COASTAL DUNES AND DUNE VEGETATION: INTERDISCIPLINARY RESEARCH ON STORM PROTECTION, EROSION, AND ECOSYSTEM RESTORATION

A Dissertation
by
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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

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August 2017

Major Subject: Marine Biology

ABSTRACT

Coastal dunes offer many communities around the world a means to naturally mitigate the damage caused by coastal storms. This dissertation will address some of the knowledge gaps concerning the cost effectiveness of dunes in terms of storm damage mitigation, the role of dune vegetation in erosion resistance during storm surges, and the best techniques for restoring dune vegetation. To determine dune storm damage mitigation value, Hurricane Ike FEMA insurance claims for over one thousand homes in Galveston County, Texas were analyzed (multivariate regression) with respect to the size of the dunes protecting those homes. The dunes in this area provided over 8 million dollars in protection across the study area during Hurricane Ike. Dunes were generally cost effective (>$50 of damage mitigation per cubic meter of dune sediment) and were a viable hazard mitigation strategy. With regards to dune vegetation's role in erosion resistance, the effects of different plant features and species on swash hydrodynamics, sediment properties, and erosion was evaluated utilizing multivariate regression and a simulated storm surge/wave attack within a wave flume. Aboveground plant surface area was significantly related to decreased swash flow velocity, turbulent kinetic energy, and wave reflection while fine root biomass density was significantly related to increased sediment shear strength. These results indicated that both above- and belowground features of plants play a role in reducing dune erosion during storm surges. Lastly, a variety of dune restoration techniques and the broader ramifications of planting vegetation on dune biogeomorphology were evaluated to identify effective dune restoration practices for the Texas Coast. *Sargassum* baling, useful for transporting the nuisance seaweed from beaches, was minimally impactful on plant growth while using rooted plants and native mycorrhizal fungal inoculations generally increased the accumulation of plant biomass. Dune vegetation planting also initially promoted accretion but lowered plant diversity compared to a naturally colonized dune. The research detailed in this dissertation contributes to the growing body of knowledge concerning engineering with nature and provides additional support for the integration of coastal dune restoration into sustainable coastal hazard mitigation strategies.

ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Armitage, my committee co-chair, Dr. Figlus, and my committee members, Dr. Crawford and Dr. Feagin for their guidance and support throughout the course of this research.

Thanks also to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I want to also thank Matt Power, Katie Bowers, Carolyn Weaver, Rebekkah Bergren, Allison Rathert, Deidra Dittmer, Mick Prouse, and Cory Tyler for helping me in the wave flume laboratory, processing samples, watering plants, conducting elevation surveys, and planting vegetation during the dune restoration project. Thanks also to Dr. Highfield for his contributions to Chapter 2 and his advice on spatial data analysis. I am also very appreciative of the support provided to me by my wife and family during my doctoral program.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a dissertation committee consisting of Professor Armitage (advisor) of the Department of Marine Biology, Professor Figlus (co-advisor) of the Department of Ocean Engineering, Professor Crawford of the Department of Biology and Biochemistry at the University of Houston, and Professor Feagin of the Department of Ecosystem Science and Management.

Some of the data analyzed for Chapter 2 was provided by Professor Highfield of the Department of Marine Sciences. Dr. Highfield also helped edit and advise the research in Chapter 2 for publication.

All other work conducted for this dissertation was completed by the student independently.

Funding Sources

Graduate study was supported by fellowships, teaching assistantships, and research grants from the Department of Marine Biology at Texas A&M University and research assistantships from the Texas General Land Office and Texas Sea Grant. Travel funding was also supported by the American Shore and Beach Preservation Association.

TABLE OF CONTENTS

Page

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

1. INTRODUCTION TO COASTAL SAND DUNES AND NATURE-BASED STORM DAMAGE MITIGATION

Hurricanes and tropical storms cause substantial damage to coastal communities and ecosystems worldwide. Storm surges (massive increases in water levels) flood neighborhoods and storm waves destroy homes and infrastructure in coastal areas, causing massive economic losses. In the United States alone, hurricanes and tropical storms have caused roughly $10 billion per year (normalized) in economic damage over the last century (Pielke *et al.*, 2008) and will likely trend upwards in the future. Over the last 15 years, largely due to continuous coastal development and population growth, hurricane damage in the US exceeded 26 billion dollars per year (Blake *et al.*, 2011). Loss of life is also a common occurrence during these storms due to extreme flooding and wind conditions, particularly in poorer communities (Gemenne, 2010; Pèrez-Maqueo *et al.*, 2007). Furthermore, social crises can result from refugee evacuations from flooded areas (Gemenne, 2010). Lastly, flooding, barrier island breaching, wave attack, and salt water intrusion can cause extensive damage to coastal ecosystems (Williams *et al.*, 2009) which humans depend on for subsistence and recreation. Sea level rise will further exacerbate hurricane damage, causing storm surges to propagate further inland while simultaneously forcing the retreat of coastal ecosystems which serve as a natural buffer for coastal communities.

Mitigating the damage of hurricanes and tropical storms will undoubtedly be one of the great challenges of the next century. Many different approaches can be taken to address this problem, ranging from building regulations to sea walls to extensive evacuation plans. One approach that has gained traction recently is "engineering with nature", or the restoration and maintenance of various coastal ecosystems which can function as a sustainable means to mitigate storm damage (Costanza & Farley, 2007). The benefits of nature-based approaches are far reaching; extending beyond storm protection to encompass other services such as nursery grounds for recreational and commercial fisheries (Boesch & Turner, 1984), habitat for wildlife and endangered species (Maslo *et al.*, 2012), tourism and recreation (Everard *et al.*, 2010), carbon sequestration (Mcleod *et al.*, 2011), accretion and erosion control(Gedan *et al.*, 2011), and water filtration (Shapiro *et al.*, 2010). Coastal sand dunes are one such ecosystem which offer numerous services in conjunction with storm protection for homes and infrastructure adjacent to beaches. However, substantial knowledge gaps exist with regards to restoring, constructing, and maintaining coastal dunes as an effective means of storm protection. This dissertation will fill some of these knowledge gaps through interdisciplinary research and will provide an outlook for future research.

The first knowledge gap that will be addressed is that the direct storm damage mitigation value for coastal dune ecosystems has not yet been quantified based on real storm damage data. Some studies have done alternative cost analyses for coastal dunes (Barbier, 2007; Taylor, 2014), or the cost to replace large dune systems with sea walls, but such analyses lack a direct link to actual storm damage data. Alternative cost assessments also fail to characterize whether dunes possess value even when they are breached. In other words, a sizable dune that resists breaching during an extreme storm event essentially functions like a large seawall from the perspective of storm damage mitigation (alternative cost assessment). However, a smaller dune that is breached would likely still buffer homes in some capacity, but this buffer value cannot be analyzed using an alternative cost assessment. In Chapter 2 of this dissertation, a novel, multivariate regression analysis of coastal dunes and home damage will be used to evaluate the worth of dunes using real storm damage claim data.

Another knowledge gap exists with regards to the active role that vegetation could play in coastal dune erosion resistance and protection capabilities during storm surges and wave attacks. Vegetation attenuates wave energy, reduces flow velocity, and lessens erosion in other coastal ecosystems (Gedan *et al.*, 2011); will it do the same for coastal dunes under surge and wave conditions during a storm? Chapter 3 of this dissertation will explore these concepts in a wave flume experiment, focusing on what biological aspects of plants are crucial in this process and what specific physical sediment and hydrodynamic processes plants modify. Knowledge of these biophysical mechanisms could help inform dune restoration and management strategies.

Lastly, restoring and constructing dunes can have inconsistent results and often lack tangible techniques, guidelines and goals with the specific aim of creating a buffer capable of resisting erosion. Coastal dunes can be harsh environments and dune restoration success can be limited by the physical stresses of the habitat. Chapter 4 evaluates the effects of various dune restoration techniques on dune transplant growth and survival. Beyond transplant growth and survival, the purpose of dune restoration is generally to circumvent the slow ecological and geomorphological succession mechanisms that produce a stable, vegetated dune system. Chapter 5, as part of the same research project as Chapter 4, will examine the biogeomorphological evolution of a planted dune compared to a naturally colonizing dune. This biogeomorphological monitoring will seek to inform dune restoration guidelines on the potential tradeoffs that may occur when succession is circumvented by vegetation planting. All four of these chapters relate to coastal sand dune storm damage mitigation but will have their own background information, methods, results, and discussion sections. This interdisciplinary dissertation will incorporate methodologies and topics from multiple scientific fields (*e.g.* ecology, engineering, economics) to further develop the implementation of coastal sand dunes in hazard mitigation strategies.

2. THE ECONOMIC VALUE OF COASTAL VEGETATED DUNE PROTECTION: A MULTIVARIATE, GIS-BASED ANALYSIS OF HURRICANE IKE [1]

2.1 Background Information

2.1.1 The Challenge of Coastal Protection

Hurricanes and tropical storms inflict a massive economic and social strain on coastal communities worldwide. Much of this damage is concentrated in coastal areas adjacent to water where storm surges flood neighborhoods and large waves pummel homes and infrastructure. Coastal barriers and other structural flood mitigation strategies (*e.g.*, sea walls, levees, rock revetments) can reduce the economic damage for these areas, though often with large financial and environmental costs (Long *et al.*, 2011; Pilkey & Wright, 1988). Due to these large costs, nature-based solutions to storm damage have been sought in coastal planning (Costanza *et al.*, 2006). Such solutions offer multiple benefits, such as tourism and recreation, accretion, and erosion control in conjunction with storm protection. However, there are limitations with nature-based approaches and it is important to approach these limitations in an honest and frank manner. The purpose of this chapter of the dissertation is to explore the storm protection benefits and limitations of one such ecosystem: vegetated coastal sand dunes.

Dunes form a sharp contrast with hard-structures in terms of storm protection and this contrast drives not only the critical areas of research needed for dunes but also the shape of public discourse regarding investment in dunes. Dunes form a much more dissipative surface than seawalls and other hard structures (West, 2014). In dune systems, wave energy is mainly dispersed rather than violently reflected, reducing scouring and erosion on beaches during wave contact. This scouring effect can cause large amounts of erosion at the base of seawalls, making the long-term retention

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[1] Author's Note on Copyright: Much of the material in this chapter has been accepted for publication in the Journal of Coastal Research in 2016 under the title, "The Effects of Coastal Dune Volume and Vegetation on Storm-Induced Property Damage: Analysis from Hurricane Ike". For referencing, please cite that publication instead of or in conjunction with this dissertation. The Journal of Coastal Research publication should be considered the original source for the figures and statistical models described in this chapter (see references for publication info).

of beach sediment difficult to maintain even in the wake of small storms. Additionally, incoming waves which approach the shoreline at a non-perpendicular angle can be deflected off the seawall to erode nearby shorelines, particularly at the seawall's corners. With sea level rise also threatening coastal areas worldwide (Rahmstorf, 2007), these issues only worsen and the long-term sustainability of beaches in front of sea walls is questionable. In front of the Galveston Seawall, beach nourishment projects totaling in the tens of millions of dollars each year are already taking place (Bassett, 2016; Rice, 2014). Beaches are an enormous tourism industry for many coastal communities, meaning that implementation of sea walls to protect beach communities may undermine the beach community's economic means of subsistence.

In contrast, dunes come in many different forms, shapes, and sizes, but generally are not as reliable as seawall in terms of shoreline protection. Dunes can generally be grouped into two main categories: engineered and naturally forming. Because dune erosion and overtopping can be quite accurately numerically modeled (Roelvink *et al.*, 2009), engineered dune levees can in concept be designed to withstand a particular storm scenario. However, in many areas, a lack of funding or sediment for engineering projects leaves dunes vulnerable to breach by surge and waves (Stockdon *et al.*, 2009). Naturally forming coastal dunes are made by windblown sediments typically trapped by vegetation. Depending on the sediment supply and prevailing winds for an area, natural dunes can be quite large or small (Luna *et al.*, 2011). In many developed shorelines, the constriction caused by shoreline retreat and sea level rise on the seaward side of dune systems and home construction on the landward side prevents adequate space for natural dune fields to form. In either case, engineered or natural, dunes would need to be larger, both in height and cross-shore width, than a sea wall in order to resist a comparable extreme storm scenario (Taylor, 2014). This discrepancy in protection is caused by dune sediment eroding to the point of breach during a storm. In contrast, a seawall represents an immovable object under almost all storm scenarios. Additionally, once the storm has passed, dunes need to be rebuilt, either by natural means of accretion or by shipping in sediment, the latter of which can be expensive.

Government policy falls in alignment with this outlook on dunes. Often after storms, dunes are observed to be destroyed and breached (Williams *et al.*, 2009), raising the question of whether they offer any meaningful protection against storms. Dunes which are not large enough to resist breaching are not officially recognized as mitigating storm damage by FEMA (Federal Emergency Management Agency (FEMA), 1988), the agency responsible for dictating flood insurance policies. FEMA policy states that unless homes are buffered by a dune with a 540 ft^2 cross sectional area (50.2 m^2) above the 100 year flood level (the "540" value was obtained by quantifying dune erosion for various storms), the dunes will not be considered as an effective barrier to the surge. For the Texas Coast during Hurricane Ike, no dunes, whether engineered or natural, fit this criteria as the average dune ridge height was 2.6 m above sea level (NAVD88) while storm surge heights ranged from 3.5 m to 5 m above sea level (Houston and Galveston Texas Forecast Office, 2008; Sebastian *et al.*, 2014). Were the dunes on Texas Coast, despite being small and not "designed" to withstand Hurricane Ike, worthless? This chapter will explore this topic by examining patterns of storm damage caused by Hurricane Ike, making a case for a more nuanced view of dunes and storm protection.

2.1.2 A Conceptual Framework for Dune Storm Surge Resistance

There are various mechanisms by which a small/breached dune could still offer protection to landward homes and infrastructure during a storm. It is imperative that these mechanisms be understood in that they determine what aspects of a dune could be altered to improve storm resistance. When a storm approaches a shoreline, it brings a storm surge that is mainly generated by wind pushing against a body of water. The surge brings water into contact with landward structures (dunes, homes, roads, etc.) but also exposes these structures to massive wind generated waves. When dunes are present, waves collide with the seaward dune face or overtop the dune entirely depending on surge and wave heights (Donnelly *et al.*, 2006). An example of this wave collision scenario is visualized in Figure 2.1. In such a scenario, waves first impact the dune system and sediment is eroded from the dune face. Sediment is transported offshore by storm waves and may create a submerged bar feature and elevated off-shore profile that causes waves to break and dissipate their energy further away from the shoreline (Figure 2.1, Panel A + B). After continuous wave collision (Figure 2.1, Panel C), the dune is breached and landward homes are exposed to waves and currents. However, because the coastline was extensively modified by the eroding dune, wave energy reaching residential areas is substantially reduced. Furthermore, the time it took for the dune to breach was a reduction in the time that landward properties were exposed to hazardous conditions.

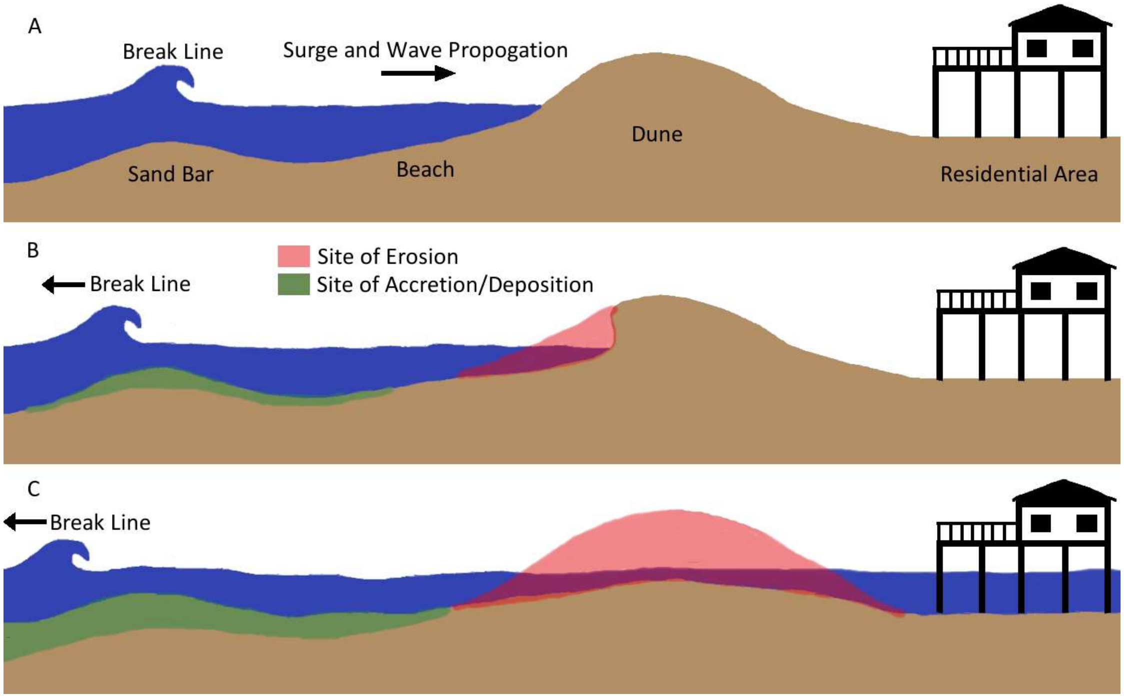

Figure 2.1: A cross-shore diagram for dune erosion and protection during a severe storm. During the course of the storm, sediment is eroded from the dune face and carried offshore. Deposition of carried sediment can create an enlarged bar feature, modifying the shoreline to a more dissipative state with regards to incoming wave energy.

Following this conceptual framework, there would be two main features of a dune that would influence it's protective capabilities: geometry and texture. The geometry of a dune, both size and shape, influences the way it erodes during a wave collision scenario with size as the principal component. In general, a larger dune serves as a larger buffer containing a higher volume of sediment and taking longer to erode. The additional time that a larger dune takes to erode means a reduction of wave exposure to landward homes. Furthermore, a larger amount of eroded sediment would be deposited into the near-shore zone, creating a larger sand bar which would dissipate more wave energy. The second feature can broadly be defined as texture, which can be further broken down in two main components: surface roughness and sediment composition. The surface roughness of the dune in mainly determined by structural features on the dunes, which, in the case of most dunes, are predominately dune vegetation. Vegetation may dissipate the energy of incoming storm waves and swashes, reducing the rate of erosion similar to what has been found in laboratory conditions (Chapter 3 will feature an extensive review of this topic). With regards to sediment composition, grain size is the dominant factor. The grain size of the material that composes a dune influences how it behaves during water-based erosion events with finer sand being more easily entrained and carried away by moving water. Sandy soils are also prone to slumping and sliding which can take place on the dune face during wave attack. Plants can also play a role in these two areas. Roots can reinforce soils, improving soil strength and reducing its tendency to slump. Plants roots and their associated microbial communities can bind soil particles together, effectively increasing the average grain size of the sediment (reducing surface area to mass ratios) and making the sediment more resistant to erosion. Both a dune's volume and the amount of vegetation growing on it are therefore likely determinants of a dune's protective capabilities.

2.1.3 Modeling Dune Value

If the conceptual framework laid out in the previous paragraphs were correct, it would be expected that homes behind larger or more vegetated dunes would sustain less damage. In concept, this relationship could be modeled for a storm-damaged coastline if there was variation in both dune parameters and storm damage to homes. However, there would be other variables that could also influence home storm damage. These variables broadly break into geographic and build categories. Primary geographic variables can further be reduced to home proximity to shoreline and home proximity to the storm's path. Homes further from the shoreline generally would experience reduce wave energy and flow velocities due to dissipation across the greater distance. Areas further from a storm's path experience reduced surge and wave heights (Sebastian *et al.*, 2014), hence it would be expected that homes further from the storm's path would experience less damage.

Built variables impacting home damage would be those that impact a home's ability to resist storm damage. A home's age (the time elapsed since construction) could be a useful predictor as older homes are made of more deteriorated materials, potentially leaving them more vulnerable to collapse. Additionally, over time building codes for the Galveston area have generally dictated that homes be built with higher base elevations for stilted homes (Tanner *et al.*, 2009), meaning many older homes have lower base elevations and increased vulnerability to surge and waves. Home value could also be a meaningful predictor for sustained storm damage. More expensive homes are of higher risk of monetary damage simply because they are worth more. Conversely, more expensive homes could also be built to a higher structural standard and be less susceptible to damage. The objective of this chapter was to use a multivariate regression analysis to model storm damage by all of the following variables: dune volume, dune vegetation area, home distance from the shoreline and from a storm's path, home age, and home value. This model would not only provide insights into the conceptual framework by which dunes mitigate damage but also determine the storm damage mitigation value for coastal dunes. Understanding this mitigation value is essential to implementing dunes in coastal protection strategies.

2.2 Methods

2.2.1 Area of Study

Hurricane Ike made landfall on September 10, 2008 between Galveston Island (hereafter referred to as Galveston) and Bolivar Peninsula (hereafter referred to as Bolivar) on the Texas Coast (Figure 2.2). It was an uncharacteristically broad category 2 storm with at least some surge encountered along the majority of the Gulf of Mexico shorelines. It directly caused 12 fatalities in the US and roughly 27.5 billion USD in damages to the Texas and Louisiana coastlines (Berg, 2009; DeBlasio, 2008). Offshore significant wave heights ($H_{1/3}$) up to six meters were recorded by NOAA buoys moored off the Texas Coast (Doran *et al.*, 2009). The east side of the hurricane impacted Bolivar and had higher wind speeds and more severe surge and wave conditions. This increased severity is in part due to counterclockwise rotation of the hurricane wind field with predominantly onshore directed winds east of the eye and offshore directed winds west of the eye at landfall. Sustained wind speeds on Bolivar were between 130-148 km/h while on the west end of Galveston sustained wind speeds were between 120-130 km/h (Overpeck, 2009). The surge impacting Bolivar was roughly one third higher than the surge for Galveston (3.5 meters at the west end of Galveston and nearly 5 meters in Bolivar) (Houston and Galveston Texas Forecast Office, 2008; Sebastian *et al.*, 2014). The surge and waves from Hurricane Ike impacted coastal dunes and the many landward structurally elevated communities located on West Galveston Island and Bolivar. The surge also impacted areas of the city of Galveston that were protected by the Galveston Seawall, but these areas are not bordered by any dune structures and therefore were not included in this analysis.

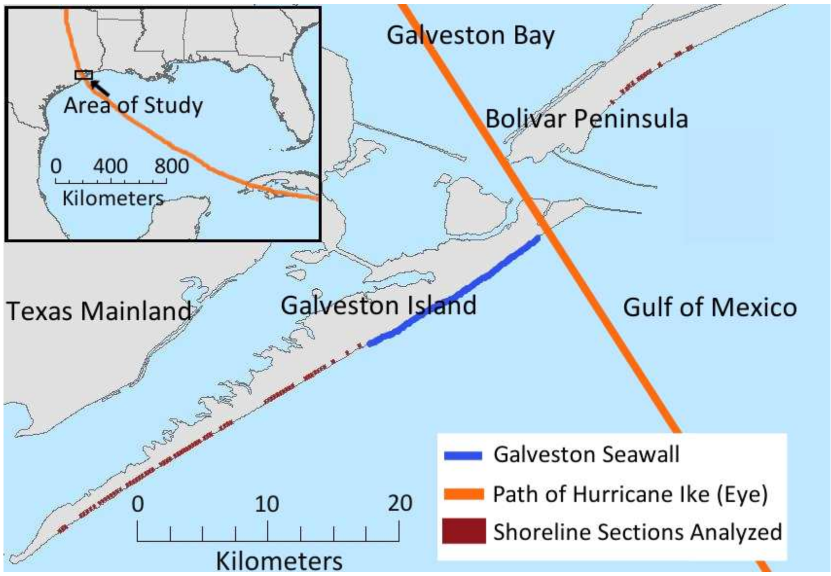

Figure 2.2: Location map of the study area. The path of Hurricane Ike split the regions of Bolivar Peninsula and Galveston Island. Homes that were protected by the Galveston Seawall were not included in this analysis.

2.2.2 GIS setup

ArcMap 10.1 was used for all spatial data development and manipulation. Shoreline blocks were defined as 300 m cross-shore by 200 m along-shore sections; 78 blocks (65 in Galveston and 13 in Bolivar) containing 1,030 homes (878 in Galveston and 152 in Bolivar) were created in total. Blocks were separated by a >40 m buffer to promote independence of samples in different blocks. As homes along the study area were distributed in clusters of small communities, randomizing block locations along the entire stretch of coastline was not practical. Rather, blocks were defined specifically in representative residential areas with the intention of including as many homes as possible for the analysis. Of all potential homes within 300 meters of the water's edge along this stretch of coastline, over 70% were included in this analysis (those excluded fell between gaps in the shoreline blocks). Dune regions within blocks were defined by shoreline slope, which was calculated from LiDAR data using ArcMap's slope function (Figure 2.3). The beach and near-shore along Galveston and Bolivar have very shallow slopes, ranging between 1/50 to 1/30, typically creating an upward angle between 1.14^o - 1.91^o (Morton & Paine, 1985). Therefore, a spatially-continuous line of topography that exceeded a threshold of 6^o was used to distinguish coastal dunes from the beach and shore (Figure 2.3). The 6^o threshold ensured that all shoreline blocks possessed some dune volume and vegetation quantity, even if they only contained shallow-sloped embryonic dunes.

Several ecological, built-environment, and geographical variables for each block or home were also evaluated for relation to the predicted variable: dollar value of residential structural damage sustained during Hurricane Ike (log transformed). Data on property damage was obtained from National Flood Insurance Program (NFIP) claims from the United States Federal Emergency Management Agency (FEMA) after Hurricane Ike. The ecological predictor variables were dune sediment volume and vegetated area and were determined using 2006 LiDAR data and spectral analysis of 2006 aerial photography (Aerials Express LLC, 2006; Department of Commerce (DOC), National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), and the Office for Coastal Management (OCM), 2007); this process is shown in Figure 2.3. Though these data sources were collected two years prior to Hurricane Ike, they were the temporally closest LiDAR and aerial photography datasets available for the region. Furthermore, there were no major storm events in this two year period prior to Hurricane Ike, meaning that dune parameters were

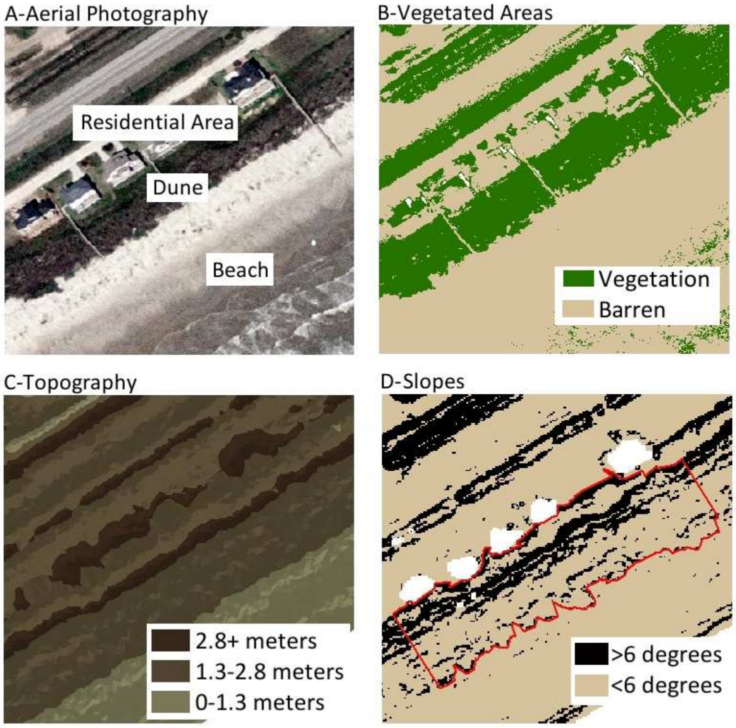

Figure 2.3: Example of a shoreline block used in the multivariate analysis. Panel A shows aerial photography for a section of Galveston Island. A simple spectral threshold was used to differentiate darker vegetation from whitish beach and dune sand. The LiDAR-based topography, shown in Panel C, of the region was used to generate the slope map in Panel D. The red line indicates the boundaries of a 6^o threshold.

unlikely to change drastically. A simple spectral threshold was used for the aerial photography dataset to distinguish vegetated areas from whitish sand. Minor interference can be seen on some darker rooftops and out in the surf zone (Panel C of Figure 2.3), but such areas were manually excluded from the dune boundaries. These ecological variables were then quantified for each shoreline block, resulting in a quantitative measurement for dune size which could be used in multivariate analysis (Figure 2.4). The built predictor variables of home structure value and age were obtained from the Galveston County Appraisal District. The geographic predictor variables were home distance from the shoreline and from the eye of Hurricane Ike at landfall and were calculated in ArcMap 10.1.

Figure 2.4: All ecological variables are summarized in this diagram (the red line denotes the slope threshold, green is the location of vegetation along the dune topography).

2.2.3 Statistical Analysis

A robust-clustered, stepwise, backwards, multivariate regression analysis was used to identify significant ecological, built-environment, and geographical predictors of the dollar value of residential structural storm damage. Spatial regression analyses were not used because spatial variables were included in the analysis and no spatial autocorrelation was detected. A Chow test was applied to determine that Galveston and Bolivar should be modeled separately because surge, wave, and wind conditions were different for each area. It is likely that dunes reduce surge and wave damage to homes within close proximity of the shoreline, but it is not known how far away from a shoreline this protection extends. Therefore, multiple Chow tests were also used to assess if different quartile zones of Galveston, organized by distance from the shoreline, could be modeled separately. This provided insight into which homes were most impacted by dunes and the limit of a dune's landward influence across a coastline. Bolivar was not divided into quartile shoreline zones because it had fewer homes (152) and blocks (13) compared to Galveston (878, 65). Lastly, hierarchal partitioning, a statistical technique which evaluates each predictor variable's average independent contribution to R^2 based off every possible model (Chevan & Sutherland, 1991; Mac Nally, 1996), was used to identify the variables that explained the most variability in the predicted variable for all models.

The modeling technique used for this analysis contains two distinct sample sizes for different variables. Because dune ecological variables (dune vegetation and volume) could only be quantified by shoreline block, their sample size is the same as the total number of shoreline blocks (65 for Galveston, 13 for Bolivar). To maintain variation among the built and geographic variables (i.e., retain values for each individual home for these variables to maximize the power of the analysis), observations were not aggregated by shoreline block but were analyzed at the level of homes (878 for Galveston and 152 for Bolivar). In other words, each home had a specific value for built (home age and property value) and geographic (shoreline set back distance and distance from the eye of the storm) variables, but shared values with other homes within their block for ecological (dune volume and vegetation area) variables. To compensate for the intra-block correlations and redundancies in the dataset, robust standard errors were clustered by shoreline block (Huber, 1967; Zeileis, 2004).

The value of the dune ecosystems in terms of storm damage mitigation was estimated using the principle of log-linear model semi-elasticity. This technique approximates the average per unit value of dune ecosystem variables based on the derivative of the modelâĂŹs equation with respect to a dune variable (Wooldridge, 2000). However, because the model's semi-elasticity operates at the level of homes, per unit values obtained by this technique were aggregated by shoreline block and averaged (1).

$$DV = \frac{\sum_{n=1}^{n_s}(\sum_{i=1}^{n_{hx}} \beta d * y_{ix})}{n_s} \qquad (1)$$

Where: DV = *The per unit value of a dune variable*

$\beta\ d$ = *Coefficient of a dune variable*

y_{ix} = *Property damage sustained by home i in shoreline block x*

n_{hx} = *The number of homes within shoreline block x*

n_s = *total number of shoreline blocks*

This valuation methodology equates to the average amount of damage reduction brought about by a unit change of a dune variable (*i.e.* adding a cubic meter of sediment or a square meter of vegetation prior to the storm), roughly being the equivalent of the value of investment in dunes.

For the total value of all dunes within the study area, two model states were compared. In the first state, existing pre-storm dune values were used to compute the total expected damage (2).

$$TEPD = \sum_{i=1}^{n} e^{(\beta_1 V_{1i} + \beta_2 V_{2i} + \ \dots \ + \beta_D V_{Di})} \qquad (2)$$

Where: $TEPD$ = *The Total Expected Property Damage*

V_{1i} *is a the value corresponding to a home for the model's first significant predictor variable*

β_1 *corresponds to the slope of the first significant predictor variable of the model*

V_{Di} *is the value of a dune-related variable (e.g. dune vegetation area, sediment volume) for a given home*

β_D *corresponds the slope of dune variable* V_D

n is the total number of homes analyzed

The property damage dataset was log transformed, hence the exponential formulation

In the second state, a model was once again evaluated but with a minimal dune size value rather than the actual value (3).

$$TEPDwD = \sum_{i=1}^{n} e^{(\beta_1 V_{1i} + \beta_2 V_{2i} + \ \dots \ + \beta_D V_{Dm})} \qquad (3)$$

Where: *TEPDwD = Total Expected Property Damage without Dunes*
V_{Dm} *is the minimal dune value for the study area*

The difference between these two states is the predicted total damage mitigated by the presence of dunes for the study area (4).

$$Total\ Storm\ Mitigation\ Value\ of\ Dunes = TMV = TEPDwD - TEPD \qquad (4)$$

In other words, if all dunes had been removed (or reduced to a minimal state) prior to the storm, how much more damage would have been sustained? This value could then be divided by the total number of homes for an estimate of dune worth to the average homeowner. All dollar values mentioned throughout this paper were converted to 2015 US Dollars (using the Bureau of Labor Statistics Consumer Price Index Inflation Calculator).

