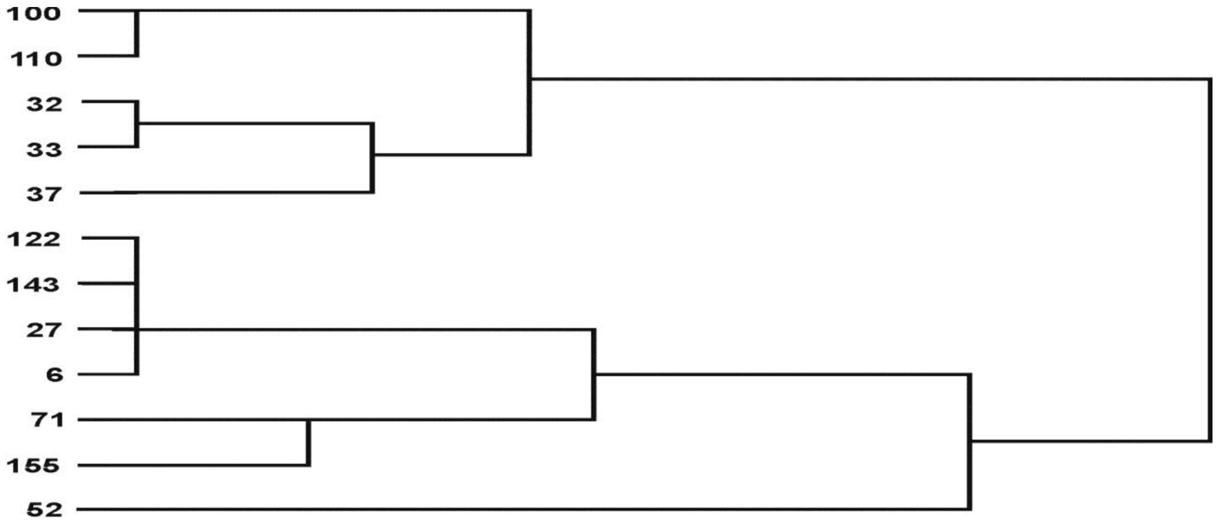


Figure 6.30 – Cluster analysis dendrogram for all 12 vegetation profiles. The strongest relationships occur between highly eroding sites (R100, R110), prograding sites (R32, R33, R37), and slower prograding sites (R6, R27, R122, and R143). Stable and slightly eroding sites (R155 and R71, respectively) demonstrate fewer similarities, and the tallest foredune at an eroding location shows the least commonalities with any of the other site groupings.

The cluster analysis demonstrates that there are strong relationships between profile sites (R6, R27, R122, and R143,) which are all prograding and have very similar dune heights (3.2-3.5 m above MSL). These sites are dominated by pioneering species *Uniola sp*. and *Andropogon sp.* Spatially adjacent profiles R32, R33, and R37 have slightly higher dunes and are also well correlated on these prograding sites near the spit tip. Similarly, highly erosional sites and spatially adjacent sites R100 and R110 have very similar vegetative arrangements, though they differ in that they have less dominance of pioneer species. The largest outlier of the foredunes, or the foredune profile with the greatest vegetation dissimilarities surveyed occurs on profile R52, the tallest foredune, which has the greatest variances from all other foredunes' vegetation. This highlights the foredune's state of landward translation into more late successional species found on the older, landward dunes.

6.6 Chapter Summary

Thirty species of vegetation were found on the twelve foredune profiles surveyed in the study area. The primary and pioneer species, *Uniola paniculata*, is the most widespread grass on southern coastal dunes (Craig, 1991) and was the most common species found on the foredunes surveyed. However, profiles surveyed in locations with eroding shorelines were comprised of distinctly different species. For example, *Quercus spp*. were only found where the coastline was eroding and significant foredune erosion had occurred.

The pioneer dune building grasses, *Uniola sp*. and *Andropgon sp.,* were the dominant species on Gulf County foredunes. *Uniola sp*. was predominantly found on the seaward-facing or stoss slopes, and *Andropgon sp.* was found to be dominant on the inland or lee slopes of foredunes. While they are present on all foredunes, their presence and percent cover are dominant on prograding coasts and the adjacent incipient dunes and foredunes. On the most eroding shores (e.g. the Cape) these species are absent; on moderately eroding beaches, they are found in low numbers and extending across limited distances.

The Shannon-Wiener diversity (*H'*) is found to be greatest on the tallest and, generally, eroding dunes. Erosion has eliminated the pioneer species to various degrees on the larger, older dunes. Yet these foredunes are shoreward translational and cannibalize older, landward dunes and as a result are dominated by later successional species, which are more abundant than pioneer and early shrub vegetation associations. They also probably have higher nutrient levels from preceeding vegetation stands than the newly developing incipient foredunes. This is supported by the results shown in the cluster analysis dendrogram.

Prograding beaches had higher Sørensen Index values (i.e. higher similarities) than did the foredune-vegetation profiles on eroding beaches in Gulf County, Florida. Further supporting the variations between erosional and accretional sites, the analyses of relative importance indicates that pioneer species are the most important in prograding sites, while local 'climax' or late successional species are most important in erosional sites, with a gradient in between these two.

This chapter supports studies by Levin et al. (2008) in that specific plants, their distribution across a dune, and plant associations can provide insight to the beach-dune's morphodynamic state. There are moderate to strong correlations between foredune height/volume and species diversity and richness, respectively. Observations of foredune species richness, diversity, profile similarities, and the use of the indexes and analyses above can provide excellent proxy evidence of shoreline dynamics in the absence of historical erosion/accretion data.

Chapter 7
A New Cycle of Foredune Evolution

7.1 Introduction

Foredune development models such as Short and Hesp (1982) and Psuty (1988, 2004) do not apply to Gulf County, Florida. The following chapter will examine conditions discussed in Gulf County necessary to develop a new model that can be applied to the study region. Additionally, the new model will be applicable to other locations to which the aforementioned models are not ideally suited. This Cycle of Foredune Evolution will be more holistic and take into account more unique features of the beach, thus providing a more accurate tool for future analysis of similar areas.

7.2 Using elements of previous models

The Psuty model (1988) and continuum (2004) are well documented in the literature, but they are not globally applicable and do not characterize the foredunes of Gulf County, as shown in Chapter 4. Utilizing sediment availability to the foredune is a starting point for identifying how foredunes evolve, and was used in creating this new model. The Sherman and Bauer (1993) model used this starting point as well. The Psuty Morphologic Continuum (2004) may have filled in the blanks, or Sherman and Bauer's (1993) "indeterminate dune forms." However, the Psuty models were shown to be inapplicable to the study area.

What is unclear in Psuty (1988 – 2004) and Sherman and Bauer's (1993) work is a clear identification of the dune sediment supplies. What was apparent from studying the foredunes in Gulf County is that identifying one source of dune and/or aeolian sediment is not as clear as the other models may allude to. Rather, in Gulf County, emerging bars and the landward dunes, or the “antecedent geology”, may play just as an important role in foredune development as any other source of aeolian transport.

