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Innovative Technology Seaweed Prototype Dunes Demonstration Project

Final Technical Report

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Several Texas A&M graduate and undergraduate students contributed to the project by helping with the field work and wave flume experiments. We would like to mention specifically Robert Cory Tyler, Kevin Frost, Matthew Power, and Bryan Myres. In addition, it has to be noted that this project would not have been successful without the tireless efforts of our TAMUG administrative staff, most importantly, Tony Eliaz.

Finally, we would like to dedicate this report to our dear colleague and friend, Captain Robert Webster. Robert's dedication to Texas beaches will always be remembered - specifically through his contributions to this project which kept him going even when his illness was getting worse. He died just two days after the project was officially completed.

Abstract

The project detailed in this report is the first ever to utilize compacted seaweed wrack material to enhance coastal dune cores. In a pilot study carried out by Texas A&M University Galveston Campus (TAMUG), an 800-foot test dune was built on Galveston Island and monitored for more than one year to investigate the technical feasibility of this innovative approach to coastal management.

A healthy beach-dune system is the most economical and the most aesthetically pleasing natural coastal protection against storm surge and wave attack. Large stretches of Galveston Island lack a well-developed dune system. At the same time Texas beaches experience frequent seaweed (Sargassum) landings that can be up to 4 feet in height for a single landing, practically blocking access to the water for beach users. For this project seaweed wrack material from heavy landings in 2014 was collected, compacted and incorporated into sections of the newly built dune to test the applicability and potential benefits of this practice. The idea was to find an adequate use for heavy Sargassum landings and to reinforce coastal dunes in a sustainable fashion without disturbing the upper beach template. A win-win situation.

The whole project includes several components: Prototype construction, monitoring, and wave flume testing. A prototype dune was constructed at the high tide line on the East End Park on Galveston Island and monitored for more than one year. The dune is comprised of four segments - two with the new seaweed reinforcement, two without. The seaweed reinforcement was in the form of compacted Sargassum, i.e. "seabales" which were incorporated into the berm of the dune and covered with sand. In order to prepare seabales from Sargassum wrack landings a specialized vertical compacter was developed based on modified industrial vertical compaction equipment. The evolution of these test dunes (seabale decomposition, spurred vegetation growth, erosion and accretion patterns, etc.) was monitored throughout the duration of the project. Data were collected quarterly and included beach and dune profiles, sediment parameters, penetrometer readings, and vegetation parameters. In addition, live video feed of the project site was provided via two wirelessly connected cameras. Physical model experiments conducted in the movable-bed wave flume of the Ocean Engineering Department at TAMUG complimented the field study. Different model test dunes enhanced with artificial laboratory seabales were subjected to elevated water levels and irregular wave forcing to investigate the effects of the incorporated seabales.

The study showed that building or restoring dunes with seabale cores provides a viable beach

management alternative with an array of short-term and long-term benefits. Short-term benefits include removal of heavy Sargassum landings from the beach leading to reduced smell and easier access, reduced Sargassum volume through compaction and increased erosion resistance of the dunes offered by the dense, wave energy-absorbing seabales. Long-term benefits include spurred vegetation growth, enhanced capture of aeolian sediment transport, and overall increase in dune resilience to drought and erosive conditions. Repeated seabale enhancement of dunes may help sustain and grow healthy dune systems over time and should be investigated further.

After the successful completion of this pilot project we feel confident that the concept could be extended to various stretches of the Texas coast, potentially improving currently employed coastal maintenance strategies and providing an answer to the question many Texas beach goers have when faced with heavy seaweed landings: What to do with the Sargassum?

Chapter 1

Introduction

1.1 Motivation

Coastal dunes provide a natural protective barrier against damages resulting from storm surge impact. These damages can be in the form of loss of life or property and infrastructure damage due to wave impact or flooding. During elevated storm water levels dunes dissipate wave energy by providing sacrificial material to be eroded. In addition, coastal dunes provide valuable ecosystem functions and harbor dozens of plant species to make them an extremely valuable asset along our coastlines. In fact, vegetated natural dunes are an essential part of most of the world's sandy coastlines. While these dunes occupy a rather small areal footprint compared to other terrestrial landforms, they fulfill a large variety of beneficial functions in this highly dynamic coastal zone. As an integral part of the coastal morphology, they are a sacrificial sand source during storm events when water levels are high enough for attacking waves to erode the dune substrate. In this process, wave energy is dissipated as waves break in the surf zone, run up and down the beach and dune face, and mobilize sediment for offshore transport. This offers protection to landward infrastructure against storm surge and wave action damage and reduces hinterland flooding. Vegetation influences dunes in many ways. Plants can help to gradually grow and replenish dunes by trapping wind-blown sediment on the beach. Plant roots bind sediment grains together, which may lead to improved erosion resistance. In addition to their aesthetic appeal, vegetated dunes also have value as unique ecosystems and eco-corridors providing habitat to local plants and wildlife as well as shelter and food for migratory species traveling along coastlines. Furthermore, healthy dune systems in conjunction with adjacent beaches may attract tourists and can play an important role in supporting local tourism industries. But coastal dunes are also unique in geometry, volume, sediment composition, plant life, and behavior to their specific location. Thus, it is important to develop appropriate regional dune management strategies and concepts that can address local coastal zone issues while preserving and even growing coastal dunes. Knowing how to best manage our dunes locally will be increasingly valuable as we seek natural, sustainable, soft solutions to combat the effects of growing pressure on our coastlines from population increase, rising sea levels and increased storm frequency and intensity.

This project addresses an issue very specific to Gulf of Mexico coastlines and of particular interest to the upper Texas coast, but the concept could be utilized in many coastal areas. Almost every summer during peak tourist season a large amount of Sargassum sea algae washes up on Texas beaches. Sargassum is commonly called 'seaweed' by Texas beach-goers and piles of it can be up to 4 feet in height. While the floating mats of Sargassum in the ocean provide shelter for many fish species and thus play an integral part in the food chain, once the material is washed onto the beach and becomes Sargassum wrack, the decaying organic matter contained within starts to create unpleasant odors and when present in large quantities may even become a hazard to beach goers and deter visitors from Texas beaches. Coastal managers frequently utilize heavy machinery to scrape the material off the beach to avoid complaints from beach users. The material is then dumped or pushed near the vegetation line or in front of the seawall in the case of Galveston, creating massive stacking areas with a mix of seaweed and sand scraped from the beach. The photos shown in the four panels of Figure 1.1 illustrate the underlying motivation for this project. Panel 1 displays a freshly washed-up Sargassum patch on the beach. In Panel 2 destruction and erosion of beach front property from storm impact as a result of inadequate protection is shown. A particularly heavy landing of Sargassum material in the summer of 2014 is displayed in Panel 3 where removal with heavy front-loader equipment was conducted. Panel 4 illustrates the stacking practice where a mix of scraped off sand and Sargassum is piled up near the vegetation line or the seawall in Galveston.

The fact that large stretches of the upper Texas coast are lacking significant dune systems, often due to limited sediment supply and continual erosion, combined with the necessity of removing heavy Sargassum landings from the water line area, led to the idea to build dunes incorporating the Sargassum wrack material in a beneficial way. In this project washed up Sargassum wrack material was collected and mechanically compacted into "seabales" which were then used as core material hidden inside a newly constructed test dune. In the short-term (weeks to years) it was anticipated that the Sargassum-enhanced dunes will provide immediate protection against storm surges and wave impact. In the long-term (years to decades) the material may decay and spur growth of dune vegetation which in turn will help sustain and even grow the dunes through entrapment of wind-blown sediment and added biomass. It is the intent that the project will allow Galveston, and in the future also other Texas coastal communities, to create a best practice management strategy for its sand, beaches and dunes including the beneficial use of Sargassum wrack to continuously grow and enhance dune systems. The motivation for this project included some of the following expected benefits:

- Gentle removal of heavy Sargassum landings from the beach without major disturbance of the sand surface and without removing the material from the beach/dune template
- Access for residents and tourists to the beach after heavy Sargassum landings
- Reduction of seaweed wrack material volume via mechanical compaction
- Elimination of odor and dust from decomposing wrack material

- Improved protection of infrastructure and property against erosion, surge, and wave attack (via dense seabales in the short-term and spurred vegetation growth and trapped wind-blown sediment deposits in the long-term)
- Growth of natural-looking vegetated dune systems
- Provision of new beach management strategy that keeps all material within the beach dune template

Figure 1.1: *Photos depicting the motivation for this project. Panel 1: Washed-up Sargassum wrack material; Panel 2: Erosion on Galveston Island; Panel 3: Heavy single Sargassum landings can accumulate up to 4 foot high and require heavy machinery to be removed; Panel 4: Current management practice includes front-stacking of seaweed and sand mixture at the seawall or vegetation line.*

1.2 Background

The island of Galveston is a sand-starved barrier island located 50 miles southeast of Houston along the upper Texas coast approximately 60 miles from the Louisiana state line (LAT:

29°18′17″; LON: 94°46′30″). Most of the island is eroding with erosion rates up to approximately -5.0m/yr west of the seawall (Paine et al., 2012). Accretion occurs only in few areas but can be up to +10 m/yr near the South Jetty.

Previous erosion response efforts have included veneer nourishments, with supplemental larger projects implemented by the GLO and the City of Galveston. Previous dune projects have included both round and rectangular hay bale projects and larger geo-textile tube core projects constructed west of the seawall. The hay bale projects performed poorly under wave attack due to the low density of the hay which allows it to easily float away once exposed. There is also anecdotal evidence from Galveston West End communities of Christmas trees being buried under sand. A recent USACE report investigated sand management strategies based on the computed sediment budget for Galveston Island (Frey et al., 2014).

The societal importance of coastal sand dunes as protective barriers against storm surge and as a valuable ecosystem has received increased attention in recent years (e.g. Everard et al., 2010). Our understanding and predictive capabilities of the erosion processes occuring during wave and storm surge impact on a dune have improved as well (e.g. van Rijn, 2009). Most studies on dune erosion have been conducted in laboratory wave flumes (e.g. van Gent et al., 2008; de Vries et al., 2008; Figlus et al., 2011) although some field studies have been reported in the literature (e.g. Fisher et al., 1986; Dette and Uliczska, 1987). In this study field and laboratory investigations are combined to research the behavior of seabale-enhanced dunes.

1.3 Project Overview

This demonstration project was the first of its kind to test the behavior of compacted Sargassum bales inside a sand dune. For that purpose an 800-foot test dune was built in the summer of 2014 at Apffel Park on Galveston Island's East End. Sargassum wrack material was collected from the beach in front of the new dune and mechanically compacted using a generator-powered, vertical-style compactor mounted on a flatbed trailer as will be explained in more detail in Chapter 2. The resulting seabales were then placed inside the berm of the dune and covered with sand. A schematic of the concept and a photo of the dune immediately after construction is shown in Figure 1.2. The dune was built with the help of Galveston Parkboard of Trustees staff and equipment, as well as Texas A&M Galveston researchers, graduate and undergraduate students. Figure 1.3 shows the prototype dune 9 weeks after completion. The official project start and end dates were 2/1/2014 and 8/31/2015, respectively, with an official contract execution date of 5/6/2014 and funding start date of 6/3/2014. After permit clearance and initial construction the test dune was monitored in regular intervals via video cameras, beach profiles, penetrometer tests, sediment samples and vegetation testing to track the development of the dune, the incorporated seabales and the dune vegetation. Different segments of the dune were used to test various vegetation techniques in order to obtain a better understanding of the impact on dune restoration. In addition, laboratory physical model tests were carried out in the TAMUG moveable-bed wave flume facility to explore the effects of seabale cores on dune erosion in a controlled setting under varying conditions. Chapter 3 discusses the physical model test setup in detail.