2.3 Results

The dataset resulting from this analyses required multiple models to be summarized. First, a Chow Test indicated that a structural break in the dataset occurred along the lines of East/West orientation to the eye of Hurricane Ike (Chow Test $p < 0.001$). Additionally, dune vegetation area and dune sediment volume were highly collinear (Figure 2.5). Therefore, for the purpose of modeling and value calculations, these dune variables were modeled separately. This created four distinct models for all homes in the dataset, every combination of Galveston (West of Storm) and Bolivar (East of the Storm) modeled by dune sediment volume and dune vegetation areas. Furthermore, Chow Test for different shoreline quartile zones for Galveston revealed that all shoreline zones, apart from the two nearest to the shoreline, can be modeled separately (Table 2.1). This outcome created a need for three additional models for each distinct zone, which were not separated by volume and vegetation because these models were not needed for value estimations (rather, these shoreline zone models were important for determining the relative importance of dunes for each region). The four models separated by Galveston/Bolivar and volume/vegetation will be summarized in the next section while the three shoreline zone models will be summarized in the section after that.

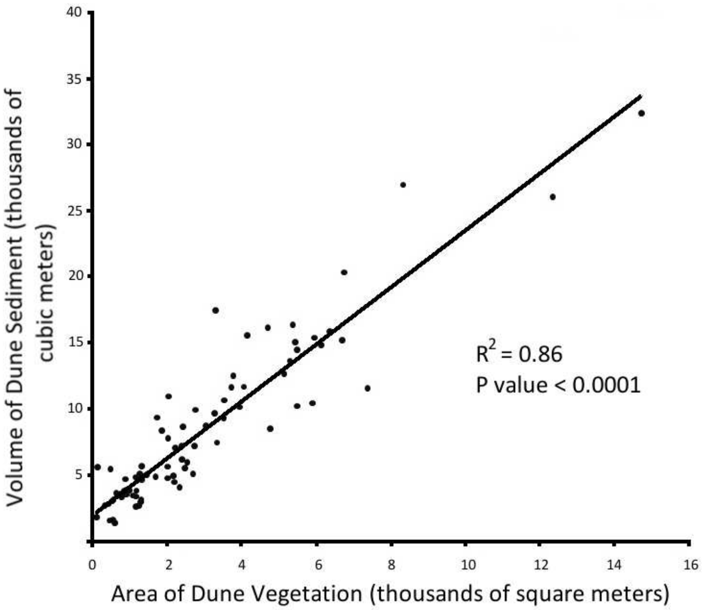

Figure 2.5: The variables of dune vegetation area and dune sediment volume were collinear.

Table 2.1: Chow test p-values for Galveston shore quartiles

	Shoreline Quartile 2	Shoreline Quartile 3	Shoreline Quartile 4
Shoreline Quartile 1	0.509	< 0.001	< 0.001
Shoreline Quartile 2		0.0118	< 0.001
Shoreline Quartile 3			0.0294

2.3.1 Galveston/Bolivar and Sediment Volume/Vegetation Modeling and Evaluation

The four distinct models for each combinations of Galveston/Bolivar and Sediment Volume/Vegetation are summarized in Table 2.2. Table 2.2 shows the slope coefficient of significant predictor variables as related to the predicted variable: log transformed dollar value of residential structural damage (hereafter, when reference is made to home "damage", it will be in this sense). Significance of a given slope coefficient is noted by asterisk and standard error is noted in parentheses. Negative slopes indicate that sustained flood damage is reduced by an increase of a given variable, the opposite for a positive slope. R^2, AIC, and BIC are reported as goodness of fit measures. Lastly, pie charts indicate each variable's individual percentage contribution to R^2, calculated by hierarchal partitioning (Figure 2.6).

All four multivariate models had a significant negative shoreline distance coefficient, a positive building age coefficient, and a positive home value coefficient. In other words, older, more valuable homes which were closer to the shoreline sustained significantly more damage across the entire study area. In Galveston, both dune vegetation area (Table 2.2, Model 1.1) and sediment volume (Table 2.2, Model 1.2) were significantly ($p < 0.01$) and negatively related to sustained property damage; larger and more vegetated dunes reduced damage. In Bolivar, dune vegetation area (Table 2.2, Model 1.3) and sediment volume (Table 2.2, Model 1.4) were also negatively related to sustained damage, but had higher p values than the Galveston models (5.01E-2 and 0.387, respectively). On average, homes on Bolivar sustained 472.8% more damage during Hurricane Ike than those on Galveston ($146,700 and $25,600, respectively). This occurred despite Bolivar having 12.8% larger dune ridge heights (2.91 m above sea level NADV88 compared to Galveston's 2.58 m above sea level NADV88) and homes being set back 27.1% further from the shoreline on Bolivar (192.5 m from the shoreline for Bolivar, 151.4 m from shoreline for Galveston). The storm surge in Bolivar was, however, more than a meter higher than in Galveston (5 m in Bolivar compared to roughly 3.5 m in Galveston) (Houston and Galveston Texas Forecast Office, 2008; Sebastian *et al.*, 2014). Median home value for Galveston and Bolivar were comparable ($156.7k and $157.6k, respectively, and both datasets were right-skewed) while homes on Bolivar were 38.2% older than on Galveston.

In Table 2.3, the property damage offset values of dune variables are summarized for Models 1.1 - 1.4. The per unit value of dune sediment was 76.6% lower on Bolivar.

Table 2.2: Galveston and Bolivar regression models

	Model 1.1: Galveston (Vegetation)	Model 1.2: Galveston (Vegetation)	Model 1.3: Bolivar (Sediment)	Model 1.4: Bolivar: (Sediment)
Ecological Variables				
Dune Vegetation Area (10^4 m^2)	-4.024** (1.395)	NA	-0.2557† (0.1295)	NA
Dune Sediment Volume (10^4 m^3)	NA	-1.498** (0.5804)	NA	-0.07678 ‡ (0.08142)
Geographic Variables				
Home Distance from Shore (10^2 m)	-1.918*** (0.2014)	-2.005*** (0.1979)	-0.1255† (0.06512)	-0.1485* (0.05714)
Home Distance from Eye of Storm (km)	NS	NS	NS	NS
Built Variables				
Time Since Home Construction (Years)	0.1134*** (0.01365)	0.1324*** (0.01372)	0.01479*** (0.003985)	0.01535*** (0.004123)
Value of Home (Log Transformed)	0.7734** (0.2527)	0.6827** (0.2328)	0.4826*** (0.1166)	0.4854*** (0.1240)
Intercept	-0.3037 (3.036)	1.003 (2.998)	5.725*** (1.387)	5.700*** (1.466)
R^2	0.3269	0.3246	0.3286	0.3168
AIC	4424.61	4427.63	259.459	262.091
BIC	4453.28	4456.29	277.602	280.234
n (total homes)	878	878	152	152
Shoreline Blocks	65	65	13	13

Notes: Values outside parentheses indicate the slope coefficient (values inside parentheses indicate standard error)
**$p \leq 0.001$ **$p \leq 0.01$ *$p \leq 0.05$ †$p \leq 0.1$ ‡ $p = 0.3868$, reported for consistency
NS = p was not significant, variable removed by stepwise
The hierarchal partitioning of variance for these models is summarized in Figure 2.6.

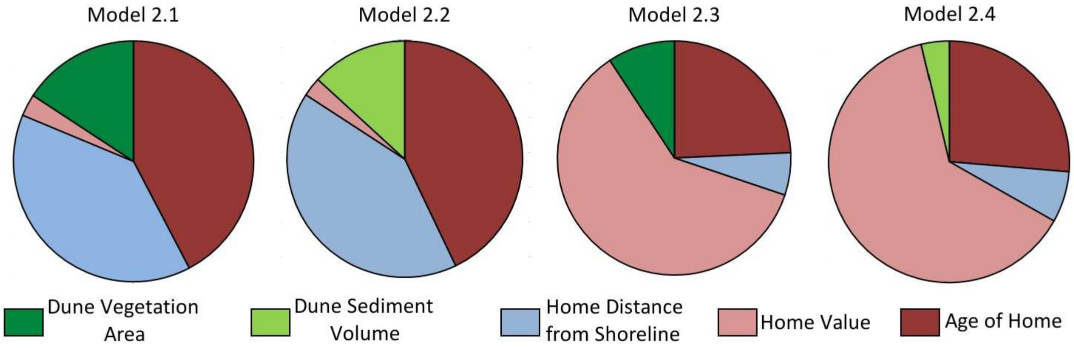

Figure 2.6: Hierarchal partitioning of variance for significant variables for Models 1.1 - 1.4. These pie charts indicate each variable's unique contribution to the model's R^2.

Likewise, the per unit value of dune vegetation was 68.5% lower on Bolivar than in Galveston. The worth per cubic meter of dune sediment for Galveston and Bolivar was mapped by shoreline block in Figure 2.7. Galveston was highly variable in this regard with some areas displaying high dune sediment worth (> \$50 per cubic meter) while others displayed fairly low worth (< \$10 per cubic meter). Bolivar had less spatial variability with worth in different blocks ranging from \$4.20 per cubic meter to \$21.47 per cubic meter. The minimum dune comparison technique described in Equations 2 - 4 estimated the total mitigation value of dunes within the study area was 8.43 million USD. Due to collinearity of dune variables, this total was the average obtained from using vegetation models (Table 2.2, Models 1.1 & 1.3) and sediment models (Table 2.2, Models 1.2 & 1.4). For the average homeowner living in these areas, dunes were worth roughly \$8,200.

Table 2.3: Per unit value in terms of storm protection of dune parameters

Area	Worth per m^3 of Dune Sediment	Worth per m^2 of Dune Vegetation
Galveston	\$51.83	\$139.25
Bolivar	\$12.13	\$43.87

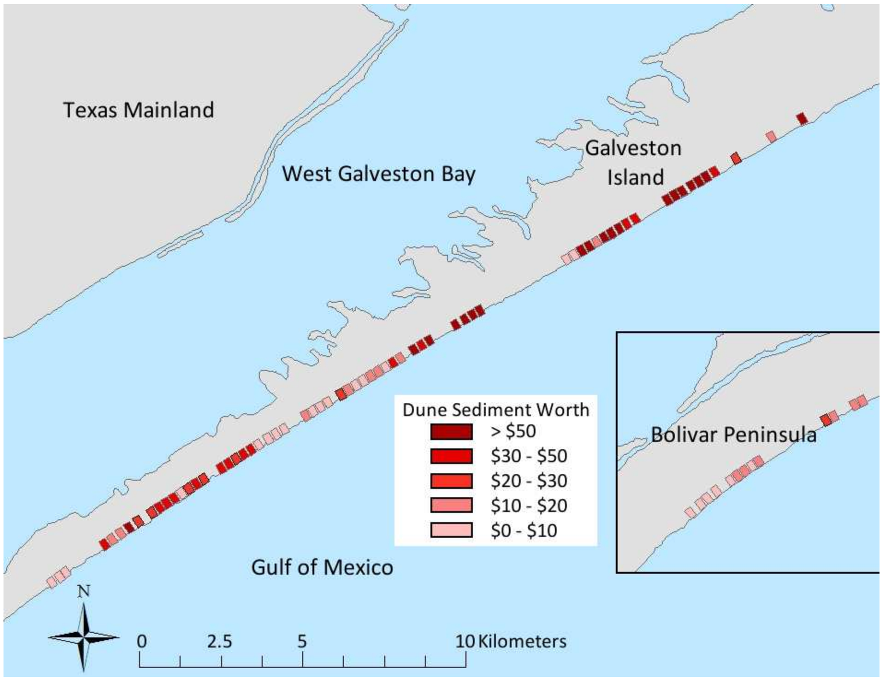

Figure 2.7: The value of dune sediment within each shoreline block is visualized using the Galveston and Bolivar sediment models (Models 1.2 & 1.4) and Equation 1 (without averaging values of different shoreline blocks).

2.3.2 Galveston Modeling by Shoreline Zone

As the cross-shore extent of dune protection was not understood prior to analysis, different Galveston shoreline quartile zones were tested for structural breaks with Chow tests and summarized in Table 2.1. Chow test results indicate that all shoreline zones, apart from the two nearest to the shoreline, can be modeled separately. Table 2.4 shows a summary of these shoreline zone models and Figure 2.8 summarizes the hierarchal partitioning for these models. All three zones had a significant positive building age term, where older buildings sustained more damage. The zone furthest from the shoreline (Table 2.4, Model 1.7) lacked a significant dune related term but was the only model in which the distance from the eye of Hurricane Ike was a significant term, with homes further away from the eye sustaining less damage. Homes in the closest shoreline zone (Table 2.4, Model 1.5) sustained 65.1 % more damage ($42,300 of damage per household) than Galveston as a whole ($25,600), while the middle zone (Model 1.6) sustained 60.6% less damage ($10,100) and the furthest zone (Table 2.4, Model 1.7) sustained 70.3% less damage ($7,600).

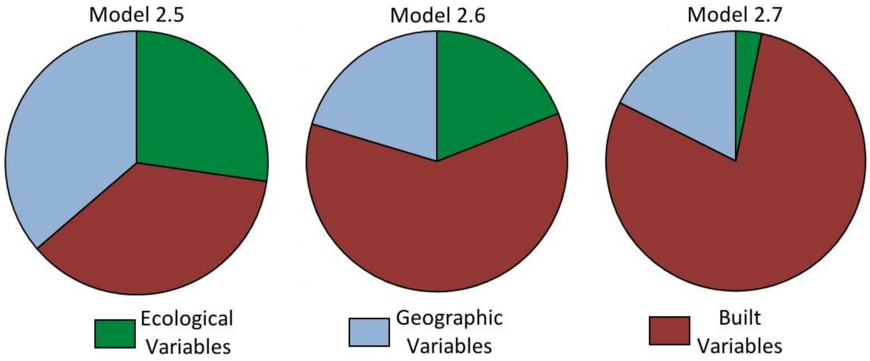

Figure 2.8: Hierarchal partitioning of variance for significant variables for Models 2.5 - 2.7. These pie charts indicate each variable's unique contribution to the model's R^2.

Property damage offset values were significantly related to dune variables, but only in the two zones closest to the shore. The closest zone (Table 2.4, Model 1.5) had a relatively lower *p* value for the dune vegetation area term and the middle zone (Table 2.4, Model 1.6) had a relatively lower *p* value for the dune sediment volume

Table 2.4: Galveston regression models divided by shoreline section

	Model 1.5: Homes 48-135m from Shore	Model 1.6: Homes 136-187m from Shore	Model 1.7: Homes 187-300m from Shore
Ecological Variables			
Dune Vegetation Area (10^4 m^2)	-3.597** (1.244)	NS	NS
Dune Sediment Volume (10^4 m^3)	NS	-1.907* (0.7929)	NS
Geographic Variables			
Home Distance from Shore (10^2 m)	-3.444*** (0.4389)	-4.528** (1.742)	NS
Home Distance from Eye of Storm (km)	NS	NS	-0.09553* (0.03687)
Built Variables			
Time Since Home Construction (Years)	0.05397*** (0.009296)	0.1645*** (0.02752)	0.1273*** (0.01473)
Value of Home (Log Transformed)	NS	1.841*** (0.4863)	NS
Intercept	12.23*** (0.5321)	-10.60 (6.826)	5.870*** (1.190)
R^2	0.2402	0.3225	0.2215
AIC	1945.84	1153.57	1170.18
BIC	1966.28	1173.91	1183.74
n (total homes)	440	219	219
Shoreline Blocks	53	44	37

Notes: Values outside parentheses indicate the slope coefficient (values inside parentheses indicate standard error)

$^{**}p \leq 0.001$ $^{**}p \leq 0.01$ $^{*}p \leq 0.05$ $^{\dagger}p \leq 0.1$

NS = p was not significant, variable removed by stepwise

The hierarchal partitioning of variance for these models is summarized in Figure 2.8

term, hence the step-wise retention of each term in its respective model. Both terms had negative coefficients, indicating that larger and/or more vegetated dunes reduced the dollar value of landward property damage. Hierarchal partitioning indicated that the explanatory power of dunes in mitigating home damage diminished as homes were set back further from the shoreline. In the closest shoreline zone (Table 2.4, Model 1.5), ecological dune variables accounted for 27.3% of the model's explained variation, trailing off to 19.0% for the middle zone (Table 2.4, Model 1.6) and 3.2% for the furthest zone (Table 2.4, Model 1.7). The difference between dune volume and dune vegetation was negligible for all shoreline zones.

Geographic variables showed a similar pattern of diminishing importance for homes set further back from the shoreline. Specifically, the shoreline setback distance decreased in importance (Closest Zone Model 1.5: 34.8%, Middle Zone Model 1.6: 8.0%, Furthest Zone Model 1.7: 0.4%) while the distance of a home from the eye of the storm increased in importance (Closest-Zone Model 1.5: 1.5%, Middle-Zone Model 1.6: 12.4%, Furthest-Zone Model 1.7: 17.1%). Built variables show the opposite pattern, becoming more important for homes further from the shoreline. For the built category, building age was the dominant variable impacting sustained damage across all shoreline zones.

2.4 Discussion

2.4.1 Model Summaries and Applications

This study presents evidence that coastal sand dune ecosystems have significant and meaningful economic value when it comes to storm protection. Both dune vegetation and sediment variables showed a negative relationship with property damage, though these predictor variables were collinear (Figure 2.5). This collinearity could have been caused by a variety of factors. First, the cross-shore width of a dune field largely determines each of the variables (all dune regions had the same along-shore length). When the cross-shore width is larger, there is both a larger potential area for vegetation growth and a larger area component for the sediment volume calculation. Secondly, there is already an established linkage between vegetation and sediment accretion (Buckley, 1987; Luna *et al.*, 2011; Mendelssohn *et al.*, 1991). Vegetation traps windblown sediments, gradually building dunes in the process. Eventually, areas with the most vegetation naturally tend to become volumetrically large.

The dune sediment value ranged from $12.13 per cubic meter for Bolivar to

$51.83 per cubic meter for Galveston. Dune vegetation value ranged from $43.87 per square meter for Bolivar to $139.25 per square meter for Galveston. Because dune sediment volume and vegetation area were highly collinear, these two variables should not be summed for a total dune value. The reason for the relatively higher value for vegetation is due to the nature of area vs. volume calculations for a region; volume is always larger than area if the average elevation is greater than one (as was the case, typically, for this study area). In no way should these results be interpreted as supporting the notion that dune vegetation is "more valuable" than dune sediment. The two variables are interchangeable from a modeling perspective and simply operated on slightly different scales due to their area or volume-based nature.

Figure 5 illustrates the spatial variability of dune worth within Galveston and Bolivar. Understanding this variability is a useful application of dune modeling in that investment in certain critical areas along a coastline could yield a higher return on dune investment. Many areas in Figure 2.7 have fairly low per unit values of investment. However, investment in dunes for certain areas, particularly in the middle of Galveston where heavy shoreline retreat has been occurring for years (Paine, 2012), would, in concept, yield a high return. This is because homes in these blocks either have small dunes seaward of them, are close to the shoreline, are older, are highly numerous or valuable, or are a combination of these factors. Strategic targeting of these areas for dune construction and restoration projects could have mitigated a substantial amount of property damage during Hurricane Ike. Future planning along these same lines could be an effective means to reduce damage for the next hurricane. However, it is imperative that paradoxical and non-sustainable coastal planning is avoided: dune value is conceptually bolstered in areas with highly valuable or a large number of homes which justifies investment in better dune protection, which then leads to the construction of additional homes in the area because it is better protected and so on.

By some estimates, coastal marshes provide between roughly $2,000 and $10,000 (these values were also converted to 2015 US Dollars for consistency) of storm protection per hectare per year, depending on location and method of analysis (Costanza *et al.*, 1989, 2008). From our models' estimates, vegetated dunes offered roughly 1.23 million USD of storm protection per hectare during Hurricane Ike along Galveston and Bolivar. Examining the frequency of storms for this area over the last 115 years

(0.07 hurricanes per year directly hit Galveston over this time period [Roth, 2010]), this equates to roughly $86,000 dollars per hectare per year for this concentrated buffer ecosystem. It should be noted that this dune value is only based on one storm in one area, whereas wetland evaluations typically rely on multiple storms or numerical models of shoreline retreat and surge propagation (Costanza *et al.*, 1989, 2008). Additional assessments of other dune systems and storms would be necessary to determine if the dune value found in this paper for the Texas coast during Hurricane Ike was typical. These values are not mentioned to downplay the importance of wetlands, which offer many critical ecosystem services that dunes do not (*e.g.*, nursery habitat for fishing industries, water filtration, carbon sequestration), but rather to acknowledge the critical importance of dune ecosystems in coastal management and hazard mitigation in conjunction with wetlands.

The total value of dunes for this entire region was estimated by using the minimal dune state comparison (Equations 2 - 4) on Models 1.1 - 1.4 (Table 2.2). This technique estimates the amount of damage that was mitigated by the presence of dunes, or, in other words, how much more damage would have occurred if dunes had been removed (or put to a minimal state) prior to the storm. After averaging the total values of both dune variables (due to collinearity of sediment volume and vegetation), this equates to 8.43 million USD in total dune storm protection value across the entire study area. For the average homeowner living in these areas, the presence of dunes mitigated roughly $8,200 of damage to their home. There were an additional 321 homes on Galveston and 975 homes in Bolivar within 300 meters of the shore that were also protected by dunes but were either between the shoreline blocks or outside the range of the aerial photography, suggesting that the total value of dunes could potentially be even higher.

Modeling dune value also provided insight into non-dune related determinates of sustained property damage. The distance a home was from the shoreline was a crucial predictor of its sustained damage. Wave energy dissipates as it penetrates further landward across shore, therefore homes further from the shore experience less wave energy and current flow on average regardless of the state of seaward dunes. The distance of a home from the path of Hurricane Ike was not an important determinant of hurricane damage for our study area. The diameter of Hurricane Ike's hurricane strength wind field was $>$ 400 km during peak strength (Gutro, 2008) while the analysis described in this chapter only covered a 26 km stretch of Galveston and an

8 km stretch of Bolivar. Therefore, our analysis may not have had a large enough span to model the expected trail-off in damage with increasing distance from the storm's path. The time since the construction of a home (building age) was also a principal determinant of sustained damage. Building codes were less strict for older homes (Tanner *et al.*, 2009), meaning home age also could correspond to lower base elevation for the stilted homes and increased vulnerability. Lastly, home value was also consistently a significant variable and was very meaningful in explaining variation in Bolivar's sustained damage. This was likely because home damage was so severe in Bolivar that more expensive homes simply represented a much higher risk of damage. If a certain number of homes in an area are structurally compromised due to severe storm conditions, more expensive homes would mean that more damage would be sustained.

Models 1.5, 1.6, and 1.7 (Table 2.4) break down Galveston by quartile zones of different distances to the shoreline, showing that dunes diminish in importance for homes set back further from the shore. The only model in Table 2.4 where dunes were not a significant or meaningful variable was the quartile zone of homes furthest from the shoreline, where dunes only accounted for 3.2% of the model's explained variation (Table 2.4, Model 1.7). This could represent the "reach" of the dune protection during Hurricane Ike for Galveston. As these homes were the furthest away from the shoreline, they were less likely to be influenced by storm surge and therefore any protective value of dunes. This was also the only model to find the distance from the eye of the storm to be a significant determinant of sustained damage. This implies that a wind gradient along Galveston (Overpeck, 2009) could have played a larger role for damage in this zone of homes.

2.4.2 Limitations of Models

Sediment volume as a predictor of dune storm protection capabilities has limitations. Hypothetically, dune protection will increase with dune volume, but this is not necessarily the case. Figlus *et al.* (2011) demonstrated that volumetrically similar dunes with different morphologies possess differing breaching rates and protective capabilities. This finding can be attributed to differences among dune morphologies in terms of wave energy dissipation; the positioning of sand in front of the main dune (either in the form of fore-dunes, a protective seaward berm, or simply a multi-ridged dune) dissipates wave energy more efficiently. Therefore, volumetrically similar dunes could behave differently in terms of protection and storm damage mitigation. An inclusion of dune morphology categorization could refine our method of multivariate analysis in future studies. Also, the dune volume quantification technique used for this analysis depends on the way the area of the dune region is defined (i.e. the slope threshold that is used) as well as how the volume of sediment is vertically sliced above the beach. For this analysis, a conservative plane elevation of 0.92 meters above sea level (the average beach elevation of Galveston Island) was used to define the lower vertical boundary of dunes. Using a higher slice threshold would have created a smaller dune volume and, in turn, a higher per unit storm protection value.

The total vegetated area of a dune also has limitations as a predictor to dune stability and storm resistance. Though dune vegetation in general will likely improve dune sediment aggregation, sediment shearing resistance (Figlus *et al.*, 2014), wave energy dissipation, and erosion resistance in general (Sigren *et al.*, 2014; Silva *et al.*, 2016), different kinds (i.e. species, morphotypes) of vegetation would likely affect these processes in different ways. Such discrepancies in wave resistance and erosion control between different kinds of vegetation have been observed in coastal and transitional ecosystems (Burri *et al.*, 2011; Charbonneau *et al.*, 2017; Coops *et al.*, 1996; De Baets *et al.*, 2008; Leonard & Luther, 1995; Ysebaert *et al.*, 2011). In other words, our analysis treated all vegetation as being equal with regards to storm protection when in all likeliness it is not. This technique could be improved by collecting plant community data in conjunction with aerial photography to associate spectral signatures to different types of vegetation. Then a similar analysis as ours could determine if certain types of dune vegetation make greater contributions to storm protection. Furthermore, all sediment volume and vegetation area calculations were based off of LiDAR and aerial photography datasets that were collected two years prior to Hurricane Ike. Any accretion or erosion that took place in those two years would have added noise to the model.

There is also the additional limitation that the overarching methodology used in this paper in not necessarily applicable to all dune systems. This evaluation depends on using variation in the volume and vegetation area of dune systems to create a model. This approach works best for areas with naturally variable dune systems or where there is a combination of large restored dunes and natural systems. However, in locations with large uniform dunes, such variation along a shoreline in dune parameters may not exist and any attempt at modeling that dune's value would have little resolution. For a uniform dune system that is sufficiently large as to not be breached during a storm, an alternative or replacement cost analysis (Barbier, 2007) could be a more appropriate evaluation technique. Dunes tend to morph under natural Aeolian and hydrological processes though, potentially generating volume and vegetation variation over time for uniform dune systems. This natural tendency towards variability could allow modeling of initially uniform dunes, given enough time has elapsed since construction. Furthermore, modeling storm damage by non-dune related variables can still provide useful insights for coastal management.

2.5 Concluding Statements

Coastal sand dunes, both in regards to vegetation area and sediment volume, significantly reduced sustained property damage for portions of the Texas Coast during Hurricane Ike. The total property damage offset worth of coastal dunes within the analyzed shoreline blocks during Hurricane Ike was in excess of 8 million USD, likely totaling to even more when considering dunes around other portions of the Gulf of Mexico that encountered Hurricane Ike's broadly-distributed surge. The covariates of home age, value, and shoreline setback were also significant predictors of sustained damage. These covariates, along with dune variables, characterize the pre-storm state of a coastal area and can inform predictions about how much damage it will sustain during a storm. This pre-storm state also determines the cost efficacy of investing in dunes for a particular area, potentially allowing for strategic hazard mitigation planning. Our results indicate that dunes should play an integral role in coastal hazard mitigation strategies and offer a unique opportunity of bioengineering green infrastructure as an alternative to hard coastal structures.

3. PARSING THE ROLE OF DUNE VEGETATION IN SHAPING SEDIMENT PROPERTIES, SWASH HYDRODYNAMICS, AND EROSION: A FLUME TEST UTILIZING MULTIPLE PLANT SPECIES [1]

3.1 Background Information

3.1.1 Vegetation and Dune Erosion Resistance

The results from Chapter 2 indicate that dunes possess substantial value with regards to storm protection. However, multivariate modeling of storm data was unable to parse out whether vegetation was an independent factor for dune storm protection and erosion resistance. The observed linkage between vegetation and the accretion of dune sediment (Buckley, 1987; Luna *et al.*, 2011; Mendelssohn *et al.*, 1991) would mean vegetation plays an indirect role in storm protection because any additional sediment volume that is built up over time would act as a larger buffer during a storm. Such long term benefits to vegetation are likely to be true (Feagin *et al.*, 2015), but the question remains: does vegetation play an active role during a storm? If so, what specific biophysical interactions are crucial in shaping this role?

Several flume studies have shown vegetation reduces erosion in small scale dune settings (Sigren *et al.*, 2014; Silva *et al.*, 2016). However, the physical causal role that vegetation plays in dune erosion resistance has not been established. This physical causal role is likely to be complex, involving both above- and belowground characteristics of vegetation. The objective of this chapter will be to analyze and assess these specific interactions between vegetation, sediment, and hydrodynamics to form statistical models for vegetation's role in dune erosion resistance. Understanding this causal role could shape the discussion of dune restoration and management in that practices and goals could be set to maximize certain protective aspects of vegetation.

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[1] Author's Note on Copyright: Some of the material in this chapter has been published in Shore and Beach in 2014 under the title, "Coastal sand dunes and dune vegetation: Restoration, erosion, and storm protection". For referencing, please cite that publication in conjunction with this dissertation.

3.1.2 Above- vs. belowground Aspects of Vegetation

Reduced erosion caused by plants has been observed in marsh (Gedan *et al.*, 2011), mangrove (Thampanya *et al.*, 2006), creek bank (Coops *et al.*, 1996), and terrestrial ecosystems (O'Dea, 2007) and provides a basic framework for the ways in which vegetation could affect erosion in coastal dunes. Dunes, however, differ from these other ecosystems in that during a storm surge, waves break onto and run up steep dune slopes, creating a unique swash/surf zone. In general, there are two ways in which plants can impact erosion in dunes during a storm surge: hydrodynamic modification aboveground and substrate modification belowground. The stems and leaves of plants provide resistance to attacking waves and currents (Augustin *et al.*, 2009; Leonard & Luther, 1995; Yang *et al.*, 2012; Ysebaert *et al.*, 2011), reducing the amount of erosion occurring in landward sediment (Coops *et al.*, 1996; Thampanya *et al.*, 2006). Belowground, plant roots and their associative microbial communities, primarily arbuscular mycorrhizal fungi, interact with surrounding sediment to reduce erosion by improving soil aggregation and shear strength (Burri *et al.*, 2011; Fan & Su, 2008; Miller & Jastrow, 1990; O'Dea, 2007).

These above- and belowground roles of dune vegetation are shown in Figure 3.1, which revisits the conceptual framework for dune erosion outlined in Figure 2.1 of Chapter 2. As a storm surge raises water levels above the natural beach area, storm waves impact the seaward facing slopes of coastal dunes. Plants in these regions become emergent or submerged and interact with wave uprush and downrush events in the swash zone, potentially reducing the amount of energy eroding landward sediments (Figure 3.1 Panel A). Such interactions could increase the dissipation of wave energy across a shoreline, reducing wave reflection, swash/backwash velocities, and turbulence. Reduction of wave energy (Yang *et al.*, 2012; Ysebaert *et al.*, 2011), flow velocity, and turbulence (Leonard & Luther, 1995) caused by vegetation has been observed in other ecosystems with emergent and submerged vegetation. The amount of energy dissipation that occurs depends on the type of vegetation and the rigidity and surface area/density of the aboveground plant structures (Augustin *et al.*, 2009; Bouma *et al.*, 2010).