The Short and Hesp (1982) model was noted as a “…starting point for further investigations of particular sites or environments.” (Short and Hesp, 1982; 282). Gulf County has highly variable rates of shoreline erosion and accretion and variations in sediment supply not found in the Short and Hesp model (Short and Hesp, 1982). While the Short and Hesp model was attractive in its simplicity, and worked well in southeastern Australia, its minimalism limited it from broader applications, including the Gulf of Mexico coast, where a range of foredune morphologies or types exist. In Gulf County, all foredunes occur on reflective beaches, and, as a result, more details are necessary to explain the Gulf County foredunes.

Longshore sandwaves (Saunders and Davidson-Arnott, 1990) appear to play a major role in the elongation of the spit, and may play a major role in beach/dune ridge development along the medial to distal end of the spit. The emergent bars recorded on St. Joseph Peninsula (near Profile R33,) also play a pivotal role in the development of foredunes, and indicate the necessity for an event addition to foredune development. The emergent bars, or longshore sand waves, play a pivotal role in foredune development, and highlight what may happen when sediment supply is halted. The timing of these events, or the event synchronization, is also important in the development of foredunes. Following storms, when vegetation is not able to re-establish, or the foredunes are unable to recover in height and volume, there is the potential for the beach to only have time for hummocky incipient dunes to develop (Stallins and Parker, 2003; Houser and Hamilton, 2009). These events, either erosional or accretionary, should be incorporated in some form into a new model of foredune development. Additionally, the extent and/or types of vegetation, specifically pioneer species versus late successional (or climax) species, can be incorporated as a key indicator of the state of the foredunes age and evolutionary development.

Additionally, the incorportation of large storms such as hurricanes should be added to any beach-dune interaction model if it is to be applied on open coasts, such as Florida's coastlines. Cleary and Hosier's (1979) and Ritchie and Penland (1990) models both demonstrated the importance of storm occurrences in their models. This has been emphasized more recently by Houser (2009) and Houser and Hamilton (2009), that the nature and timing of these events are critical to beach-dune development.

7.3 New Model Development

Aeolian research has made huge improvements in quantifying sediment transport. However, identifying and quantifying aeolian transport is still in a state of near infancy, as it may apply to macro-scale modeling (Bauer et al., 2009; Namikas et al., 2010; Delgado-Fernandez, 2011). Therefore, identifying micro-scale tendencies was not within the scope of this project. Rather, identifying dune heights and volumes and their changes was incorporated into the new model. For this new model, micro-scale processes are not identified; the focus of the new model relies on an examination of dune sizes and the changes to the foredunes. The foredunes as described in Chapter 4 form a basis for the division of the dunes in Gulf County and are identified as low, medium, or high dunes (Figure 7.1).

In addition to the foredune heights (Figure 7.2), the cycle of change between these foredunes will be form a portion of the new cycle. The erosion/accretion rate of the shoreline and the large-scale events that alter the coast were also incorporated into the new model.

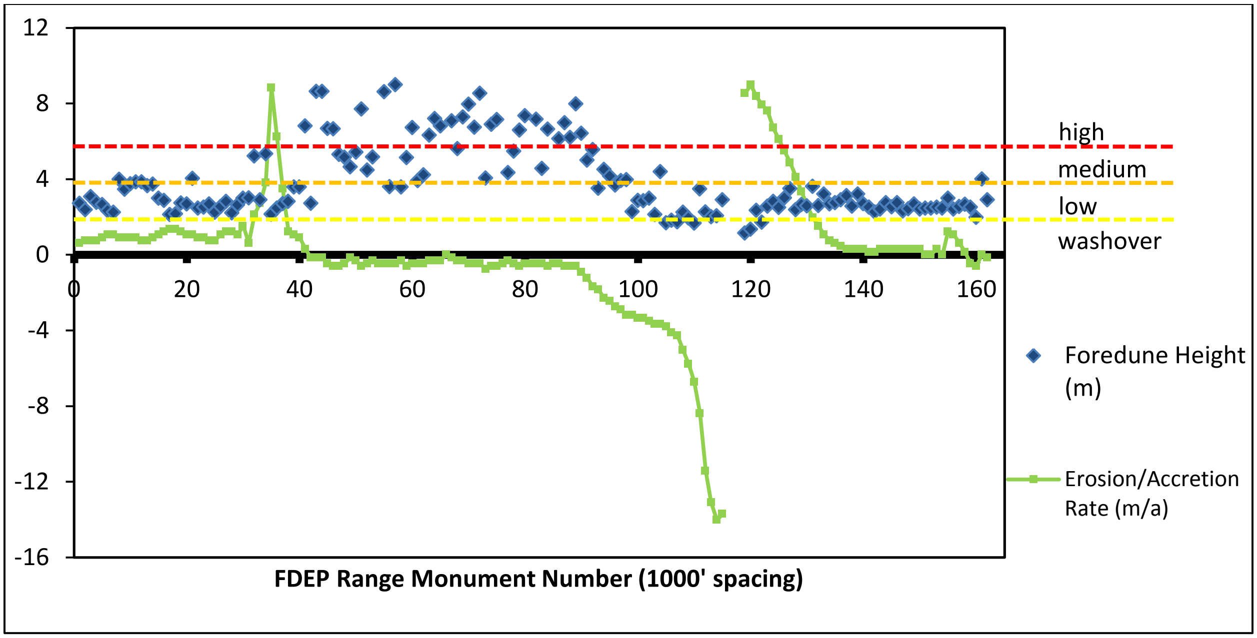


Figure 7.1– Foredune heights (crest height above MSL) and 30 year erosion/accretion rate as previously described in section 5.2. Foredunes were classified as low dunes (1.9 - 3.8 m), medium (3.8 - 5.7 m), or high (> 5.7 m) based on the average foredune height and one standard deviation below, one standard deviation above, and greater than one standard deviation above the average foredune height respectively.

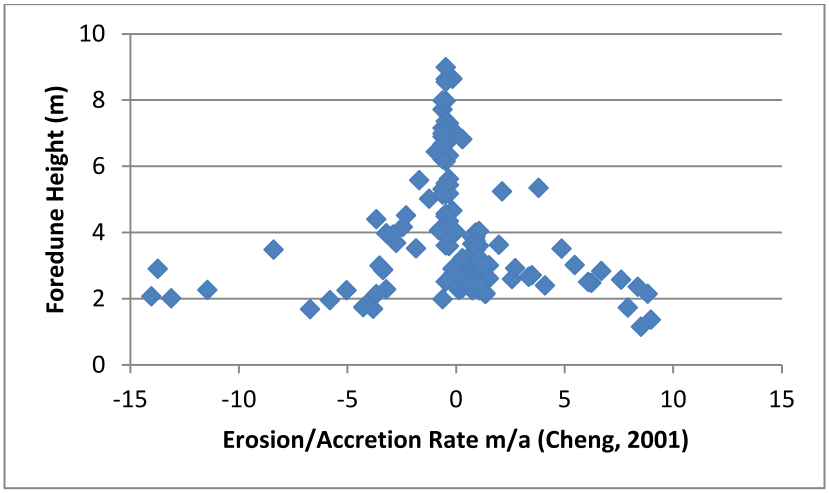


Figure 7.2– Foredune heights (FDEP) and Foster and Cheng's (2001) 30-year erosion/accretion rate. The plotted quantitative data was used as a basis to develop the new cycle of foredune evolution.