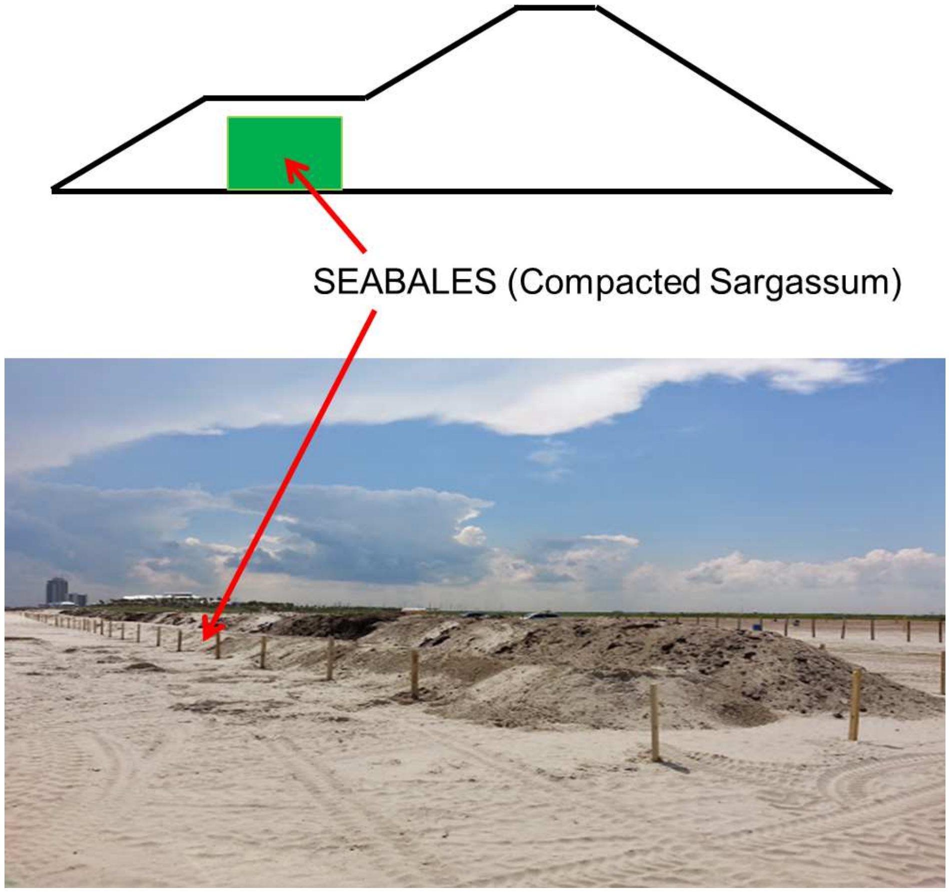

Figure 1.2: *Schematic cross-section and prototype photo of seaweed-enhanced dune. Compacted Sargassum bales (seabales) are placed inside the berm of the newly constructed sand dune.*

The overall goal for this project was to investigate through rigorous monitoring efforts, the evolution of the seaweed-enhanced dunes, and in particular the evolution of the sand-covered seabales inside the dune. The Sargassum material is free and in many places already being removed from the beach in an effort to provide beach access for residents and tourists. Our project will provide a framework for beneficial use and application of the material and provide a beach management option to deal with heavy Sargassum landings. Project execution was sequenced in steps as follows:

1. Permit clearance: since located above the high tide line, no U.S. Army Corps of Engineers permit was required; City of Galveston and General Land Office permits were acquired and were sufficient.
2. Seabale production: Purchase, assemglage and testing of a prototype seaweed baling

Figure 1.3: *Photo of prototype dune nine weeks after vegetation planting. Each segment was roped off to avoid disturbance from foot traffic across the dune.*

system and production of seabales.

3. Dune construction: Construction of 800-foot dune with half including seabales inside the dune berm.

4. Research and monitoring: Quarterly surveys of beach and dune profiles, collection of sediment samples, penetrometer testing, vegetation testing, and wave flume testing.

5. Project report: Write and submit final project report to GLO and Park Board of Trustees; present work at national coastal conferences.

The effect of this project on beaches and public infrastructure includes multi-facetted benefits if the suggested management practice is adapted. Public safety is enhanced by avoiding the current management practice of seaweed stacking areas which pose a hazard when entered, take up too much space on already narrow beaches (i.e. in front of the seawall), and under dry conditions can cause breathing problems (e.g. through inhalation of dry dust from decomposed seaweed wrack). Beach access for tourists and residents is improved by removing heavy seaweed landings from the beach using a gentle process (i.e. chain-belt rakes rather than front loaders) that does not aggressively dig into the beach sand, thus reducing the volume of sand disturbed. In the summer of 2014 seaweed wrack piled up as high as 4 ft along the Texas coast line, effectively blocking access to the water and causing dangerous swamp-like conditions in areas of standing water. The added surge protection through new dunes also provides more protected beach access on top of the added protection offered to public infrastructure and property. The intended project location fronts public property. The developed concept of building dunes with seabale cores, however, is intended to pave the road for future incorporation of this seaweed management and coastal protection practice in other areas suffering from frequent seaweed landings and lack of self-sustaining dune growth (e.g. Galveston West End, Galveston Seawall area, Bolivar Peninsula, etc.). This approach could also be extended to areas fronting private property in the future. The most apparent benefit is the reduction in storm surge damage and improved surge suppression afforded by the healthy vegetated dunes including the dense seabale core.

Furthermore, this innovative technology project has a positive effect on natural resources. It makes more efficient use of existing materials and provides an alternative to current beach management strategies that may reduce the impact of current beach grooming techniques. The main goal is to recycle the naturally occurring seaweed material within the beach system to grow and sustain healty dune systems that in itself are a valuable natural resource threatened by erosion. The compacted seabales are intended to spur vegetation growth, aid in making vegetation more drought resilient by time-release of nutrients and moisture and initially provide a strong fabric for plant roots to establish before decomposing. Healty vegetated dunes provide important coastal ecosystem functions to both plants and animals. In the future, even the beneficial use of dredged material to build and sustain seabale-enhanced dunes is possible in combination with the techniques developed through this project.

In addition, this project provides a relatively inexpensive test for the first time application of seabale cores to build dunes in a sustainable manner. The development of this technique may lead to additional cost savings in coastal management practices which had to rely on costly removal of seaweed from the beach template at times of heavy landings as was the case in 2014. In addition, the potential for added resilience of the seabale-enhanced dunes may lead to future savings from avoided infrastructure and property flood damage. Finally, having a sustainable plan that can deal with heavy seaweed landings while at the same time growing coastal dunes where they are most needed leads to satisfied residents, tourists and long-term cost savings.

Chapter 2

Field Study

In this chapter information on how the field study was setup and conducted are given. The project site is presented and details on dune design and construction are discussed along with a more in-depth explanation of the compacted Sargassum seabales and the vegetation planting efforts on the prototype dune.

2.1 Project Site

A location map of the project site and prototype dune is given in Figure 2.1. This project site on Galveston Island's East End at Apffel Park was chosen based on several logistics considerations. The Park Board of Trustees manages the site and collects parking fees which allows for some control and supervision to limit potential vandalism. The site was easily accessible by car and heavy equipment and offered a wide, accreting beach template without any existing dunes. Furthermore, the proximity to a designated sand borrow area (Big Reef) adjacent to the South Jetty of the Bolivar Roads navigational channel simplified dune construction and minimized required sand transportation. Local amenities and infrastructure offered through the closeby East End beach pavillion (computer server room, electrical power, internet access, WiFi, etc.) further simplified project execution. In addition, the project site was located only 15 minutes from the TAMUG campus which made project monitoring, data collection, troubleshooting, and project management easier compared to a more remote location. One of the drawbacks of the chosen field site was the fact that the particular stretch of coastline is accreting, in part due to its close proximity to the South Jetty. This was not necessarily an issue for this project since the main goal was to observe the evolution of the dune and seabale cores under normal conditions but in the future another test site on an eroding beach may be beneficial to have more exposure to hydrodynamic forcing from storm events. Nonetheless, tropical depression "Bill" did produce storm surge and waves large enough to affect the prototype dune as will be explained in more detail in Chapter 4.

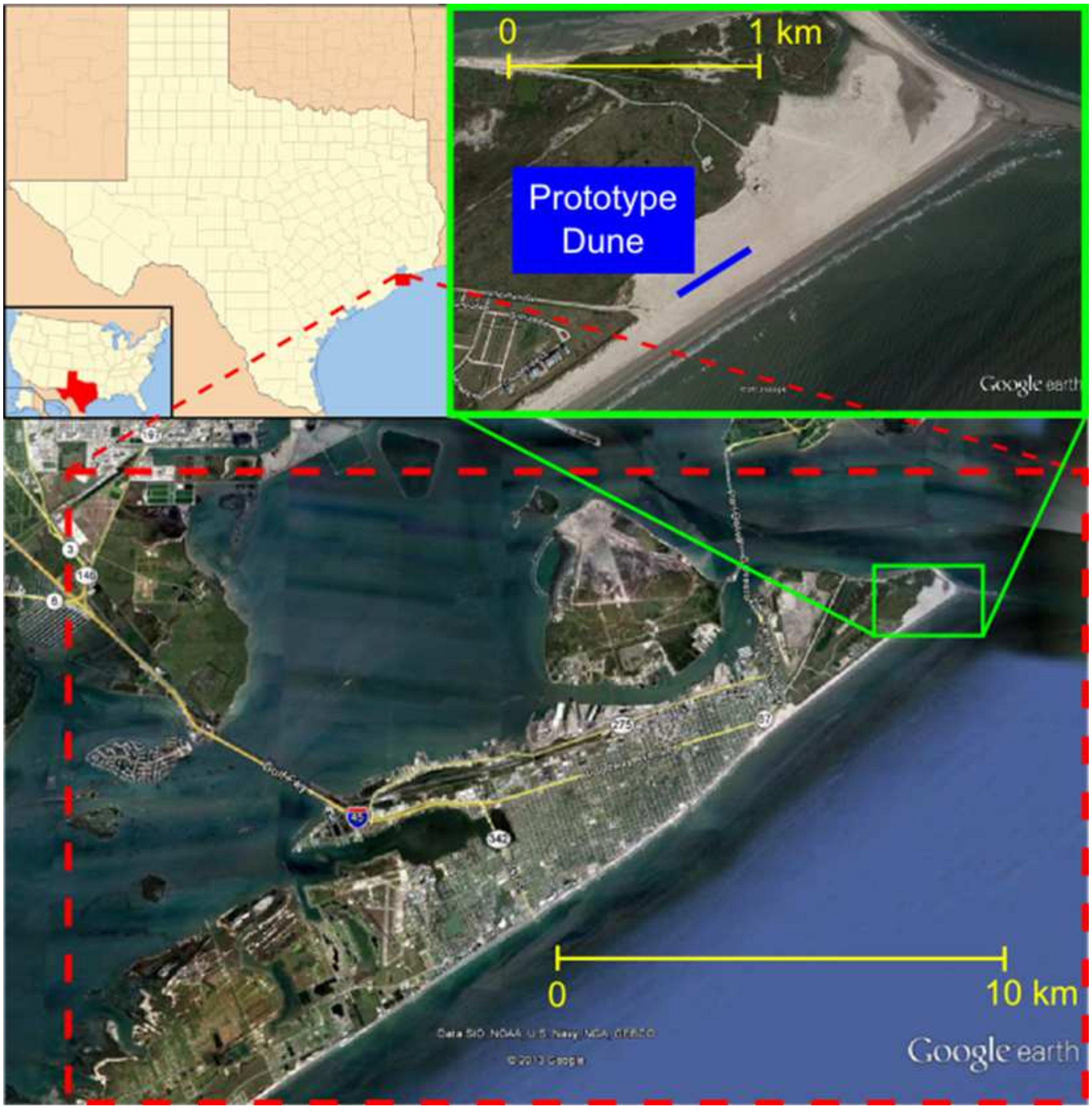

Figure 2.1: *Field site location map. The field site is located on Galveston Island's East End in an area called Apffel Park.*