As waves come into contact with the dune face, plant rhizospheres are exposed, sediment is eroded, and a dune scarp (*i.e.* cliff) forms (Figure 3.1 Panel B). Plant roots could potentially influence erosion outcomes during this wave collision in two ways. The first involves belowground soil aggregation/binding which influences the

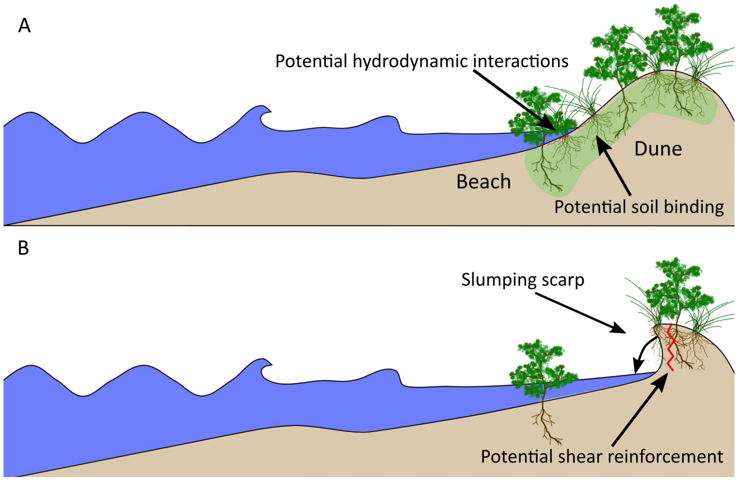

Figure 3.1: A: A storm surge creates a wave collision scenario where waves are coming into contact with the seaward facing slope of a dune and the vegetation growing on it. The aboveground structures of vegetation potentially alter the hydrodynamics within the swash zone. Belowground, interactions between roots, microbes, and decaying materials could act as binding agents for the sediment. B: The dune face has eroded away to form a scarp, exposing the root systems of plants. At this stage, shear stress is created along the dune scarp and roots could reinforce the scarp to resist slumping.

general erodability of sediment. This binding of particles, which can take place over a long time scale (Forster & Nicolson, 1981), involves bacterial and fungal decomposition, secretion of adhesive compounds, and entanglement of sediment particles by root hairs and fungal hyphae (Miller & Jastrow, 1990) (Figure 3.2). Bound sediment conglomerates have a lower surface area to mass ratio, conceivably causing them behave like larger particles when exposed to hydrodynamic stresses. This soil binding would therefore increase a the dune sediment's "effective" grain size, making the sediment more resistant to entrainment by the pressures exerted by moving water. Potentially, higher amounts of mycorrhizal activity and roots present in a soil could increase this binding of sediment and erosion resistance.

Second, plant roots increase the shear strength of sediment (De Baets *et al.*, 2008; Fan & Su, 2008). As waves erode the base of the scarp, gravity pulls on the overhanging sand, inducing shear stress across the dune sediment. Additionally, dune sediment would be wet under this scenario and would be in a weakened state with regards to shear strength because water has infiltrated pore spaces (Fan & Su, 2008; Dafalla, 2012). At a critical overhang mass and wetness, the scarp will break off and slump into the oncoming waves. Plant roots could prolong this process as the tensile strength of roots resists the shear stress (Genet *et al.*, 2007). Higher root densities in a soil would therefore increase dune erosion resistance through the physical mechanism of shear stress reinforcement.

Figure 3.2: The root system of *Sporobolus virginicus* (a common dune grass) is shown at 20× magnification. Note the binding of sediment particles by roots, fungal hyphae, and organic material. This sample was submerged in water, meaning that this conglomerate was water stable under calm conditions.

3.1.3 Parsing the Important Aspects of Vegetation

The above- and belowground processes laid out in the previous section provides a conceptual framework for how dune vegetation could influence erosion but is mostly dependent on observations made about plants in other ecosystems. To fill this knowledge gap concerning coastal dunes, the overall objective of the research in this chapter was to determine the importance of dune vegetation in erosion resistance and to explore which aspects of vegetation (*e.g.* surface area and rigidity of plant stems, root biomass, mycorrhizal activity) and which physical processes (*e.g.* turbulence, swash velocity, wave reflection, shear stress reinforcement, sediment binding) are linked to enhanced erosion resistance. To accomplish this objective, a wide range of variation in above- and belowground aspects of vegetation was tested within a controlled wave flume setting. During testing, data was collected on erosion, shoreline morphology, sediment properties, and swash hydrodynamics so that these processes could be statistically modeled and linked to the vegetation aspects. Do aboveground aspects of plants matter in erosion resistance? Do they reduce wave reflection and decrease turbulent kinetic energy within the swash zone? If aboveground aspects are important in these areas, it would be expected that wave flume trials with higher amounts of aboveground vegetation (*e.g.* stem and leaf surface area) would have less erosion, wave reflection, and turbulent kinetic energy. The same logic could be applied to other plant features and physical process (*e.g.* root density's effect on sediment shear strength, mycorrhizal activity on sediment binding/effective grain size) to enhance our understanding of vegetation's role in dune erosion resistance and storm protection. Understanding these biophysical linkages could inform dune restoration and management practices and allow for the optimization certain protective aspects of vegetation.

3.2 Methods

3.2.1 Overarching Modeling Approach and Rationale

The overall objective of this flume experiment was to create variation with regards to above- and belowground aspects of vegetation and statistically model the impact of this variation on sediment properties, swash hydrodynamics and ultimately dune morphological changes and erosion. Table 3.1 shows the various models that were made from the data collected during this experiment. Each model has a predicted variable (*i.e.* a variable where linkages to vegetation are of interest), a pool of vegetation-related variables that could be linked to the predicted variable, and a pool of variables that could influence the predicted variable but were outside of the experimenter's control (confounding variables). For example, small differences in the wave flume water level at the setup of a wave run could influence swash zone hydrodynamics, acting as a confounding variable. Turbulent kinetic energy, swash velocity, wave reflection, sediment shear strength, and sediment aggregation could also be used as predictive variables with regards to dune erosion as these are the underlying physical processes that are linked to erosion. Therefore, these linkages between physical processes and dune morphological changes were also modeled. For example, aboveground structures may reduce swash zone turbulence which, in turn, decreases erosion because fewer sediment particles are entrained by turbulent forces and carried offshore.

Swash turbulence (and turbulent kinetic energy) has never been empirically analyzed for dune and beaches systems using live vegetation. For turbulence modeling (Model 2.1, Table 3.1), plant structures could influence turbulence in two different ways. Plant structures could break up a smooth stream of water, creating additional turbulent eddies and increasing turbulent energy in the swash zone. Conversely, in an already turbulent body of water, plant structures may break large turbulent eddies into smaller ones, enhancing turbulent dissipation (the rate at which energy is transferred down a cascade of smaller turbulent vortices and eventually into heat energy) and generally reducing turbulence in the swash zone. Vegetation reduces turbulent kinetic energy in tidal water flows (Leonard & Luther, 1995), meaning this latter scenario may be more likely. More rigid structures produce higher drag (Augustin *et al.*, 2009), potentially enhancing the effect of plant structures for either scenario.

If plants greatly obstruct water flow in the swash zone (both uprush and backwash), the average cross-shore water velocity in the swash zone may be reduced (Model 2.2, Table 3.1). This concept is best illustrated by imagining water flowing through a straight channel vs. winding through a maze. Even if in both scenarios water is flowing at the same speed, the water traveling through the maze will have a lower net velocity for any given direction. In a dune and swash scenario, large amounts of plant structures act as the maze and net uprush/downrush flow velocities in the cross-shore direction are potentially reduced (along with the sediments they carry/erode). A greater surface area of plant structures (a larger maze) would bring a greater expected amount of water baffling. More rigid plant structures would also conceptually generate increased water baffling (*i.e.,* completely flexible maze walls would cease to function as walls). Alternatively, plant structures could constrict the amount of space that water can flow through, compressing streamlines and potentially increasing flow velocities through plant structures.

Related to both swash velocity and turbulence, wave reflection serves as a measurement of the dissipative efficiency of a shoreline (Model 2.3, Table 3.1). Every ocean wave can be viewed as an efficient package of energy (shifting between kinetic and potential) traveling in deep water. As the wave approaches a shoreline and water depth becomes roughly 1.3× the wave's height, the mechanisms that maintain

Table 3.1: List of modeled variables.

Predicted Variable	Potential Predictive Plant Variables	Potential Confounding Variables
• Model 2.1 Turbulent Kinetic Energy • Model 2.2 Swash Velocity • Model 2.3 Wave Reflection	• Stem Rotational Stiffness • Plant Surface Area	• Wave Height • Sand Bar Location • Sand Bar Size • Shoreline Slope • Time of Wave Exposure • Acoustic Doppler Velocimeter Distance from Sediment Bed
• Model 2.4 Sediment Shear Strength • Model 2.5 Sediment Aggregation	• Fine Root Biomass • Coarse Root Biomass • Mycorrhizal Colonization	NA
• Model 2.6 Dune Erosion • Model 2.7 Scarp Retreat • Model 2.8 Cross-Shore Centroid Shift	• Stem Rotational Stiffness • Plant Surface Area • Root Biomass (Both Fine and Coarse) • Mycorrhizal Colonization	• Initial Cross-Shore Profile Centroid • Wave Height

this propagation of energy break down and the wave itself "breaks". At this point it is called a uprush and be viewed as a mass of moving water containing a certain amount of kinetic energy. As this mass of water moves up the beach slope, some of this energy moves sediments and other structures (*e.g.* wrack, vegetation) or can be dissipated in the form of turbulence. The remaining energy then shifts back to potential energy as the wave travels up the slope and at the peak of uprush, kinetic energy is at a minimum. Lastly, the remaining energy travels back offshore in the form of a backwash and outgoing wave. The proportion of reflected outgoing energy relative to incoming energy is known as wave reflection and is indicative of the efficiency at which a shoreline dissipates energy. Typically, less reflective shorelines are less erosive and less violent. In reflective shorelines, extensive scouring can occur at the point of reflection and the energetic backwash/reflected wave can transport more sediment offshore. Over the course of a storm surge wave collision scenario, beach/dune systems will tend to become more dissipative as the system moves towards a state of equilibrium. Plant structures could reduce wave reflection, enhancing the dissipative nature of a shoreline and modifying the equilibrium profile.

When statistically modeling the effect of vegetation on hydrodynamic variables (Models 2.1 - 2.3, turbulence, uprush/downrush velocity, and wave reflection models in Table 3.1), confounding variables that could also affect the dependent (predicted) hydrodynamic variable would need to be addressed. The confounding variables are the result of unintentional, researcher-caused variations in the initial setup of experimental controls. Also, shoreline characteristics change and evolve during wave exposure and would influence swash zone hydrodynamics. The confounding variables consisted of wave height (variation could have occurred as a result of slightly different flume water levels at setup) and shoreline profile characteristics (sand bar location and size, shoreline slope, sediment bed changes at the location of the turbulence/velocity measurements). Variation in shoreline confounding variables could result from either small differences in the initial dune/beach morphology setup between trials or the natural rearrangement and redistribution of sediment caused by wave attack as the trial proceeded. All of these confounding variables could alter swash zone hydrodynamics and addressing them added resolution to statistical modeling plant variable influence.

The tensile strength of roots can reinforce sediment shear strength (*i.e.,* how much the sediment resists breaking apart when force is applied across a plane that is parallel to the force) (Model 2.4, Table 3.1). Fine roots typically have a higher tensile strength in proportion to their weight when compared to coarse roots (Genet *et al.*, 2007). Roots are composed a tough outer layer of cellulose and an weaker inner layer of starch, the cellulose being the main contributor to the root's tensile strength. Coarse roots have larger cross-sectional areas, but this larger area is composed principally of an enlarged inner layer of starch, hence the proportionally lower tensile strength. Both fine and coarse roots could be linked to sediment shear strength, though the former is likely to be proportionally more impactful.

Sediment aggregation is the process by which sediment particles are bound together by organic adhesive compounds and fibrous materials (Model 2.5, Table 3.1). Arbuscular mycorrhizal fungi excrete adhesive compounds which can act as binding elements in sediments and are considered to be prominent contributors to soil aggregation (Forster & Nicolson, 1981; Miller & Jastrow, 1990; O'Dea, 2007). Additionally, mycorrhizal hyphae can entangle sediment particles into larger conglomerates. Microscopic roots hairs from plants could also act in these capacities as well. These larger aggregates are more resistant to entrainment by moving water because they have lower surface area to mass ratios. Due to all the processes laid out in Models 2.1 - 2.5 (Table 3.1), all of these plant features (both above- and belowground) have the potential to ultimately affect dune erosion, scarp retreat, and profile cross-shore centroid shift (Models 2.6 - 2.8, Table 3.1).

3.2.2 Vegetation Setup

To establish a wide range of above and belowground variation for different flume trials, two vegetation growth parameters were manipulated. The first was that four different species of plants, each a unique morphotype, were tested in different flume trials. The species used were *Panicum amarum*, *Rayjacksonia phyllocephala*, *Sesuvium portulacastrum* and *Sporobolus virginicus* (Figure 3.3). *Panicum amarum* is a tall dune grass that can grow over a meter in height with rigid stems. However, the majority of the plant did not interact with waves because it was taller than the scaled down swash zone of the wave flume. This species also has a dense, adventitious root system featuring large rhizomes (> 1 cm in diameter). *Rayjacksonia phyllocephala* is a dune forb/shrub which grows typically about 50 cm in height, though shorter 5 - 10 cm tall seedlings were used within the flume. This species had a woody stem and tap root with few fine roots. *Sesuvium portulacastrum* is a spreading dune vine which rarely grows higher than 5 cm off the ground. This species forms a dense matrix of structures close to the ground but is flexible compared to the other species. *Sesuvium portulacastrum* also occasionally grows taproots from nodes on stolons. Moderately dense networks of fine roots radiate from these taproots. Lastly, *S. virginicus* is a short dune grass roughly 5 - 15 cm in height with weak stem rigidity and a dense network of adventitious fine roots.

The second growth parameter that was manipulated was plant age (length of time grown). For each species, plants were grown in a greenhouse for 3, 6, and 9 weeks prior to transfer into the wave flume. These different increments of growth allowed a gradual accumulation of biomass within plant pots, creating additional variation between trials with regards to above- and belowground aspects. All plants were grown in pots (cylinders with a 16 cm diameter and a 16 cm depth) in a greenhouse over the spring and summer of 2016. All plants were watered comparably, fertilized with 7 g of Osmocote slow release fertilizer, and grown in the same sediment as was used in the wave flume. For each trial, 15 plant pots were transplanted to the seaward facing slope of a dune within the wave flume in a 5 × 3 grid. A total of 15 wave flume trials were conducted, 3 controls trials without plants and 12 trials with plants (4 species × 3 growth intervals).

3.2.3 Flume Setup

All tests were carried out in a 15 m long × 1.3 m deep × 60 cm wide wave flume on the campus of Texas A&M at Galveston (Figure 3.4 Panel A & B). Sediment within the flume consisted of sand from a Texas sand pit with a median grain diameter of 152 microns. The sediment's grain size distribution is summarized in Figure 3.5 and was determined using a sieve tower. The beach slope was 1/25 and the seaward facing dune slope was 1/2. The dune was trapezoidal with a 120 cm base width, a 30 cm crest width, and a height of 20cm. The initial dune and beach morphology were maintained constant for all trials using a cross-shore acrylic template positioned along the inside wall of the wave flume. This template allowed sediment elevations to be consistently aligned to the template before the start of each trial, though some slight variation between initial dune morphologies did occur. However, this initial dune morphology was parameterized so it could be modeled as a confounding variable. Nine capacitance wave gauges measured the free surface elevation of water within the flume and were positioned at various locations in the flume. This wave gauge data was

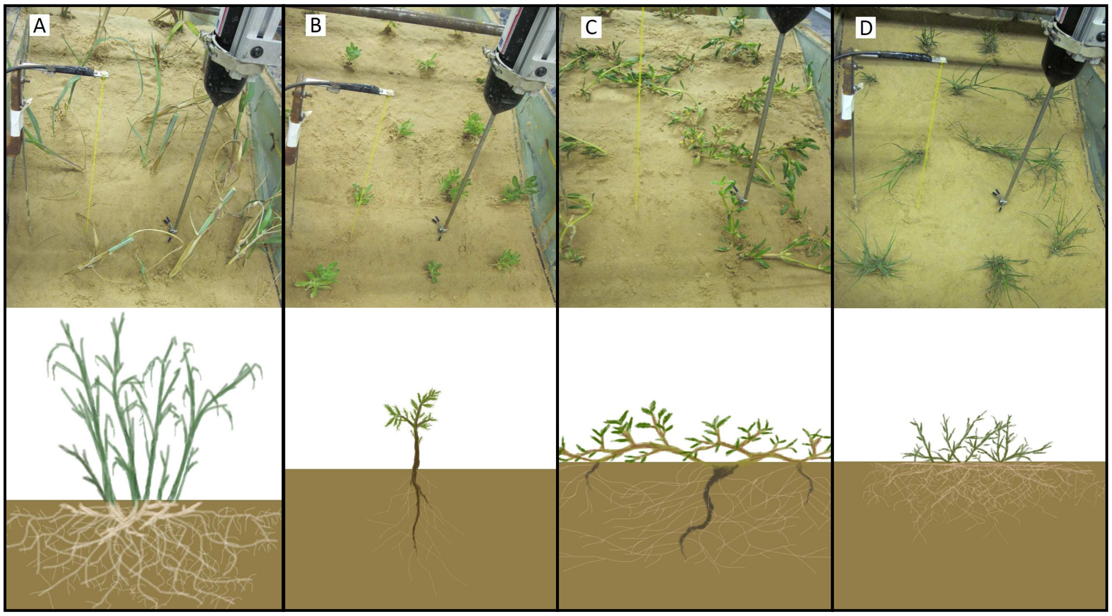

Figure 3.3: Four species/morphotypes of plants were used for this experiment: A tall grass (A - *Panicum amarum*), a small forb (B - *Rayjacksonia phyllocephala*), a spreading vine (C - *Sesuvium portulacastrum*), and a short grass (D - *Sporobolus virginicus*).

used to calculate wave statistics (wave height, wave period, spectral energy density) and will be described in additional detail in subsequent sections. Additionally, a "side-looking" Nortek Vectrino Plus (a type of acoustic Doppler velocimeter or ADV) was placed near the dune base within the swash zone. This instrument recorded water velocities at 200 Hz and these data were used to calculate turbulent kinetic energy and average swash velocity (additional details in subsequent sections). Each trial consisted of 12 wave runs, each wave run lasting 210 seconds. An irregular, JONSWAP wave spectrum (Figure 3.4 Panel C) with a 6.7 cm significant wave height and a peak period of 0.53 seconds was used for each run.

3.2.4 Dune and Beach Morphological Data Collection

An automated Acuity AP820-1000 laser scanner mounted to a movable cart measured dune and beach morphological profile changes. Six scans were conducted for each trial: An initial scan and then after wave runs 1, 2, 4, 8, and 12 (or 3.5, 7, 14, 28, 42 minutes, respectively). Scans consisted of a 50 cm along-shore length in the middle of the flume (5 cm were excluded from each side as to minimize in-

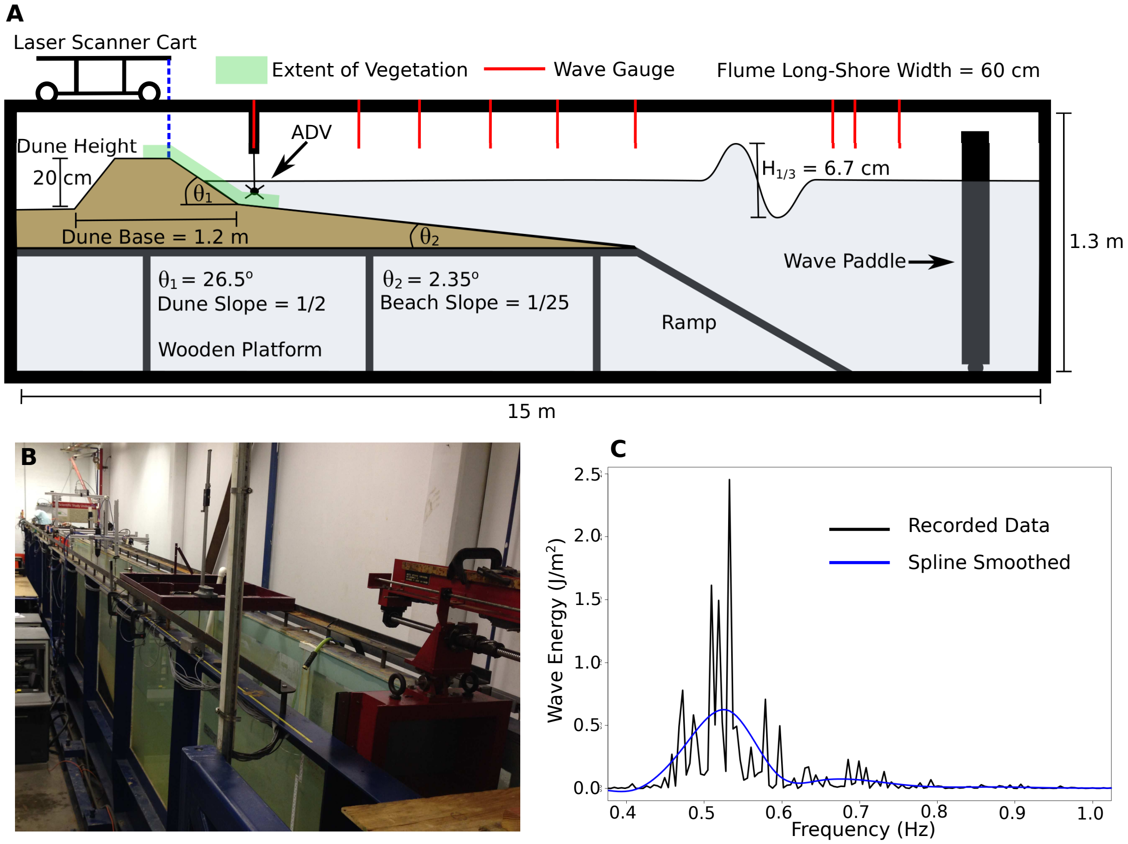

Figure 3.4: A: Specifications (not drawn to scale) of the TAMUG wave flume with regards to dimensions, hydrological parameters, and shore morphology. B: Photo of the wave flume. C: The JONSWAP wave energy spectrum that was used for each wave run carried out in this experiment, recorded by the wave gauge closest to the wave paddle (1.5 m away from the wave paddle, 1.03 m depth).

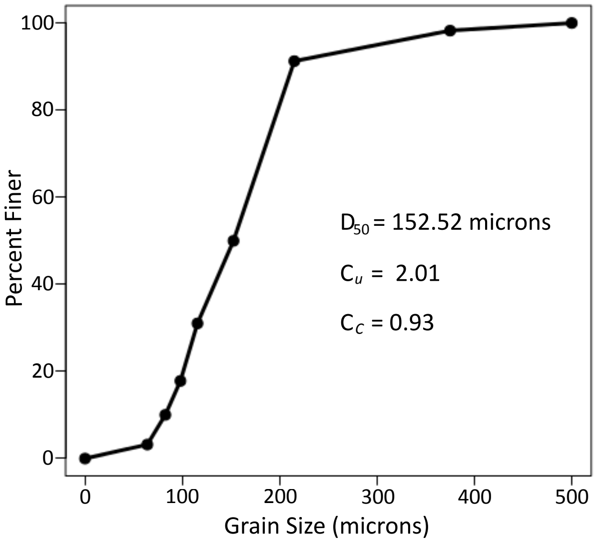

Figure 3.5: The cumulative grain size distribution of the sediment used in the TAMUG wave flume. D_{50} refers to the median grain size, C_u refers to the coefficient of uniformity, and C_c refers to the coefficient of curvature.

terference with the walls of the wave flume) at 1 cm cross-shore increments. For every cross-shore increment, only values less than the mean elevation were used because laser signals reflected off plant structures, obscuring the actual sediment bed at many locations. By only using values less than the mean, plant structures were consistently removed from all the laser scan data from all trials. After filtering out plant interference, the three-dimensional morphological plots were averaged at each cross-shore increment. The resulting two-dimensional profiles were used to calculate three erosion/morphological change parameters: eroded volume of sediment, scarp retreat, and profile cross-shore centroid shift (Figure 3.6).

For every final and initial profile comparison, there is a point (near the base of the dune for this wave scenario and shore morphology) which marks the transition between erosion and accretion (see the shift between the red and green regions in Figure 3.6). All erosion that occurred landward to this point (the red region in Figure 3.6) was summed (and multiplied by the width of the flume) for the eroded volume of sediment. Scarp retreat was defined as the distance from the initial base of the dune to steepest portion of the dune in the final profile. Lastly, to quantify the average off-shore distance shifted by the sediment over the course of the trial, the cross-shore centroid (for the region from the back of the dune to the location of closure) was compared for the initial and final profiles. Cross-shore centroids were calculated by treating sediment profiles like frequency distributions (5).

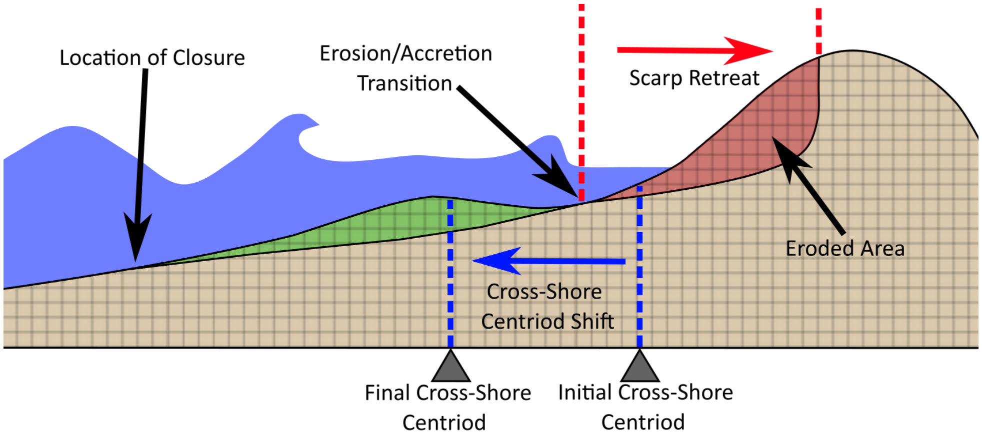

Figure 3.6: Schematic explaining the three morphological change metrics that were measured: volume/area eroded, scarp retreat, and cross-shore centroid shift. In this diagram, the initial profile is composed of red + tan areas while the final profile is composed of green + tan areas. The location of closure (cross-shore position of the depth of closure) represents the point at which the shoreline is no longer active during the flume experiment, or, in other words, the point at which there are no profile differences between the initial profile and the final profile.

$$C = \frac{\sum_{x=1}^{x_{lc}}(E_x \times D_x)}{\sum_{x=1}^{x_{lc}}(E_x)} \qquad (5)$$

Where: C = *Cross-shore centroid*

x = *A point along the averaged cross-shore 2D shore profile. x=1 would represent the point along the active shoreline furthest from the wave paddle.*

x_{lc} = *The location of closure*

E_x = *The elevation at point x*

D_x = *The distance from the wave paddle at point x*

The cross-shore centroid shift (a proxy for the distance that sediment was transported offshore during the trial) was calculated from the difference between the final and initial shoreline cross-shore centroids (6).

$$S = C_f - C_i \qquad (6)$$

Where: S = *Cross-shore centroid shift*
C_f= *Cross-shore centroid after the last wave run (final profile)*
C_i= *Initial cross-shore centroid*

3.2.5 Hydrodynamic Data Collection and Analysis

The swash zone water velocity was collected for every wave run and trial at 200 Hz using a “side-looking” Nortek Vectrino Plus acoustic Doppler velocimeter (ADV). This instrument had to be started manually and was therefore out of sync with wave gauge files and all velocity data were out of sync with one another. For proper comparison between different runs and trials, cross-correlation was used to sync all velocity data to a single control wave series and to their corresponding wave gauge (the wave gauge closest to the dune was at the same location as the ADV). The ADV relies on Doppler shifts in reflected acoustic bursts to determine the velocity of particles moving in water. When exposed to air, the ADV records only noise and for this reason bubbles in water will also cause erroneous readings. Both of these sources of error were filtered out (filtering techniques are detailed in subsequent paragraphs).

Because the ADV sensor head was placed in the swash zone, data were logged both in and out of the water (incoming waves would submerge the sensor head, but large backwashes would momentarily leave the sensor head out of the water). This dynamic created a data series that alternated between valid data (ADV head submerged in water) and noise (ADV head out of the water). Based off each ADV dataset’s corresponding wave gauge data, ADV data were filtered out when the local water free surface elevation was less than 0.5 cm below the still water level. As reference, the center of the ADV head was roughly 1 cm above the sediment bed and the tips of the top-most receiver prongs were roughly at the surface of the water (Figure 3.7). The 0.5 cm below still-water mark was the minimum level at which the ADV sensor head could record data.

This technique filtered out the noise generated by air exposure for the ADV data so that turbulence and velocity calculations could be made. It should be noted that even though the center of the ADV sensor head was on average around 1 cm

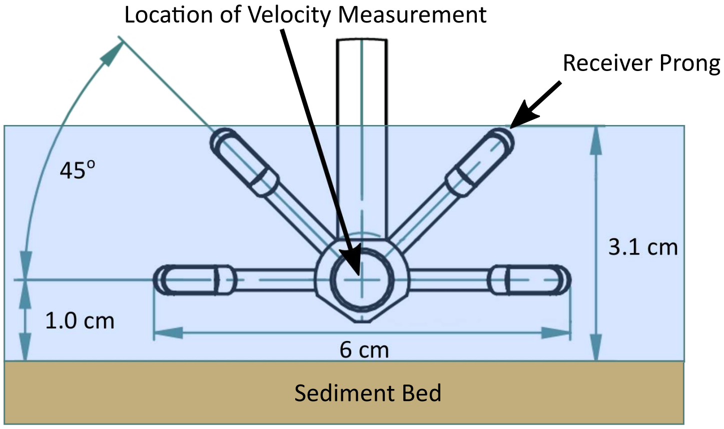

Figure 3.7: Schematic of ADV sensor head swash zone location relative to the sediment bed and water depth. Water depth represents still water. Figure is based on an image from the Nortek website (www.nortek-as.com).

above the sediment bed over the course of all trials and wave runs, the sediment bed would shift slightly at this location (+/- 1 cm). For this reason, the distance from the sediment bed to the ADV sensor-head was used as a confounding variable for multivariate modeling of swash velocity and turbulent kinetic energy.

After data filtering, turbulent velocities were obtained by calculating the difference between a running average, or the mean flow (n=21 or a 0.1 sec window), and the measured velocity for a location within the swash zone. This location of velocity measurement was the same for each trial: behind the first row of plants approximately at the transition point between erosion and accretion seen in Figure 3.6. If a turbulent velocity exceeded the magnitude of the running mean (*i.e.* mean flow) for any increment in time, it was also filtered out as these typically were indicators of bubbles (bubbles in the water column could also generate random noise in the data that also needed to be removed). After filtering, the turbulent kinetic energy (TKE) of the each wave run for each trial was calculated (7). The absolute value of remaining velocity data in the cross-shore direction was averaged, representing the mean swash velocity of both the uprush and downrush of waves.

$$TKE = \frac{1}{2}(\bar{u'^2} + \bar{v'^2} + \bar{w'^2}) \qquad (7)$$

Where: $TKE = Turbulent\ kinetic\ energy$

$u' = Turbulent\ velocity\ in\ the\ cross\text{-}shore\ direction$
$v' = Turbulent\ velocity\ in\ the\ along\text{-}shore\ direction$
$w' = Turbulent\ velocity\ in\ the\ vertical\ direction$

Nine capacitance wave gauges collected data for every wave run in every trial at 20 Hz and were used to calculate the wave reflection coefficient as well as every other wave parameter reported in this chapter. Wave reflection coefficients were calculated using the closest three wave gauges to the wave paddle (1.9 m, 2.1 m, and 2.9 m from the wave paddle). Each incoming wave that breaks into a shoreline has a certain amount of its energy reflected back offshore in the form of an outbound wave. Cross correlation was used to determine the time shift of each incoming wave with regards to the three closest wave gauges. From the distance and time shift between gauges, wave speed was calculated and used to determine when the wave would arrive back at the wave gauges after reflecting off the beach and dune. The outbound wave's height relative to the inbound wave's height was then quantified as the wave reflection coefficient (8). Wave reflection coefficients were calculated for every two series of wave runs (400 second increments).

$$R = H_r/H_i \qquad (8)$$

Where: $R = Wave\ reflection\ coefficient$
$H_r = Reflected\ wave\ height$
$H_i = Incident\ wave\ height$

3.2.6 Sediment Properties Data Collection

Data were collected for two sediment properties: sediment shear strength and sediment aggregation. As these two properties could not be sampled from the wave flume either before or after a trial without interrupting the trial or being disrupted by wave action, samples were taken from a harvested pot representative of each plant trial (control samples were simply collected from the flume sediment without plants present). Shear strength was measured by applying shear forcing across a 6 cm long, 7 cm diameter core using a rudimentary soil shearer (Figure 3.8). Cores were sheared at a speed of approximately 1 mm per second over a distance of 2.5 cm. Shear curves were created by reviewing video footage from a mounted camera. Both peak shear and cumulative shear (the area under the shear curve) were calculated from the curves, as well as the fine and coarse root biomass from each core. Sediment aggregation was measured from a small sample ($\approx$ 50 g) of sediment obtained from the same harvested plant that was run through a sieve tower submerged in water and placed on an INNOVA 2100 platform shaker at 80 RPM for 20 minutes. The advantage of using a water submerged tower was that unaltered sediment could be used (not dried, frozen, or ground up). Unaltered sediment would have various binding properties (adhesive compounds, mycorrhizal entanglements, etc.) intact. The resulting grain size distribution would represent the sediment's effective grain size during a water-based forcing event. The sieve sizes of 63, 125, 180, and 250 microns were used and provided high resolution for this sediment's grain size distribution.