7.3.1 A Baseline Utilizing Erosion/Accretion Rate

Psuty's models (1988-2004), as well as the Sherman and Bauer's (1993) model, make reference to a beach sediment supply. While this is not explicitly expressed, nor can we identify an exact sediment transport potential based on a set beach width, it is assumed that when a minimum beach width is found, that sediment may be transported into the foredune or a new incipient dune. However, if the beach is substantially narrower, then conditions for sediment transport may not occur.

While these assumptions are not validated empirically in their models, in Gulf County the long-term beach erosion/accretion rate provided a substitute for beach sediment supply. In Gulf County, Foster and Cheng's (2001) erosion/accretion rate was used to identify a pattern or groupings of foredunes in different stages of a cycle of development from incipient and low dune forms, to larger foredunes (Figure 7.2). This erosion/accretion rate is the baseline for the new Cycle of Foredune Evolution.

7.3.2 Foredune Growth

The development or growth of a foredune occurs when aeolian sediment transport increases the size and dimensions of the foredune. The growth is enhanced by beach/dune vegetation growth, such as *Uniola paniculata*, which grows upward as the pioneering grass is buried. As the sediment transport continues, the incipient dune or foredune will continue to grow to a larger size. This was seen in the Gulf County study as the foredunes continued to grow, albeit very slowly, on the prograding coasts.

The growth will continue until a new incipient foredune is established by a new seaward line of vegetation, which occurs most frequently on the more rapidly prograding coasts (cf. Hesp, 2002; Hesp and Walker, in press). These incipient and low foredunes are found all over the prograding coasts in Gulf County (Figure 7.1). However, if allowed to continue to grow without a new incipient dune forming, the foredune may grow into a larger foredune, or a medium height foredune as has been found at profile R37. Profile R37 had the largest foredune growth through the 2006-2007 study period. The largest foredunes are found when beach erosion conditions occur and the foredune toe is scarped, and a new dune ramp allows the foredune to grow to even greater heights (Carter, 1988; Arens and Wiersma, 1994; Hesp, 2002). These large dunes are only found on eroding coasts in Gulf County.

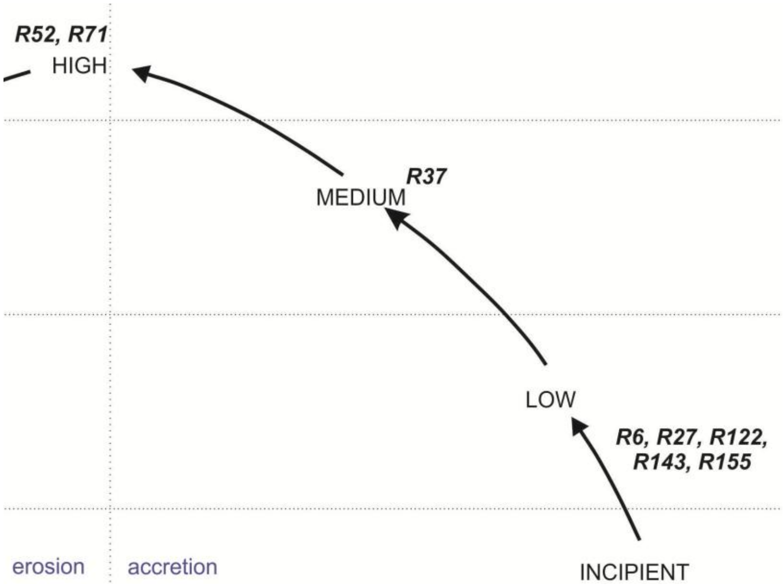


Figure 7.3 – Conceptual development of incipient to larger foredunes on prograding coasts. Incipient and low dunes are found on the fastest accreting coasts as the sediment transport to the foredune is limited by new incipient dunes forming seaward of the previous foredune, and thus minimizing the sediment supply to the landward dunes, as was seen on profile R155.

7.3.3 Erosive conditions

Beach erosion will lead to foredune loss if no sediment is available to be transported into, and/or aid in the rebuilding of the foredune. If there is beach sediment available for transport, the scarp will fill and sediment may then be potentially transported up the scarp and over the dune crest, and therefore, in some cases, increase dune size (Hesp et al., 2005; Davidson-Arnott et al., 2005). Landward translation of the foredune can also lead to cannibalisation of older, landward dunes, and so the foredune can also build by this mechanism. The largest dunes are found on the eroding coasts in Gulf County (Figure 7.1). However, if there is no sediment supply available for rebuilding the foredune, continued erosion will occur to the dune. This is occurring at profiles R100 and R33, where there is a gradual decrease in foredune volume over time. Due to the rapid beach erosion at profile R110, no new foredune has been identified since the first FDEP survey in 1973. Erosive conditions occur as a result of both gradual beach erosion from cyclonic storm related wave activity as well as erosion events caused by storm surges and elevated wave heights during hurricanes.

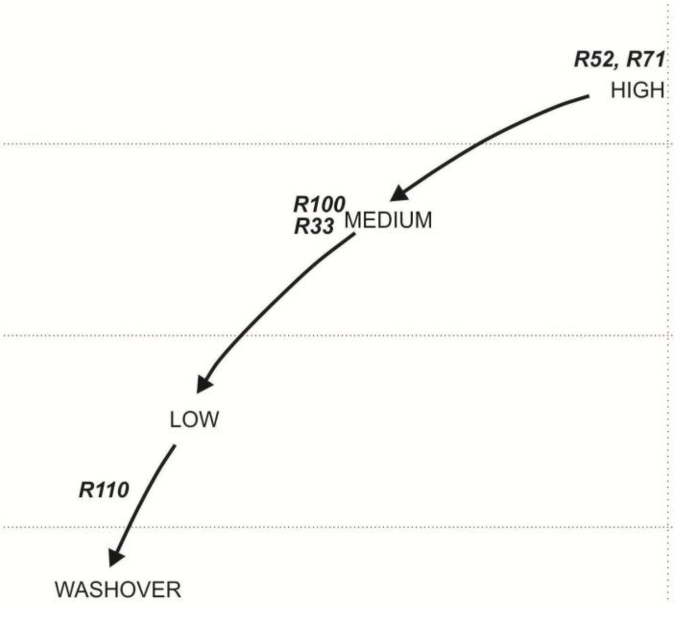


Figure 7.4 – Beach erosion may ultimately lead to foredune loss if no sediment is available for transport into, and aid in the rebuilding of the foredune. This is occurring at profile R100, and R33 where there is a gradual decrease in foredune volume. Due to the rapid beach erosion at profile R110, no new foredune has been identified since the first FDEP survey in 1973.