2.2 Dune Design and Construction

The design of the prototype cross-section was mainly dictated by the available volume of sand (approx. 2200 yd^3) and followed a dune with berm template. Sand to build the dune was collected from accretionary mounds on East Beach including previously stacked mixed seaweed and sand material. Two reasons led to the choice of template: for one, the dune with berm setup has been shown to be more resistent to wave overtopping and overwash than other geometries (Figlus et al., 2011). Secondly, the chosen cross-section allowed for easy incorporation of the seabales inside the berm of the dune. The main dune could be constructed initially and the seabales could be placed in front of it before being covered with sand to form the berm. This geometry also is beneficial for future repeated application of seabales since it does not require the entire existing dune to be replaced. Rather, new seabales can be added in front of the dune, effectively growing the dune in base width and height, while maintaining its geometric shape. Figure 2.2 displays the design dimensions including a base width of $W = 22ft$, a crest height of $H_c = 5.5ft$, a berm height of $H_b = 3.5ft$ and a berm crest width of $W_b = 5ft$. All slopes were set to $\tan\alpha = 0.7$. The sand veneer covering the

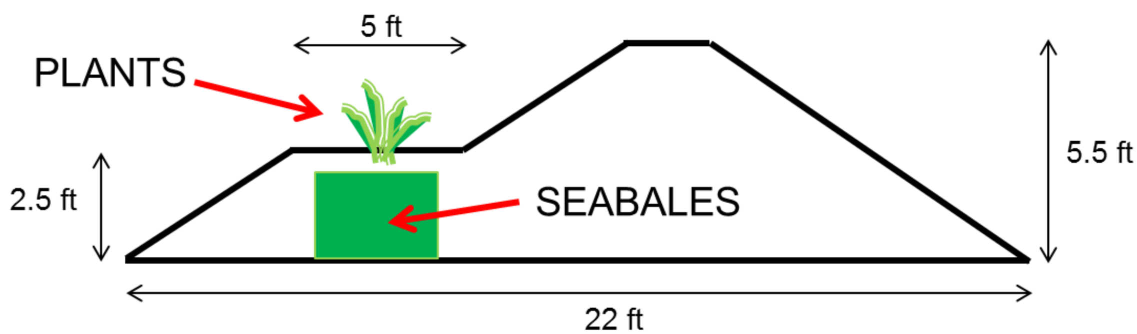

Figure 2.2: *Schematic of prototype dune cross-section and basic dimensions. The dune design features a main dune and berm section. Seabale and plant placement is illustrated, respectively.*

seabales inside the berm was set to $0.5ft$ to prevent exposure of the seabales throughout the project lifetime while still allowing plant roots to reach the seabale substrate with ease. Table 2.1 gives the complete set of dune geometry design parameters with explanations. Total test dune length was set to $L = 800ft$ but for practical reasons the dune was constructed in four equal-length segments of $200ft$ each with three approximately $15ft$ wide gaps in between. The gaps were deemed necessary to facilitate foot traffic by beach goers between the parking area behind the dune and the beach. Providing these gaps also reduced the likelihood of beach visitors crossing the actual dune and trampling over vegetation. The gap size was chosen to accommodate for Park Board maintenance or emergency vehicles if necessary. Furthermore, project description signs educating the public were placed at each gap to take advantage of the concentrated foot traffic in those areas. Signs also urged pedestrians not to trespass into the dune area. In addition, each dune section was fenced off to prevent intrusion onto the dune system by the public.

The four $200ft$ dune segments were used to realize different dune vegetation treatment options and to compare dunes with and without seabale core. It has to be noted that research into vegetation planting techniques and plant development was not part of the project scope but was carried out in an effort to provide additional insight into dune restoration since dune vegetation is linked directly to dune performance. More detailed information on the vegetation

Table 2.1: *Dune Geometry Design Parameters*

Parameter	Unit	Value	Description
H_c	$[ft]$	5.5	height of dune crest above base
W_c	$[ft]$	2.0	width of dune crest
$\tan\alpha$	$[-]$	0.7	slope of dune (dz/dx)
L	$[ft]$	800	length of dune
H_b	$[ft]$	3.5	height of berm crest above base
W_b	$[ft]$	5.0	width of berm crest
W	$[ft]$	22	width of dune base
S	$[ft]$	0.5	sand veneer around seabales
A	$[ft^2]$	72	area of dune cross-section (sand only)
V	$[ft^3]$	$58,000$	volume of entire dune (sand only)

planting is given in Section 2.4. From West to East, dune segments were labeled 1 through 4 as shown in Figure 2.3. All segments were constructed using the same cross section template (2.2). However, only two of the four segments were built with seabales inside the berm. The two other segments did not include seabales at all. Furthermore, two of the dune segments included plantings of *Panicum amarum* on top of the berm, whereas the other two were left bare to vegetate naturally. Altogether this led to four unique dune segments with different combinations of seabales and planted dune vegetation. Segment 1 included plants and seabales, segment 2 included only plants, segment 3 comprised only seabales, and segment 4 acted as a control segment with neither plants nor seabales (Table 2.2).

Figure 2.3: *Planview of dune segment layout. The prototype dune has four segmentss (200ft each).*

Table 2.2: *Explanation of Dune Segments*

Dune Segment	Type
1	plants and seabales
2	plants only
3	seabales only
4	control

Construction of the dune segments was carried out in two phases. At first, the main dune without berm was built using front loader equipment (Figure 2.4). A mix of sand and seaweed wrack material was collected from the water line and from existing stacked mounds in the immediate vicinity. The material was then placed landward of the high tide line to create the four different dune segments. Care was taken to align the dune segments with the shoreline and to maintain consistency in cross-sectional geometry. Once the main dune was in place, a single row of seabales was placed in front of segments 1 and 3. More details on seabale construction is given in Section 2.3. After the seabales were in place, the berm in front of all dune segments was created. Segments with seabales were covered with approximately $0.5ft$ of sand veneer to build the berm. Segments without seabales received a plain sand berm to create segments with similar initial geometry.

Figure 2.4: *Photo of dune construction and seabaling operations. The dune was constructed using heavy front-loaders.*

2.3 Seabales

As fresh Sargassum wrack landed along the shoreline of Apffel Park, it was mechanically raked and deposited near the prototype dune. Using pitch forks, the freshly raked Sargassum material was shoveled into the vertical compactor and compacted 3 times, loading more material after each compaction (Figure 2.5). The resulting bales weighed roughly $180lbs$ and were $2.5 \times 2.5 \times 2ft$ in dimension. This equates to a density of $14.4lbs/ft^3$ (Figure 2.6). After compaction, the bales were tied and transported to the dune berm using a front loader. Seabales are up to eight times more dense than the washed-up Sargassum wrack material.

Figure 2.5: *Photo of seaweed baling equipment. A vertical compacter powered by a generator was used to produce seabales for the prototype dune. The entire assembly was mounted on a flatbed trailer.*

Seabales were positioned adjacent to each other in a long-shore line fashion and covered by roughly $0.5ft$ of fresh sand, also using a front loader. Bale ties were removed from the dune after placement as they were not biodegradable. The entire baling process took place over July and August 2015, with work being dependent on fresh Sargassum loads on the beach. In total, 160 seabales were made and positioned along $400ft$ of the prototype dune berm. This amounts to roughly 15 tons of Sargassum which was removed from Texas beaches and out of sight of the public.

Figure 2.6: *Photo of finished seabale with approximate dimensions of* $2.5 \times 2.5 \times 2.0\ ft$. *A single seabale weighs approximately* $180 lbs$.

2.4 Vegetation Planting

In late August 2015, 300 culms of *Panicum amarum* (know commonly as Bitter Panicgrass) were restored to two sections of the dune system, one with sea bales and one without. Plants were positioned in two rows along the dune berm and were spaced $2.5ft(0.75m)$ apart (Figure 2.7). For the baled dune, this meant that the plants were positioned adjacently along both sides of the bale. Plants were watered once a week for 2 weeks after planting using $8oz.(250mL)$ of water per plant.

2.5 Monitoring Methodology

Each of the four segments of the dune was monitored quarterly for grain size, sediment organic content, sediment moisture content, soil penetration resistance, and beach/dune profile changes. Vegetation monitoring took place biannually for each dune segment. For sediment grain size, organic content, and moisture content, samples were taken from the dune crest

Figure 2.7: *Photo of initial vegetation planting. Panicum amarum was planted on the berm of dune segments 1 and 2 after initial dune construction was completed.*

surface, the berm surface, and $1ft$ below the surface at three locations along each dune. Soil penetration resistance data was collected using an Agratronix penetrometer ($0.75 - in$ tip base diameter, $1.5 - in$ tip cone height) at three locations along each dune berm. Twelve beach/dune profile transects were taken to cover the entire dune prototype (Figure 2.8). Two of the transects included near shore bathymetry, extending out to the depth of closure. Depth of closure surveys were only carried out once at the end of the project. Profile data was collected by a Texas licensed surveyor (Naismith Marine Inc.) using a Real Time Kinematic Global Positioning System (RTK GPS). Grain size distributions and median grain size estimates were determined via sieve analysis. Roughly $50g$ of combusted sediment (to remove organic material which can bind sediment grains together) was used for each sample. Organic content was determined by a before and after weighing of samples combusted at $500°C$ for $8hrs$. Moisture content was similarly determined by before and after weighing of samples dried at $60°C$ for two days. The vegetation coverage of each dune was measured twice, once in October, 2014 and once in May, 2015. Vegetation coverage was obtained by taking pictures of randomly selected square meter quadrats along a transect of the dune berm. Ten pictures were analyzed per dune. A spectral analysis using ArcMap 10.1 determined which part of the pictures were green (vegetation) and subsequently the percentage vegetation was computed.

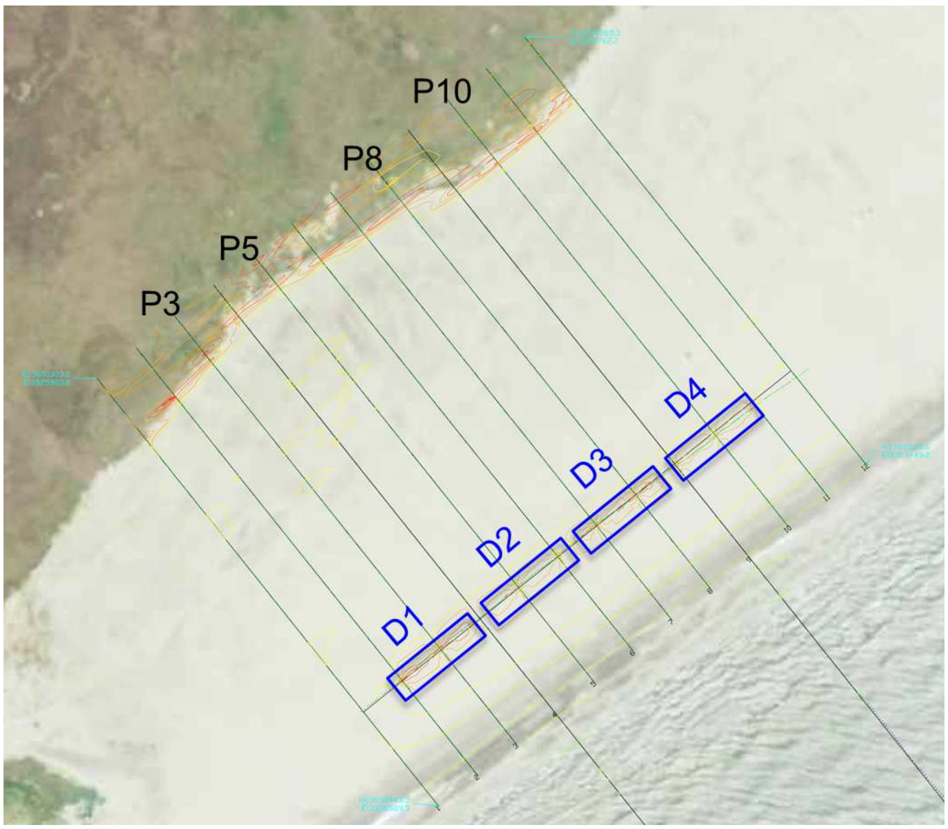

Figure 2.8: *Layout of beach and dune profile survey lines. Twelve wading depth profile lines were surveyed quarterly to track the beach and dune evolution. The last survey also included two depth-of closure lines. P3, P5, P8, and P10 were chosen as representative cross-sections for dune segments D1 through D4, respectively.*

Chapter 3

Laboratory Wave Flume Experiments

The wave flume experiments described in this chapter were conducted to add further insight on the effect of seabale cores on dune erosion under wave attack. Wave flume testing allows for repeatability and parameter flexibility that does not exist in prototype conditions.