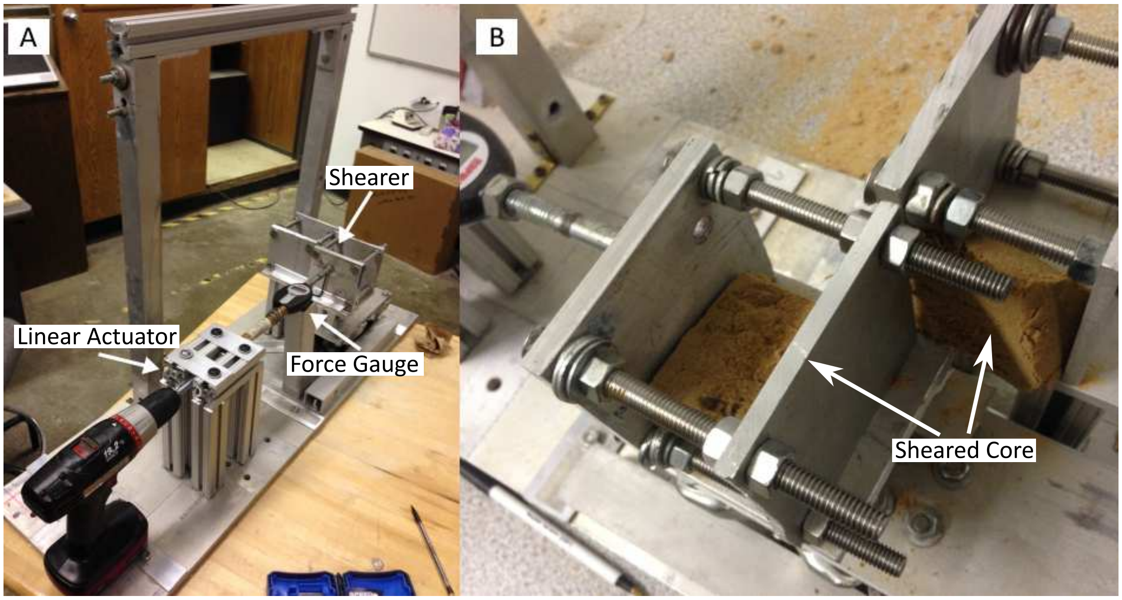

Figure 3.8: A: Soil shearer designed and built by the researcher. B. Close-up photo of a core after it has been sheared in half.

3.2.7 Vegetation Data Collection

After each trial, all plants were exhumed from the flume sediment, washed, separated into aboveground and belowground components, dried, and weighed for biomass. Belowground components were separated into fine roots (diameter < 1 mm) and coarse roots (diameter > 1 mm). The number of stems was counted prior to drying.

S. portulacastrum possess laterally growing stolons which are anchored at nodes by roots. For this species, each time the plant emerged from a rooted stolon node was counted as a stem. The average surface area for each stem (attached leaves included) was calculated by taking a picture of five sample stems against a white sheet of paper with a length benchmark (ruler). Care was taken to make sure no plant structures were stacked on top of one another. Images were then spectrally analyzed in ArcMap. The number of pixels that were plant material (green) was summed and the benchmark was used to determine the number of pixels per square cm. This technique allowed for the calculation of the average two-dimensional surface area for each stem and the total surface area for each trial (average surface area of each stem × the total number of stems). Only the bottom 5 cm of plant stem pixels were summed as this length was the maximum depth in the swash zone (to determine if surface area displayed a relationship to measured hydrodynamic data, only plant material coming into contact with waves and currents would be relevant).

A sample of five stems from each trial was also tested for stem rotational stiffness. This variable was measured by applying a force to a known location while the stem was anchored on one side. The angle of deflection of the stem could then be used to obtain rotational stiffness (9). Lastly, mycorrhizal colonization was measured by staining a subsample of fine roots with Trypan Blue (Morton & Amarasinghe, 2006). Stained roots were placed on a slide and 35 cm of roots (at 1 cm cross increments) and were examined at 200X magnification. Presence of mycorrhiza was identified when hyphae, arbuscule, vacuole, or spore structures were identified within or on the plant root. The percentage of roots with mycorrhizal presence could then be calculated.

$$RS = \frac{F \times D}{\theta} \qquad (9)$$

Where: RS = *Rotational stiffness*
F = *Magnitude of the force applied to the plant stem*
D = *Distance of the applied force from the anchor of the plant stem*
θ = *Angle of deflection caused by applied force*

3.2.8 Statistical Analysis

Stepwise multivariate regression analysis was used to model the relationships in Table 3.1. However, due to a large number of variables, a dredge algorithm (Barton, 2015) was used to narrow the list of predictor variables from the large pool. This algorithm is a type of automated model selection that creates all possible models (every combination of predictive/independent variables) and produces a ranking of the best possible fit models based off R^2. Step-wise forwards and backwards modeling techniques along with collinearity assessments (Variable Inflation Factors - VIFS) were then used on the dredge-optimized models to create a coherent model with only significant ($\alpha < 0.05$) predictive variables for each predicted variable in Table 3.1.

Some predicted variables could be modeled by the number of trials (n=15) while others could be modeled by the number of wave runs (n=180). This sample size discrepancy is because dune morphological change variables (eroded volume, scarp retreat, and cross-shore centroid shift) only had one data point per trial (one can only make the calculations based off the initial and final wave run of the dune/beach profiles). Alternatively, hydrodynamic data (turbulent kinetic energy, swash velocity, wave reflection) were collected for each wave run and though there were repeated vegetation conditions for some wave runs, they were independent of each other. For example, turbulent kinetic energy for any given wave run would depend on the shoreline, wave, and vegetation characteristics of that particular wave run and was modeled as such. It should be noted that if a variable was not found to be a significant predictor of any given outcome, it does not necessarily mean it is not related or causally linked to that outcome, but simply could mean that an inadequate range of that variable was tested during the flume trials. This concept could apply to either vegetation or confounding variables. Additionally, if two plant variables are collinear, the modeling techniques used in this analysis would not be able to detect the independent importance of each plant variable with respect to a predicted variable.

Linking models together is largely a matter of perspective of underlying causal mechanisms. There is no statistical way to establish causality or causal linkages between variables but statistical modeling can lend support and clarity to conceptual frameworks. For linking models, the perspective was taken that vegetation variables would affect physical properties (hydrodynamic and sediment properties such as turbulence or sediment shear strength) which in turn would affect dune/beach morphological changes. For example, vegetation aboveground surface area (a vegetation variable) could be a significant predictor of turbulent kinetic energy (a hydrodynamic variable) during wave runs (10).

$$SA \rightarrow TKE \qquad (10)$$

Where: SA = *Aboveground surface area*
TKE = *Turbulent kinetic energy*

In other words, there could be a significant tendency that as aboveground plant surface area increases, turbulent kinetic energy either decreases or increases and that tendency is not well explained by random variation in the two datasets. Additionally, vegetation aboveground surface area could be a significant predictor of cross-shore centroid shift (a beach/dune morphological change variable) during trials (11).

$$SA \rightarrow S \qquad (11)$$

Where: S = *Cross-shore centroid shift*

The average turbulent kinetic energy for any given trial, though, could also be a significant predictor of cross-shore centroid shift during trials (12).

$$TKE \rightarrow S \qquad (12)$$

In such a scenario, there would be statistical support that aboveground surface area affects cross-shore centroid shift and that it does so through hydrodynamic modifications to swash turbulence (13).

$$SA \rightarrow TKE \rightarrow S \qquad (13)$$

All of the models described thus far were linked together in this way (if significant) to create a cohesive, statistically supported framework for vegetation impact on dune/beach morphological changes and the underlying physical causes though which these impacts occur.

3.3 Results

3.3.1 Descriptive Overview of Flume Test Proceedings

As waves approached the shoreline, they began to shoal and eventually break between 40 (for the smallest waves) and 80 cm (for the largest waves) from the dune's base. The swash then passed through the first row of vegetation and then the ADV sensor head. Vegetation structures had a visible effect on water flow, ripples forming behind stems as the swash traveled up the beach profile. Scour marks occurred in the sediment bed in front of and along the sides of the vegetation stems. Vegetation structures moved as the swash passed, motion being proportional to the rigidity of the plant structures. *Panicum amarum* moved hardly at all while *S. portulacastrum* undulated greatly with each passing uprush and backwash. During the first wave run, the uprush passed through three rows of vegetation and nearly to the crest of the dune before running out of momentum and returning offshore in the form of a backwash/reflected wave.

As waves began washing up onto the dune during the first wave run, dune sediment became wet and was pulled into the swash zone by attacking waves. By the end of the first wave run, rapid erosion to the dune seaward slope had taken place to form a dune scarp. Typically, this dune scarp started between the 3rd and 4th rows of vegetation and stood 5 to 6 cm high. During the second wave run, the erosion dynamic shifted. Smaller waves from the JONSWAP spectrum began having less impact, barely running up to the base of the scarp. Larger waves, however, would collide with the dune scarp base and continue to erode sediment. This dynamic created a scarp overhang which would eventually slump into the swash zone as the scarp base was undermined by attacking waves. The occurrence of slumping therefore appeared to be a dominant driver of erosion. When the overhang remained intact, minimal sediment was carried offshore from the dune. When the overhang collapsed, sediment slumped into attacking waves and the more active zone of the shoreline. After this slumped sediment was moved offshore by waves, the previous dynamic of scarp overhang and base erosion was restored.

For trials without plants, two or three major slumping events would take place over the duration of the wave attacks. For plant trials, often no or only one major slumping event occurred. As slumping occurred during plant trials, large cracks formed on the dune crest and plant roots were observed to span these cracks, providing a source of attachment of the slumping sediment to the rest of the dune. Plant trial slumping events would generally be prolonged and less violent.

3.3.2 Variability of Vegetation Aspects for Flume Trials

Substantial variability in different aspects of vegetation was observed as a result of using multiple plant species and growth increments, as summarized in the green star plots of Figure 3.9. The radial axes of the green star plot represent the following terms: fine root biomass, coarse roots biomass, aboveground swash zone surface area of stems and leaves, stem rotational stiffness, and mycorrhizal colonization. The rings of the star plots represent data values relative to all other trials. For example, *S. portulacastrum* at 6 (SP6) weeks growth had the highest amount of aboveground plant surface area as indicated by a farthest reaching spoke on the "SA" axis. The axis for mycorrhizal colonization, however, simply represents percent colonization with each ring representing a 20% increment. Each control trial consists of a small center star (the center ring is actually zero).

Generally, trials can be grouped into three categories based off the approximate green area of the plant star plots: controls, low vegetation, and high vegetation. These trial groupings experienced differing amounts of erosion. The radial axes of the brown star plot (or triangle plot, rather) represent relative amounts of the following beach/dune morphological change variables: eroded volume, scarp retreat, and cross-shore centroid shift. Controls (C1, C2, C3) have zero vegetation and experienced high amounts of erosion (a large brown star plot area = high erosion, mean 64.8 cm of scarp retreat, mean 18379.4 cm^3 of dune erosion, and mean 11.9 cm for cross-shore centroid shift). Low vegetation trials (*P. amarum* 3 weeks [PA3], *R. phyllocephala* 3,6, and 9 weeks [RP3, RP6, RP9], *S. portulacastrum* 3 weeks [SP3], and *S. virginicus* 3 and 6 weeks [SV3, SV6]), which typically were below average for all vegetation variables, experienced less erosion (mean 57.9 cm for scarp retreat, mean 17588.5 cm^3 for erosion, and mean 10.7 cm for cross-shore centroid shift). Higher vegetation trials (*P. amarum* 6 and 9 weeks [PA6, PA9], *S. portulacastrum* 6 and 9 weeks [SP6, SP9], and *S. virginicus* 9 weeks [SV9]), which typically were above average for at least one vegetation variable, experienced much less erosion (mean 51.3 cm for scarp retreat, 13610.1 cm^3 for erosion, and mean 6.6 cm for cross-shore centroid shift).

Differences can be seen in the growth patterns and vegetation characteristics of

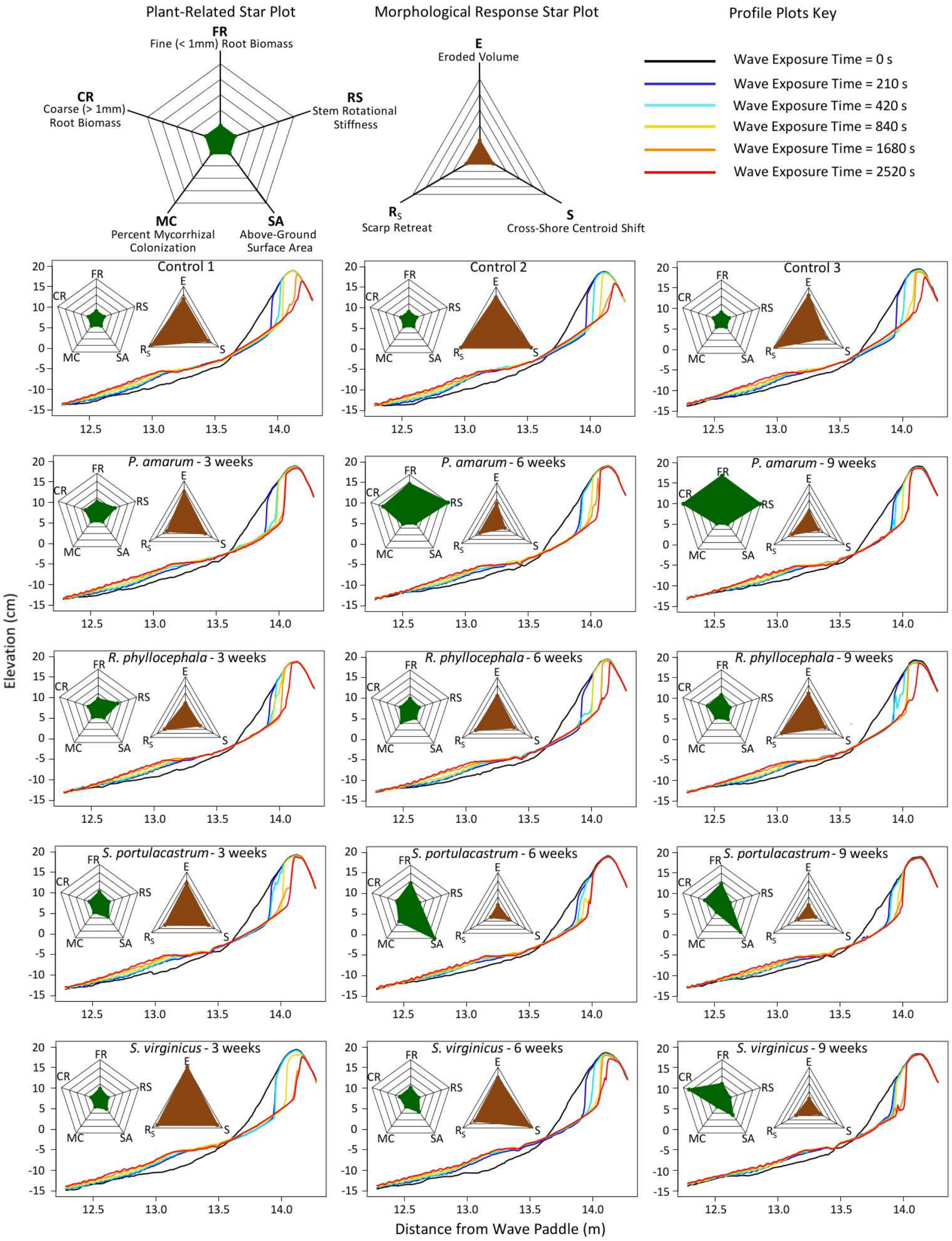

Figure 3.9: Sediment bed profile changes for all trials and wave runs along with star plots summarizing plant and beach/dune morphological change data.

the four plant morphotypes. *Panicum amarum* accumulated large amounts of both coarse and fine roots but had low amounts of aboveground surface area. This lack of surface area was largely a function of low stem density and taller plant heights which caused the majority of the plant to be above the scaled-down flume's swash zone. *Panicum amarum* also showed the highest amount of stem rigidity. *Rayjacksonia phyllocephala* did not grow much over its 9 week growth period and primarily had low amounts of all aspects of vegetation for all growth time increments. *Sesuvium portulacastrum* accumulated moderate amounts of fine and coarse root biomass and a large amount of aboveground surface area. This high amount of aboveground surface area accumulated was primarily caused by the spreading nature of this plant, where nearly all of its aboveground structures were submerged in the swash zone. This plant lacked rigidity, however. Lastly, *S. virginicus* slowly accumulated high amounts of coarse roots and moderate amounts of fine roots and aboveground surface area. This plant also lacked rigidity. No morphotypes displayed substantial mycorrhizal colonization, the lowest value being 0% and highest being 34.6% (mean = 5.4%).

Multivariate statistical modeling of these vegetation variables with regards to erosion and other physical processes will add specificity to these generalizations and are detailed in subsequent sections. It should be noted that the several of the plant variables (fine root biomass, coarse root biomass, mycorrhizal colonization, plant surface area, and stem rotational stiffness) that were analyzed in the context of swash hydrodynamics, sediment properties, and erosion responses were collinear (Figure 3.10). Fine and coarse root biomass were strongly and positively correlated to one another. Both fine and coarse root biomass were also strongly and positively correlated to rotational stiffness. Lastly, mycorrhizal colonization showed a moderate correlation to plant surface area.

3.3.3 Hydrodynamic Results

Data were collected for three hydrodynamic parameters during the flume trials: turbulent kinetic energy, average swash velocity (cross-shore direction), and wave reflection. Swash zone turbulent kinetic energy (TKE) for each wave run for each trial is summarized in a heat map (Figure 3.11). TKE tended to decrease as the time of wave exposure increased. The average TKE across all trials for the first 210 seconds of wave exposure was 0.027 J/KG and for the last 210 seconds of wave exposure was 0.015 J/KG. Plant trials, notably *P. amarum* 9 weeks (PA9), *S. portulacastrum* 6

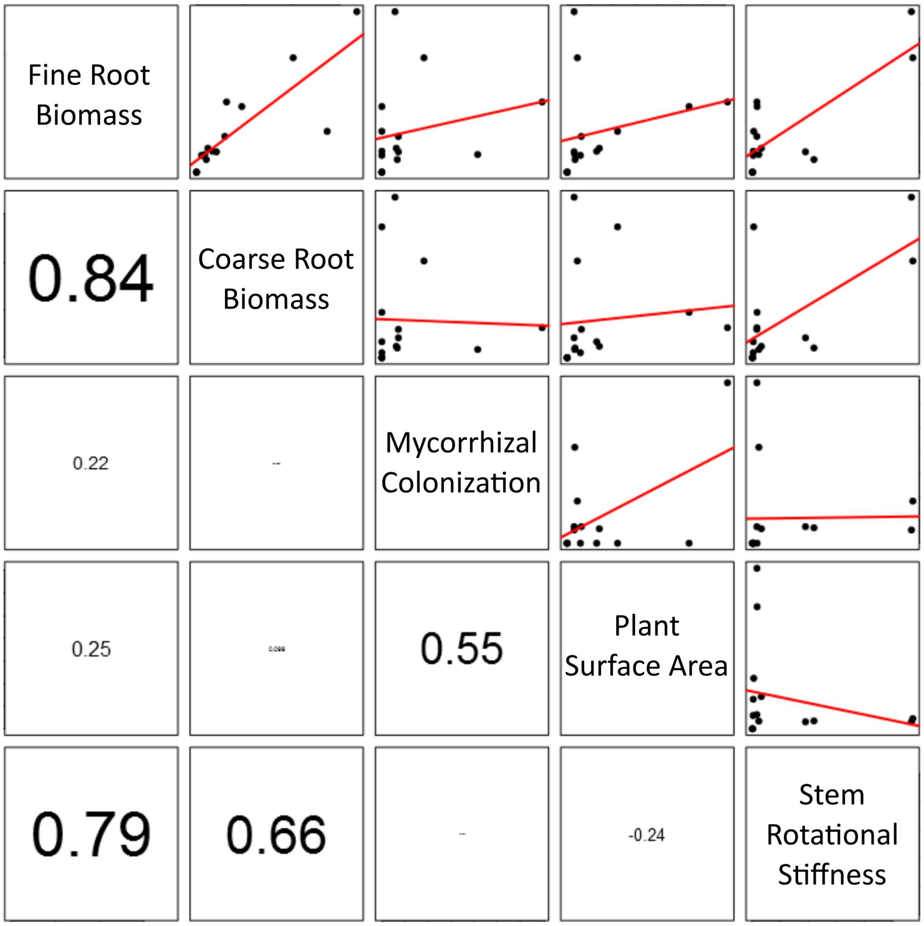

Figure 3.10: Collinearity between plant variables. These variables are aligned diagonally from top left to bottom right. The top right half of the figure is composed of scatter plots and trend lines for each combination of plant variables. In a mirror image, the bottom left half of the figure contains the correlation coefficients (r) for each combination of variables (text size is indicative of the strength of the correlation).

and 9 weeks (SP6, SP9), and *R, phyllocephala* 9 weeks (RP9), had lower TKE by the end of wave exposure than other trials (indicated by the dark blue in Figure 3.11). TKE was modeled by vegetation and confounding variables and was summarized in Table 3.2 (Model 3.1). The aboveground plant surface area of stems and leaves were negatively and significantly related to TKE, wave runs with more abundant aboveground structures had reduced swash turbulence. Additionally, a larger distance from the ADV sensor head to the sediment bed and larger wave heights significantly increased TKE while a longer elapsed time of wave exposure significantly decreased TKE.

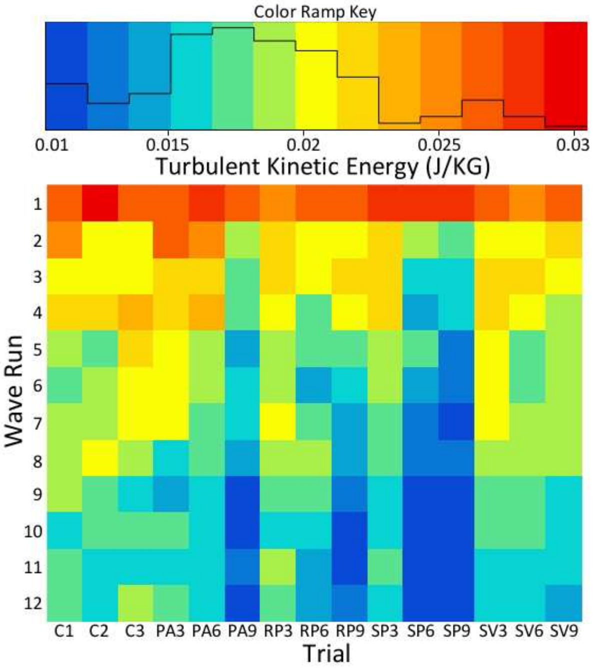

Figure 3.11: Heat map summarizing turbulent kinetic energy (TKE) by trial and wave run. Each wave run represents 210 seconds of wave attack. Trial abbreviations: C = Control, PA = *P. amarum*, RP = *R. phyllocephala*, SP = *S. portulacastrum*, SV = *S. virginicus.* 3, 6, and 9 refer to 3, 6, and 9 weeks of growth for the plants. For the controls, 1, 2, and 3 simply refer to the 3 control replicates.

Swash zone velocity (both uprush and downrush, cross-shore direction) for each wave run for each trial is summarized in a heat map (Figure 3.12). Unlike TKE,

Table 3.2: Model 2.1: Predicting the turbulent kinetic energy by vegetation and other confounding parameters.

Variable	Slope	Standard Error	p value
Aboveground Plant Surface Area (cm^2/cm)	-4.476E-04	8.304E-05	5.4E-16
ADV Distance from Sediment Bed (cm)	0.002365	5.926E-04	9.7E-05
$H_{1/3}$ (s)	0.002062	8.236e-04	0.0132
Time of Wave Exposure (s)	-3.647E-06	2.571e-07	<2.0E-16
Intercept	0.008014	0.005499	0.15
Adjusted R^2			0.705
Overall p value			<2.2E-16
n = 180			

Notes: The plant-related and confounding variables that were modeled can be seen in Table 3.1.

swash velocity tends to be more erratic, typically increasing initially and then decreasing after further wave exposure. Generally, plant trials tended to have lower swash velocities than controls trials (controls mean velocity = 0.272 m/s, all plants mean velocity = 0.238 m/s). Swash zone velocity was modeled by vegetation and confounding variables and summarized in Table 3.3. Similar to TKE, plant surface area was also a significant predictor of reduced swash velocity. Confounding variables that significantly related to swash velocity were as follows: deeper sand bar depths (a less developed sand bar) and steeper shoreline slopes increased swash velocity while the elapsed time of wave exposure and the distance from the ADV sensor-head to the sediment bed decreased swash velocity.

Wave reflection coefficients for each 400 second wave series for each trial are summarized in a heat map (Figure 3.13). Generally, the shoreline was more dissipative across most plant trials and decreased over the course of each trial. The average reflection coefficient for all trials from 1 - 400 seconds (the first 2 wave runs) was 0.28, whereas at 2201-2400 seconds (the last 2 wave runs) was 0.23. Across all plant trials, average wave reflection coefficient was 0.23 compared to 0.27 for control trials. The wave reflection coefficient is modeled by vegetation and confounding variables and is summarized in Table 3.4. Numerous variables significantly predicted the amount of wave reflection during a wave run. The only vegetation parameter to significantly relate to wave reflection was the aboveground plant surface area, more plant surface

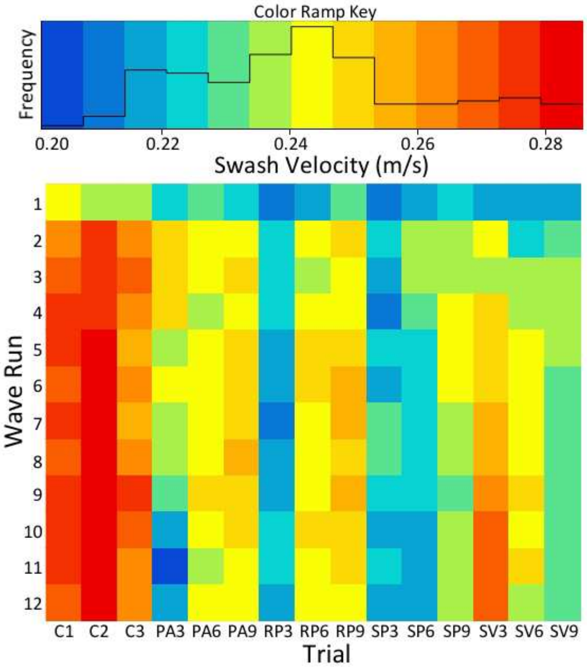

Figure 3.12: Heat map summarizing swash velocity by trial and wave run. Each wave run represents 210 seconds of wave attack. Trial abbreviations: C = Control, PA = *P. amarum*, RP = *R. phyllocephala*, SP = *S. portulacastrum*, SV = *S. virginicus*. 3, 6, and 9 refer to 3, 6, and 9 weeks of growth for the plants. For the controls, 1, 2, and 3 simply refer to the 3 control replicates.

Table 3.3: Model 2.2: Predicting swash velocity by vegetation and other confounding parameters.

Variable	Slope	Standard Error	p value
Aboveground Plant Surface Area (cm^2/cm)	-0.001584	3.096E-04	8.2e-07
Sand Bar Depth (cm)	0.02644	0.003883	1.5E-10
Swash Zone Slope (degrees)	0.01511	0.001669	2.80E-16
ADV Distance from Sediment Bed (cm)	-0.01469	0.003529	4.9E-05
Time of Wave Exposure (s)	-4.910E-05	1.730E-06	0.0051
Intercept	0.01414	0.02377	0.55
Adjusted R^2			0.510
Overall p value			$< 2.2E-16$
n = 180			

Notes: The plant-related and confounding variables that were modeled can be seen in Table 3.1.

area decreasing the amount of reflected energy from a shoreline. Other significant confounding variables included: the depth of the sand bar, the location of the sand bar, the slope of the shoreline, and the time of wave exposure. A larger sand bar depth (a less developed sand bar), a sand bar that was closer to the shoreline (further from the wave paddle), and a steeper shoreline slope increased wave reflection. A longer amount of wave exposure decreased wave reflection.

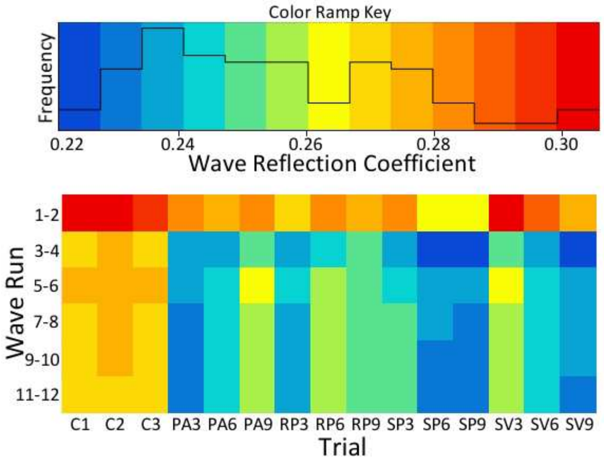

Figure 3.13: Heat map summarizing wave reflection by trial and wave run. Each wave run represents 210 seconds of wave attack (each row in this figure therefore represents 420 seconds). Trial abbreviations: C = Control, PA = *P. amarum*, RP = *R. phyllocephala*, SP = *S. portulacastrum*, SV = *S. virginicus*. 3, 6, and 9 refer to 3, 6, and 9 weeks of growth for the plants. For the controls, 1, 2, and 3 simply refer to the 3 control replicates.

TKE, swash velocity, and wave reflection were all significantly related to aboveground plant surface area. Additional modeling showed that TKE and swash velocity were positively related to wave reflection, though not significantly related to one another (Figure 3.14). Furthermore, wave reflection was positively related to both TKE and swash velocity simultaneously in a multivariate model (Table 3.5). This implies that TKE and swash uprush/backwash velocities form an intermediate linkage between aboveground vegetation and shoreline dissipation efficiency (wave reflection).

Table 3.4: Model 2.3: Predicting the wave reflection coefficient by vegetation and other confounding parameters.

Variable	Slope	Standard Error	p value
Aboveground Plant Surface Area (cm^2/cm)	-0.002054	3.226E-04	9.6E-09
Sand Bar Depth (cm)	0.03384	0.005814	1.0E-07
Sand Bar Location (cm from Paddle)	8.347E-04	3.029E-04	0.0071
Swash Zone Slope (degrees)	0.005831	0.001732	0.0012
Time of Wave Exposure (s)	-2.630E-05	8.233E-06	0.0020
Intercept	-2.376	0.8377	0.0057
Adjusted R^2			0.5881
Overall p value			6.1E-16
n = 90			

Notes: The plant-related and confounding variables that were modeled can be seen in Table 3.1.

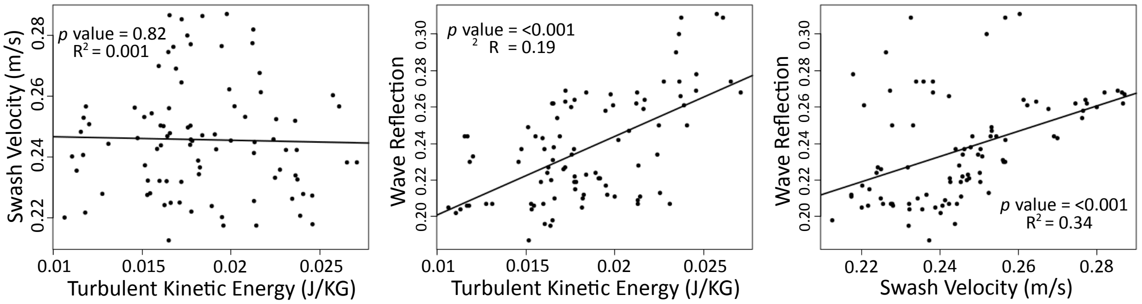

Figure 3.14: A: Collinearity of TKE and swash velocity. B: Collinearity of TKE and wave reflection. C: Collinearity of wave reflection and swash velocity.

Table 3.5: Model 2.3.1: Predicting the wave reflection coefficient by turbulence and swash velocity.