7.3.4 Largest dunes / Antecedent Geology

As previously stated, the largest foredunes are found when beach erosion conditions occur and the foredune toe is scarped, and a new dune ramp can facilitate the foredune to grow to greater heights (Carter, 1988; Arens and Wiersma, 1994; Hesp, 2002). While this holds true, in locations where there is no longer a sediment supply, neither seaward (minimal beach width) nor landward, the foredune's fate will lead to a loss of volume and ultimately could lead to washover conditions. In the eroding part of the cycle described above (section 7.3.3), this will lead to smaller dunes (eg. R100), and washover conditions (eg. R110). However, some of the largest foredunes in Gulf County are found on eroding portions of the coast with similar beach erosion rates. This is seen when comparing sites R52 and R71, in which R71 has no backing dunes to cannabalize , and therefore is decreasing in total volume with each successive erosion event. On the other hand, R52 has a large source of sediment landward of the foredune in the form of large dunes. The "*Antecedent Geology*", or the pre-existing geology that is located immediately landward of these foredunes can provide the sediment necessary to continue to build and rebuild a foredune. Therefore, the largest foredunes in Gulf County are found where a) there are slightly beach eroding conditions, and b) an abundant sediment source in the form of older dunes landward of the current foredune. Thus, the a*ntecedent geology,* is available to play an important role in development of the modified foredune.

The *antecedent geology* is pivotal in maintaining an adequate sediment supply for the translating foredunes where aeolian sediment supplied from the beach is not sufficient to maintain a foredune's height or volume. While the portions of St. Joseph Peninsula with minor beach erosion have a range of heights, the maximum heights are found in locations that have a large sediment supply landward of the foredune, which can be cannibalized into a new foredune, or the translating landward foredune. For the new cycle of foredune evolution to address the nature of low through tall foredunes in eroding conditions, an extension to include the antecendent geology has been added (Figure 7.5). On the eroding coasts, the foredune may be scarped or fully eroded, or reduced from a high dune to washover. However, the antecedent geology, or coastal dunes that were previously foredune material when the beach was prograding, can be cannibalized, or allow the foredunes to increase in size from smaller to larger foredunes.

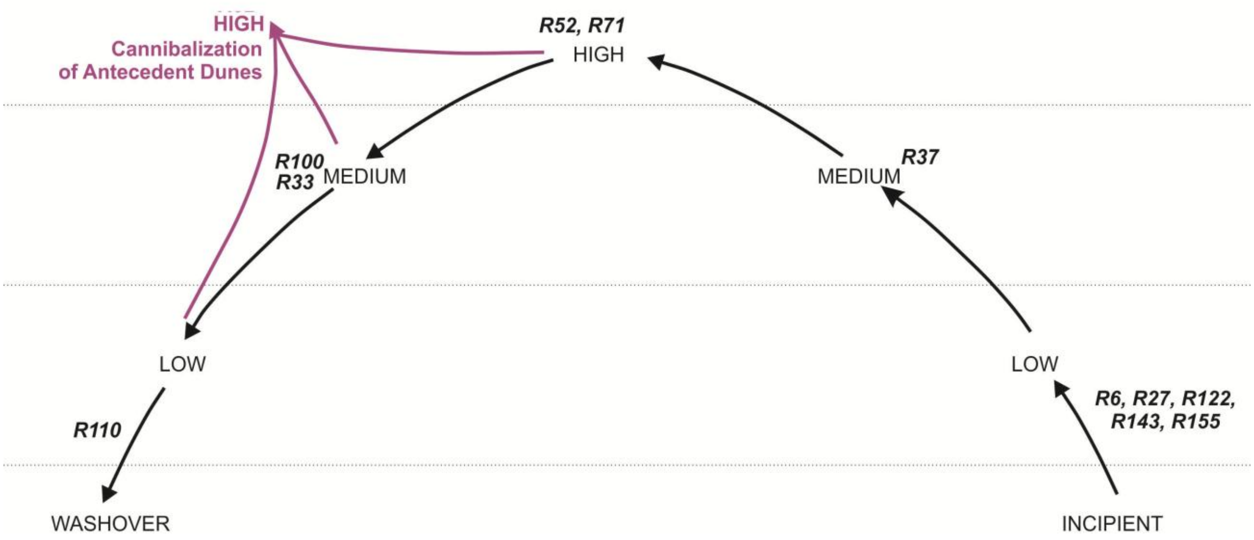


Figure 7.5 – The addition of antecedent geology into the foredune model. Landward dunes provide an ample source of sediment which may be incorporated into the foredune through cannibalization of the landward dunes by the landward translating foredune.

7.3.5 Cycle Nexus

The cycle of foredune evolution may end in washover conditions. However, a beach sediment supply input, (natural or anthropogenic) into the system, especially combined with a delay in the event-timing of a new major erosive event, (or event synchronization,) may allow new incipient foredunes to form on the beach. If a new line of pioneer species, such as *Uniola* *paniculata,* can take root, a new series of small hummocky dunes may provide for the inception of a new foredune line. However, as is the case in highly eroding locations, such as Cape San Blas, beach erosion will continue and no new incipient dunes will form. The timing of erosion or accretion, and the synchronicity of these events will give rise to the formation of incipient foredunes if accretion occurs, or more washover if beach erosion continues. Locations similar to profile R110 and the entire Cape, may go back and forth between low incipient dunes to washover conditions on the beach if beach sediment supply is ever favourable for incipient growth (Figure 7.6).

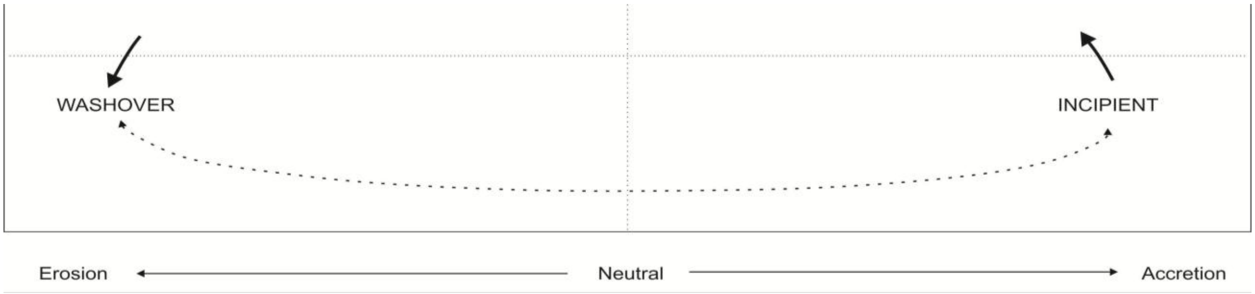


Figure 7.6 – Cycle Nexus: A shoreline undergoing highly erosional conditions (either gradual, or from storm events,) may exhibit washover conditions. However, if beach accretion occurs, and pioneering vegetation such as Uniola paniculata takes root, new incipient foredunes may form which may either be washed out if the beach returns to erosive conditions, or may continue to create a foredune if accretion continues.