3.1 Physical Model Setup

Irregular wave testing with artificial seabale-enhanced dunes was carried out in TAMUG's moveable-bed wave flume (dimensions: $L \times W \times H = 50 \times 2 \times 4.3ft = 15 \times 0.6 \times 1.3m$), a schematic of which is shown in Figure 3.1. The beach and dune profiles were constructed using 8 cubic yards ($6m^3$) of fine sand ($D_{50} = 0.14mm$) placed on top of a plywood bottom to reduce the overall sand volume required for testing. A smooth ramp connected the sand profile portion of the flume to its deep water portion. The initial geometry included a 1:20 beach slope in front of the dune which is close to upper Texas coast beach profiles. The dune volume and crest were chosen such that a significant volume of sand was available for erosion without allowing for wave overtopping of the dune crest. Four major tests were conducted to experiment with different dune geometries and seabale placement options. Test PD0 comprised of a plain dune without seabale core, whereas Test PD1 had the same initial plain dune shape but included a seabale core. The initial dune geometry for Test BD0 was more closely modeled after the prototype in the field and included a bermed dune without seabale core. Test BD1 had the same inital dune and berm setup and included a seabale core inside the berm as was the case for two of the field prototype segments.

3.2 Seabale-Enhanced Laboratory Dunes

Artificial seabales were made out of plastic aquarium plant material. It was tied into a cylindrical shape representing a row of seabales $25in.$ long and $2.5in.$ in diameter. In total it

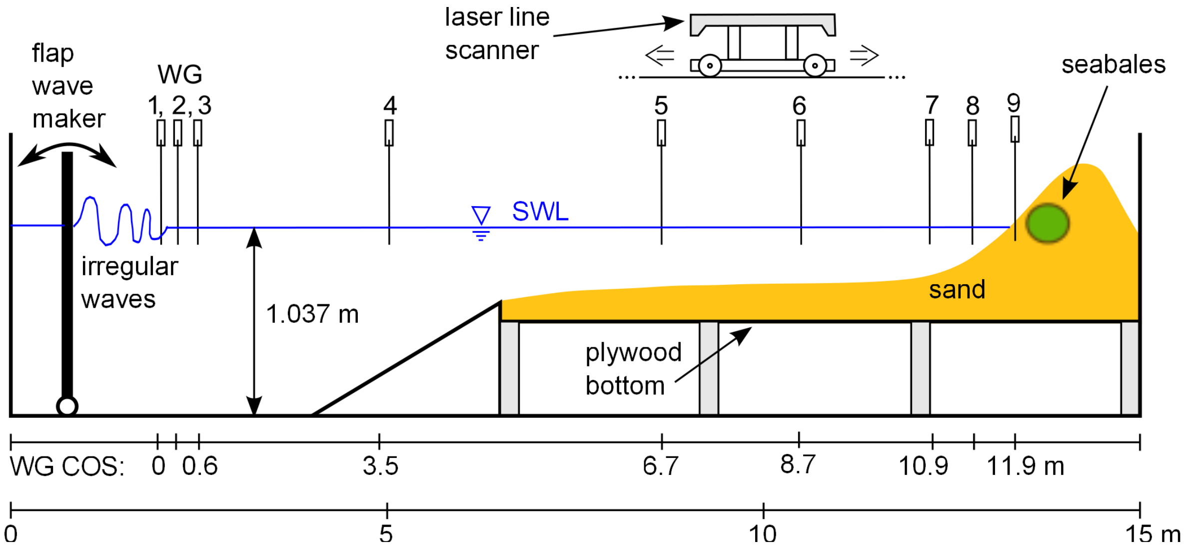

Figure 3.1: *Schematic of the TAMUG moveable-bed wave flume.*

weighed $10.7oz.$ with a density of 9.4 lb/ft^3. Though it was not identical to the real seabales, it represents a soft but interconnected material with both a higher shear resistance than plain sand and the ability to attenuate wave energy.

To evaluate the impact of a seabale on wave-induced erosion in a dune system, two dune profiles and artificial sea bale placement options were tested in this experiment as indicated in section 3.1. The first was a plain dune where the seabale was positioned in a way as to brace the dune scarp during a wave collision event (PD0 and PD1). The other tested dune profile was a bermed dune similar to the prototype built on Apffel Park (BD0 and BD1). For this dune profile, the artificial seabale was placed inside the sacrificial berm where it could play a swash-attenuating role (BD1). For both of these initial dune profiles, a control dune without any seabale was also tested for comparison. The initial beach and dune profile as well as the still water level (SWL) and irregular wave pattern were kept the same for each test, respectively.

3.3 Hydrodynamics

Each of the four tests consisted of 16 identical $3.5 - min$ wave bursts for a total of $56min$ of wave action per test. Wave bursts were produced by a flap-type wave maker based on a JONSWAP spectral shape resulting in a significant wave height $H_s = 6.9cm$ and a peak period of $T_p = 1.2s$ in front of the wave maker. The still water depth at that location was kept constant throughout at $h = 103.7cm$. Wave bursts were limited to $3.5 - min$ each to avoid excessive distortion of the results from wave re-reflection and seiching and to facilitate intermittent laser scans of the profile. Nine capacitance wave gauges (WG1 - WG9) placed

Figure 3.2: *Photos of artificial seabale material used in flume testing. Off the shelf plastic aquarium plants were chosen to model the Sargassum seaweed. Individual pieces were glued together and buried inside the dune to simulate seabales.*

strategically along the center line of the flume measured free surface fluctuations from deep water to the dune at a frequency of $20Hz$. The origin of the local coordinate system is set at the cross-shore location of WG1. The x-axis coincides with the center line of the flume at still water level (SWL) pointing positive onshore. Transformation characteristics of the shoaling waves approaching the dune were tracked by WG4 - WG9, with WG7 - WG9 located directly in front of the dune or on the dune face, respectively. Table 3.1 gives a summary of all relevant test parameters and includes the cross-shore locations of all gauges in local coordinates (x = 0 at WG1 positive onshore).

3.4 Morphodynamics

For every laser scan, the water level in the flume was lowered and then filled back up to the previous level before the next wave burst. An Acuity AP820-1000 laser line scanner system

Table 3.1: *Summary of Wave Flume Test Parameters*

Test Names	PD0, PD1, BD0, BD1
Number of $210 - s$ bursts per test	16
Total duration per test (min)	56
Water depth (cm)	103.7
Average incident H_s (cm)	6.9
Average incident T_p (s)	1.2
Number of profile scans per test	6
Time of profile scans (min)	0, 3.5, 7, 14, 28, 56
WG x-locations (m)	0, 0.25, 0.6, 3.5, 6.7, 8.7, 10.9, 11.4, 11.9

mounted on a moveable cart above the flume measured the beach and dune profile six times per test between wave bursts at 0, 3.5, 7, 14, 28, and $56min$, respectively. The system utilized a high-power blue laser diode ($540nm$ wave length) in concert with a $200Hz$ 2D charge-coupled device (CCD) detector to measure the elevation of the sand surface. The laser diode was set up to project an alongshore blue laser line vertically down onto the beach and dune surface. The CCD detector registers the diffuse reflected laser light and computes elevation with millimeter accuracy based on reflective light intensity. No "time-of-flight" measurement of the laser light is necessary for this method which increases accuracy significantly. For this experiment the cart was moved in the cross-shore direction along the flume and line scans were carried out every $1 - 2cm$ in the most active profile region on and near the dune and every $10 - 20cm$ further offshore where less profile changes were observed. The resulting detailed 3D representation of the measured surface elevations were used to verify alongshore uniformity of the beach and dune evolution process. For further analysis the 3D profiles were collapsed into single average profile lines for evaluation.

Chapter 4

Results

In this chapter results from the prototype monitoring efforts as well as from the wave flume experiments are presented.

4.1 Prototype Dune

The following sections show findings from quarterly profile measurements of the beach and dune area, penetrometer readings at various locations along the dune segments, and sediment analysis (grain size, moisture and organic content) of grab samples taken from the dune segments throughout the project duration.

4.1.1 Beach and Dune Profiles

Beach and dune profile measurements were collected on a quarterly basis by a team of professional Texas licensed surveyors with years of experience in coastal area surveying (Naismith Marine Services). The four survey dates throughout the project were September 2014, December 2014, March 2015, and June 2015. Measurements were collected using Real-Time Kinematic (RTK) GPS rover and base station units with direct reference measurements to local benchmarks. Survey results were provided in Texas state plane coordinates (units: feet). The survey setup was discussed in section 2.5 and Figure 2.8 shows the exact location of the twelve profile lines used to cover the entire project area from the landward end of the parking area behind the dunes to wading depth and, for two survey lines in June 2015, all the way to the offshore depth of closure. Figure 4.1 shows the evolution of the four different prototype dune segments as captured by the four profile surveys. The zoomed-in views to a $300 - ft$ window encompassing the dune and forebeach ($800 - 1100ft$ in local cross-shore coordinates) display representative profile lines and show clearly how the four dune segments performed throughout the project duration. Green rectangles and plant symbols, respectively, indicate whether a specific set of profiles covers a dune with seabales (green rectangles) and/or planted vegetation (plant symbol).

Dune profile changes are usually a result of a combination of many different processes occuring at various time scales and intermittency. They may include hydrodynamic forcing from wind, currents, and waves as well as morphology changes due to wind-driven sediment transport and subsequent deposition on the dune profile. Plants may significantly affect deposition patterns. Human interventions, of course can play a role as well.

For the prototype dune under investigation profiles were observed to change due to several of these processes including the effect of the buried seabales. Seabale decomposition over time led to berm height reduction as plant roots extracted nutrients from the bales and sediment deposits on top of the berm increased the overburden pressure on the bales. Further details on this process are discussed in Section 4.1.2. The seabales inside the dune berms of segments 1 and 3 (P3 and P8 in Figure 4.1, respectively) decomposed to thin layers of several inches thickness over the first three months after placement.

Aeolian transport of sediment drove fine sand grains toward the dune where they were captured by the existing dune and specifically by the dune vegetation. The amount of aeolian sediment transport depends on many factors including prevalent winds, sediment supply, ambient humidity, sediment moisture content, dune geometry and plant morphology. Winds need to be strong and sustained enough to mobilize and carry fractions of the available sediment and need to blow in directions from a potential source to the dune. Large sandy beach or back dune areas with fine material need to exist for aeolian sediment transport to take place. These conditions were given at the project site. In addition, dry sand is mobilized more easily than wet sand leading to preferetial transport during dry periods of time. The capability of plants to reduce wind velocity near the bed and trap sediment varies based on plant type, maturity, and above-ground biomass characteristics. Deposition of wind-blown sediment was observed most noticeably on top of berm sections with dense vegetation.

The most significant and sudden dune profile changes occured due to hydrodynamic forcing from tide, storm surge, and wave impact as dunes were subjected to elevated water levels and wave attack. Due to the location of the prototype dune above the high tide line, water actually reached the dune foot only three to four times throughout the project duration without noticeable morphology changes. Tropical storm Bill (June 16, 2015), however, provided a perfect test scenario for dune performance in light of wave attack. The storm produced large enough surge levels to reach half way up the seaward dune face above the berm allowing waves to attack and erode portions of the seaward dune face. Results show that the dune as a whole withstood the impact from tropical storm Bill. Photos taken immediately after the storm (Figure 4.2) indicated that the dune segments with well established vegetation aided by seabale cores suffered less erosion compared to ones with sparser vegetation and specifically compared to segment 4 which had no seabales and no planted vegetation.