Variable	Slope	Standard Error	p value
Turbulent Kinetic Energy (J/KG)	4.389	0.5232	8.0E-13
Swash Velocity (m/s)	0.7167	0.1113	6.4E-09
Intercept	-0.01972	0.02928	0.50
Adjusted R^2			0.5464
Overall p value			4.3E-16
n = 90			

3.3.4 Sediment Properties

Data were collected on two sediment properties: shear strength and effective grain size (aggregation). For shear testing, both cumulative shear (the area under a shear curve) and peak shear were evaluated for relationships with root properties within tested cores. Peak shear showed no correlation to any root properties measured from the core. However, fine root biomass was positively and significantly related to cumulative shear (Figure 3.15) and displayed a stronger relationship than coarse root biomass or total root biomass. Figure 3.16 shows a comparison of sediment shear curves between a core taken from *S. virginicus* at 9 weeks (SV9, the plant/growth increment with the highest cumulative shear as well as the highest fine root density) and a control core. The two shear curves have similar peaks but the core with plant material resisted a continuously high shear stress throughout the full length of the shear test. In contrast, the control core essentially crumbled when shear stress built up. No significant trend was found between sediment aggregation (effective grain size) and mycorrhizal colonization or fine root biomass (Model 2.5, p value = 0.70, $R^2 = 0.15$).

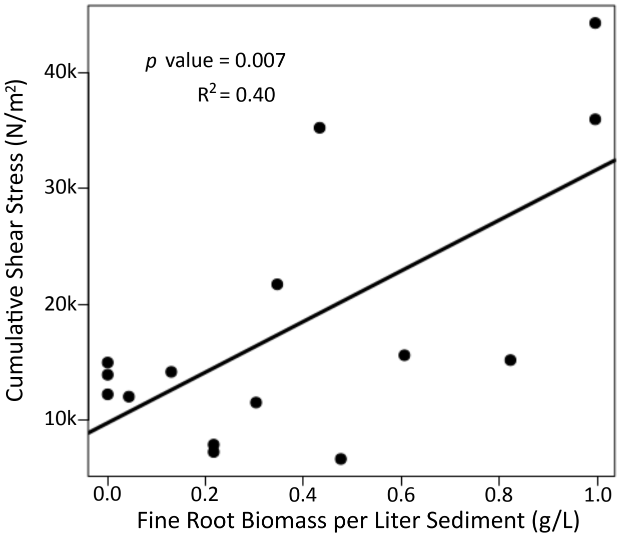

Figure 3.15: Linear regression model (Model 2.4) for cumulative sediment shear strength as predicted by the fine root biomass density in the sheared sediment.

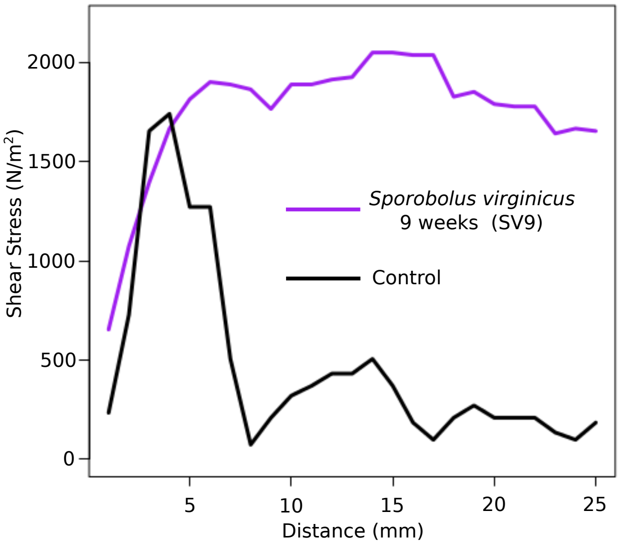

Figure 3.16: A shear curve comparison between a core taken from *S. virginicus* at 9 weeks and a control core.

3.3.5 Beach and Dune Morphological Changes

Three erosion metrics were calculated from the beach and dune morphological data from each trial: volume of eroded sediment, scarp retreat, and the offshore centroid shift. All three of these variables were modeled by vegetation variables as well as confounding variables. Eroded volume modeling is summarized in Table 3.6. Fine root biomass and aboveground plant surface area were significantly and negatively related to eroded volume of sediment that occurred during a trial, less erosion occurred for trials with higher amounts of fine roots and aboveground plant surface area. For each additional 0.1 g/L of fine roots (dry), erosion was reduced by roughly 1.2k cm^3 or about 6.6% of the average erosion that occurred during the control trials. Erosion was reduced by roughly 380 cm^3 ($\approx$ 2.1% of the average erosion that occurred during the control trials) for each cm^2 of plant surface area per long-shore cm of shoreline. Also, the initial cross-shore centroid of the near shore zone positively and significantly related to eroded volume of sediment, more erosion occurred in trials where sediment was initially distributed higher up on the beach and dune profile. Additionally, eroded volume was modeled by each trial's average wave reflection coefficient in the place of aboveground plant surface area (Table 3.7).

Table 3.6: Model 2.6: Predicting dune erosion by vegetation and other confounding parameters.

Variable	Slope	Standard Error	p value
Fine Root Biomass (g/L)	-1.213E04	4383	0.018
Aboveground Plant Surface Area (cm^2/cm)	-377.28	10.25	0.024
Initial Cross-Shore Centroid (cm from Paddle)	257.3	98.88	0.0036
Intercept	-39,490	13,570	0.031
Adjusted R^2			0.743
Overall p value			3.9E-04
n =15			

Notes: The plant-related and confounding variables that were modeled can be seen in Table 3.1.

Table 3.7: Model 2.6.1: Predicting dune erosion by wave reflection and fine root biomass as a proxy of sediment shear strength, as well as confounding variables.

Variable	Slope	Standard Error	p value
Fine Root Biomass (g/L)	-1.336E04	5774	0.0392
Wave Reflection Coefficient	6.234E04	2.342E04	0.021
Intercept	-2508	5688	0.66
Adjusted R^2			0.528
Overall p value			0.0044
n =15			

The scarp retreat model is summarized in Table 3.8. For this model, again both fine root biomass and aboveground plant surface area were significantly and negatively related to dune scarp retreat, less scarp retreat occurred for trials with higher amounts of fine roots and aboveground plant surface area. For each additional 0.1 g/L of fine roots (dry), scarp retreat was reduced by roughly 3 cm or about 4.6% of the average retreat that occurred in the control trials. Scarp retreat was reduced by roughly 1.1 cm (≈ 1.7% of the average scarp retreat that occurred during the control trials) for each cm^2 of plant surface area per long-shore cm of shoreline. There were no confounding variables that significantly predicted scarp retreat. Scarp retreat was also modeled to wave reflection in substitution to aboveground plant surface area (Table 3.9).

Table 3.8: Model 2.7: Predicting scarp retreat by vegetation and other confounding parameters.

Variable	Slope	Standard Error	p value
Fine Root Biomass (g/L)	-29.82	9.486	0.0086
Aboveground Plant Surface Area (cm^2/cm)	-1.083	0.2355	6.12E-04
Intercept	61.46	1.103	7.4E-16
Adjusted R^2			0.697
Overall p value			3.1E-04
n =15			

Notes: The plant-related and confounding variables that were modeled can be seen in Table 3.1.

Table 3.9: Model 2.7.1: Predicting scarp retreat by wave reflection and fine root biomass as a proxy of sediment shear strength, as well as confounding variables.

Variable	Slope	Standard Error	p value
Fine Root Biomass (g/L)	-18.62	6.603	0.015
Wave Reflection Coefficient	212.4	26.80	4.1E-06
Intercept	7.990	6.510	0.24
Adjusted R^2			0.866
Overall p value			2.3E-06
n =15			

Lastly, off-shore centroid shift of sediment in the beach and dune region is summarized in Table 3.10. Consistent with the other measures of erosion, off-shore centroid shift was also significantly and negatively related to fine root biomass and aboveground swash zone surface area. In trials with more fine roots, stems and/or leaves (aboveground surface area), the offshore shift of sediment was reduced. For each additional 0.1 g/L of fine roots (dry), off-shore centroid shift was reduced by roughly 1.1 cm or about 9.6% of the average centroid shift that occurred in the control trials. Cross-shore centroid shift was reduced by roughly 0.2 cm ($\approx$ 1.8% of the average off-shore centroid shift that occurred during the control trials) for each cm^2 of plant surface area per long-shore cm of shoreline. Additionally, when the initial shore profile centroid was more landward on the dune and beach profile, the cross-shore centroid shift during wave exposure was increased. These three models (Models 2.6 - 2.8) all had similar predictive variables, likely because the predicted beach and dune morphological change variables (eroded volume, scarp retreat, and offshore centroid shift) were correlated to one another (Figure 3.17). Nevertheless, vegetation variables consistently and significantly reduced the magnitude of morphological changes in the beach/dune profile.

Table 3.10: Model 2.8: Predicting off-shore centroid shift for sediment in the beach and dune region by vegetation and other confounding parameters.

Variable	Slope	Standard Error	*p* value
Fine Root Biomass (g/L)	-11.44	3.031	0.0031
Aboveground Plant Surface Area (cm^2/cm)	-0.2228	0.07091	0.0094
Initial Cross-Shore Centroid (cm from Paddle)	0.5130	0.06835	1.2E-05
Intercept	-693.0	93.86	1.39E-05
Adjusted R^2			0.901
Overall *p* value			2.1E-06
n = 15			

Notes: The plant-related and confounding variables that were modeled can be seen in Table 3.1.

3.3.6 Model Integration

All the models described in previous sections of this chapter are summarized in Figure 3.18, with lines representing significant relationships (models) between variables.

Table 3.11: Model 2.8.1: Predicting off-shore centroid shift by wave reflection and fine root biomass as a proxy of sediment shear strength, as well as confounding variables.

Variable	Slope	Standard Error	p value
Fine Root Biomass (g/L)	-9.792	3.405	0.012
Wave Reflection Coefficient	34.02	13.72	0.03
Initial Cross-Shore Centroid (cm from Paddle)	0.4951	0.07738	5.1E-05
Intercept	-677.1	105.4	4.9E-05
Adjusted R^2			0.880
Overall p value			6.2E-06
n =15			

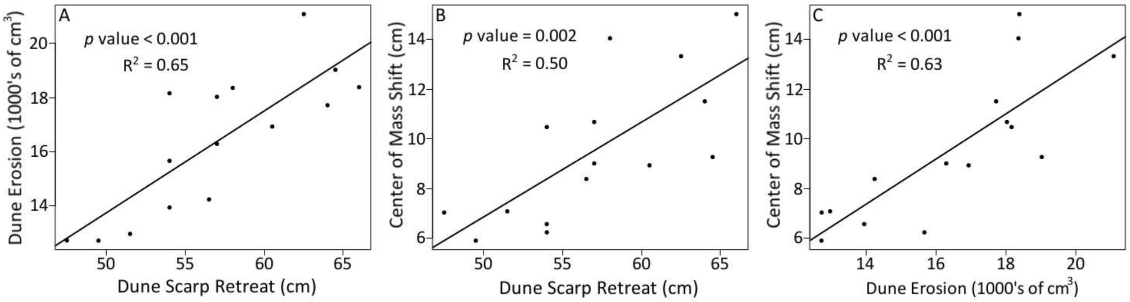

Figure 3.17: A: Collinearity of dune erosion and scarp retreat. B: Collinearity of offshore centroid shift and scarp retreat. C: Collinearity of offshore centroid shift and dune erosion.

Dune morphological change variables (eroded volume, scarp retreat, and off-shore centroid shift) have been collapsed into one variable (erosion) for clarity due to their collinear nature. Lines pointing to the dune morphological change box imply that a significant relationship was found for all three dune morphological change variables. No confounding variables were shown in this diagram. The key plant-based determinants linked to dune morphological changes during these tests were aboveground surface area and fine root biomass. Statistically, both of these variables were significantly and directly tied to dune morphological change and were also linked to these dune morphological changes via physical processes. Plant surface area was negatively related to both swash zone TKE and uprush/downrush velocity, which, in turn, were both positively related to wave reflection. Wave reflection, a proxy for the dissipative efficiency of a shoreline, was also consistently and significantly linked to dune morphological changes. Because sediment shear data were based on cores taken from a harvested plant, there was no way to link shearing data directly to dune morphological change data collected for each flume trial. However, fine roots biomass was significantly related to both cumulative sediment shear strength and dune/beach morphological changes. Because fine roots were correlated to both in this experiment, it seems likely that sediment shear strength is the causal link between fine roots and erosion resistance.

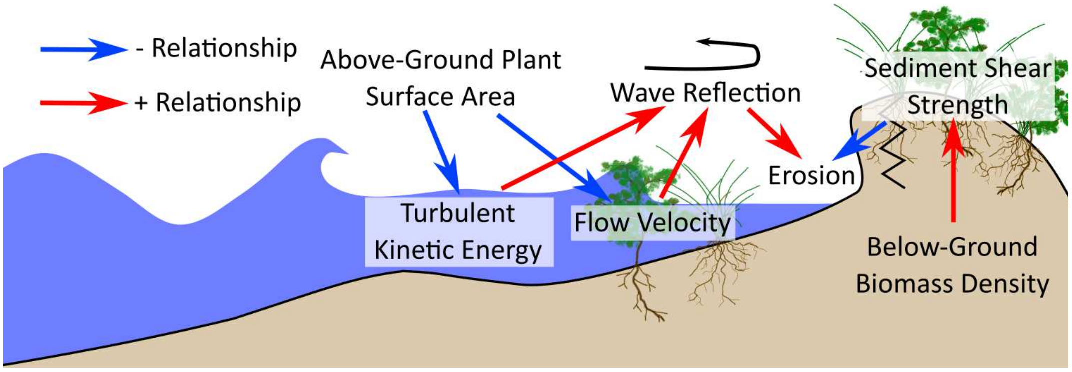

Figure 3.18: All model results pertaining to the relationships of vegetation to sediment, hydrodynamics, and dune morphology changes.

3.4 Discussion

3.4.1 Model Summaries and Research Outlook

This flume experiment showed that both aboveground and belowground aspects of vegetation are relevant in dune protective capabilities and erosion resistance. The surface area of aboveground plant structures was a key determinant of erosion reduction by creating a more dissipative shoreline and a less energetic swash zone. This calming effect in both turbulence and flow velocity has been observed in other hydrological settings with emergent vegetation (Leonard & Luther, 1995), but this is the first time it has been observed in a swash setting for a beach/dune profile using real plants. The fine roots of plants were also key determinants of erosion reduction, enhancing sediment shear strength and making dune systems less prone to slump and collapse.

The effect of vegetation on erosion was substantial. Under this flume's experimental conditions, based off Model 2.6 in Table 3.6, vegetation with the aboveground surface area of *S. portulacastrum* at 9 weeks growth and the fine root biomass of *P. amarum* at 9 weeks growth would have experienced roughly 37% percent less erosion than a trial without vegetation. This is comparable to the results of other flume tests with vegetation, which also found that erosion was reduced by a factor of $^1/_3$ when vegetation was present on a dune's seaward face (Kobayashi *et al.*, 2013; Sigren *et al.*, 2014; Silva *et al.*, 2016). This erosion reduction, because it occurs over a period of wave exposure, is also a reduction in the rate of erosion. If wave attack was allowed to continue until the dune breached, presumably dune breach would be delayed by the presence of vegetation. A prolonged dune breach could mean that dune storm damage mitigation with regards to homes and infrastructure is enhanced by vegetation, though that would depend on the flume results scaling to larger systems (discussed later in this section).

Following this train of thought, managing and restoring dunes so that the aboveground surface area of plant structures and fine root biomass are increased would, in concept, create a dune system capable of mitigating more storm damage. This management practice would likely have to rely on multiple plant species, some that have higher allocation of resources to aboveground structures and some that have extensive and dense root systems. Additionally, aboveground structures would have the greatest impact in an area where they are coming into contact with incoming waves, notably the seaward base of the dune and embryonic dune systems (at least for a wave collision scenario that is similar to one that was used in this flume experiment). Roots, on the other hand, are more important in areas where a scarp (the dune ridge and slopes) forms because of their contribution to sediment shear strength. Targeting different zones of the dune with specific plant morphotypes in this way could further enhance dune protective capabilities.

3.4.2 Limitations and Scaling of Experiment

There are numerous limitations to the approach taken in this experiment. Plants used during flume testing were grown in pots before being transplanted into the flume setting and subjected to wave attack. There was no acclimation period, meaning that root systems were contained with pot-like shapes below ground and aboveground plant structures were interspersed in an unnatural manner. This arrangement is not comparable to real systems, where plant features are interconnected and fairly equal in dispersal. The usage of pots therefore could have altered erosion, sediment, and hydrodynamic properties and makes direct extrapolation of results to real systems questionable. However, the general trends that were observed would still occur.

Due to the usage of a small-scale wave flume, the obtained results are not necessarily applicable to larger dune systems. In other words, if we added a comparable density of vegetation as was used in the *S. portulacastrum* 9 weeks (SP9) flume trial to a Galveston sand dune and the dune was impacted by a larger surge and wave regime, it should not be expected that a comparable amount of erosion reduction would occur. For one, this flume's scaling down of dune volumetric size and wave energy does not scale down grain size. This lack of scaling is because it would shift sediment size into the fines range (silts and clays), which possesses cohesive properties and would alter erosion greatly. Therefore the sediment used in this experiment would be more comparable to coarse sand or fine gravel and therefore the dynamics of the erosion that occurred would be different than a dune in Galveston.

Moreover, the real plants that were used in this experiment could not be scaled down in any way. For example, *S. portulacastrum* would likely function differently on a large dune during a storm surge. In the flume trial, the swash zone depth was only around 5 cm deep, meaning that the aboveground plant structures of *S. portulacastrum* extended into the entirety of the water column. In a scaled up dune and surge, this plant would only be at the very bottom of the swash water column and would likely not affect swash zone hydrodynamics in the same ways. Additionally, during the flume experiment, the roots of *S. portulacastrum* extended deep into the dune, almost down to the base when planted on the top of the dune ridge. However, in a scaled up scenario, *S. portulacastrum* root systems would be shallower with respect to a large dune. These shallow roots would not be able to reinforce the entirety of any scarp that formed, only the sediment near the surface of the dune. This difference in sediment shear strength reinforcement could cause a scaled up scenario to deviate from the scaled down flume results. Alternatively, *P. amarum* would likely grow much deeper roots *in situ* than in a pot, potentially reinforcing *in situ* dunes more than the scaled down flume dune. Additionally, due to the nature of *in situ* sand burial of plant structures over time (Mendelssohn *et al.*, 1991), plant roots can extend deep into a dune's base as sediment builds on top of the dune plant over time. This dynamic could create a scenario where *in situ* dunes are more deeply reinforced with roots than the dune tested in this wave flume experiment.

This experiment also treated all plant species the same with regards to vegetation aspects. For example, one gram of fine root biomass for *P. amarum* is equivalent to one gram fine root biomass of *R. phyllocephala* with regards to its impact on sediment shear strength. However, by dividing the cumulative shear curve model into each component species (Figure 3.19), it can be seen that each species differentially affects cumulative soil shear. *Panicum amarum* and *S. portulacastrum* show little to no trend between fine root biomass and cumulative shear whereas *R. phyllocephala* and *S. virginicus* show a strong positive trend (though none of these trends are significant due to the small sample size). It was observed by the researcher when separating coarse and fine roots that *P. amarum* and *S. portulacastrum* root structures were weaker than the other species. Presumably, the underlying physiology and anatomy of these species' root systems causes them to have lower tensile strength in proportion to their mass. The differences in various non-quantified aspects of these species could have added noise to the modeling process and needs to be explored further.

Lastly, even if a variable was not demonstrated to be a significant determinant of erosion or physical processes, it does not necessarily mean that it is meaningless in this regard for *in situ* dune systems. Rather, the methodology utilized to model variation in these variables could have been inadequate. For example, sediment aggregation should, in concept, lead to less erosion in sand dunes. That is to say, if a substantial amount of sediment particles are bound together in a water-stable

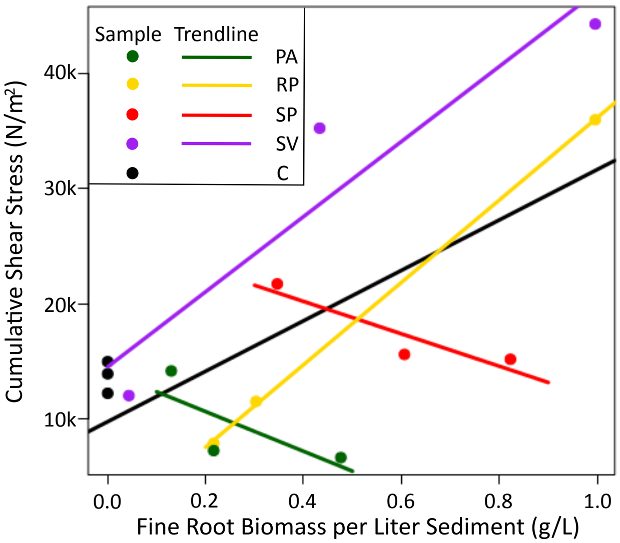

Figure 3.19: Linear regression model for cumulative sediment shear strength as predicted by the fine root biomass density in the sheared sediment subdivided by species. PA - *Panicum amarum*, RP - *Rayjacksonia phyllocephala*, SP - *Sesuvium portulacastrum*, SV - *Sporobolus virginicus*, C - Control. The black line indicates the trend line for the entire data set.

manner as to shift that sediment's effective grain size distribution, less erosion would take place. Such sediment binding has been measured in dune systems (Forster & Nicolson, 1981), but may take place over a number of years as organic materials build up in soil and mycorrhizal fungi increase in abundance. The time allotted for plant growth in this experiment (3 - 9 weeks) was probably not a long enough time for these soil structures to develop. Additionally, the sediment utilized in the wave flume contained clay which was already bound into large aggregates, creating a somewhat gap-graded sediment grain size distribution. Such large clay conglomerates, combined with the small sample of sediment that had to be used with the wet sieving methodology ($\approx$ 50 g), could have added noise to statistical modeling. The topic of sand dunes and biologically driven soil structure development needs to be explored further to illuminate its importance in erosion resistance.

Additionally, the collinear relationship of certain plant parameters means that statistical modeling techniques could not verify each variables effect on dependent variables. Fine and coarse roots, for example, were collinear during this experiment. Fine root biomass density was found to be a more significant predictor of dune erosion during statistical modeling but both variables could be important to dune erosion resistance. Further testing of a broader range of variable combinations (a non-collinear dataset) would need to be conducted to parse the independent contribution of these two belowground variables.

3.5 Concluding Statements

In conclusion, this flume experiment showed that both above- and belowground aspects of vegetation are meaningful and significant determinants of dune erosion. The surface area of aboveground plant structures was related to decreases in turbulence and uprush/backwash velocities, helping create a shoreline that was more effective at dissipating incoming wave energy. Fine roots increased the mechanical strength of sediment, making it more resistant to shearing forces and preventing sediment from slumping into incoming waves. In concept, increasing the amounts of these above- and belowground aspects of vegetation for a dune would create a dune system more resistant to erosive forces. However, the nature of the flume experiment, both with regards to transplant usage and scaling, makes direct *in situ* extrapolation of these results not possible. Nevertheless, these results provide additional insight on the ongoing conversation about using natural systems to carry out sustainable engineering goals. Future research on this topic should expand upon these findings at larger scales, both regards to size and time, with the ultimate aim of guiding coastal dune management and restoration techniques.

4. LESSONS FROM TEXAS COASTAL DUNE RESTORATION PART 1: THE EVALUATION OF MULTIPLE RESTORATION TECHNIQUES [1]

4.1 Background Information

4.1.1 The Challenges of Dune Restoration

In the last chapter, it was postulated that targeting specific morphotypes or species of dune plants could enhance resistance to erosion. Additionally, increasing the root biomass or aboveground structure density of a dune system could also enhance erosion resistance. Ultimately, coastal stakeholders want dunes that are resistant to breach and erosion during storms (at least for areas where dunes are protecting homes and infrastructure, a more thorough assessment of dune restoration goals and tradeoffs will be discussed in Chapter 5). However, the best way to accomplish this goal is not well understood for Texas dune systems. A large issue hampering dune restoration is the stressful and inhospitable nature of the coastal dune environment. Dune plants experience salt spray, wind abrasion and sand burial, low soil moisture due to rapid drainage of sandy soils, potential salt water intrusion during spring tides and storms, and low nutrient levels in soils (Gilbert *et al.*, 2008; Wilson & Sykes, 1999). Due to these inhospitable conditions, restoration of dunes can often result in low transplant survival and growth (Feagin *et al.*, 2009; Mendelssohn *et al.*, 1991). Therefore, restoration techniques need to be developed for this coastal ecosystem that compensate for the challenges of the harsh environment.

4.1.2 Mycorrhizal Fungi Inoculation

Arbuscular mycorrhizal fungi (AMF) are abundant plant endosymbionts. Dune plants and AMF can enter into a beneficial relationship that mutually improves survival and fitness of both fungi and the plant host. These fungi embed into the root cortex cells of numerous plant species, funneling nutrients from the surrounding soil through hyphae (root-like structures) to their host plant and receiving plant sugars

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[1] Author's Note on Copyright: Some of the material in this chapter has been published in Shore and Beach in 2014 under the title, "Coastal sand dunes and dune vegetation: Restoration, erosion, and storm protection". For referencing, please cite that publication in conjunction with this dissertation.

in compensation. They also can increase their plant host's salt and drought tolerance (Augé, 2001; Füzy *et al.*, 2008), diminish the presence of root parasites (Moon *et al.*, 2013), improve soil stability (Tisdall & Oades, 1982), and reduce erosion (O'Dea, 2007). Because of their potential to increase plant fitness, the integration of AMF into restoration ecology is gaining traction (Eviner & Hawkes, 2008). Numerous studies have utilized AMF inoculum (a source of active AMF that colonizes plant roots) in ecosystem restoration, including coastal sand dunes, to increase restored plant growth, coverage, reproductive output, and survival (Gemma & Koske, 1997; Smith *et al.*, 1998; Sylvia *et al.*, 1993).

Coastal sand dunes are prime candidates for AMF inoculum usage in habitat restoration for two reasons. First, AMF are exceptionally prevalent in coastal dune plants (Corkidi & Rincòn, 1997) as many of the benefits they provide alleviate the stresses that are common in dune habitats. Secondly, the nature of AMF dispersal and dune geomorphology make it unlikely for degraded or newly constructed dunes to naturally possess AMF. AMF possess large spores and no broadcast reproductive structures. Instead, they rely on the erosion and deposition of topsoil by wind for dispersal. Because coastal dune formation depends on ocean winds blowing beach sediment (devoid of plants or AMF) landward, most sand entering coastal dunes ecosystems likely does not contain any AMF spores. Cores taken from the Texas Coast found that vegetated areas in dunes had more that 50× more AMF spores than non-vegetated areas (Sigren *et al.*, 2014). One of the objectives of the research conducted for this chapter was to evaluate the impact of different microbial inoculums (*e.g.,* commercially available mycorrhiza, native soils with a more complete microbial biota) on transplant growth and survival.

4.1.3 *Sargassum* (Seaweed) as a Resource

Sargassum natans and *Sargassum fluitans* wash onto the beaches of Texas and other Gulf Coast states in large mats, disrupting local tourism during the late spring and summer (Webster & Linton, 2013) (Figure 4.1). Beaches are often raked to remove the unsightly material and encourage tourism, but the issue of what to do with the raked material remains unresolved. Excessive and nuisance macroalgae have been used as compost material to increase coastal dune plant growth (Winberg *et al.*, 2013), including *Sargassum* and Texas plant species (Williams & Feagin, 2010). *Sargassum* wrack contains nitrogen and phosphorous (Oyesiku & Egunyomi, 2014), which can be limiting factors of dune plant growth (Gilbert *et al.*, 2008; Hester & Mendelssohn, 1990; Kachi & Hirose, 1983). Large scale implementation of *Sargassum* in sand dune restoration could solve two problems at once: boosting tourism to beaches by removing the material while bolstering dune plant growth in a nutrient starved ecosystem. Another restoration technique that was evaluated in this chapter was the use of "*Sargassum* bales", or *Sargassum* that was compacted into dense blocks before being buried in sand to create a dune.

Figure 4.1: *Sargassum* wrack washes up onto the beach in front of the Galveston Seawall, disrupting beach access and tourism.

4.1.4 Sprigs vs. Rooted Plants

Many dune grasses have the ability to generate roots from root and stem nodes. For this reason, simply planting clippings/sprigs of these grasses is a commonly used restoration practice for Texas dunes (Patterson, 2005). However, it has not been determined how successful this technique is compared to the conventional - but more expensive and time consuming - growing of potted plants for transplant. A study conducted on tropical rainforest trees found that transplanted tree stakes (full grown trees with branches removed but root systems largely intact) outperformed both transplanted saplings and seeds in terms of canopy coverage, root biomass, and aboveground biomass over a three year period (Zahawi & Holl, 2009). Moreover, they found that the ecological benefits of using larger plants outweighed their cost and labor. Whether or not this pattern occurs with coastal dunes when comparing sprigs to potted plants is unknown. Conceptually, potted plants would have more developed root systems and larger energy reserves for growth which would give them an advantage upon transplantation. Therefore, another objective of this research project was to determine if there were any differences in plant growth and survival when using these different planting techniques. All of the research objectives of this chapter are summarized in Table 4.1, organized by the different sections which compose this chapter.

Table 4.1: Summary of Objectives

Section	Research Objectives
Greenhouse	• Observe the effect of mycorrhizal inoculum on *Panicum amarum* growth in a controlled setting • Grow materials for dune transplantation
Individual Transplant Monitoring	• Observe the effect of mycorrhizal inoculation, *Sargassum* bales, and planting technique (rooted plants vs. sprigs) on *in situ Panicum amarum* growth and survival • Examine the interactions between treatment effects

4.2 Methods

The following research in this chapter (methods, results, and discussion) is composed of two subsections: a greenhouse experiment and dune transplant monitoring. The primary objectives were to evaluate the effect of mycorrhizal inoculation, *Sargassum*, and planting technique (sprig vs. potted plant) on dune vegetation transplant growth and survival. However, because sprigs were compared to potted plants, it meant potted plants needed to be grown prior to restoration in a greenhouse. This setup created the opportunity to test mycorrhizal inoculation in a more controlled environment within a greenhouse. A subset of plants were harvested after the greenhouse growth period, prior to transplantation, to observe the effects of mycorrhizal inoculum on plant growth. This growth is described in the greenhouse subsection in this chapter (Table 4.1, Row 1). After this sampling, plants were transplanted to the dune and sampled for growth and survival after 12 and 36 weeks, described in the second subsection (Table 4.1, Row 2). At this point, individual transplant markers had been buried due to sand accumulation and transplants had overgrown one another. As transplants were no longer discernible from one another, individual transplant monitoring was discontinued.

4.2.1 Greenhouse Preparation and Sampling Prior to Restoration

P. amarum was the species of dune grass used for this experiment. This species was selected because it has high survival following transplantation (Mendelssohn *et al.*, 1991). Three mycorrhizal treatments were evaluated during this experiment. The first was a native inoculum containing soil, spores, hyphae, and plant roots from a local sand dune ecosystem (with *P. amarum* present) in Galveston, Texas. The second was a commercial inoculum (BioOrganics Endomycorrhizal Inoculant containing spores of *Glomus aggregatum, G. etunicatum, G. clarum, G. deserticola, G. intraradices, G. monosporus, G. mosseae, Gigaspora margarita*, and *Paraglomus brasilianum*). The third and last treatment was a control with no active mycorrhizal spores. All inoculums contain sterilized (by heating inoculums to 150^{o}C for 4 hrs) versions of the other inoculums to control for nutrient input.

P. amarum sprigs were harvested from Galveston, TX (29.3170281,-94.8227785) and planted into two liter pots containing sand from a Texas coast sand pit (same as the wave flume sand in Chapter 3). As this sand was dug out of a sand pit (historically buried sediment) and stored indoors, it was assumed to be sterile of mycorrhizal spores. All roots were removed from belowground nodes of sprigs before the mycorrhizal inoculation was added to the soil surrounding the sprig. All sprigs contained at least one belowground node. Sprigs were planted and inoculated in June 2014 and allowed to grow for one week indoors before being transferred to a greenhouse for 10 weeks. Plants were watered with 1.5 liters of water per week and were fertilized with 5 grams of Osmocote brand slow release fertilizer. At the end of the 10 week growth period (prior to transplantation) 11 potted plants for each treatment (33 total) were harvested and analyzed for aboveground biomass, belowground biomass, and mycorrhizal colonization. Mycorrhizal colonization was measured by staining a subsample of fine roots with Trypan Blue (Morton & Amarasinghe, 2006). Stained roots were placed on a slide and 35 cm of roots (at 1 cm cross increments) were examined at 200× magnification. Presence of mycorrhiza was recorded when hyphae, arbuscule, vacuole, or spore structures were identified within or on the plant root. The percentage of roots with mycorrhizal presence could then be calculated.