7.3.6 Accretion Events

Beach accretion plays a critical role in building the beach and increasing the potential sediment supply for foredunes. The accretion may occur as a gradual building, as is often found on prograding beaches, which widen with the delivery of sediment via cross-shore or longshore transport, as seen in Gulf County on profiles R32 and R37.

Accretion may also occur in rapid fluxes, such as when a longshore sandwave coalesces with the beach as described by Saunderson and Davison-Arnott (1990). A large widening of the beach may also occur as a result of an emergent bar coalescing with the shore or by having its resulting bay filled in via aeolian or hydraulic sediment transport. This can be observed in different phases elongating and widening St. Joseph Peninsula, especially at the distal end of the tip (Figure 7.7), which is currently occurring at profile R33. Similar to the return to accretion events after washover conditions occur (as occurred on Profile R122 post-Hurricane Dennis), as a beach widens, new lines of pioneer vegetation may take root, and a new incipient foredune will rise. This can occur after washover events, or as new incipient dunes grow seaward of the present foredune, regardless of the state of previous foredune (Figure 7.8). This can be seen in prograding conditions wherever new foredunes are created with the inception of new vegetation to capture sediment from the widening beach. In Gulf County, this was documented at Profile R71, where the system was enhanced with new anthropogenic *Uniola paniculata* plantings, thus creating a new incipient foredune in St. Joseph Peninsula State Park, near profile R71. This occurred naturally at profiles R32 and R155, where new incipient dunes have started to create new foredunes.

7.3.7 Erosion Events

Storm events can also play a critical role in eroding the beach and its potential sediment supply to foredunes. These storm events can play a critical role in the erosion and/or destruction of the foredunes as well. As seen in figure 7.9, Cape San Blas has had over 40 hurricanes (Saffir-Simpson Category 1-5) recorded over the past 100 years (NOAA, 2012). Each one of these storms may have a critical impact on the beach and foredune system, depending on the

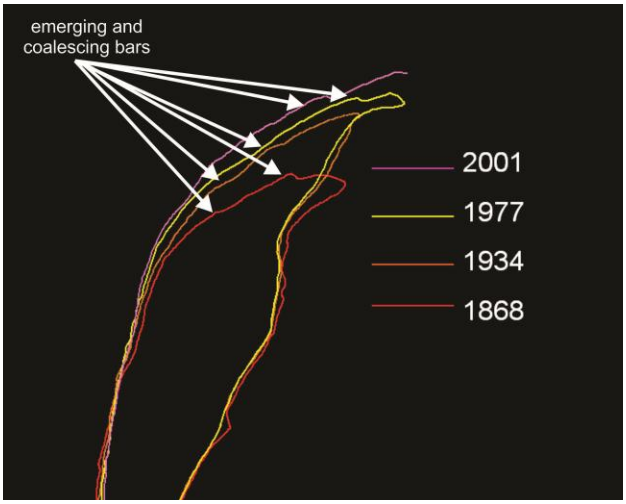


Figure 7.7 – Historic emerging and coalescing bars, (or longshore sandwaves,) found on historical shoreline maps (USGS, 2009) of St. Joseph Peninsula. When these bars join the mainland, they produce a large increase in beach width and sediment available for aeolian transport into vegetation. When an ‘accretion event’ occurs, it can trigger the development of a new incipient dune.

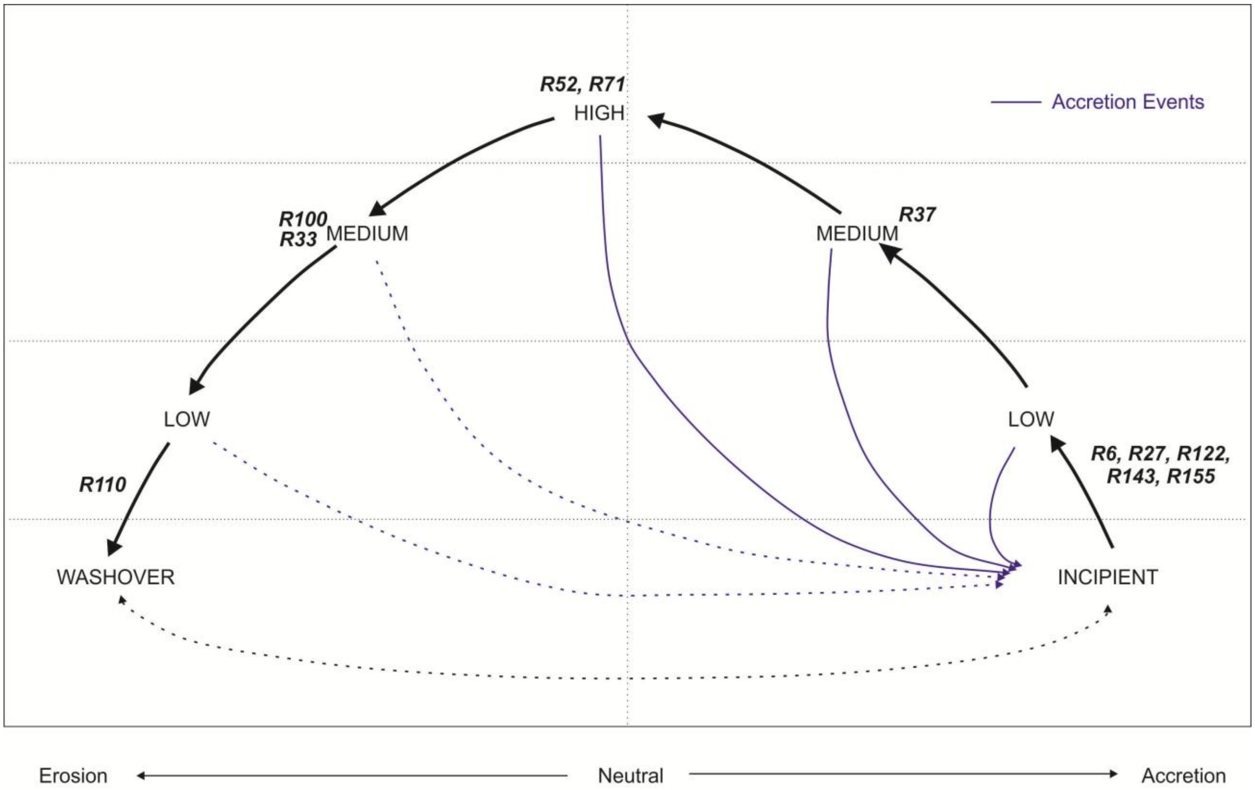


Figure 7.8 –Cycle of Foredune Evolution with accretion events. Beach accretion and the coalescing of emerging sand bars, will allow a wider beach to be present, which may allow the development of a new line of vegetation, and then a new foredune to develop.

storms' strength and track. Smaller extra-tropical storms as well as frontal storms can have an impact on the beach, and if successive storms have impacted the beach, the foredune may be eroded as well. When these synchronous events occur (Houser, 2009), a foredune may decrease in height and volume, and may in-turn increase in size during a post-storm foredune rebuilding phase. However, as has been found on St. Joseph Peninsula, large storms have led to foredune volume loss along the coast (NOAA, 2005). This has been documented for sites R52, R71, and R100. While R51 has an ample sediment supply available landward through dune cannibalization, R71 and R100 do not, and may continue to decrease in height and volume. This is noted in the decreasing foredune size in the new cycle of foredune evolution presented. Additionally, storm event erosion can lead to massive foredune loss and washover conditions as was documented by Sugg and Pelissier (1968), when Hurricane Beulah's (1967) 5.49 m surge cut right through Padre Island in 21 locations, and Stone et al. (1997) documented storm surge and waves produced by strong hurricanes along the Louisiana Coast typically move barrier islands up to 100m. Hurricane Ivan did similar damage to the foredunes along Santa Rosa Island just west of Gulf County (NOAA, 2005). Profile R122 in Gulf County exhibited washover conditions post-Hurricane Dennis. Washover conditions were already present and enhanced at the highly eroding Cape San Blas as well.