In Figure 4.1 profiles colored in green, blue, red, and magenta represent the four dates of quarterly profile measurements September 2014, December 2014, March 2015, and June 2015, respectively. Dune segment 1 (seabales and planted vegetation) is represented by profile line

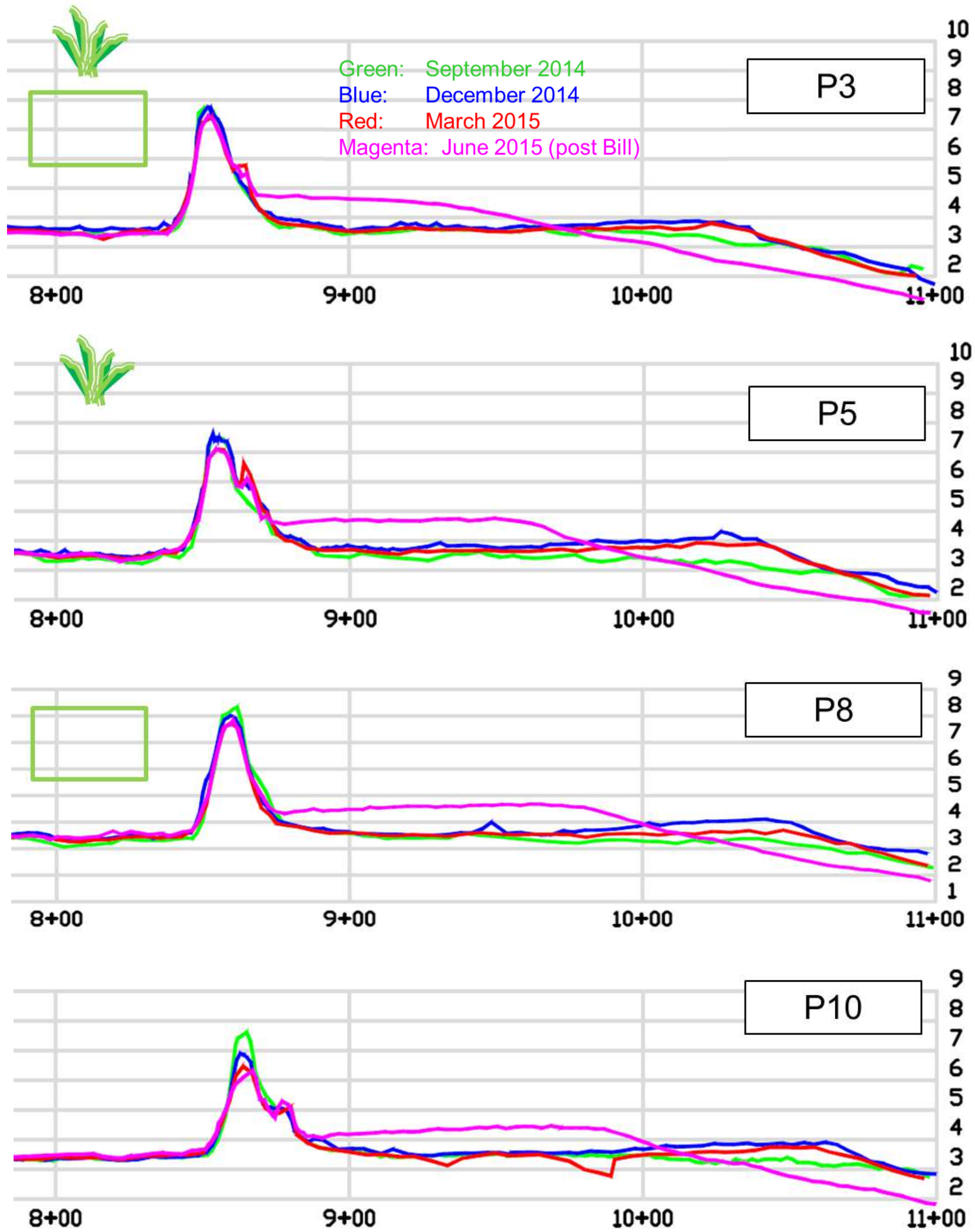

Figure 4.1: *Measured beach and dune profiles. Results from the quarterly beach and dune profile surveys are displayed for profile lines P3, P5, P8, and P10 respectively to represent the four different prototype dune segments. Survey times are indicated by different colors. Symbols for seabales and plants explain the setup for each dune segment.*

Figure 4.2: *Photos of the prototype dune taken one day after tropical storm "Bill" hit the Texas coast on June 16th, 2015. Top left: Dune segment 1 performed extremely well since the combination of planted vegetation and seabales had created a strong berm to withstand the wave attack during the storm. Top right: The tilted project sign in a gap between two dune segments illustrates the wind and water forces acting on the area during Bill. Bottom left: Strong currents flowed through the planned gaps between dune segments eroding some of the edge material. Bottom right: Dune segment 4 without seabales and initial vegetation showed the most significant erosion and dune scarp retreat caused by Bill.*

3, dune segment 2 (planted vegetation, no seabales) is represented by profile line 5, dune segment 3 (no planted vegetation, with seabales) is represented by profile line 8 and dune segment 4 (no planted vegetation and no seabales) is represented by profile line 10. Both dune segments including seabales inside their berms showed signs of berm height reduction due to the decomposing seabale material between the first two profile surveys. Segment 1, however, was able to recover and even increase its berm crest elevation by means of deposition of wind-blown sediment trapped by the flourishing vegetation as indicated in subsequent surveys. Dune segment 4 which had no initial planted vegetation and no seabales showed the most crest reduction from wind erosion and the most dune scarping from wave action during Bill. The other segments with either planted vegetation or seabales or both were able to trap wind-blown sand better and were able to withstand wave attack by protecting sediment from being washed out. In general, the profile measurements show that vegetation is beneficial to erosion control and that seabales can play an important role in providing substrate for vegetation both with and without initial planted vegetation.

The foreshore showed deposition between Sept. 2014 and Dec. 2014 which is typical for this accreting area. During the winter months between Dec. 2014 and March 2015 the accretion was practiclly stalled, and even reversed in some instances, due to heightened wave energy levels in those months. Tropical storm Bill caused significant erosion to the foreshore. The high water levels and wave energy steepened the nearshore profile significantly, eroding up to $2ft$ from the foreshore and depositing over $1ft$ of sand in front of the prototype dune (magenta lines in Figure 4.1).

4.1.2 Penetrometer Testing

The prototype dune was tested with a standard penetrometer commonly used to assess the density of hay bales. The device consists of a graduated stainless steel rod (Length = $30in.$, Diameter = $1/2in.$) with a cylindrical tip on the bottom end and a calibrated pressure gage at the handle. The dial reading refers to the resistive force per unit area (penetration pressure) in pounds per square inch (psi) the device experiences as its tip is driven into the test material. Sections of the test material with a higher density will cause higher penetration pressure readings, whereas sections with voids or lower density will produce lower readings, respectively. As a reference, the hard compacted sand surface of the beach at the project site resists penetration with approximately $80psi$. Care was taken to drive the penetrometer vertically downward into the prototype dune at a constant pace for data collection. Every three inches of penetration depth, a pressure reading was recorded to give a depth profile of penetration pressure for each location tested. For each dune segment three locations on the dune crest, and on the berm crest, respectively, were sampled. The three locations were spread out over each segment to obtain a good representation of the entire dune segment. Penetrometer samples were collected in quarterly intervals, shortly after each profile survey. Figure 4.3 shows the change of the penetration pressure profiles for the berm locations over time as averages over each dune segment. The berm location is shown here since it includes the seabales and initial vegetation plantings and due to its lower elevation allows for the penetrometer to reach all the way to the original beach surface.

The September 2014 pressure profiles clearly show the difference between dune segments with fresh seabales (Dune 1 and 3) and dune segments without seabales (Dune 2 and 4). Compared to the sand cover the fresh seabales offer very little resistance to penetration. While the sand above the seabales had about $15psi$ of resistance, the fresh seabales themselves offered less than $5psi$. The dune berms without seabales had about $5psi$ of resistance throughout. As the penetrometer reached the original hard compacted beach surface on which the prototype dune was constructed, the readings jump up to approximately $80psi$. It is assumed that the

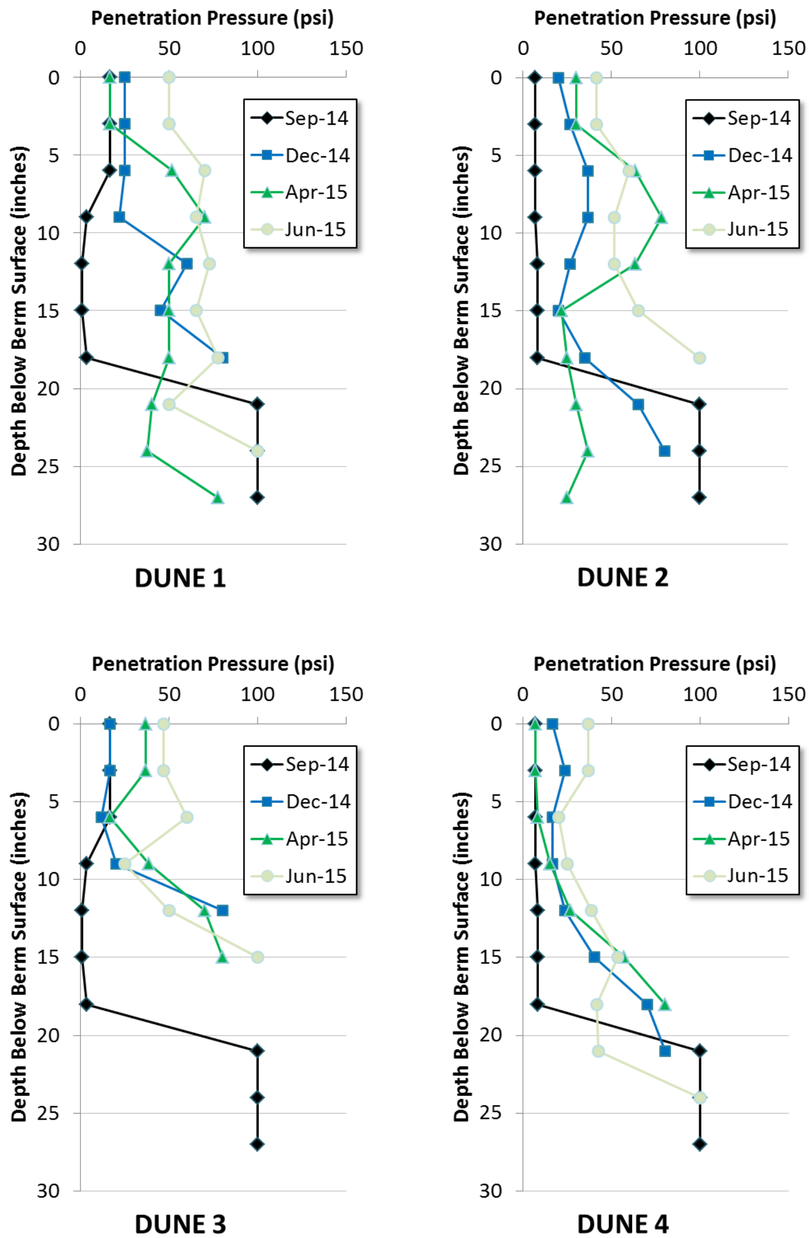

Figure 4.3: *Results from quarterly penetration tests. Each of the four panels shows averages of the changing pressure required to penetrate the dune berm at increasing depths. Data collection dates are represented by different colored lines and symbols, respectively.*

pressure readings of the sand above the seabales is higher than the readings of the same sand without seabales because of initial settling of sand into the void spaces of the seabale material. In all panels, depth profiles are referenced to the berm surface. This means that if the berm surface increases or decreases in elevation, so does the reference point. Thus, for accreting areas the penetrometer may not reach all the way down to the original beach surface whereas for eroding areas, the beach surface may be reached after a shorter distance. This gives another independent measurement of erosional or accretional trends.