An ANCOVA (type II) was used to evaluate the significance of mycorrhizal inoculum treatments. Multiple confounding variables were incorporated into the analysis, including one continuous variable (hence the usage of the ANCOVA). The side of the greenhouse (which had an north-west/south-east orientation) on which a plant was growing was a categorical confounding variable. The initial sprig wet biomass was a continuous confounding variable with the expectation that larger sprigs would have larger energy stores and grow faster. Tukey's Honest Significant Differences (HSD) post hoc test (covariate adjusted, R package: multcomp, Hothorn *et al.*, 2008) was used to determine significant differences between mycorrhizal treatments for significant ANCOVA results. Additionally, because mycorrhizal contamination occurred during the course of this experiment, a separate ANCOVA was used to evaluate the effect of mycorrhizal colonization on plant growth in substitution of the mycorrhizal treatment factor.

4.2.2 Dune Construction and Restoration

Dune construction was completed in early August 2014 followed by planting in late August 2014. The dune was constructed in four sections in total and was located at Apffel Park in Galveston, TX (29.3263582,-94.7358278). Two sections contained *Sargassum* bales and two sections contained no *Sargassum* bales, which were made by compressing *Sargassum* into dense blocks. *Sargassum* bales lined the front berm of the dune and were approximately 75 cm by 75 cm by 60 cm and weighed approximately 80 kg each (Figure 4.2). A total of 300 plants of *P. amarum* were transplanted into two sections of the dune (150 planted in a *Sargassum* bale section and 150 planted in a dune section without *Sargassum* bales). Plants were spaced 75 cm apart in two rows along the berm of the dune. This positioning put plants on either side of the *Sargassum* bales (for the sections with *Sargassum* bales) so that plant roots could grow into the *Sargassum* material.

Of the total 300 transplants, 150 were rooted plants (grown in the greenhouse in the same conditions as described above) and 150 were sprigs which were inoculated with the three mycorrhizal inoculum treatments on site. This created 12 total treatments by three different variables with 25 transplants per treatment: every combination of mycorrhizal inoculation (native, commercial, and absent), *Sargassum* bales (bales vs. no bales) and planting technique (rooted plants vs. sprigs). Sprigs were also fertilized with 5 grams of Osmocote brand slow release fertilizer on site (the same amount as was used with the rooted plants in the greenhouse). Sprigs were also prepared in the same manner as described in the previous section (roots removed, at least one belowground node). All plants were watered with roughly one liter of water initially after transplantation and again after four days had elapsed.

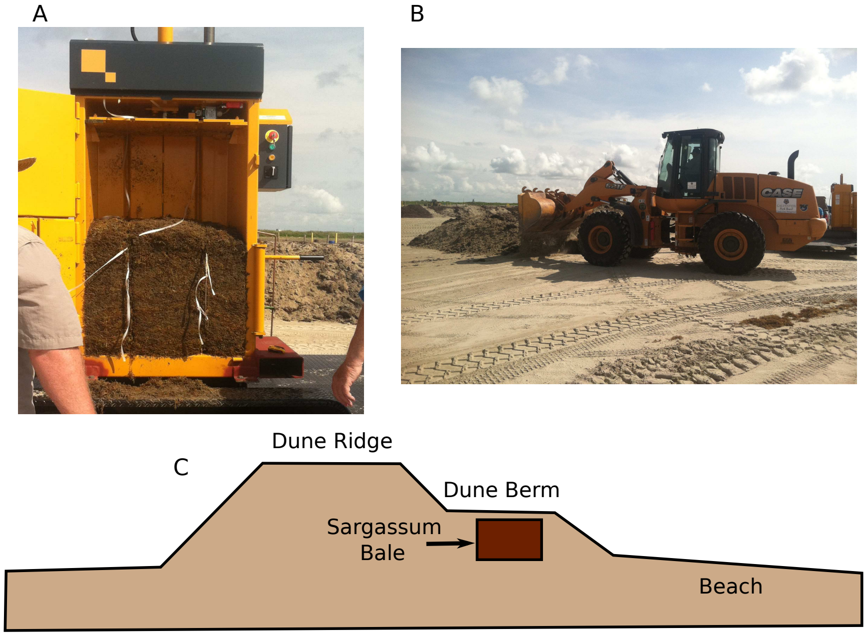

Figure 4.2: Prototype dune construction. A - The baling process for the *Sargassum* material. B - The *Sargassum* bale was positioned in front of the dune and was then covered in sand to form a seaward dune berm. C - Cross-shore diagram of the prototype dune.

4.2.3 Individual Transplant Sampling

Dune transplant sampling events took place during the late October 2014 (12 weeks after restoration) and early May 2015 (36 weeks after restoration). Each of the 300 transplants were evaluated for survival at 12 weeks. The threshold for determining survival was any green tissue in a transplant's aboveground structures. Five randomly selected surviving transplants for each of the 12 treatments were sampled for a variety of metrics at both sampling intervals. Aboveground characteristics were measured at both intervals but by different methods. At the 36 week sampling interval, aboveground biomass was clipped from a 0.0675 m^2 quadrat. However, because transplants were still young 12 weeks after restoration, no clippings were taken (*i.e.,* clippings in some instances would have removed all of the aboveground biomass of a transplant). Digital photography and spectral analysis was used to non-invasively estimate percent cover for a 0.25 m^2 area around transplants as a proxy for aboveground biomass.

Belowground biomass density was sampled from a soil core (7 cm diameter, 30 cm depth) at both 12 and 36 weeks. Soil cores were taken away from the original potted root ball of the rooted plants in order to sample new growth. Soil organic content was measured from a 50 g subsample of soil cores at the 12 week interval as a proxy for how much *Sargassum* was present in the soil. At this sampling interval, little detritus had built up and the majority of organic content was *Sargassum.* Moisture content was also measured for this soil subsample. Mycorrhizal colonization was measured from a subsample of fine roots from the soil core at both 12 and 36 weeks. After 36 weeks, excessive accretion of sediments buried the markers for the transplants, meaning that further monitoring of individual transplants was impossible.

For transplant data, an ANOVA (type II) was used to evaluate the effects of the different treatment variables as well as interactions between variables. This ANOVA was composed of three categorical treatment variables (mycorrhizal inoculation type, *Sargassum* bale treatment, and planting technique). Additionally, as mycorrhizal contamination was again an issue dune transplantation (as transplant rhizospheres expanded outward, they would inevitably contaminate one another), another ANCOVA was created where mycorrhizal colonization was included in substitution of mycorrhizal treatment. Additionally, soil organic (a proxy for *Sargassum* content) was also used as a continuous variable within the ANCOVA models for the 12 weeks sampling (this data was not collected for the 36 weeks sampling). This variable was included as some *Sargassum* material was present in the soil for no *Sargassum* bale transplants (confounding variable). Tukey's HSD tests (covariate adjusted, R package: multcomp, Hothorn *et al.*, 2008) and examination of interaction plots provided context for the ANOVA/ANCOVA results in terms of relative differences between groups when interactions between treatment effects were found. For additional explanations of the analyses conducted, see Table 4.2.

Because all transplants of a given treatment of *Sargassum* bales were located on either one dune or another, this arrangement would be characterized as an example of pseudo-replication. In other words, it cannot be certain that any observed treatment effects for *Sargassum* bales were actually caused by the treatment instead of spatial or environmental effects caused by the two separate dune systems. To compensate for this pseudo-replication caused by spatial effects, ANOVA/ANCOVA models were evaluated for spatial autocorrelation using an Moran's I Test. If significant spatial autocorrelation was detected, spatial cluster terms were also tested and included in the ANOVA/ANCOVA model when significant (cluster sizes evaluated = 5, 10, and 20 m). By modifying the ANOVA/ANCOVA in this way, the statistical analysis could compensate for any environmental/spatial clustering effects, partially alleviating the issue of pseudo-replication.

4.3 Results

4.3.1 Mycorrhizal Effects In Greenhouse

Native mycorrhizal inoculums increased below- and aboveground biomass as well as mycorrhizal colonization for plants grown in the greenhouse (Table 4.3, Figure 4.3). No treatment effects were observed for above:belowground biomass ratio. Both the confounding variables of initial sprig mass and greenhouse side had significant effects on plant growth with larger initial sprig masses and the south-east side of the greenhouse increasing biomass accumulation. Larger sprigs also tended to have slightly higher above:belowground ratios (p value = 0.058). Mycorrhizal colonization (as an independent continuous variable) was also positively related to above and belowground biomass of plants (Table 4.4). In other words, higher amounts of mycorrhizal colonization tended to cause plants to accumulate more biomass. Based off this variable's slope coefficient, a change from 0% to 100% mycorrhizal colonization would yield an additional 7.8 grams of total dry plant biomass, which translates into roughly a 62% increase for the average plant. Greenhouse and initial sprig biomass

Table 4.2: Summary of Transplant ANOVA/ANCOVA Details

Sampling Interval	Categorical Variables	Continuous Variables	Model Type
12 Weeks, Mycorrhizal Treatment	• Mycorrhizal Inoculum • *Sargassum* Bales • Planting Technique	• Soil Organic Content (proxy for *Sargassum* Content, Confounding Variable)	ANCOVA
12 Weeks, Mycorrhizal Colonization	• *Sargassum* Bales • Planting Technique	• Soil Organic Content • Mycorrhizal Colonization	ANCOVA
36 Weeks, Mycorrhizal Treatment	• Mycorrhizal Inoculum • *Sargassum* Bales • Planting Technique	• None	ANOVA
36 Weeks, Mycorrhizal Colonization	• *Sargassum* Bales • Planting Technique	• Mycorrhizal Colonization	ANCOVA

displayed the same trends in the context of the mycorrhizal colonization ANCOVA (Table 4.4).

Table 4.3: Greenhouse ANCOVA results (p values) by Mycorrhizal Treatment

Dependent Variable	Mycorrhizal Treatment	Initial Sprig Mass	Greenhouse Side
Belowground Biomass	0.011	0.029	< 0.001
Aboveground Biomass	0.015	< 0.001	< 0.001
Total Biomass	0.0039	< 0.001	< 0.001
Biomass Ratio (Above:Below)	NS	0.058	NS

Notes: Red cells mark positive relationships.

Table 4.4: Greenhouse ANCOVA results (p values) by Mycorrhizal Colonization

Dependent Variable	Mycorrhizal Colonization	Initial Sprig Mass	Greenhouse Side
Belowground Biomass	0.020	0.090	0.0046
Aboveground Biomass	< 0.001	< 0.001	< 0.001
Total Biomass	< 0.001	< 0.001	< 0.001
Biomass Ratio (Above:Below)	NS	0.033	NS

Notes: Red cells mark positive relationships.

4.3.2 Individual Transplant Results

Dune restoration was generally successful and transplant survival was high after 12 weeks. Over 99% percent of rooted plants survived and 83% percent of sprigs

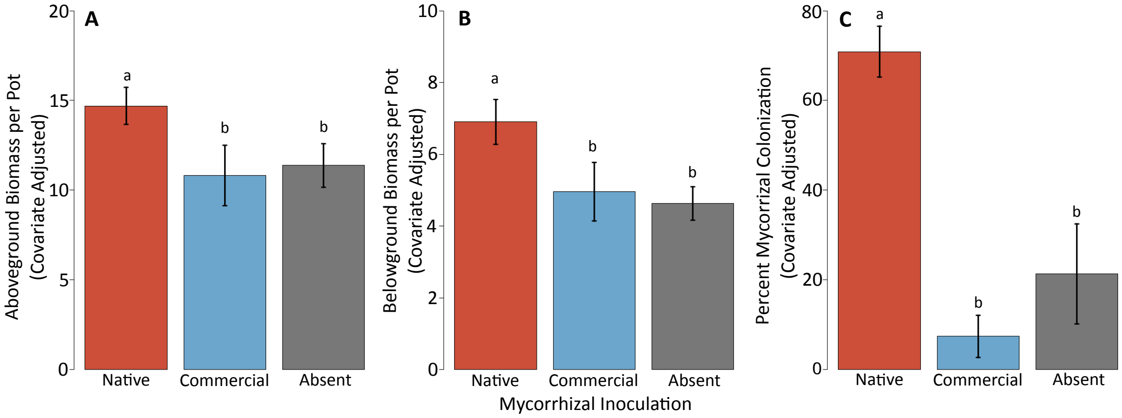

Figure 4.3: Comparison of mycorrhizal inoculation treatment effects on aboveground biomass, belowground biomass, and mycorrhizal colonization. Significant differences determined by Tukey's HSD test with $\alpha = 0.05$. Bars show standard error.

survived (chi test p value < 0.001). There were no significant differences in survival that depended on mycorrhizal inoculums or *Sargassum* bale treatments. During dune construction, much of the sediment used to create the dune and berm contained *Sargassum* wrack. This contamination was caused by the overwhelming abundance of *Sargassum* material that washed up onto Galveston shorelines during the summer of 2014. Therefore, it should be noted that *Sargassum* presence in the soil was similar between dunes with bales and those without bales (Figure 4.4, p value $= 0.039$). This portion of the experiment should not be viewed as a comparison between *Sargassum* bales and "clean" sand, but rather as a comparison of tightly compacted *Sargassum* compared to less dense, interspersed *Sargassum*. Additionally, soil organic content (which, at the outset of the experiment, was almost entirely *Sargassum*) was strongly correlated to soil moisture content (Figure 4.5).

With that additional context, the results of the 12 weeks transplant sampling ANCOVA are summarized in Table 4.5. Percent coverage was significantly affected by mycorrhizal inoculum. Transplants that were inoculated with native inoculums had 34% higher percent coverage at 12 weeks compared to commercial and control inoculums. For both percent cover and belowground biomass density, there were also significant treatment effects for planting technique and *Sargassum* bales along with significant interactions between these two treatments (Figures 4.6 + 4.7). Rooted plants possessed 138.8% higher percent cover and 810.3% higher belowground

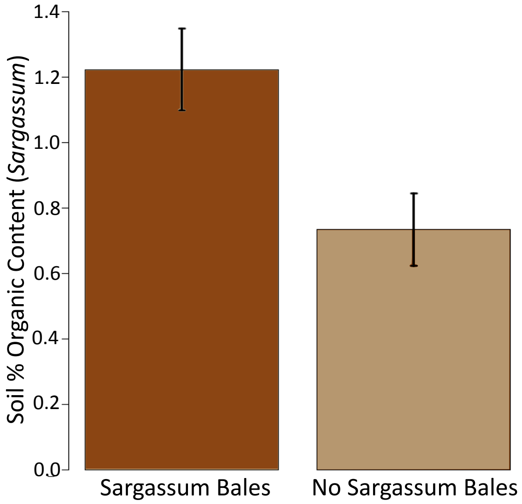

Figure 4.4: At 12 weeks - Comparison of soil organic content between *Sargassum* bale and no *Sargassum* bale treatments. As this sampling occurred relatively early in the restoration process, little detritus has built up in the soil and organic content was primarily driven by the amount of *Sargassum* in the soil. Bars show standard error.

biomass densities compared to sprigs. Transplants on top of *Sargassum* bales showed 41.2% less aboveground percentage coverage but 272.1% higher belowground biomass density. The interaction between planting technique and *Sargassum* bales differed for above- and belowground growth. Rooted transplants showed increased belowground biomass density but decreased aboveground percent coverage when planted on top of *Sargassum* bales. Sprigs showed less difference between *Sargassum* bale treatments. When mycorrhizal colonization (as a independent continuous variable) was used for ANCOVA modeling in place of mycorrhizal treatment, mycorrhizal colonization was positively related to both above and belowground growth parameters (p value = <0.0001 and p value = 0.0046, respectively), with more mycorrhiza activity in the roots relating to increased growth (Table 4.6). Similar interactions and trends also occurred for planting technique and *Sargassum* bale treatments when ANCOVA models were built with the mycorrhizal colonization term.

At 36 weeks after restoration, some significant treatment effects were still observed and are summarized in Table 4.7. Rooted transplants had 51.2% higher aboveground

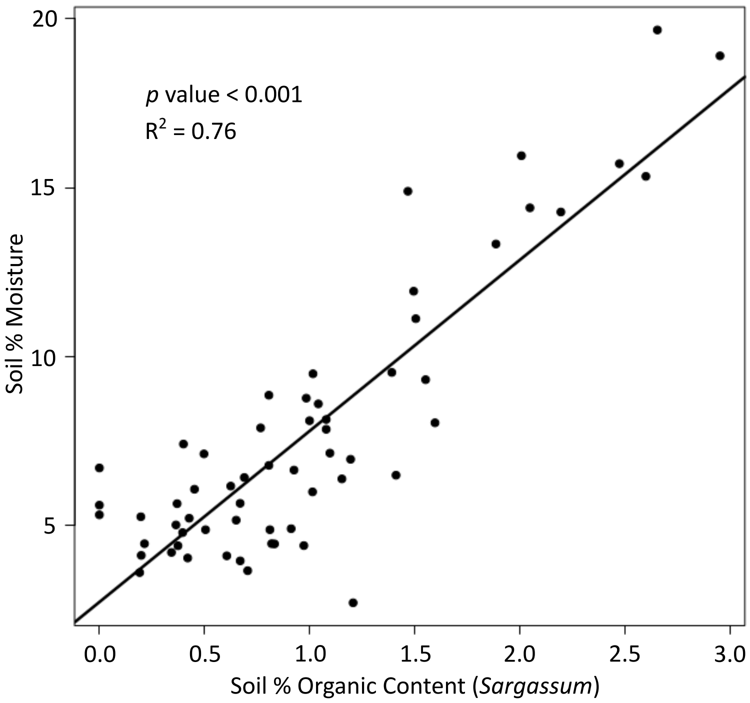

Figure 4.5: At 12 weeks, the soil organic content (proxy to *Sargassum* content) was strongly correlated to moisture content.

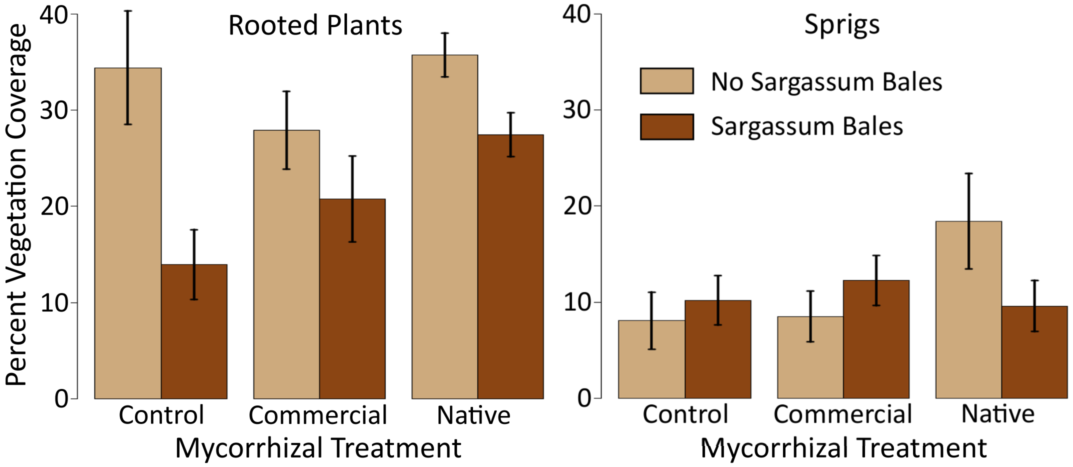

Figure 4.6: At 12 weeks - Bar plot showing effects of planting technique, mycorrhizal inoculums, and *Sargassum* bale treatments on aboveground percent coverage. Bars show standard error.

Table 4.5: 12 weeks - Transplant ANCOVA results (p values) by Mycorrhizal Treatment

Dependent Variable	Mycorrhizal Treatment (M)	Sargassum Treatment (S)	Planting Technique (P)	Soil Organic Content (*Sargassum* Content)
Percent Cover	0.040	0.0041	< 0.001	NS
Belowground Biomass Density	NS	0.014	0.0040	NS

Interactions:
Percent Cover: S × P (0.011)
Belowground Biomass Density: S × P (0.058)

Table 4.6: 12 weeks - Transplant ANCOVA results (p values) by Mycorrhizal Colonization

Dependent Variable	Mycorrhizal Colonization	Sargassum Treatment	Planting Technique	Soil Organic Content (*Sargassum* Content)
Percent Cover	< 0.001	0.0016	< 0.001	NS
Belowground Biomass Density	0.0046	NS	NS	NS

Notes: Red cells mark significant positive relationships.
Interactions:
Percent Cover: S × P (0.024)
Belowground Biomass Density: S × P (0.023)

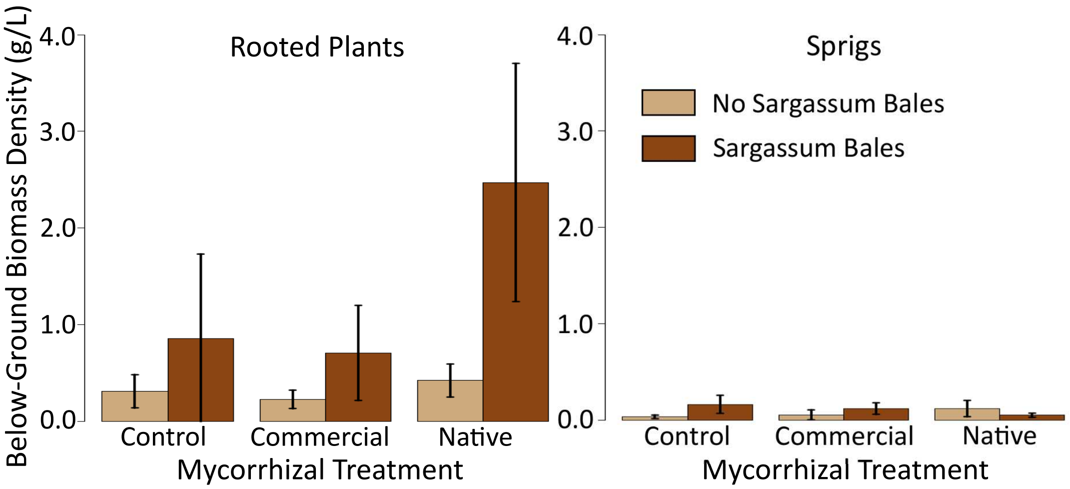

Figure 4.7: At 12 weeks - Bar plot showing effects of planting technique, mycorrhizal inoculums, and *Sargassum* bale treatments on belowground biomass density. Bars show standard error.

biomass (Figure 4.8) and 113.1% higher belowground biomass (Figure 4.9). An interaction was observed where rooted plants had higher belowground biomass density in dunes without *Sargassum* bales. Sprigs showed less difference between *Sargassum* bale or no *Sargassum* bale treatments. When modeling by mycorrhizal colonization in place of mycorrhizal treatment, there was a weak positive correlation between mycorrhizal colonization and aboveground biomass density (Table 4.8). Once again, similar interactions and trends also occurred for planting technique and *Sargassum* bale treatments when ANCOVA models were built with the mycorrhizal colonization term.

4.4 Discussion

4.4.1 Greenhouse Discussion

Greenhouse biomass accumulation (plant growth) was significantly influenced by mycorrhizal inoculum. Native inoculums outperformed commercial and control inoculums in promoting both above- and belowground growth of *P. amarum*. Spatial relationships within the greenhouse as well as initial sprig biomass (the size of the initial sprig before planting and inoculation) were also drivers of plant growth with regards to above- and belowground biomass. Mycorrhizal colonization (as an independent continuous variable) was also significantly and positively related to above-

Table 4.7: 36 weeks - Transplant ANCOVA results (p values) by Mycorrhizal Treatment

Dependent Variable	Mycorrhizal Treatment (M)	Sargassum Treatment (S)	Planting Technique (P)
Aboveground Biomass Density	NS	NS	0.0073
Belowground Biomass Density	NS	NS	0.0028

Interactions:
Belowground Biomass Density: S × P (0.073)

Table 4.8: 36 weeks - Transplant ANCOVA results (p values) by Mycorrhizal Colonization

Dependent Variable	Mycorrhizal Colonization	Sargassum Treatment	Planting Technique
Aboveground Biomass Density	0.081	NS	0.039
Belowground Biomass Density	NS	NS	0.0041

Notes: Red cells mark significant positive relationships.
Interactions:
Belowground Biomass Density: S × P (0.072)

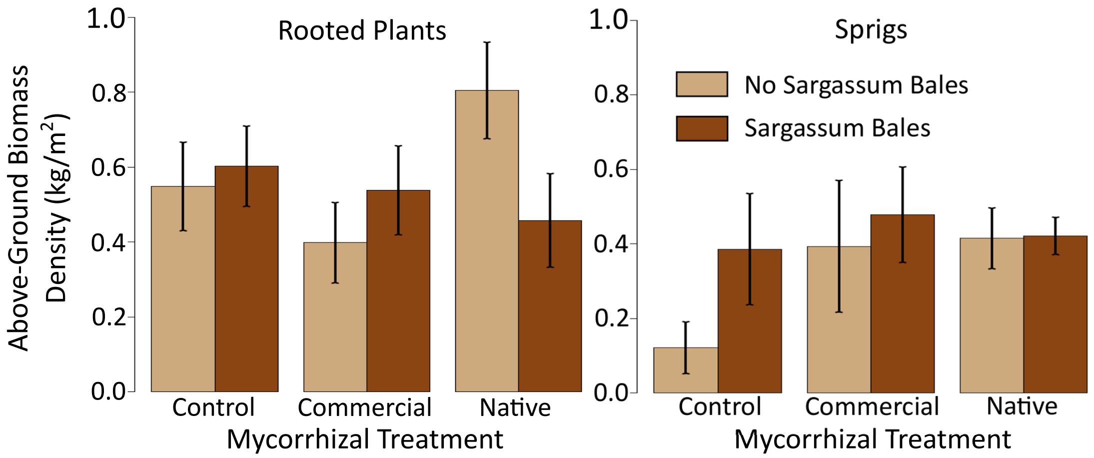

Figure 4.8: At 36 weeks - Bar plot showing effects of planting technique, mycorrhizal inoculums, and *Sargassum* bale treatments on aboveground biomass density. Bars show standard error.

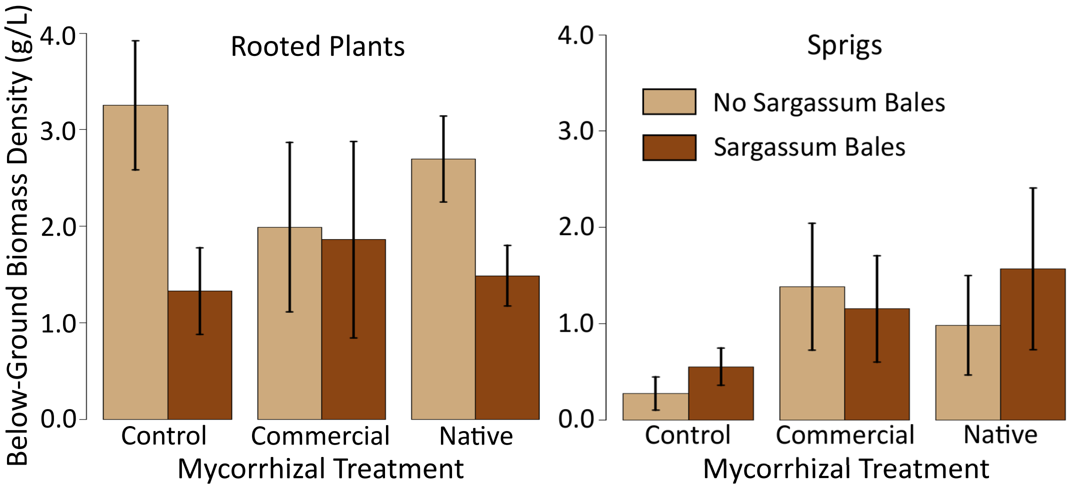

Figure 4.9: At 36 weeks - Bar plot showing effects of planting technique, mycorrhizal inoculums, and *Sargassum* bale treatments on belowground biomass density. Bars show standard error.

and belowground biomass, providing support that *P. amarum* benefits from both mycorrhizal inoculation and symbiosis. Similar beneficial aspects of mycorrhiza have been observed for other Gulf Coast dune species (Corkidi & Rincòn, 1997), including *P. amarum* (Parnell, 2012). However, mycorrhiza did not have an effect on above:belowground biomass ratio. Coastal dune plants variably allocate resources above-and belowground depending on both plant and fungal species (Corkidi & Rincòn, 1997) and likely dependent on other environmental factors such as drought stress (Jayne & Quigley, 2014). Under the growth conditions of this experiment (ample water and nutrients), mycorrhizal activity caused *P. amarum* to allocate resources equally above- and belowground.

Mycorrhizal colonization also significantly varied among mycorrhizal inoculum treatments, with native inoculations outperforming commercial and control treatments with higher amounts of mycorrhizal activity. This result could be due to native inoculum sources (taken from the roots of *in situ P. amarum* stands) being better adapted to colonize *P. amarum* compared to commercially available species. Colonization affinities between cohabitating mycorrhiza and plant hosts has been explored in agricultural settings with native species differing in effect on plant growth and soil structure development (Davies *et al.*, 2005). Alternatively, the mixed native inoculum (*in situ* soil containing mycorrhizal spores, hyphae, and colonized plant roots) could have a higher inoculation potential than the commercial inoculum which contained only spores. Varying inoculation potentials between inoculum types and mycorrhizal species have been observed in other settings and depends on fungal species (Klironomos & Hart, 2002).

Plants that were part of the control treatment did have established mycorrhiza within root systems (28.6% percent colonization of roots on average, 63.6% of plants showing some amount of mycorrhizal activity). As the inoculum was sterilized for this treatment, outside contamination must have occurred. Contamination could have occurred by a few different means, the first being via atmosphere. Though the plants were grown within an isolated greenhouse, this greenhouse was not perfectly sealed from the outside world. Open ventilation windows (which were needed due to hot Texas temperatures) occasionally allowed for a cross breeze to enter the greenhouse, potentially bringing in mycorrhizal spores. Also, burrowing insects and rodents were observed in the greenhouse and could have brought mycorrhizal colonizing agents with them as they moved from pot to pot. Lastly, sprigs had their roots removed and were washed prior to inoculation but some mycorrhizal colonizing agents could have remained (*e.g.* clinging hyphae or spores).

4.4.2 Transplant Discussion

Planting technique, *Sargassum* bale treatment, and mycorrhizal inoculums all affected plant growth, particularly in the initial period after transplantation. Planting technique had the largest impact on plant growth, rooted plants having higher above- and belowground growth at both 12 and 36 weeks. However, this growth difference between rooted plants began to converge as time progressed. At 12 weeks, rooted plants had roughly 2.5× higher percent coverage and 9× higher belowground biomass while at 36 weeks, this growth discrepancy had decreased to roughly 1.5× and 2×, respectively. Like the greenhouse portion of this project, native inoculums increased plant growth at the 12 week interval (34% higher percent coverage). Mycorrhizal colonization was also significantly and positively related to increased plant growth both at the 12 week time interval (percent coverage and belowground biomass) and the 36 week time interval (aboveground biomass).

Interactions were consistently found between rooted plants and *Sargassum* bale treatments, with *Sargassum* bales typically suppressing growth. At 12 weeks, *Sargassum* bales significantly decreased aboveground growth but increased belowground growth, particularly when combined with the rooted plant treatment (significant additive interaction). By 36 weeks, *Sargassum* bales decreased belowground growth for rooted plants. This finding contradicts the beneficial effects of *Sargassum* on *P. amarum* growth found by Williams and Feagin (2010). Williams and Feagin (2010) also demonstrated that washing *Sargassum* to remove salt water was actually detrimental to *P. amarum* growth, implying that salt exposure is not a reasonable explanation for the detrimental effects of *Sargassum* bales detailed in this chapter. They also showed that higher density of *Sargassum* material in soil generally enhanced growth compared to low density treatments. However, it is difficult to make a direct comparison between the soil *Sargassum* densities used in Williams and Feagin (2010) and those used in this chapter's research (that paper measured *Sargassum* density as wet *Sargassum* mass per volume of soil whereas this chapter's research measured *Sargassum* density via soil organic content proxy).

It is important to consider these results from the perspective that the *Sargassum* bale treatment did not have a proper control; *Sargassum* was present in the dune without *Sargassum* bales. This *Sargassum* presence was caused by a lack of available "clean sand" (not contaminated by *Sargassum*) during certain stages of dune construction. Dunes with *Sargassum* bales were placed and built personally by the author during a period when relatively "clean sand" was available. In light of this outcome, these two treatments should be viewed more as "high density *Sargassum* surrounded by relative clean sand" (*Sargassum* bale) compared to "medium density but widespread *Sargassum*" (no *Sargassum* bale) (Figure 4.10).

When considering the entirety of the dune berm where transplants were placed, there might have been more total *Sargassum* material in the dune without *Sargassum* bales than in the dune with *Sargassum* bales. In other words, if *Sargassum* bale dunes had a density of $2X/m^3$ of *Sargassum* over a volume of $100\ m^3$ (200X total) while non-*Sargassum* bale dunes had a density of $1X/m^3$ of *Sargassum* over a volume of $300\ m^3$ (300X total), the non-*Sargassum* bale dune would have more total nutrients for plants to access, just spread out over a larger volume. From this view, this medium density *Sargassum* presence in the dune without *Sargassum* bales could have increased growth, particularly for rooted plants where roots could rapidly expand outward and take advantage of the larger nutrient pool. Alternatively, the dense organic material from the compacted *Sargassum* bale could have been a less than ideal *in situ* substrate for *P. amarum*. This organic layer retained moisture (Figure 4.5) but could have created anoxic conditions for *P. amarum*, which typically grows in better-draining sandy environments.