These storms play such a large role in modifying and shaping the Gulf of Mexico coast that it is necessary to add this to the new cycle of foredune evolution. When these large erosive events occur, foredunes can be completely washed-over. In the diagram presented in figure 7.10, these events are indicated with red-lines, which can lead to these washover conditions. The dotted-lines are drawn to indicate that washover conditions are less likely to occur over larger foredunes.

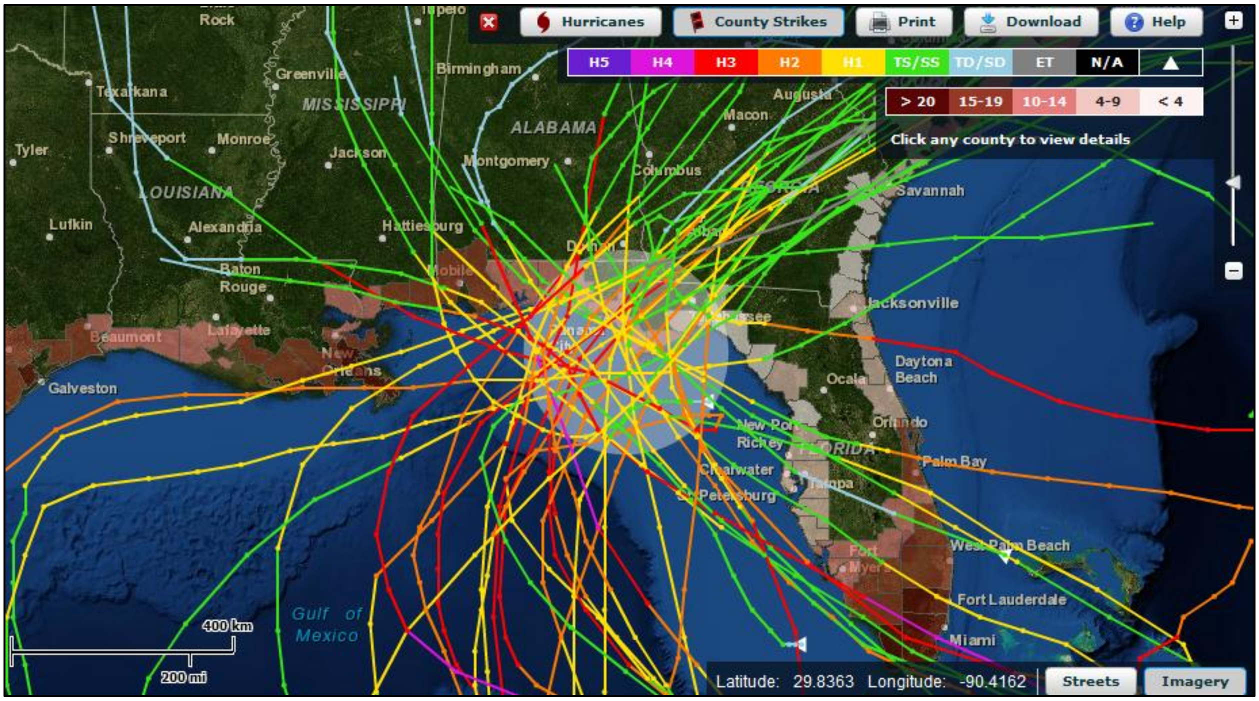


Figure 7.9 – 41 historical hurricane tracks (Saffir-Simpson Categories 1-5,) within 160 kms of Cape San Blas (Image Source: NOAA, 2012). A total of 115 tropical depressions, or greater, have crossed within 100 kms of the Cape (NOAA, 2012).

7.4 A New Cycle of Foredune Evolution

A new cycle of foredune evolution for Gulf County is presented in figure 7.11. This new model is based on the data of erosion/accretion rates and foredune heights found in Gulf County. The movement through the cycle is more complex than a simple unidirectional circle of events. Rather, there is a complex series of pathways between the dune heights from low to tall dunes. What this new cycle shows is that the erosion/accretion rates are fundamental in delineating or driving the foredune types found, and that actually artificially separating the sediment budget into beach and dune budgets as Psuty has done confiscates the morphodynamic responses of the foredunes. This is highlighted by the washover and low foredunes at the extreme ends of the erosion and accretion scales. Furthermore, the largest dunes are found in slightly eroding