All panels in Figure 4.3 show an increase of surface penetration pressure over time which can be attributed to the increased density and strength of plant roots inside the upper portions of the berm. The two dune segments with seabales (Dune 1 and 3) show a higher final resistance to penetration for the June 2015 measurement than the segments without seabales indicating improved performance. The dune segments with initial vegetation plantings (Dune 1 and 2) show significantly increased resistance by April 2015 at a depth around $5 - 10in.$ below the surface. This increase can be attributed to well established plant root systems. Dune 3 (with seabales but without initial planted vegetation) reached similar resistance much later (June 2015) and dune 4 (no seabales and no initial planted vegetation) never reached this level of resistance. This indicates that seabales can help make dunes more resistant by enhancing plant root growth but for most efficient application the combination of plantings and seabales may perform best.

Figure 4.3 furthermore shows that the typical seabale signature from the initial pressure profiles (September 2014) had disappeared by December 2014 due to decomposition, further compaction, and replacement by plant root material and accreted sand. Field core samples revealed that the seabales had shrunk down to a thin layer of organic material at the base of the berm.

4.1.3 Dune Sediment

The average median grain size for the dune sediment across all dunes, dune locations (crest and berm surface, $1ft$ depth), and time periods was found to be 124.4 μm ($0.1244mm$). There were no significant differences in median grain size for different dunes. However, grain size did change significantly (p value < 0.001) with time (Figure 4.4).

The general trend over time was a decrease in median grain size over the winter and spring months followed by an increase in June. The decrease in grain size is likely due to aeolian deposition of finer material during winter and spring months, which was subsequently eroded away during Tropical Storm Bill. This trend is consistent with the profile data, which showed accretion over the winter and spring followed by erosion during tropical storm Bill. During these accreting months, wind was predominantly out of the north (Figure 4.5). Dune accretion typically occurs when wind blows over a length of available material. Sand from the beach or back dune area can be transported into the dune system, which in the case of this prototype dune can happen almost year round due to available sand sources both landward and seaward of the dune. Aeolian transport mainly occurs during periods of dry conditions.

Moisture content within the prototype dune also fluctuated over time. Sediment moisture content is dependent on a variety of factors including ambient humidity, short term rainfall

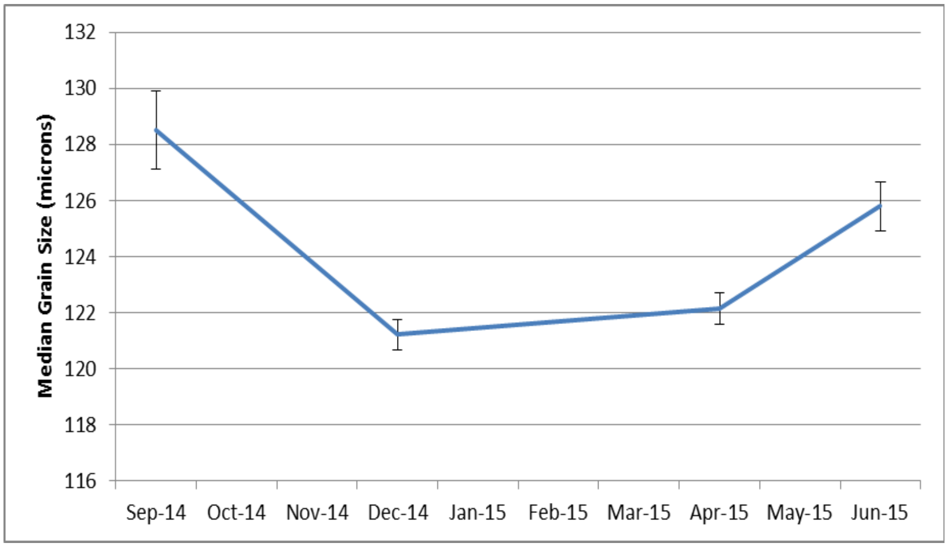

Figure 4.4: *Measured median grain size variations as a function of time. Average values over all dune segments and all measurement locations are connected by the blue solid line. Vertical bars indicate standard deviation of sediment size for each sample date.*

events, tides, and rate of soil evaporation/drainage. Rate of evaporation in turn depends on temperature, humidity, and uptake of soil moisture by plants (evapotranspiration). Figure 4.6 shows daily precipitation amounts and monthly mean temperatures in Galveston Island over this period of time as well as the dates in which the prototype dune was sampled. Moisture content across all dunes was highest in the fall and winter of 2014 when rainfall was high and temperatures were low. The lowest moisture content was recorded in the summer of 2015, when temperatures were high and rainfall was relatively low.

Moisture differences between the dune sections mainly reflected vegetation restoration efforts. At all sampling increments except for the June sampling, vegetated dunes had 62% lower soil moisture content on average when compared to the non-vegetated dunes (Figure 4.7). This suggests the plants were taking up a large amount of moisture from the sediment (evapotranspiration). The seabales themselves did not have an obvious impact on moisture. However, we will discuss the relationship between sediment organic content (i.e. Sargassum) and moisture later in this section.

Soil organic content, also for only the first 3 samplings, was reduced by the presence of plants by an average of 81.8% (Figure 4.7). Normally, plant roots and decomposing plant material make up the majority of organic content of dune sediment. However, in our prototype dune the vast majority of organic material was the Sargassum bales and ambient Sargassum present in the dune construction source material. This result implies that after restoring vegetation to the Sargassum-laden soil of the prototype dune, the plants consumed the nutrient-rich Sargassum material and reduced organic content in the soil in the process. Similar results have been obtained in greenhouse studies where it was shown that the growth of *P. amarum*

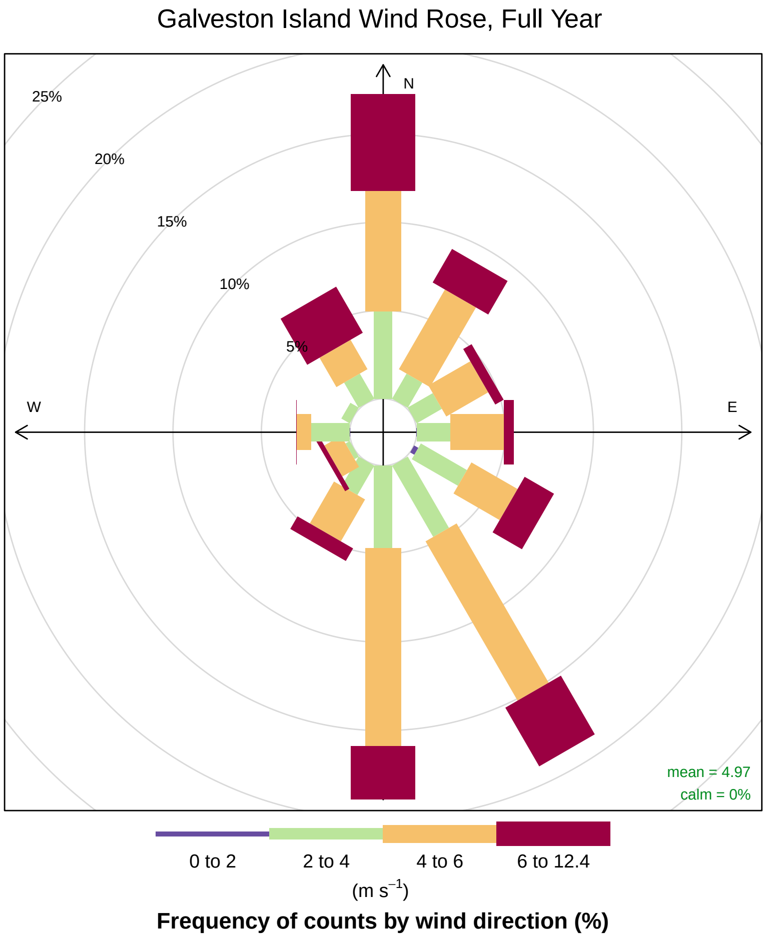

Figure 4.5: *Wind rose for Galveston Island over the entire project duration. The distribution shows that winds predominantly blow along the North-South axis which represents beneficial conditions for aeolian sediment transport for our test site since potential sediment source areas are located North (parking area) and South (open beach) of the prototype dune.*

was increased by the presence of Sargassum (Williams and Feagin, 2010). Our sampling also shows the generally decomposition pattern of Sargassum over time, with the final sampling in June 2015 only having 27% of the organic material on average compared to the initial sampling in September 2014.

Sargassum presence in soils correlated strongly and positively with moisture content over the first two sampling periods (Figure 4.8). This trend occurred only over the first two sampling periods as a significant amount of Sargassum was still present in the soil for that time period, but decayed afterward. This result shows that though the seabale dunes did not outperform the control dunes in terms of moisture retention, Sargassum presence in soil was linked to moisture. In other words, Sargassum retains moisture in soil and likely benefits plant life in

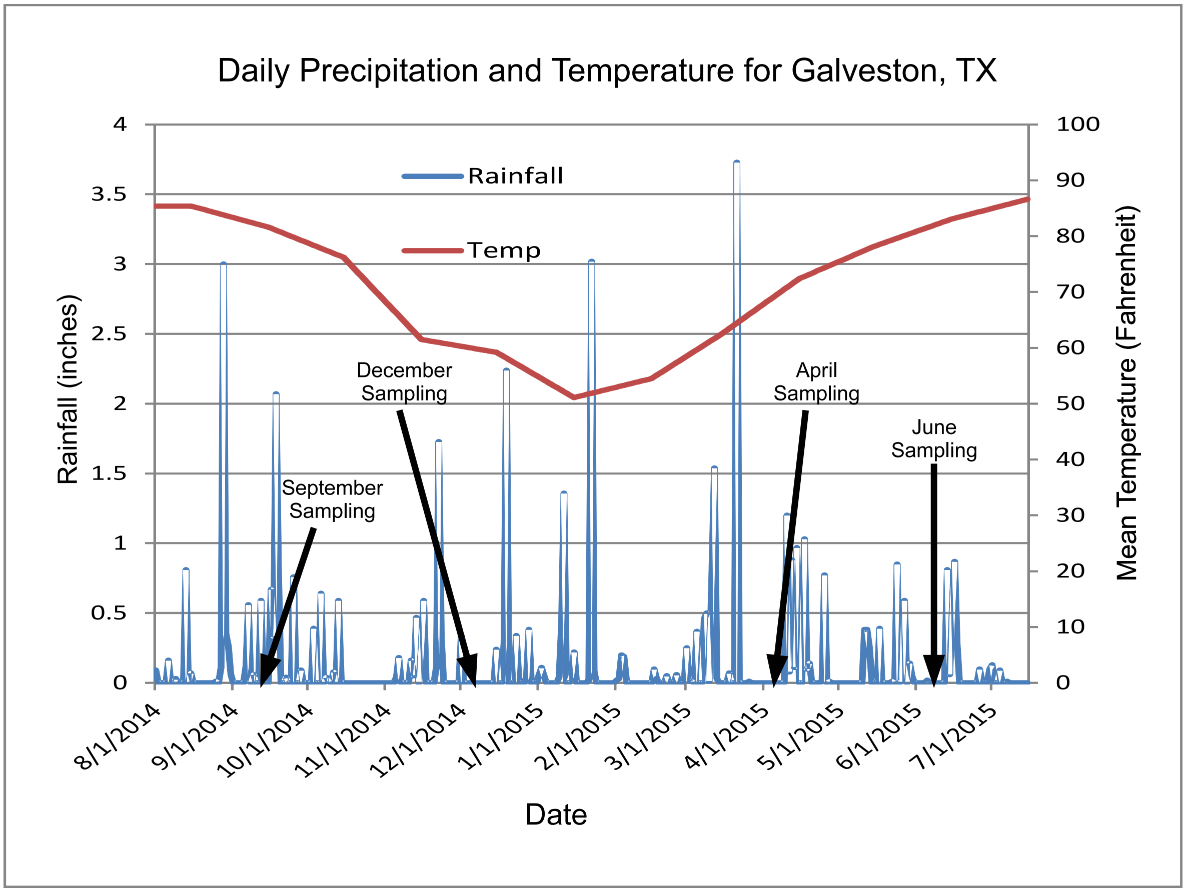

Figure 4.6: *Daily precipitation and temperature variations for Galveston Island over the entire project duration. Data sampling times are denoted by black arrows*

the process. The reason that the seabale dunes did not have more soil moisture or organic content was because the source material for dune construction was heavily laden with ambient Sargassum which confounded the data. In this respect, it seems that seabales are no better at retaining moisture than non-compacted Sargassum.