As for the increase in belowground biomass density observed in *Sargassum* bale dunes at 12 weeks, this could be explained from the perspective that it was actually belowground biomass "density" that was recorded. *Sargassum* bales compacted in the months after dune restoration. If roots grew at the same biomass density for both treatments but were then compacted within the *Sargassum* bales, it would give the appearance of added root biomass accumulation without any actually occurring. Alternatively, the high density *Sargassum* material could have produced an habitable substrate for new root growth. Initially when transplants were vulnerable to desiccation, the moisture retention ability of *Sargassum* could have been more beneficial.

Transplant survival significantly differed between rooted plants and sprigs with nearly all rooted plants surviving and roughly 4/5 sprigs surviving. After two weeks, all sprigs appeared to be dead (Figure 4.11, Panel A) but later most were observed to

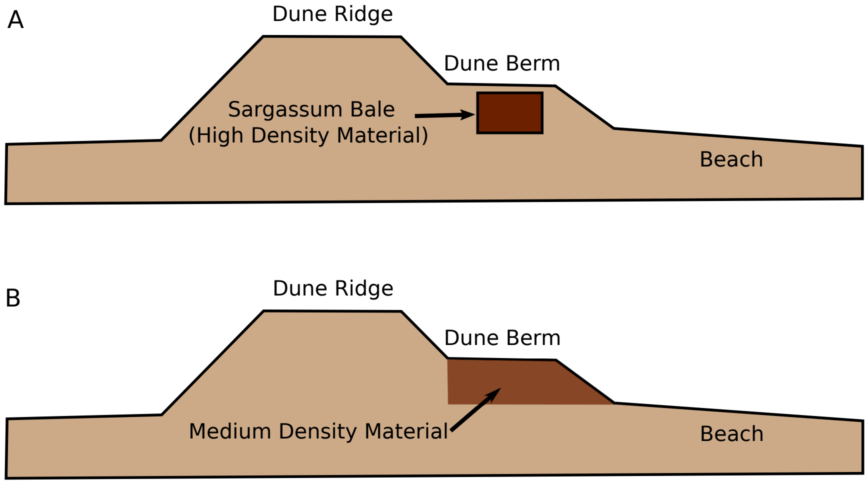

Figure 4.10: Comparison or *Sargassum* distribution between dunes with *Sargassum* bales (A) and those without *Sargassum* bales (B).

have sprouted aboveground growth from rhizomes. Overall, a survival rate of 83% for sprig transplants is much higher than some previous dune restoration projects in the Galveston area (Feagin *et al.*, 2009), though that study used a different grass species and occurred during a time of drought. Sprigs may have been more successful during our project because of a large rain event that took place within a week of planting (> 7.5 cm of precipitation, National Oceanic and Atmospheric Administration (NOAA) Staff, 2014), potentially helping sprigs survive initial transplant stress. This outcome highlights that all restoration projects are context dependent on location, weather conditions, and the species of plant used. Larger differences in growth and survival between rooted plants and transplants could have occurred in another environmental context and needs to be explored further.

4.4.3 Recommendations for Dune Restoration and Cost Efficacy of Techniques

This portion of the experiment focused on evaluating the efficacy of using mycorrhizal inoculums, *Sargassum* bales, and differing planting techniques (roots vs. sprigs). Native inoculums were the most beneficial for plant growth both in greenhouse and *in situ*. Commercial inoculums were no more effective than the control. Mycorrhizal colonization (as an independent, continuous variable) was also consistently and significantly related to improved plant growth in both the greenhouse and *in situ*. Some contamination occurred in control plants both in greenhouse and *in situ*. Similar pat-

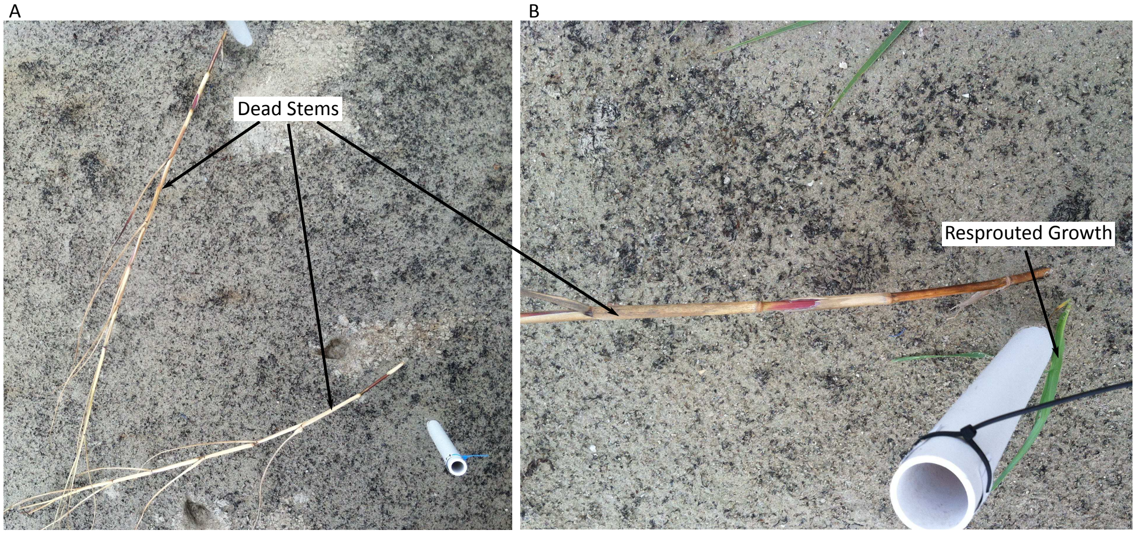

Figure 4.11: For some sprig transplants, plants died and did not show any signs of re-sprouting (A). After roughly two weeks, however, many sprigs eventually showed signs of growth (B).

terns of contamination of non-inoculated plants have been found in other dune plant restoration/greenhouse studies (Gemma & Koske, 1997). Sources of mycorrhizal contamination are abundant and mycorrhiza would likely colonize plants eventually in most dune restoration projects. However, in the greenhouse experiment detailed in this chapter, native inoculums showed a 100% colonization success rate (all native inoculated plants possessed mycorrhiza) compared to only 36.4% of commercial and control inoculated plants that possessed mycorrhiza. Using a native inoculum of local dune soils greatly enhances the probability that mycorrhiza colonization will occur in transplants.

For the native inoculum, mycorrhizal colonization was more successful when applied to sprigs within pots in a greenhouse compared to applying inoculum to sprigs *in situ*. Though the methods of measuring mycorrhizal colonization were slightly different (for *in situ* sprigs, mycorrhizal colonization rates were measured from fine roots in soil cores whereas for greenhouse plants, fine roots were taken directly from harvested plants), greenhouse sprigs treated with native mycorrhiza had 8× more mycorrhizal activity than native treated *in situ* sprigs. 100% of greenhouse native-inoculated plants had some mycorrhizal activity while only 20% of *in situ* inoculated plants had mycorrhizal activity after roughly the same amount of inoculum exposure time (11 and 12 weeks, respectively). Conceptually, this makes sense in that new root growth is confined within a pot for the greenhouse sprigs, increasing exposure of roots to the inoculum. *In situ*, roots radiate outward away from the inoculum, decreasing exposure. Therefore, it is recommended that a native mycorrhizal inoculum be used for a brief period prior to transplantation. In terms of cost, using a native inoculation is basically free aside from the labor cost of collecting local dune soil and adding it to transplants, which is minimal. For many restoration projects in the Galveston area (from personal observations), fertilizer is typically added to individual transplants. Adding a small amount of native dune soil in conjunction with the fertilizer would therefore not be onerous.

Sargassum bales were generally not impactful and, if anything, repressed growth in particular for rooted transplants though this treatment lacked a proper control. To a certain extent, using *Sargassum* "bales" is more about compacting the material for easier transportation and removal from beaches. Not compacting the material could improve growth compared to planting vegetation on top of high density material, but vegetation still grew well when planted on top of *Sargassum* bales. Panel E of Figure 5.3 (see next chapter) shows a restored dune where vegetation was planted on top of *Sargassum* bales and the ecosystem was clearly thriving. Therefore, this study provides evidence that both *Sargassum* "bales" and *Sargassum* "piles" are acceptable substrates for dune plant growth. For any given area, coastal managers should use whichever method is easier and more cost effective to implement.

Rooted plants (sprigs that were grown in pots in a greenhouse for 10 weeks) had higher rates of survival and showed more above- and belowground biomass development post-transplantation. However, the gap in growth between rooted plants and sprigs began to decrease by 36 weeks. Also, rooted plants have the added labor cost of watering and maintaining them for a duration of time. This raises the question of whether the ecosystem "jumpstart" that rooted plants provide is worth the costs of growing them. One way to determine the value of this "jumpstart" is to consider its contribution to dune stability. Dunes are vulnerable to Aeolian-based erosion initially. In Chapter 5, this vulnerability was assessed by comparing erosion/accretion for planted vs. non-planted dune systems. A high amount of erosion that took place in non-planted dunes during the first 32 weeks (see Figures 5.9 and 5.10 in Chapter 5). Non-planted dunes experienced roughly 200 cubic meters more erosion than restored-dunes over the first 32 weeks. Planted dunes actually accreted sediment over this time period, primarily in the area where restoration occurred.

The comparison of an entire dune system of rooted plants vs. sprigs was not made in this experiment. Therefore, no direct accretion/erosion comparisons can be made between these two treatments with regards to their effect on dune stability. However, sprigs, had lower percent coverage and aboveground biomasses at 12 and 36 weeks and would likely have promoted less accretion compared to rooted plants (less aboveground structures to trap sediment). This lack of accretion comes at a cost as there is less sediment in the dune ecosystem to act as a buffer for storms. For example, based off the value of sediment for an average Galveston dune during Hurricane Ike (results reported in Chapter 2), the cost of sediment loss during the first 32 weeks for the non-restored dunes was over $10,000. Though a dune entirely restored with sprigs would likely perform better than no restoration at all, it is reasonable to expect it would also experience substantial losses with regards to erosion/accretion in the time period that it catches up to a dune restored with rooted plants. Such costs would likely exceed the labor costs associated with growing potted plants for restoration. If one of the goals of dune restoration is to establish vegetation and to do it quickly, rooted plants are superior to sprigs.

4.5 Concluding Statements

Dunes are stressful and inhospitable environments, hampering both the success of dune restoration projects and the development of vegetation-stabilized dune systems. The effects of several dune restoration techniques on dune plant growth and survival were therefore evaluated. The technique that had the largest effect on plant growth and survival was planting technique (comparison between rooted plants and sprigs). Rooted plants (sprigs that were allowed to accumulate roots in pots prior to transplantation into the dune habitat) outperformed sprigs across all of the following variables: aboveground biomass growth, belowground biomass growth, vegetation coverage, and survival. Increases in these metrics could be useful to “jumpstart” the dune ecosystem and stabilize sediments.

Sargassum bales were also evaluated and may reduce plant growth slightly compared to a dune system composed of less compacted *Sargassum* material. Regardless, both *Sargassum* “bales” or *Sargassum* “piles” provided a good substrate for plant growth and this coastal resource should be used in future dune restoration projects. Utilizing *Sargassum* material in dune restoration projects removes the disruptive and unsightly material from beaches while simultaneously creating a valuable coastal ecosystem.

Native mycorrhizal inoculations (soil taken from a local dune) increased plant growth in greenhouse but contamination undermined mycorrhizal inoculation treatment effects *in situ* as time progressed. Native mycorrhizal inoculations also had 100% success rates when inoculated plants were confined within pots for a short duration. Mycorrhizal activity was also consistently related to increased plant growth both in greenhouse and *in situ*. Native mycorrhizal inoculations could therefore be useful to quickly seed this beneficial symbiont into a restored dune ecosystem. In summary, it is recommended that dune restoration projects for the Galveston area use rooted plants, native mycorrhizal inoculation, and *Sargassum* wrack (when available) to increase transplant survival and growth.

5. LESSONS FROM TEXAS COASTAL DUNE RESTORATION PART 2: THE BROADER IMPACTS OF VEGETATION RESTORATION ON DUNE COMMUNITY ECOLOGY, SUCCESSION, AND GEOMORPHOLOGY

5.1 Background Information

5.1.1 Broader Ramifications of Restoration

The objectives of the last chapter were to evaluate the effect of mycorrhizal inoculations, *Sargassum*, and different planting techniques on plant growth and survival during dune restoration. Those objectives were evaluated within a larger restoration project carried out on behalf of the Texas General Land Office (TGLO) under the Coastal Erosion Planning and Response Act (CEPRA). This larger project sought to evaluate the broader ramifications of *Sargassum* bales on dune stability and morphological evolution. For this larger project, multiple large dune systems were constructed with and without *Sargassum* bales, but vegetation was planted only on half of the dunes; natural colonization occurred on the remaining dunes. The effect of restoring vegetation and using *Sargassum* bales on dune ecosystem succession, community ecology, and geomorphology was evaluated over time. Understanding these broader biogeomorphological and community-level characteristics of restored dunes systems and how they evolve over time could help clarify the goals (and potential tradeoffs between goals) of dune restoration.

5.1.2 Dune Succession and Colonization of Vegetation

Coastal dunes are highly dynamic systems that vary spatially and temporally with regards to both ecosystem structure (*e.g.,* plant/microbe/animal community assemblages, abiotic characteristics) and function (*e.g.,* productivity, biogeochemical cycling, mobility) (Avis & Lubke, 1996; Martìnez *et al.*, 2001; McLachlan, 1991; Olff *et al.*, 1993). Spatial variability with regards to coastal dune ecosystem characteristics occurs along a cross-shore gradient that can span kilometers for some coastal dune fields (Luna *et al.*, 2011). Typically, these ecosystems occupy < 100 m cross-shore span for the upper Texas coast (based off personal observation). Temporally, dunes ecosystem succession can take place over centuries (Lichter, 1998), but for upper Texas coast dunes, succession spans years to decades. This shorter time period is mainly constrained by large coastal storm disturbances (*e.g.,* hurricanes) that periodically destroy these coastal dunes over the majority of their cross-shore span (Morton & Paine, 1985; Williams *et al.*, 2009). For the Texas coast, these episodic severe storm events occur on average once every 15 - 30 years (Roth, 2010). Cross-shore abiotic gradients (*e.g.,* salt, sand burial, wind abrasion, moisture) largely shape coastal dune plant community assemblages (Hesp & Martìnez, 2007; Martìnez *et al.*, 2001; McLachlan, 1991), but nutrient accumulation and facilitative biological processes can also drive community succession after disturbance (Emery & Rudgers, 2010; Olff *et al.*, 1993).

Post-storm plant community recovery and succession has never been extensively or empirically detailed for upper Texas coastal dunes. However, the general mechanisms of post-disturbance dune evolution and succession can be inferred from numerical modeling and observations of other systems (Hesp & Martìnez, 2007; Luna *et al.*, 2011; Miyanishi & Johnson, 2007). During a severe storm, massive amounts of wave/surge induced erosion can destroy embryonic dunes and foredunes, causing the vegetation line (the line of transition between vegetation-less beaches and vegetated dunes) to retreat landward (Hesp & Martìnez, 2007; Morton & Paine, 1985; Morton *et al.*, 1994; Williams *et al.*, 2009). Salt water inundation can also kill landward plants (Williams *et al.*, 2009). After the surge recedes and salt begins to drain out of coastal soils, colonizer species and surviving plants begin to fill the bare sediment left behind by the storm. This colonization process can span years; for example, Morton & Paine (1985) did not observe backbeach colonization until more than two years after the landfall of Hurricane Alicia in Galveston, TX in 1983.

However, once colonization occurs, upper Texas coastal dune field genesis would likely follow the high vegetation growth scenario laid out in Luna *et al.* (2011) because this area receives high amounts of precipitation ($>$ 110 cm per year). In other words, as sediment deposits onto a shoreline, high vegetation density would prevent the windblown sand from penetrating very far landward ($<$ 100 m) and embryonic dunes would form as sediments accrete around dense vegetation structures. At a certain cross-shore point, accretion will reach a maxima and a new foredune would form. Slowly, a combination of abiotic and biotic dynamics will shape the plant community assemblage and beach/dune geomorphology to resemble a pre-storm condition. The general cross-shore setup for upper Texas beach and dune systems is as follows, progressing landward from shore: beach, seaward embryonic dunes, a moderately sized foredune, and a topographically flat upland/backdune area. The full geomorphological recovery for this type of dune/beach system can take decades in Texas and other similar coastal dune ecosystems (Hesp & Martìnez, 2007; Morton *et al.*, 1994).

5.1.3 The Goals of Dune Restoration

Dune restoration for the upper Texas coast typically attempts to take a "shortcut" through these successional processes, both with regards to accretion and plant community assemblage. Accretion can be encouraged through use of sand fencing to re-establish a foredune or sand can simply be imported/worked to construct a new foredune ridge (Patterson, 2005). Reestablishment of foredunes is primarily intended to recreate the storm protective services that coastal dunes provide (see Chapter 2). Late succession plant species are predominantly used (*e.g. Panicum amarum*, *Uniola paniculata*, *Spartina patens*) in vegetation plantings of these newly established foredunes (Patterson, 2005). The aim of such plantings are not necessarily to mimic a late succession dune community in terms of structure and function, but rather to stabilize the sediments of the new foredune. However, it remains unclear if planting late successional vegetation stabilizes sediments more effectively than natural colonization and successional processes. Moreover, it is unclear if such restoration practices alter the successional trajectory of upper Texas coast restored dune ecosystems to an "unnatural" state. This altered trajectory could impact both long term ecosystem structure (*e.g.* plant/animal/microbe biodiversity) and function (*e.g.* storm protection, accretion, disturbance resistance/resilience). Such successional trajectory alterations have been observed in other coastal dune restoration/rehabilitation projects (Landi *et al.*, 2012).

These broader concepts of coastal dune ecosystem structure, function, and succession raise important questions about the long term goals of dune restoration. To start, what is the main purpose of dune restoration? Storm and erosion protection? Accretion? Restoring the community characteristics of natural dune systems (*e.g.,* plant and animal community diversity, habitat for endangered species, carbon sequestration or other nutrient cycling)? These potential goals likely apply to different scenarios depending on the needs of any given coastal location. Conceivably, these goals could act additively (*e.g.,* a dune that is restored to maximize storm protection could also be good at accreting sediments) or deleteriously (*e.g.,* seeking to improve storm protection could lead to a decrease in plant and animal diversity). Such conflicts in restoration and management goals have been explored for other coastal ecosystems (Barbier *et al.*, 2008; Caldow *et al.*, 2004) but remain unresolved and are poorly understood for coastal dunes. By monitoring dune plant communities and geomorphology, this study will also examine the interplay of these different ecosystem characteristics and how they are affected by late succession plant species restoration and *Sargassum* bales. All of the research objectives of this chapter are summarized in Table 5.1, organized by the different sections of this chapter.

5.2 Methods

In conjunction with the individual transplant monitoring that was detailed in the last chapter, the effect of vegetation planting and *Sargassum* bales on dune biogeomorphological evolution was also monitored for the same dunes where those individual transplants were planted. The biogeomorphological data in this chapter is divided by two subsections: plant community monitoring and accretion/erosion monitoring (elevation transects). Plant community ecology data was collected at 12, 36, and 62 weeks post-transplantation and represented the first subsection (Table 5.1, Row 1). Geomorphology (dune elevation transects) data were collected at 3, 16, 32, 45, and 102 weeks after restoration and this data represented the second subsection (Table 5.1, Row 2).

5.2.1 Dune Construction and Restoration

Four dunes were constructed in early August 2014 followed by vegetation planting in late August 2014. The location of constructed dunes was Apffel Park in Galveston, TX (Figure 5.1). Two sections contained *Sargassum* bales and two sections contained no *Sargassum* bales (for details on *Sargassum* bale composition, see Chapter 4). Additionally, two dunes were planted/restored with vegetation (species = *P. amarum*, 75 rooted plants and 75 sprigs for each dune, see Chapter 4 for additional details on dune geometry) while two were left bare. This setup created all four combinations of restored vegetation and *Sargassum* bales (restored vegetation and *Sargassum* bales, restored vegetation without *Sargassum* bales, no vegetation and *Sargassum* bales, and neither vegetation nor *Sargassum* bales).

Table 5.1: Summary of Objectives

Section	Research Objectives
Plant Community Ecology and Succession Monitoring	• Observe the effect of vegetative restoration/stabilization and *Sargassum* bales on dune plant community vegetation cover, species richness, species evenness, and species assemblages over a 62 week period • Compare and contrast restored/vegetation stabilized dunes, non-restored dunes, and reference dunes over a variety of ecological metrics at the end of the project period • Examine the impact of vegetation restoration on plant colonization of adjacent areas
Biogeomorphological Monitoring	• Observe the effect of vegetative restoration/stabilization and *Sargassum* bales on dune erosion and accretion over a 102 week period • Compare and contrast the effect of Tropical Depression Bill on restored and non-restored dunes

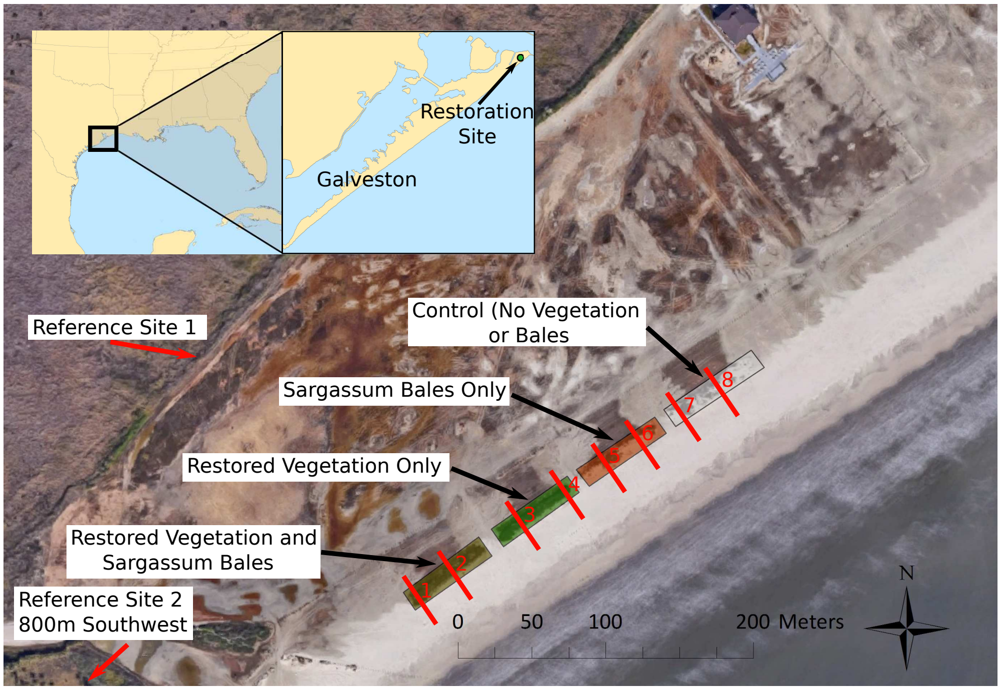

Figure 5.1: Location and layout of the dune restoration project. Red lines indicate elevation transect locations and red arrows indicate the location of reference sites.

5.2.2 Community Sampling

Sampling of the dune plant community was conducted for each of the four treatment dune systems outlined in Figure 5.1. This data was collected at 12, 36, and 62 weeks after restoration. Percentage vegetation coverage in a 1 m^2 quadrat was measured for randomly chosen points on an along-shore transect across the entire dune seaward berm. Digital photography and spectral analysis (custom-written raster algorithms) in ArcMap were used to quantify percent coverage. Also using ArcMap, percentage coverage of each species within the quadrat was computed (Figure 5.2) and was used to calculate total species richness and Shannon equitability (14).

$$E_H = \frac{\sum_{i=1}^{S}(p_i * ln(p_i))}{ln(S)} \qquad (14)$$

Where: E_H = *Shannon's equitability index*

S = *Species richness*

p_i = *The proportion of S made up by species* i

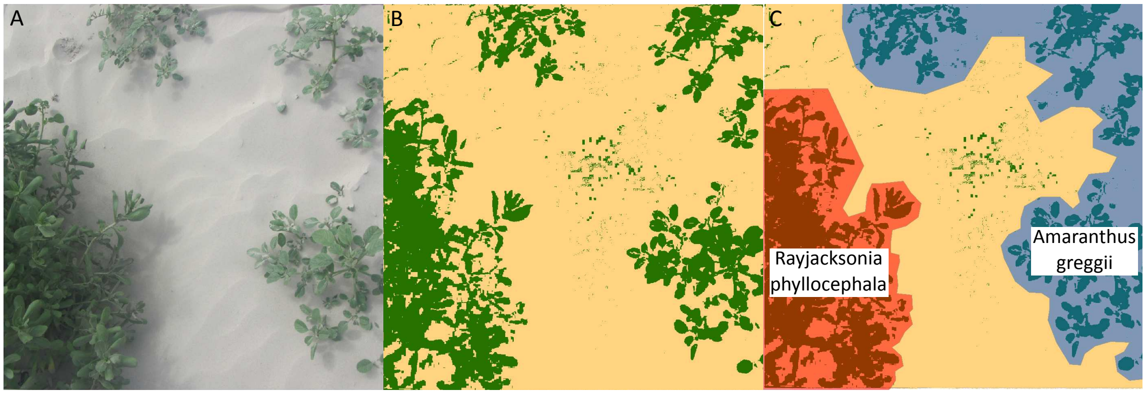

Figure 5.2: Spectral analysis of dune vegetation. A - Top-down photograph taken of a one square meter quadrat containing two species: *Rayjacksonia phyllocephala* and *Amaranthus greggii*. B - Custom-written spectral analysis algorithms distinguish green vegetation from bare sand. C - Delineation and quantification of percent coverage for each individual species.

These data were analyzed with a spatial ANCOVA (type II) with three categorical treatment variables: vegetation restoration status (restored vs. non-restored), *Sargassum* bale status (with or without *Sargassum* bales), and sampling interval (12 weeks, 36 weeks, and 62 weeks). An additional continuous variable on distance to the closest dune system was also included in the ANCOVA model. This variable would represent the closest plant source material for colonizing both restored and non-restored dunes and could have been a factor for both vegetation and diversity. Lastly, if spatial autocorrelation was detected for the model (Moran's I Test), spatial cluster terms were also tested and included in the ANCOVA model when significant (cluster sizes evaluated = 5, 10, and 20 m).

For the last sampling interval (62 weeks), more plant metrics were measured for each dune system to compare restored/non-restored dune ecosystem structure to each other and to a reference dune (Figure 5.1). Late succession communities that contained large stretches of *P. amarum* (which enabled along-shore transects and randomly selected samples to be taken) were chosen as reference sites. These reference sites were in close proximity to the treatment dunes (< 1 km) and the seaward facing slopes of these reference dunes were sampled.

During this last plant community sampling event, data were also collected on root biomass densities (divided into fine roots < 1 mm and total roots), soil detritus, aboveground biomass, plant height, and stem density along with percentage coverage, species richness, Shannon diversity index values, and plant community composition. For aboveground biomass, plant height, and stem density, data was only collected on dunes containing *P. amarum* (restored dune systems and reference dunes) principally to compare the target restored species morphology and distribution. Non-restored dunes were problematic for measuring plant height and stem densities as these communities were dominated by *Sesuvium portulacastrum*, which formed dense mats of vine-like vegetation across the surface of the dune and these metrics were not measurable.

A spatial ANOVA was used to analyze this data as there was only one categorical variable: dune system. This variable had 5 categories (Dunes with restored vegetation and *Sargassum* bales, with restored vegetation without *Sargassum* bales, no restored vegetation with *Sargassum* bales, no restored vegetation nor *Sargassum* bales, and the reference dunes). Again, if spatial autocorrelation was detected (Moran's I Test), spatial cluster terms were also tested and included in the ANOVA model when significant (cluster sizes evaluated = 5, 10, and 20 m). As there were numerous variables that were analyzed for this last sampling interval, a linear discriminant function analysis helped define clustering patterns for these different dune systems across all of these variables.

During the spring sampling (May 2015, 36 weeks after restoration), it was noted that restored dunes appeared to contain more vegetation (not *P. amarum*) in the areas surrounding plantings (*i.e.* the dune crest and landward facing slope) than non-restored dunes. Therefore, during this sampling event, additional percent coverage measurements were taken for a transect along the dune crest where no *P. amarum* had been planted; all vegetation on the dune crest colonized naturally. If there were larger amounts of vegetation in this area, it would imply that restoration of vegetation to a dune system aids in the recruitment of other vegetation for the surrounding areas. This data was also analyzed using a spatial ANCOVA with one categorical variable (dune system) and one continuous variable (distance to the closest dune system). Spatial autocorrelation was also evaluated and compensated for if detected.

5.2.3 Geomorphology Methods

Elevation transects were also conducted across the dune systems and their surrounding areas over the course of this experiment. Two elevation transects were conducted for each dune system in early September 2014 (3 weeks post dune construction), early December 2014 (16 weeks), late March 2015 (32 weeks), late June 2015 (45 weeks), and late July 2016 (102 weeks). Points along the transect were measured at 0.25 m intervals. For the last sampling (102 weeks), elevation data were interpolated along the same transects as the other sampling intervals using a krigging methodology (interpolation weights depend on the variography of the dataset) from a sampling grid (point separation distance ≈ 2 m). All elevations were measured with an RTK GPS (Real Time Kinematic Global Positioning System). The location of the transects can be seen in Figure 5.1. Erosion/accretion rates could be measured based on differences between the transects at different times.

Tropical Depression Bill made landfall along the Texas Coast (Matagorda area) on June 16th, 2015 (43 weeks after dune construction). NOAA buoys moored off the North Galveston coast recorded a 1.3 meter surge and offshore peak waves heights of nearly 3 meters. These severe wave conditions generated a small storm surge at the dune site and exposed the dunes to minor wave action. Therefore, the March 2015 elevation sampling represents a pre-storm data set and the late June 2015 represents a post-storm dataset for dune morphological changes. This contrast allowed comparison of each dune system's resilience and resistance to a minor storm surge.

5.3 Results

5.3.1 Plant Community Ecology

Large differences in vegetation coverage, diversity, and succession between dune systems were clearly visible over time (Figure 5.3). Vegetation coverage varied by restoration treatment, *Sargassum* bale treatment, and over time (Table 5.2, Figure 5.4). Initially (12 weeks), dunes with restored vegetation had nearly $34\times$ more vegetation coverage than non-restored dunes. This discrepancy diminished at the second sampling interval (36 weeks, $\approx 3.5\times$ greater coverage for restored dunes). By the third and final sampling interval (62 weeks), coverage between restored and non-restored dunes had converged again (only $2\times$ higher for restored dunes) with restored dunes decreasing in percent coverage and non-restored dunes increasing in coverage during the final time interval. Across all time intervals and dune systems (both restored and non-restored), dunes without *Sargassum* bales had 26.0% more vegetation coverage than dunes with *Sargassum* bales.

Table 5.2: Community ANCOVA results (p values)

Dependent Variable	Restoration Treatment	Sargassum Bale Treatment	Sampling Interval (Time)
Percent Coverage	< 0.001	0.024	< 0.001
Species Richness	NS	NS	< 0.001
Shannon Equitability	0.0032	NS	< 0.001

Notes: Interactions took place between restoration and time with regards to percent coverage (p value = < 0.001), species richness (p value = < 0.001), and Shannon equitability (p value = 0.013). The additional continuous variable of distance to closest established dune system was not a significant factor for any dependent variable. No significant spatial autocorrelation was detected.