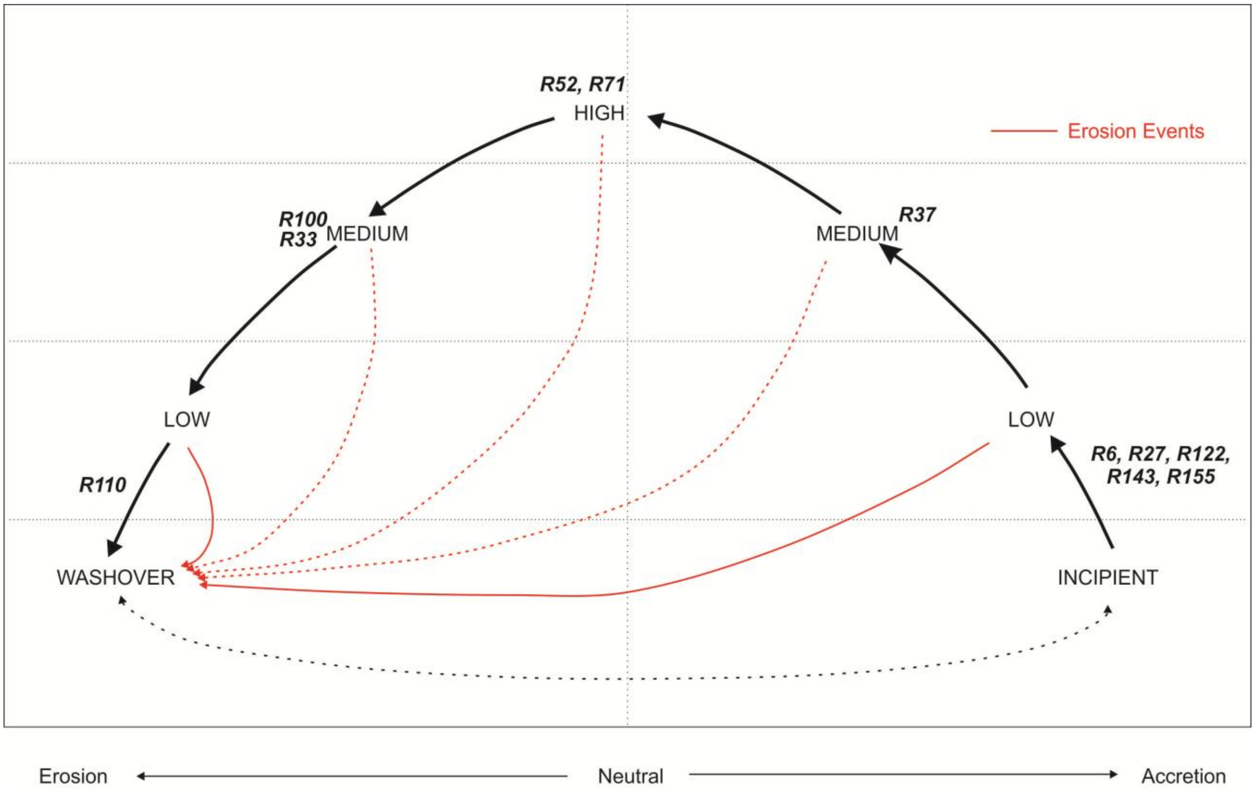


Figure 7.10 –Cycle of Foredune Evolution with erosion events added. Under beach erosion conditions, the foredune may decrease in height and volume. When large storm events occur, much more erosion may occur, which may lead to washover. Large storm events, such as a hurricane, are designated with red lines on the diagram. The dotted lines from the medium to high dunes are indicators that it is less likely for larger dunes to be completely overwashed. An example of this occurred when Hurricane Dennis overwashed the low dunes at profile R122. However, the same storm did not overwash the medium, foredune at R100, or the high foredunes at R52 and R71.

conditions as Psuty (1988), McCann and Byrne (1989), Hesp, (2002), and others have found. However, to explain all of the morphodynamic variances, the antecedent geology was added to the model, as was the synchronous accretion or erosion events that can lead to a new incipient foredune being created, or washover conditions under extreme erosion conditions.

For the cycle to be complete, and to be used as an aid in classifying foredune morphodynamic states, identifying the dominant vegetation types on the foredune is also seen as important. The addition of vegetation into the model can help one identify if it is a new foredune found on a prograding coast dominated by pioneer species, such as *Uniola paniculata*, or a foredune that has undergone a process of landward migration and cannibalization of previous dunes (Figure 7.11). In the case of eroding foredunes and landward translating foredunes, late successional vegetation species are found, which do not readily initiate growth so close to the shorelines, such as *Quercus spp*. This species identification, in conjunction with beach erosion/accretion rates and the landward antecedent geology, can all be used to identify the morphodynamic state of the foredunes in Gulf County, Florida.

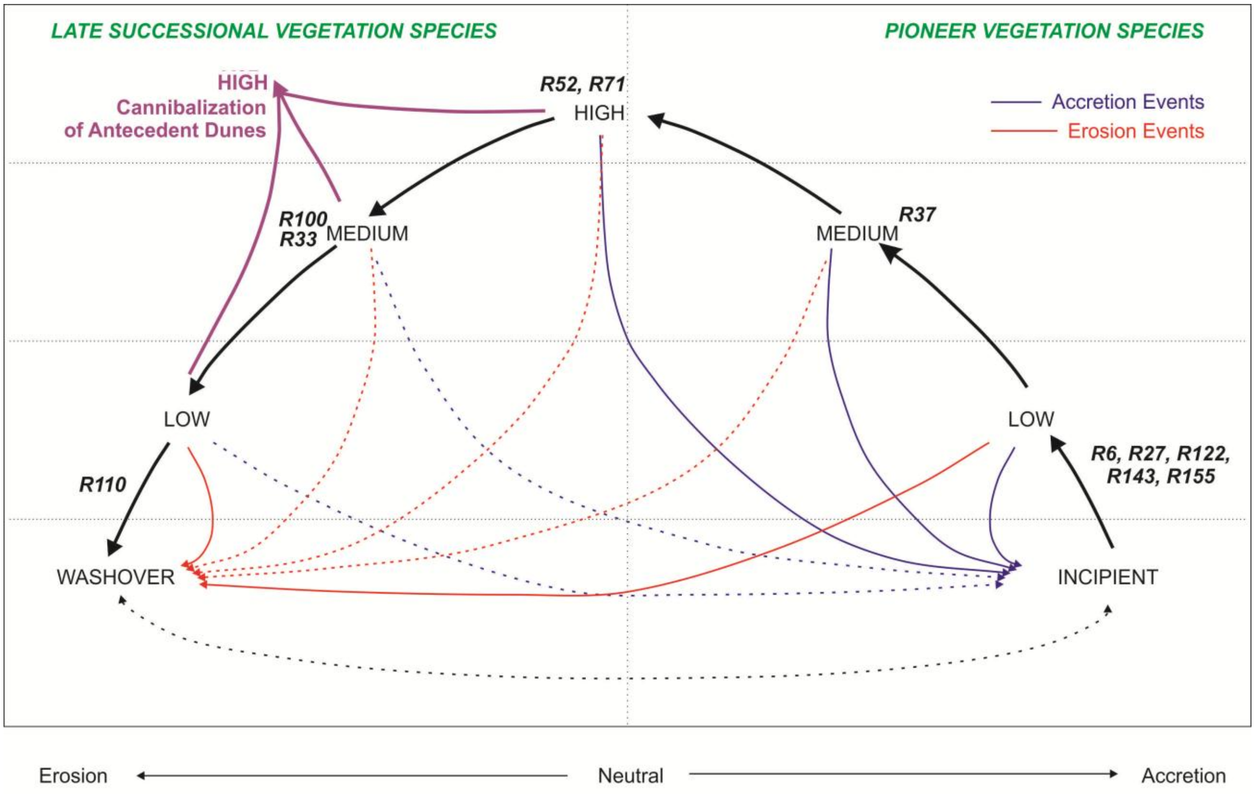


Figure 7.11 – New Cycle of Foredune Evolution for Gulf County, Florida. Profiles documented in this study are listed on the cycle based on erosion/accretion rates, and the foredune heights. Pioneer vegetation and late successional vegetation species were added to the beach accretional and erosional sides respectively.

7.5 Chapter Summary

The new cycle of foredune evolution (Figure 7.11) presented here was created based on empirical and observational evidence of morphological changes in Gulf County, Florida. The macro-scale observations were based on recent activity studied *in situ*, and based on historical records of foredune changes.

One of the greatest strengths of the new cycle of foredune evolution presented is that it is based on empirical field data and historic data collected by the Florida Department of Environmental Protection, and the conceptual model (Figure 7.12) was based on replicable data. This allows the model to be tested and compared in alternate locations on a more global scale. Thus, this allows further enhancements and modifications to be added to this model. For example, variable dune heights and/or erosion/accretion rates can be applied and tested in different locales.