4.1.4 Dune Vegetation

Vegetation plantings and research into dune vegetation evolution was not an explicit part of the CEPRA project. However, since dune vegetation has a profound influence on dune performance and seabale integration it was investigated throughout the duration of the project.

Restored vegetation grew vigorously throughout the year and restored dunes had much more vegetation at both sampling periods. In October, 2014, restored dunes had roughly 30 times more vegetation than unplanted dunes. After some opportunistic colonization, mostly by

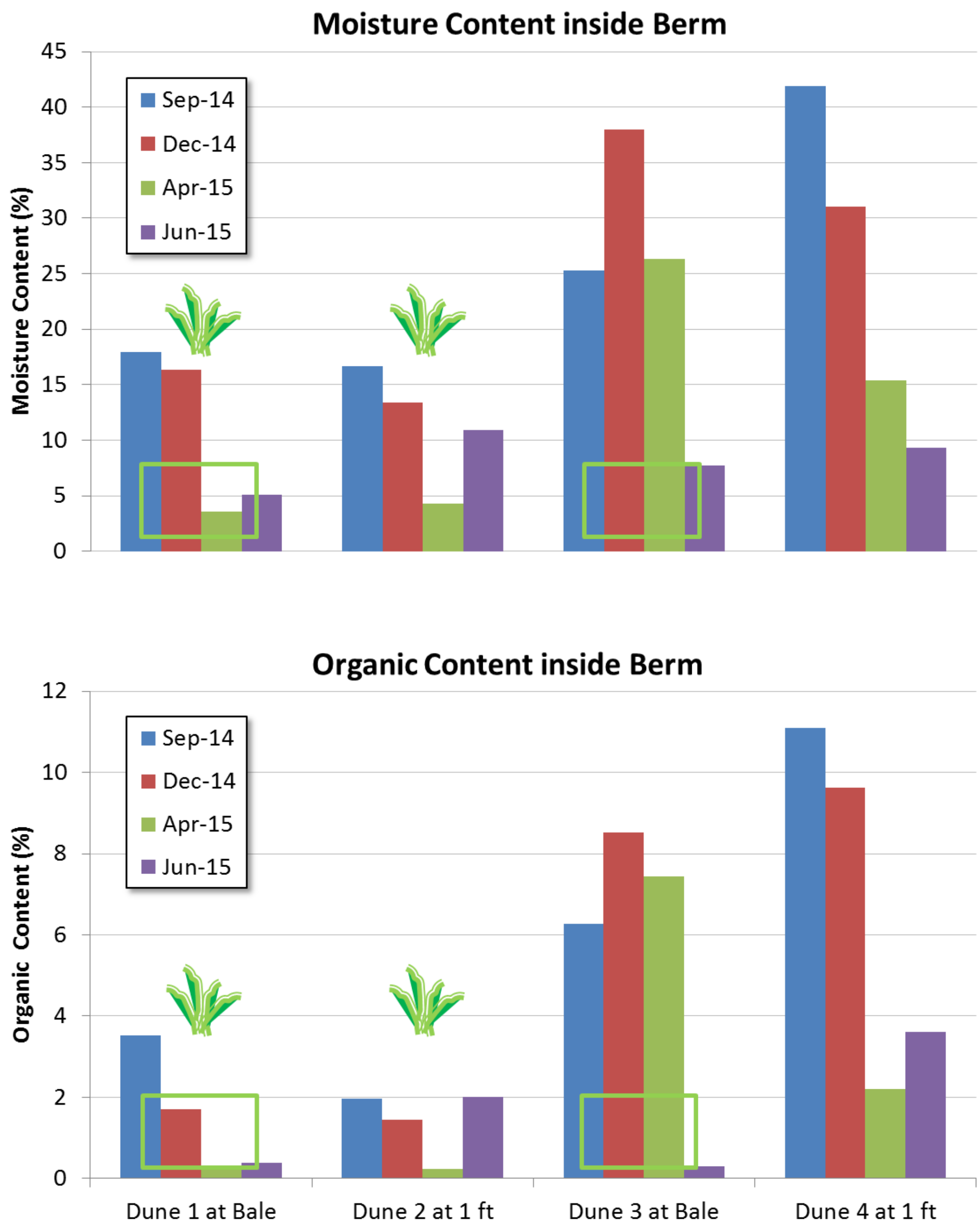

Figure 4.7: *Measured average moisture content and average organic content inside the berm of each dune segment and sampling date, respectively. The changes over time in average moisture content (top panel) and average organic content (bottom panel) show a strong correlation.*

shrubs, the restored dunes only had about 3.5 times more vegetation by May, 2015. The unplanted dune had roughly the same amount of vegetation in May, 2015 as the restored dune

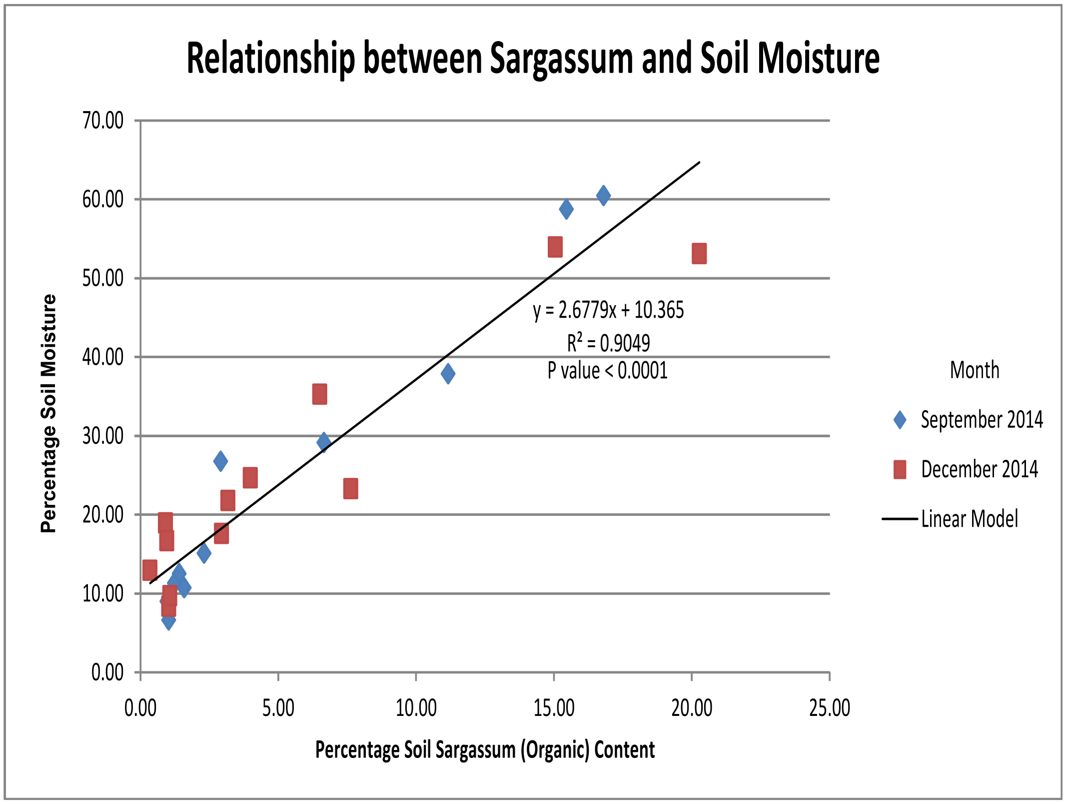

Figure 4.8: *Correlation of Sargassum and moisture content for two sampling dates. Sargassum (i.e. organic) content correlates well with moisture content indicating that seabales provide a means to store moisture inside the dune.*

had in October, 2014. This result indicates that the natural process of plant colonization lags roughly 6 months behind the restoration of vegetation, of course with differing plant species composition. After only 6 months, the non-bale restored dune had reached essentially the peak coverage for any ecosystem, averaging 97% vegetation coverage.

Seabale impacts on vegetation growth were negligible in both restored and unplanted dunes at the first sampling period (October, 2014). By May, 2015, however, dunes with seabales had less growth than non-bale dune though not by a large amount. Non-bale dunes had about a 10% increase in growth for the restored dune and a 30% increase in growth for the unplanted dune. Again, similarly to the result of sediment moisture and organic content not being higher for the seabale dunes compared to the control, vegetation showed the same trend. This also was probably caused by the large presence of Sargassum in the source material for dune construction. Baled Sargassum incorporated into a dune core would likely improve plant growth on a large scale however due to the confounding nature of the Sargassum-laden source material, we could not show this.

4.2 Wave Flume

For the moveable-bed wave flume tests, free surface elevation η was measured via WG1 - WG9 for every 210-s wave burst comprising the four tests PD0, PD1, BD0, and BD1. The measured time series were used to examine shoaling characteristics, and wave parameters of the irregular wave trains attacking the vegetated dunes. A 20-s sample of the measured free surface elevations at each gage is shown in Figure 4.9.

Inspection of the measured free surface elevations showed steepening of the wave crests as they continued to shoal over the 1:20 sediment bed slope (WG5 - WG7). At the WG8 location most waves were near their breaking point or had already broken. This produces a fairly short surf zone with most of the wave energy available to erode the dune face as would be the case during elevated water levels in nature. The swash signature of waves rushing up and down the dune face is visible in the WG9 records where distinct wave crests have transformed to broken wave bores at shallow water depths. WG9 was initially buried in the dune face above SWL and records display local bed elevation during dry periods and free surface elevation during wet periods when water is touching the gage above the bed level.

During the irregular-wave tests in the moveable-bed flume, dune and beach profiles were collected by the AP820-1000 laser line scanner at strategic intervals as listed in Table 3.1. The raw topography data allowed detailed visual inspection of the dune erosion process. Relative alongshore uniformity of the dune erosion process was observed visually during the experiment and confirmed via the 3D visualization of each measured profile from the laser scans. For further analysis of the measured data, the 3D profiles were averaged in the alongshore direction to yield 2D cross-shore beach and dune profiles. During the dune erosion process, waves attacked the dune face and transported dune material offshore to form a beach shape more closely related to equilibrium conditions with the incident wave energy. The steep dune scarp that formed during this process moved onshore with each subsequent wave burst, effectively reducing the volume of sand contained in the sub-aerial dune. Dune volumes were calculated from the 2D profiles as the volume of sand contained above SWL. Both erosion and accretion volumes along the beach and dune profile were calculated with respect to the initial profile.

The initial and final profiles for tests PD0 and PD1 are summarized in Figure 4.10. Considerable erosion occurred at the seaward dune face and was deposited in the nearshore, forming a sand bar in the process. The seabale did successfully brace the dune scarp, reducing dune scarp retreat caused by wave attack by 5 cm. However, this bracing of the dune scarp seemed to have encouraged scouring underneath the seabale, resulting in no difference in total dune erosion between the two trials. PD0 showed total erosion of $9,310\ cm^3$ and PD1 total erosion was measured to be $9,233\ cm^3$ compared with the initial plane dune profile. Thus, if dune scarp retreat is the most important parameter of concern, seabales placed in a plane dune may provide increased performance even if the total eroded volume may not be modified significantly. However, with other geometric variations and seabale placement configurations, better results can be obtained.