A second strength of the model is that, within the cycle, there are no “indeterminate” dune forms, as presented in the Sherman and Bauer (1993) model. Medium to long term foredune evolutionary trends can be gleaned from the shoreline erosion/accretion rates and the presence and dominance of pioneer versus late successional vegetation. There are no gaps in the morphologic state of the foredune, but rather the changes operate along a continuum, similar to Psuty’s (2004) morphologic continuum.

The greatest limitation of the model is its limited testing. The model was developed for Gulf County, Florida, a very low energy reflective beach environment with minimal wave energy, aside from hurricane events, which makes this new model of limited comparability to the model proposed by Short and Hesp (1982) in southeastern Australia, except for the reflective beaches portion of that model. Another limitation is the lack of absolute values for the conceptual model. The low, medium, and tall dunes are specific to Gulf County, and the erosion/accretion rates (despite having a very wide range,) are also taken directly taken from Gulf County data. However, the conceptual plot may work just as well for varying environments within the Gulf County data ranges, or with new site specific data.

The model can be applied to both marine and lacustrine environments. The model is potentially useful to land managers in different environments on the Gulf of Mexico coast, and possibly along the Atlantic and Pacific coasts. Additionally, Lake Michigan and Lake Huron foredunes, due to the antecedent geology in these locations, will be ideal locations for further observation and application of the new model.

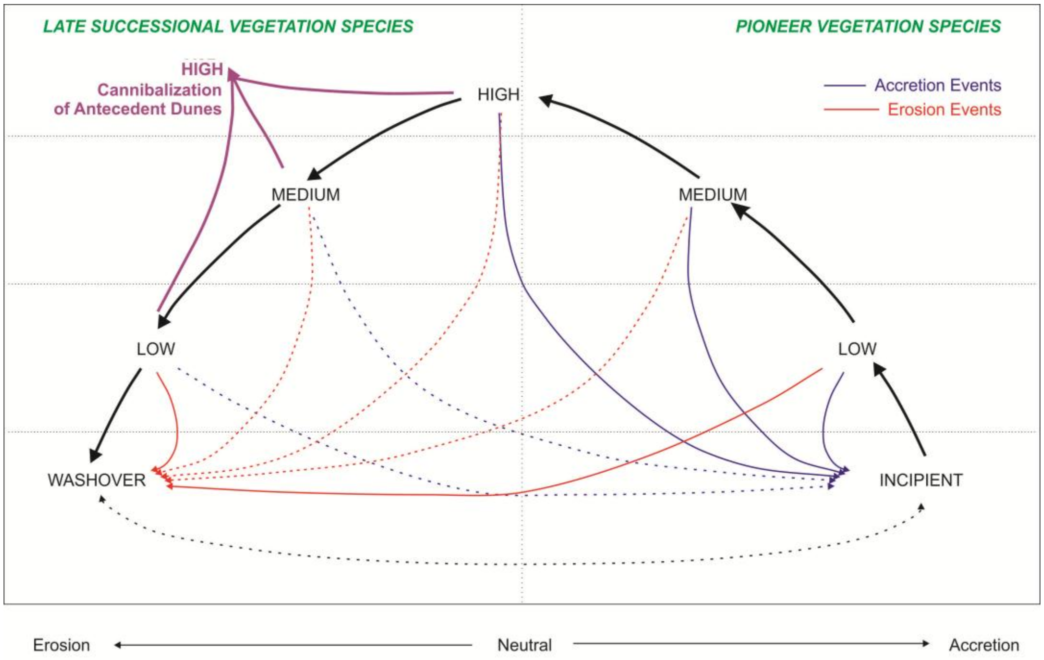


Figure 7.12 – The New Cycle of Foredune Evolution. Foredunes on accreting beaches will slowly build unless a beach accretion occurs and a new incipient foredune is initiated. On slowly eroding coasts, the largest foredunes are found due to scarping, post-scarp infilling or dune ramp development and crestal deposition, or through landward translation and creation and modification of the foredune by cannibalizing former foredunes and the landward dunes. Erosion events, such as tropical storms, will increase beach and dune erosion, and may result in washover conditions where no new sediment source is available, especially for low and incipient dunes. The presence and dominance of pioneer versus late successional vegetation help identify where foredunes are situated in their cycle of evolution.

Chapter 8
Conclusion

The foredune profiles measured during the 2006 and 2007 topographic surveys have shown very minor change compared to the historical record of Gulf County, Florida. Current models do not accurately describe the profiles and their changes over the time scales presented. The variability in sediment supply, as represented in the Psuty models, was a starting point for determining foredune processes and morphology in Gulf County, but other variables were required to understand the beach-dune interactions and foredune morphologies in this region. These variables included storm frequency, vegetation, and the antecedent geomorphology/geology. Therefore, other factors were added to the new cycle of foredune evolution, which are necessary for describing the dynamics and evolution of foredunes in Gulf County, Florida.

Some of the foredunes in Gulf County have grown in size over the survey period, but the changes are minuscule compared to the changes observed on the longer temporal scale. These long-term changes are mostly the result of hurricanes and accretion events. Gulf County foredunes will be impacted by any large storm, hurricanes in particular. Unlike the other factors examined herein, wave energy does not typically play a significant role in the development of foredunes in Gulf County. Wave energy is very low in Gulf County, Florida, averaging less than 0.30 m, excluding major storm events like hurricanes. The recovery of foredunes post-storm and after major beach progradation, was initiated when pioneer vegetation was able to re-establish, which only occurs in the absence of storm activity.

Vegetation played a key role in the development of dunes in Gulf County, Florida. The pioneer dune building grasses, *Uniola sp*. and *Andropgon sp.*, were the dominant species on Gulf County foredunes. While these species were present on all foredunes, their presence, percent cover and wide extent are dominant on prograding coasts and the adjacent incipient dunes and foredunes. Erosion reduces the presence of pioneer species on larger, older dunes, and reduces the horizontal extent of foredune plant zonation. Yet these larger foredunes may migrate landward and cannibalize older, landward dunes, which as a result are dominated by later successional species.

Dunes on prograding beaches had higher similarities in vegetation cover and species present than did the foredune-vegetation profiles on eroding beaches in Gulf County. The analyses of relative importance indicated that pioneer species are the most important vegetation types in prograding sites, while late successional species are most important on erosional sites.

The new cycle of foredune evolution presented in Chapter 7 was created based on empirical and observational evidence of morphological changes in Gulf County, Florida. One of the greatest strengths of the new cycle of foredune evolution presented is that it is based on empirical data. This allows the model to be tested and compared in alternate locations on a more global scale. It also allows further enhancements and modifications to be added to the model. A second strength of the model is that, within the cycle, there are no “indeterminate” dune forms, and as such there are no gaps in the morphologic state of the foredune, or in its evolutionary cycle. Rather, the changes operate along a continuum. The additional benefit for land managers using this model will be that, through identifying the presence and dominance of pioneer versus late successional vegetation on the foredune and *in situ* observations, even without having a background knowledge of local erosion/accretion conditions, one can determine the state of the foredune within its cycle of evolution.

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