The initial and final profiles for tests BD0 and BD1 are summarized in Figure 4.11. Again, a

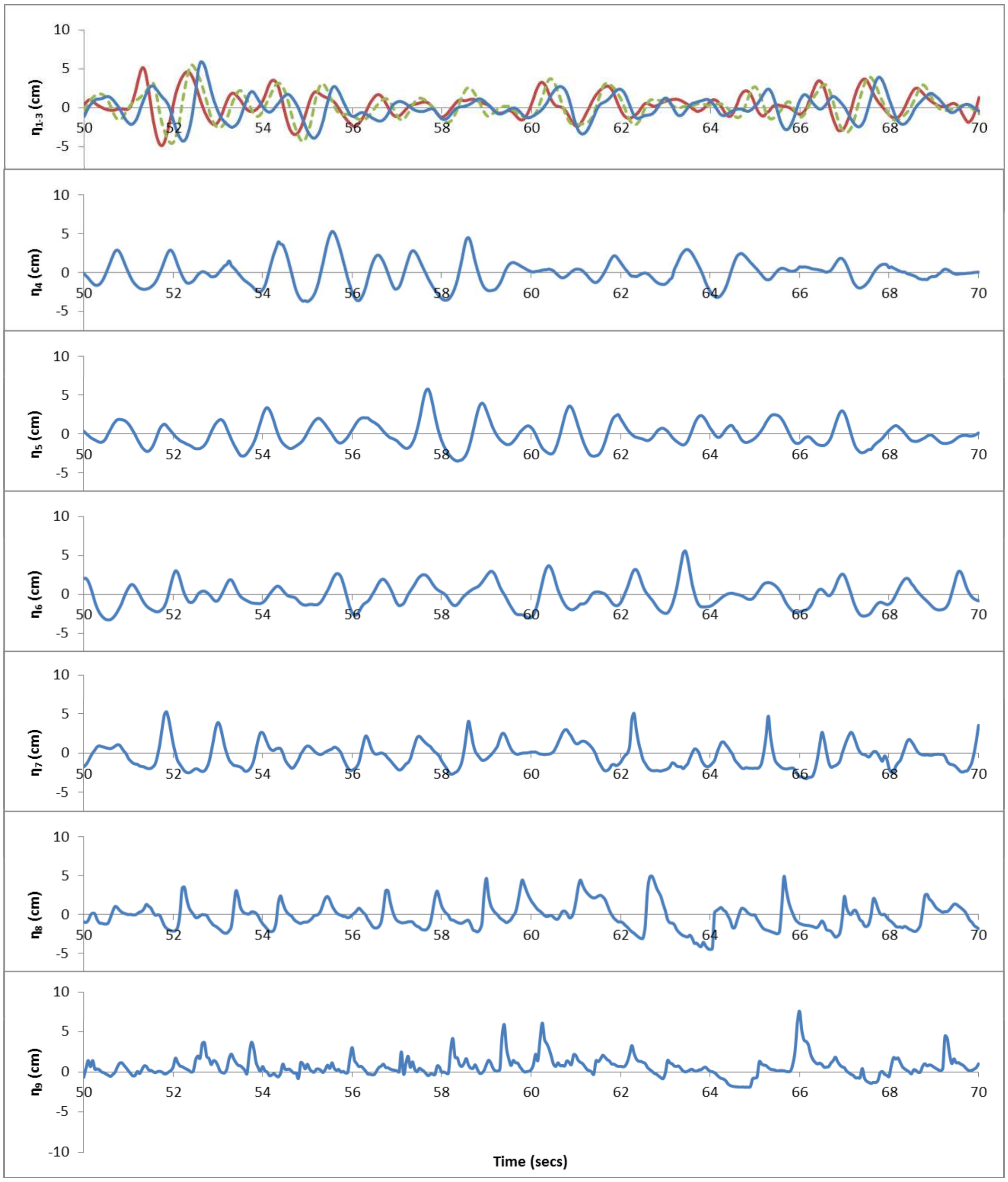

Figure 4.9: *Measured timeseries of wave flume free surface elevation η (twenty second window). Gage records for WG1-3 are shown together in the top panel where η_1 is depicted with a blue solid line, η_2 is shown as a dashed green line, and η_3 is represented by a red solid line. WG4-9 records are shown in individual panels, respectively.*

large amount of erosion occurred at the seaward dune face and was deposited in the nearshore during the profile equilibration process. For this trial, the artificial seabale core did reduce total dune erosion by nearly 10%. Total eroded volume for BD0 was $13,952\ cm^3$ whereas BD1

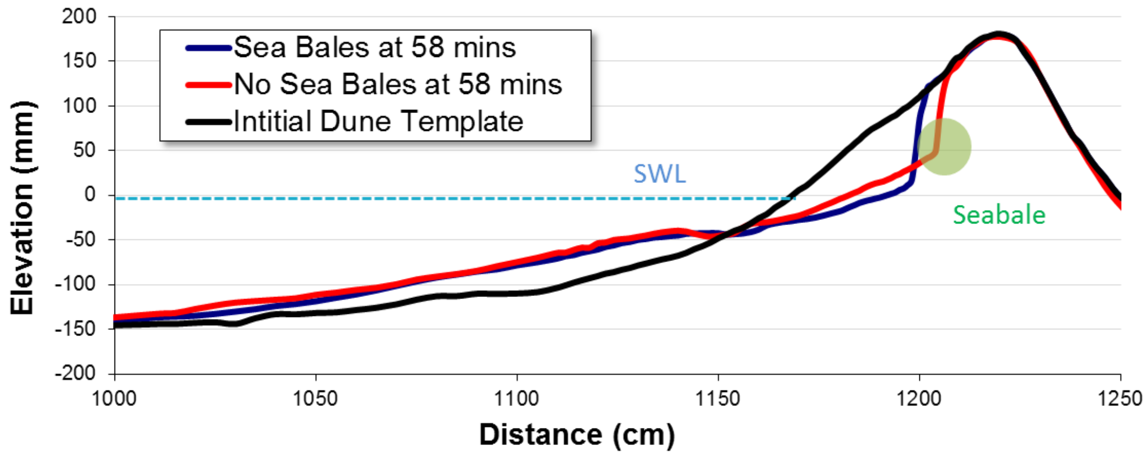

Figure 4.10: *Measured initial and final profiles for the plane dune test without (PD0) and with (PD1) artificial seabales.*

ended up with a total eroded volume of only $12,654\ cm^3$. This indicates that a seabale core placed in a sacrificial dune with berm can aid in dissipating wave energy and thus reducing the overall erosion of the dune. These results confirm the validity of initial choice of geometry and seabale placement for the prototype field dune.

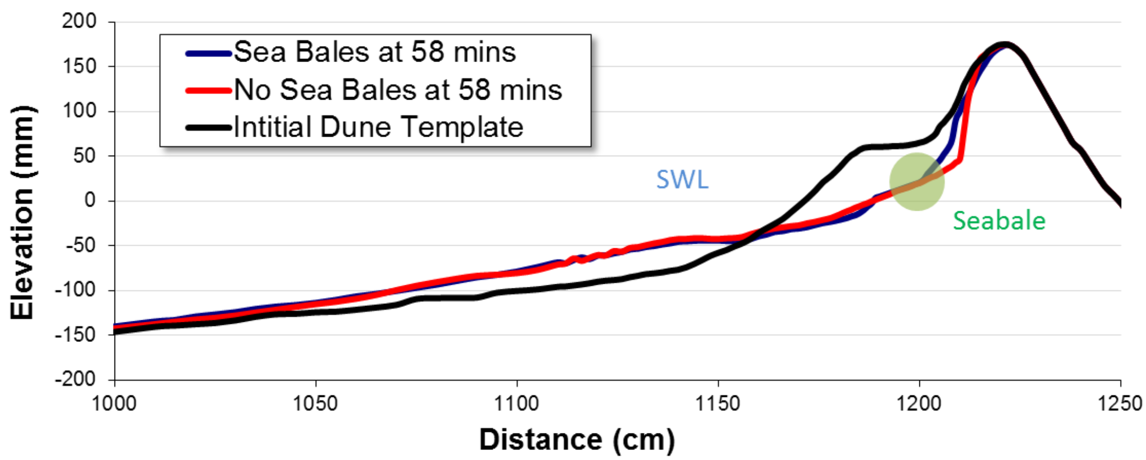

Figure 4.11: *Measured initial and final profiles for the bermed dune test without (BD0) and with (BD1) seabales.*

Chapter 5

Conclusions

The pilot field project presented in this report was the first ever to investigate the feasibility of using compacted Sargassum wrack material as core enhancement for newly built coastal sand dunes. An $800-ft$ prototype test dune was constructed above the high tide line on Galveston Island's East End (Apffel Park) and monitored for about one year. Monitoring included quarterly beach and dune profiles, sediment and vegetation sampling, as well as penetrometer testing and video capture. Four dune segments with different combinations of seabale core and initial vegetation planting were compared side by side. Seabales were produced from locally sourced washed-up Sargassum wrack material which arrived in large quantities in the Summer of 2014. The wrack material was loaded into a vertical-style compacter and compacted to form dense individual seabales with a volume of about 12.5 ft^3 each. A single row of these seabales was incorporated into the berm of two of the four dune segments making up the prototype dune. In addition, physical model tests using a moveable-bed wave flume were conducted to investigate the impact of seabale-enhanced dune cores on wave-induced dune erosion. For this purpose scaled-down sand dunes were built inside a wave tank and subjected to irregular wave trains. Using artificial seaweed material, various dune geometries and seabale placement options were investigated in light of their effects on erosion progression.

Results from both the field prototype study and the laboratory experiment showed that seabale-enhanced coastal dunes can provide superior resistance against erosion when compared with their counterparts without seabales. This became apparent in the physical model wave flume experiments and also in the analysis of tropical storm Bill impact on the prototype field dune. The benefits of seabales became especially apparent when combined with proper vegetation planting strategies. Vegetated dunes including seabales were able to develop strong root systems quicker than their counterparts without seabale cores. This may be in part linked to the moisture-retaining capabilities of the seabales and the time-release nutrient provision to the plants, making them more resistant to drought and nutrient shortage. The abundant dune vegetation supported by the seabales also captured a significant amount of wind-blown sediment which aided in fortification of the dune and continued accretion.

Constructing and restoring dunes with seabale cores provides a new beach management option for Texas coastal areas. Specifically after large single Sargassum landings the process of compacting the wrack material and incorporating it into dunes provides both short-term (order of days and months) and long-term (order of years and longer) benefits. These benefits are listed in the following.

Short-Term Benefits:

- Removal of Sargassum wrack from the water line
- Unobstructed access for tourists and residents to the water
- Reduction of odor caused by decomposing trapped organic matter
- Reduction of Sargassum volume through compaction
- Increase in erosion resistance of dunes via dense, wave-energy absorbing seabales

Long-Term Benefits:

- Spurring of vegetation growth and vegetation health through moisture retention and nutrient time-release by the decomposing seabales
- Growth of dunes through repeated application of the process via increased plant mass and capture of wind-blown sediment
- Increase in dune resilience against erosion via improved plant root densities

The Galveston barrier island and its beach-dune system protect lives and property. They are part of a critical natural resource area and provide vital protection to the bay and mainland against storm surge and wave attack. Houses and businesses located on the island behind the dune system are at high risk to be damaged or destroyed during an extreme event. Hurricane Ike's impact on the upper Texas coast forcefully demonstrated this fact. A healthy beach-dune system is the most economic and the most natural protection against extreme events. The key is to optimize dune restoration, keeping in mind local regulations, various stakeholder objectives and available material. Since sand is scarce on most parts of Galveston Island, the additional Sargassum material represents an innovative approach to reduce erosion and grow much needed coastal dunes. It is our intent that this concept can be applied to many other potential sites along the Texas coast (e.g. Galveston sea wall, Galveston west end, Bolivar Peninsula, etc.). Future work will investigate the feasibility of continued application of seabales to grow and revitalize existing dunes and on the possibility of automating the Sargassum collection and baling process.

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