Diversity, both with regards to richness and evenness (Shannon's equitability index), significantly varied with time with a spike in diversity occurring during the middle sampling interval (36 weeks) (Table 5.2). This middle sampling interval took place in the spring (early May). Non-restored dunes showed 428.4 % higher evenness on average across all time intervals, largely due to higher values during the spring (36 weeks) and second fall interval (62 weeks). Species richness did not display any significant treatment effects but an interaction did occur with non-restored dunes having lower richness at 12 weeks and higher richness at 36 weeks. Restored dunes without *Sargassum* bales only possessed monospecific stands of *P. amarum* at all time intervals. Plant community compositions also varied overtime and between dunes (Figure 5.6). Restored dunes were dominated by *P. amarum* with occasional intrusion by *Solanum ptycanthum*, particularly during the spring sampling interval

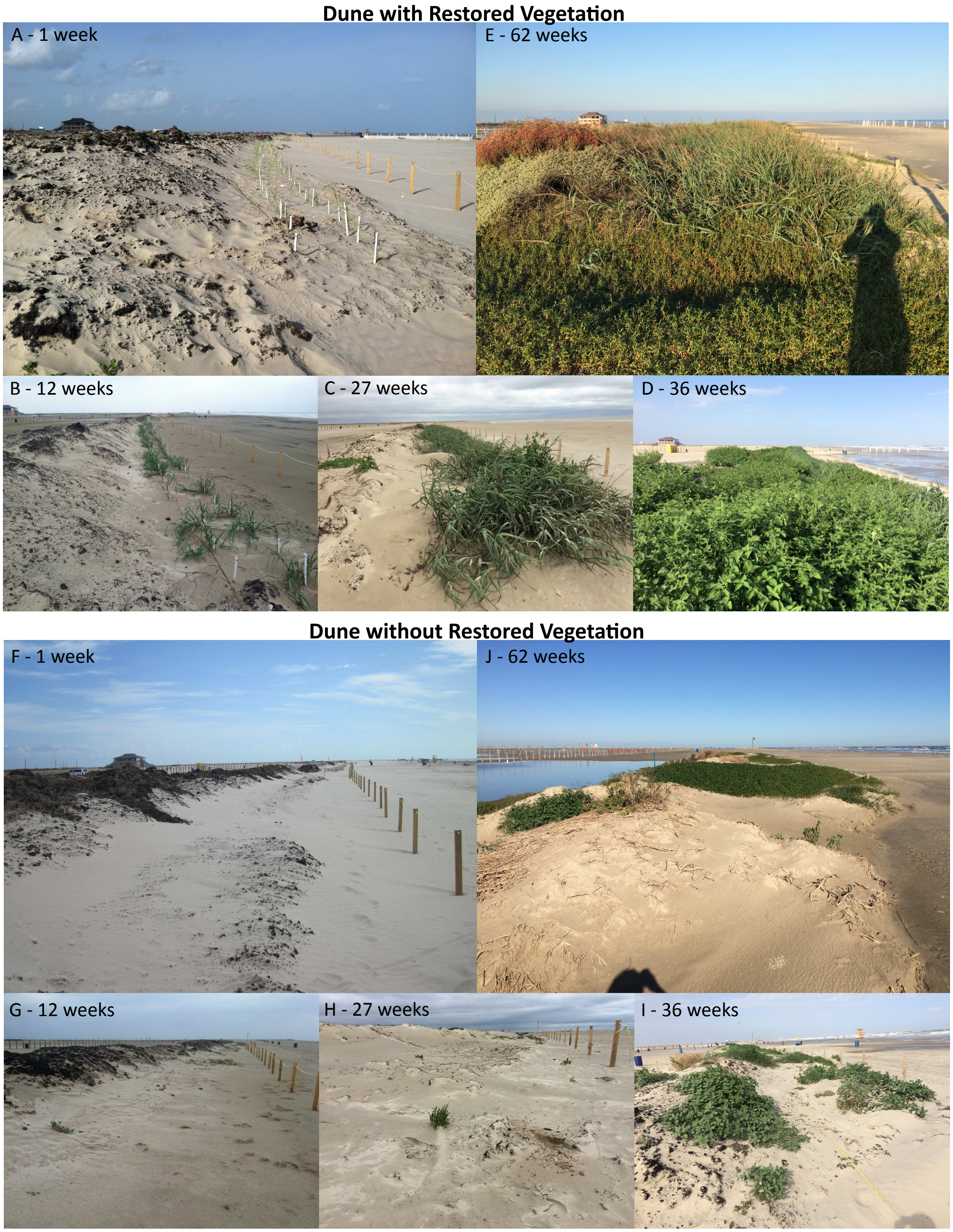

Figure 5.3: A through E shows changes in a dune system with vegetation restoration at five time intervals after restoration and F through J show changes of a dune system without vegetative restoration (natural colonization) at the same intervals.

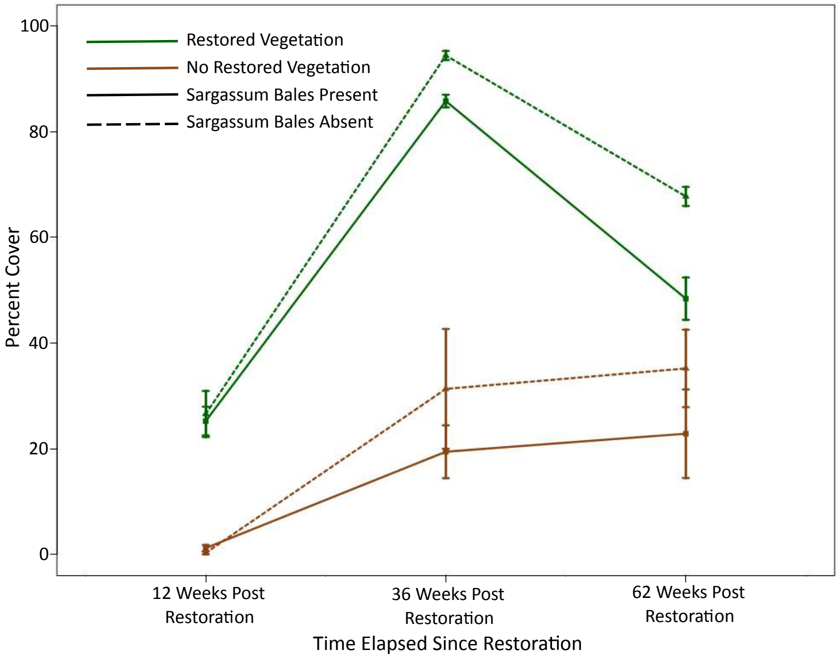

Figure 5.4: Interaction plot showing vegetation percent coverage for all treatment effects (vegetation restoration, *Sargassum* bale, and time elapsed). Bars show standard error.

(36 weeks). Non-restored dunes largely contained a mixture of *S. portulacastrum* and *Amaranthas greggii*, the former becoming more dominant over the course of the growing season. *Rayjacksonia phyllocephala* was also present in non-restored dunes during the spring sampling interval.

During the last sampling interval (62 weeks), additional data was collected on plant biomass (above- and belowground), soil detritus, mycorrhizal activity, stem count and plant height as well as plant community composition. This sampling interval also included the sampling of two late succession reference sites that contained *P. amarum*. Table 5.3 summarizes the ANOVA results for these additional data at 62 weeks. Figure 5.7 shows the general grouping trends of each dune system across all of these variables using linear discriminant function analysis. Bar plots in Figure 5.7 display significant differences (Tukey's HSD) between dune systems for the significant variables in Table 5.3.

Generally, restored dunes group together and separately from non-restored dunes, which also group together (Figure 5.7, Panel A). The reference sites were the most

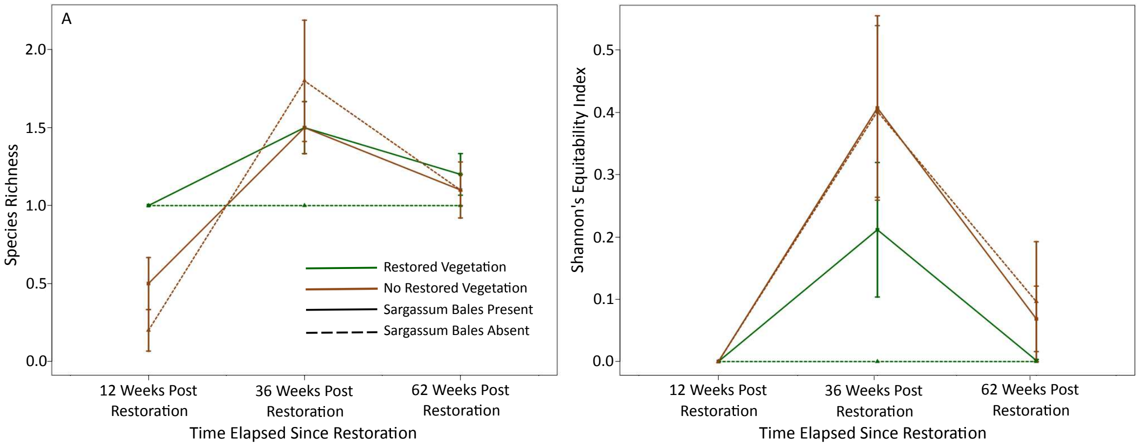

Figure 5.5: Interaction plot for species richness (A) and Shannon equitability index (B) for all treatment effects (vegetation restoration, *Sargassum* bale, and time elapsed). Bars show standard error.

Table 5.3: 62 weeks - Community ANOVA results (p values)

Dependent Variable	Dune System
Percent Vegetation Coverage	< 0.001
Fine Root Biomass	0.0019
Total Root Biomass	< 0.001
Soil Detritus	< 0.001
Percent Mycorrhizal Colonization	NS
Percent *P. amarum*	< 0.001
Percent *S. portulacastrum*	< 0.001
Species Richness	< 0.001
Shannon Equitability Index	< 0.001
Aboveground Biomass	< 0.001
Plant Height	< 0.001
Stem Count	NS

No significant spatial autocorrelation was detected for these data.

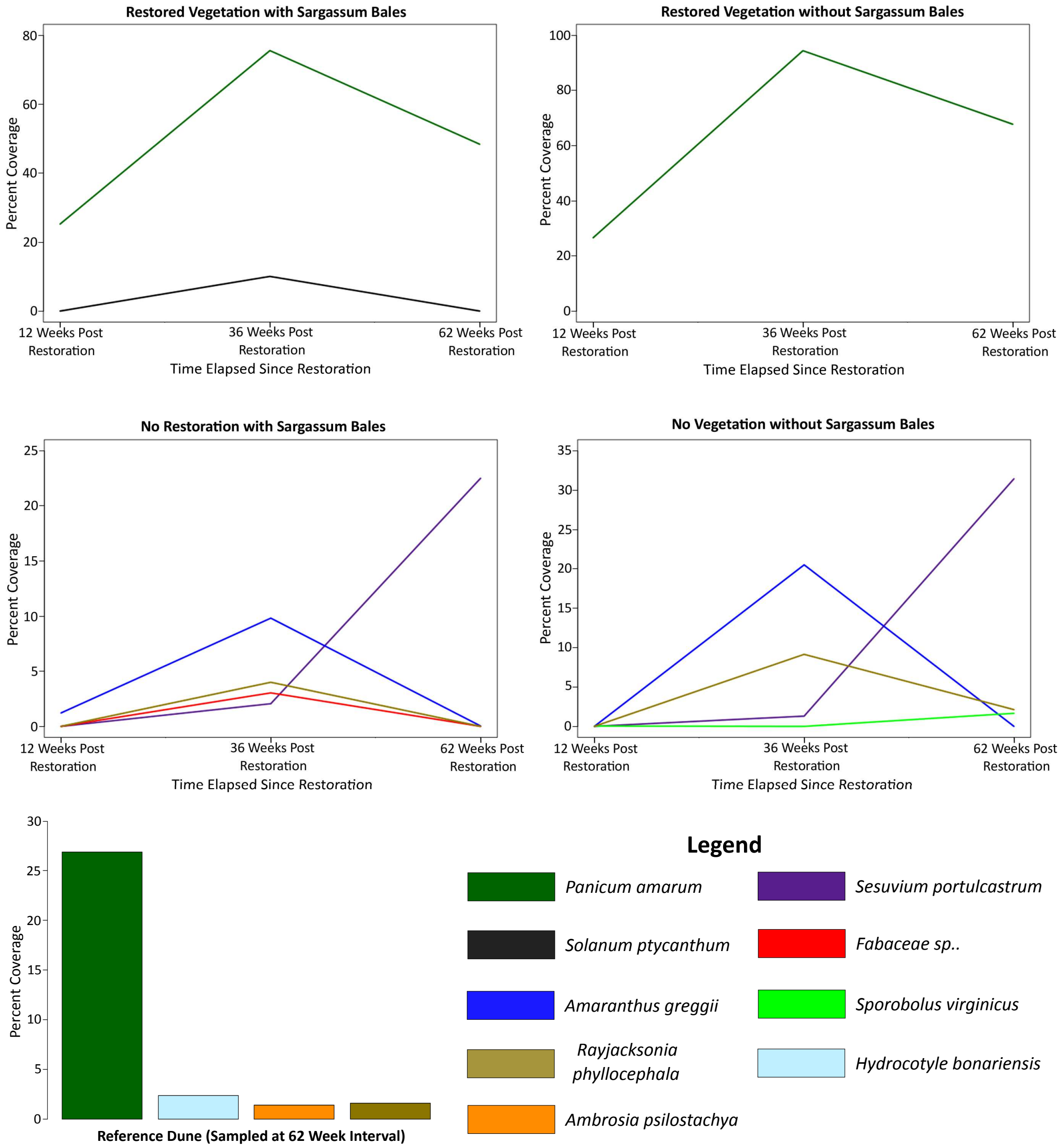

Figure 5.6: Plant community composition and successional trends of each dune with a comparison to a reference dune community. Only species with over 1% coverage for any sampling interval were shown.

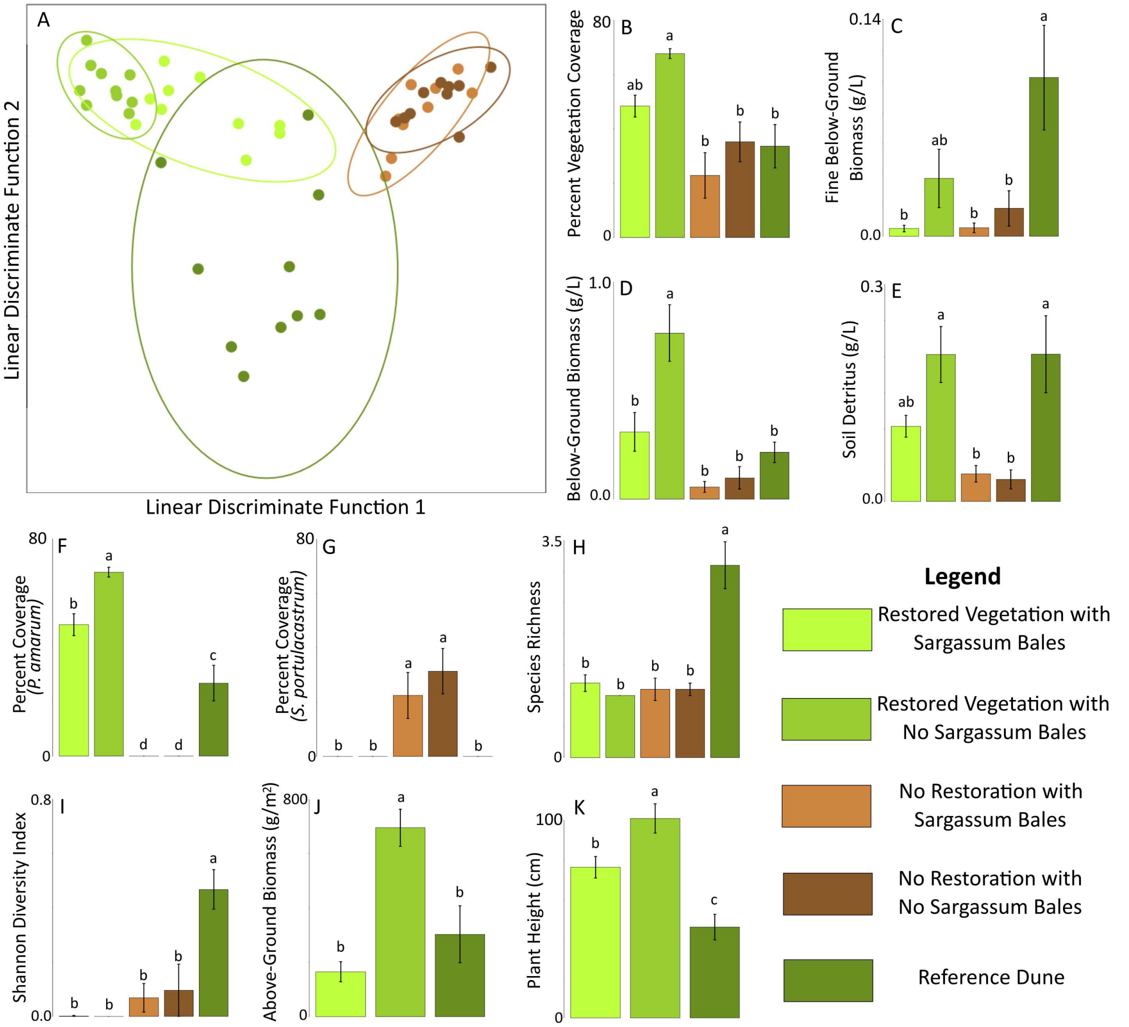

Figure 5.7: Linear discriminant function analysis comparing the five dune systems sampled at the 62 week interval along with bar plot breakdowns for all significantly different variables in Table 5.3. Ellipses in the linear discriminant function plot indicate 95% confidence intervals. Significant differences determined by TukeyHSD test with $\alpha = 0.05$. Bars show standard error.

variable (largest confidence ellipse) and grouped away from both restored and non-restored dunes with minor overlap. *Sargassum* bale treatments had less impact on grouping patterns as indicated by the lack of separation between confidence intervals for *Sargassum* treatments. However, for restored dunes, *Sargassum* bales caused the community to be more closely resembled to the reference sites with regards to the analyzed dependent variables as indicated by the larger overlap between the confidence intervals of the restored with *Sargassum* bales dune and the reference dune. The restored with *Sargassum* bales dune had similar values as the reference dunes for the variables of percent coverage, belowground biomass, aboveground biomass, percent *P. amarum* coverage, and plant heights, Figure 5.7, Panels B, D, F, J, and K).

The specific differences driving these grouping trends are summarized in the bar plots in Figure 5.7. The restored dune with *Sargassum* bales typically showed moderate values across most variables relative to the other dunes (see vegetation coverage, root biomass, soil detritus, and plant heights, Figure 5.7, Panels B, D, E, and K). This dune also had low amounts of fine root biomass, aboveground biomass, and community diversity (Figure 5.7, Panels C, H, I, J). The restored dune without *Sargassum* bales had relatively high amounts of vegetation coverage, root biomass, soil detritus, aboveground biomass, and plant heights, but had relatively low amounts diversity and moderate amounts fine root biomass (Figure 5.7, Panels B, D, E, J, K, H, I, C). Reference dunes had high amounts of fine root biomass, soil detritus, and plant species richness and evenness (Figure 5.7, Panels C, E, H, I). Reference dunes also had relatively low vegetation coverage, root biomass in general (which, combined with high amounts of fine roots means reference dune had fewer coarse roots), aboveground biomass, and shorter plant heights (Figure 5.7, Panels B, D, J, K). Non-restored dunes had relatively low values across every variable. Lastly, whereas restored and reference dunes were dominated by *P. amarum*, non-restored dunes were dominated by *S. portulacastrum* (Figure 5.7, Panels F, G).

The dune crest in Figure 4.2 was also analyzed to determine the effect of vegetation restoration on the recruitment of vegetation in adjacent areas. There was significantly more vegetation recruitment to the dune crests adjacent to restoration at the 36 week spring interval (Table 5.4, Figure 5.8). It should be noted that no *P. amarum* was observed in these dune crest areas, all vegetation present had naturally colonized. A significant spatial clustering pattern was found with four clusters (cluster size = 20 m) having a significant impact on percent coverage of the dune crest (two of which were higher than the mean and two of which were lower).

Table 5.4: 36 weeks - Vegetation Coverage ANCOVA for Dune Crest (p values)

Dependent Variable	Restoration Treatment	Distance from Adjacent Vegetation	Spatial Auto-correlation Clustering
Percent Coverage	0.012	NS	< 0.001

Significant spatial autocorrelation was detected with four clusters (cluster size = 20m) having a significant impact on percent coverage of the dune crest (two of which were higher than the mean and two of which were lower).

5.3.2 Geomorphology Results

Figure 5.9 shows geomorphological changes observed in the dune systems over a 102 week time span. Few changes occurred in the first 50 weeks, but extensive changes took place over the second 50 weeks. Initially (even before the 3 week transect), all dunes featured a seaward berm and showed some resemblance to the dune profile in Figure 4.2, Panel C (see Chapter 4 diagram of dune construction). However, at the 3 week mark (red line), this berm was not distinguishable for the dunes with *Sargassum* bales (Transects 2, 5, and 6 and to a lesser extent, Transect 1). Visible compaction and soil cracking was observed in the dune berms where *Sargassum* bales were placed, accounting for this drop in berm elevation for *Sargassum* bale dunes. Generally across all dune transects, erosion occurred on the dune crest throughout each time interval. From 3 weeks to 32 weeks (compare red to green lines), accretion occurred on the dune berm for restored dunes (most notable in transects 1, 2, and 3). In contrast, dunes without restored vegetation generally eroded in the berm region from 3 to 32 weeks (most notably transects 5 and 6). These trends can also be seen in the erosion/accretion summaries (Figure 5.10) across both the entire cross-shore profile in Panel A (for the range of distances that are visualized in Figure 5.9) and for the seaward berm and slope in Panel B.

Tropical Depression Bill promoted accretion across the entire cross-shore profile (for the range of distances that are visualized in Figure 5.9), primarily in the beach

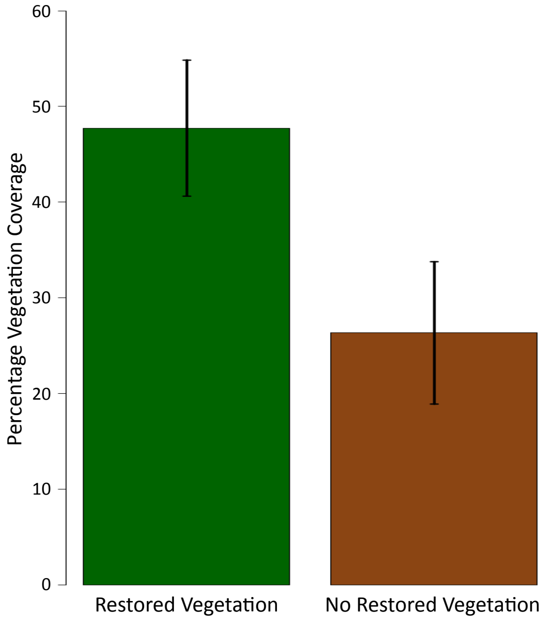

Figure 5.8: Comparison of vegetation colonization of the dune crest at 36 weeks. The dune crest represents an area adjacent to restoration where the effect of restoration on local recruitment of plants could be observed. Bars show standard error.

zone (compare the green and yellow lines in areas that are seaward to the dune). This accretion can also be seen in Figure 5.10, Panel A (note the positive trending lines in the “blue zone”). When considering only the seaward berm and dune slope (Figure 5.10, Panel B), restored dunes eroded during Tropical Depression Bill while non-restored dunes accreted. After Tropical Depression Bill, extensive morphological change occurred in the dune systems. This period was marked by accretion for all dune systems (see Figure 5.10) but was variable in terms of the location of sediment deposition along the cross-shore profile (see Figure 5.9).

5.4 Discussion

5.4.1 Community Ecology and Succession Discussion

Multiple trends in community ecology and succession were observed in the different dune systems over the course of the experiment. Vegetation coverage in the restored dune systems was 34× higher than non-restored dunes initially but had converged to only 2× higher after a year had passed. Additionally, the restored plant community

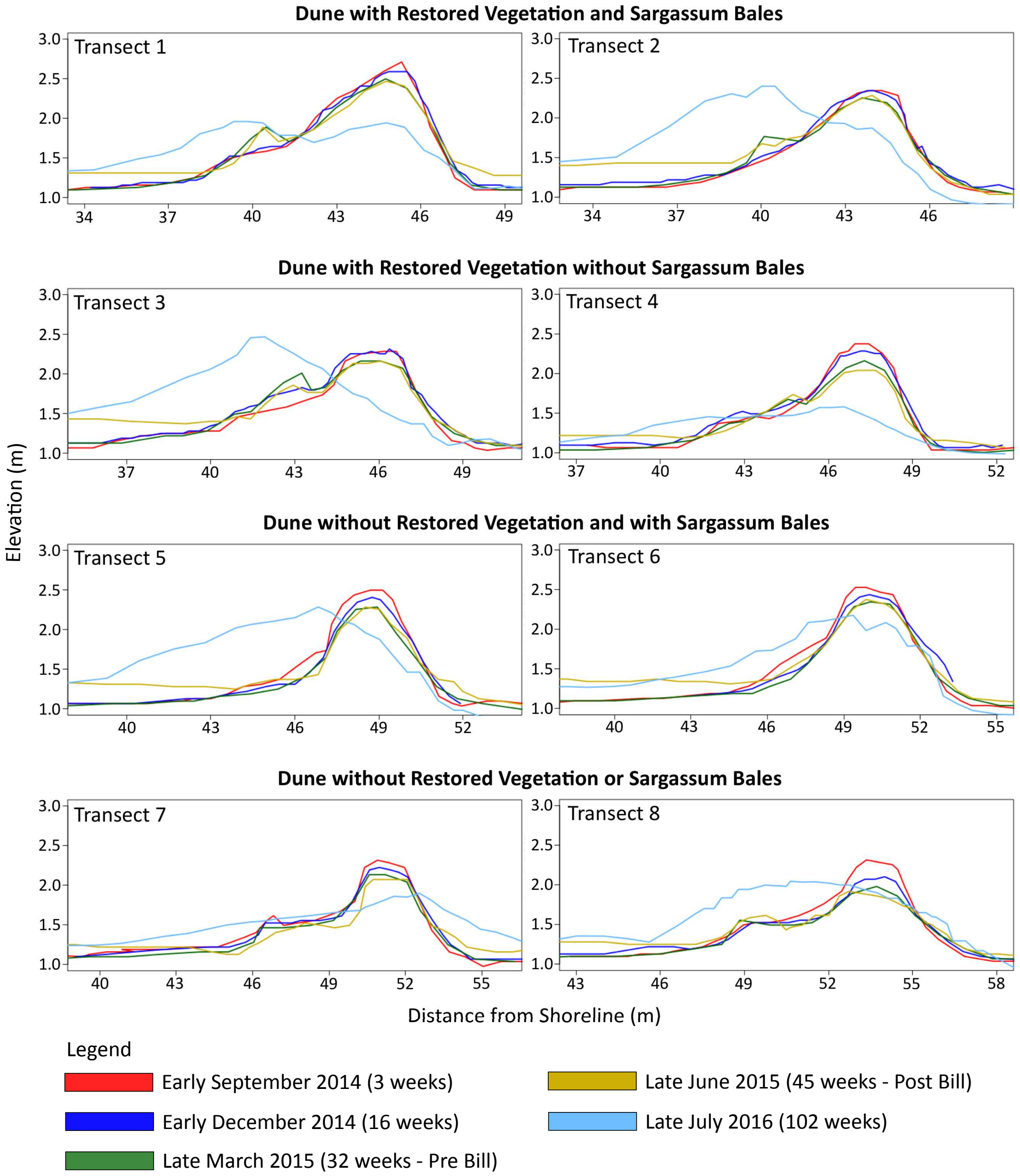

Figure 5.9: Elevation transects for the dunes systems showing morphological changes (accretion and erosion) over roughly a two year period.

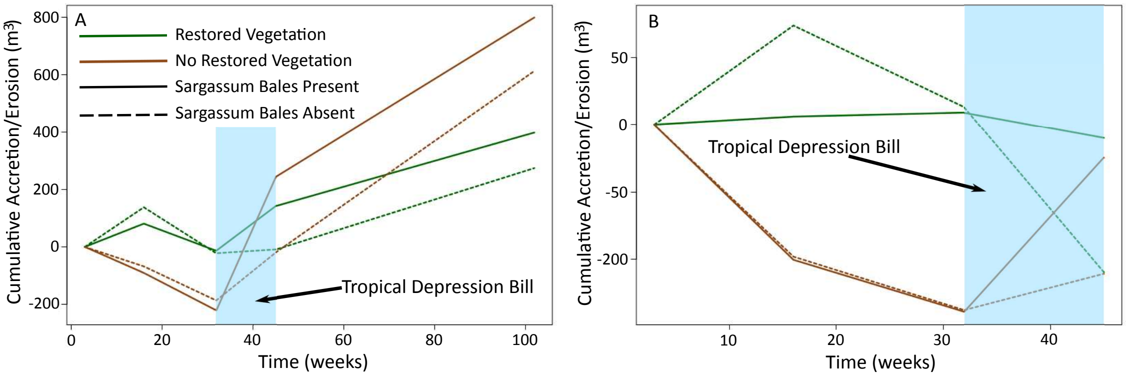

Figure 5.10: Erosion and accretion, extrapolated from two transects to the volume of each entire dune system, across the entire cross-shore profile (A) and for the seaward dune slope and berm (B). Blue shaded areas indicate the period of time during which Tropical Depression Bill occurred.

vegetation coverage spiked during the spring sampling (36 weeks after restoration) and then subsequently receded in the fall sampling (62 weeks). This recession was not caused by senescence of live aboveground plant tissue (the vast majority, 91.2 %, of plant clipped plant stems were living and green at 62 weeks). Rather, rapid accretion and sand burial that was observed after the deposition of sediment in front of the dune by Tropical Storm Bill likely decreased plant growth.

A large amount of deposition occurred between 45 and 102 weeks (the fall sampling took place between these two times at 62 weeks). Primarily, this deposition occurred in the area of the dune berm because the high density of vegetation on the berm trapped windblown sediments. Late succession dune plants (which inhabit more stable foredune and backdune environments) typically show decreased growth during periods of excessive sand burial (Gilbert *et al.*, 2008; Wilson & Sykes, 1999), hence the decrease in coverage that was observed at the last sampling interval. Buried aboveground plant structures would also no longer contribute to vegetation coverage. Non-restored dunes were dominated by *S. portulacastrum*, but this species increased in abundance during this same period of sand burial. *S. portulacastrum* is a spreading colonizer that is commonly found on coppice mounds and embryonic dunes. In other coastal dunes, colonizer species have actually shown increased growth when subjected to sand burial (Gilbert *et al.*, 2008; Martìnez & Moreno-Casasolai, 1996;

Martìnez *et al.*, 2001). This increased adaptation to sand burial could explain why this species' vegetation coverage increased during this same period.

The rate of vegetation colonization of bare substrate observed in this dune restoration project was much faster than previous observations for the upper Texas coast. Morton and Paine (1985) noted that the natural primary colonization of bare sediment left behind after a large storm disturbance started after two years. This chapter's research showed it began almost immediately (sparse colonization was observed after only 12 weeks in non-restored dunes). However, it is important to distinguish the geomorphological dynamics that were at play in both scenarios. Morton and Paine (1985) noted that the back-beach area was inundated by salt water during high tides two years after Hurricane Alicia made landfall in Galveston Island, TX. Under a normal post-storm succession scenario, lagging geomorphological processes hinder plant colonization of the bare sediment exposed by the storm. In other words, vegetation cannot re-establish into the pre-storm dune zone until elevations have been built up to a more suitable habitat. During the dune restoration project described in this chapter, the geomorphological processes that slowly build a suitable habitat were essentially skipped (the dune was constructed above the high tide line). Plant colonization therefore occurred much faster and was conceivably aided by the added nutrients provided by abundant *Sargassum*. This rapid colonization also stabilized sediment much better than anticipated, even during a storm surge (which is discussed in the next discussion subsection).

Dunes with and without *Sargassum* bales tended to diverge over time with regards to vegetation coverage. Initially, there was essentially no difference between dunes with and without *Sargassum* bales (only 1.6% higher for non-bale dunes). However, after roughly a year had passed, dunes without *Sargassum* bales had 44.5% higher vegetation coverage than dunes with *Sargassum* bales. This discrepancy between *Sargassum* vs. non-*Sargassum* bale dunes was likely also caused by the lack of control that was discussed in the context of Figures 4.4 and 4.10 (see Chapter 4). From the perspective that the non-*Sargassum* bale dunes possessed large amounts of diffusely distributed *Sargassum*, perhaps even more total *Sargassum* than the *Sargassum* bale dunes, the increase in growth that was observed in non-*Sargassum* bale dunes could be viewed as consistent with the beneficial effects of nutrients and *Sargassum* on plant growth (Hester & Mendelssohn, 1990; Williams & Feagin, 2010).

Plant diversity peaked during the middle sampling event (36 weeks), which took place during the spring. Initially (12 weeks), richness and evenness were low. This low initial diversity was caused by the lack of colonization of other species into the dune systems, leaving restored dunes with only *P. amarum* and non-restored dunes with hardly any plants at all. Texas coastal dunes are the home to many annual opportunistic plant species (such as *A. greggii*, *R. phyllocephala*, and *Cakile lanceolata*) which generally grow during the spring and summer months. These annuals were the primary constituents of the increase in diversity that was observed during the spring sampling (36 weeks). Seasonal (wet/dry) oscillations in annual plant species diversity and abundance are common in other coastal dune ecosystems (Martìnez *et al.*, 2001). Non-restored dunes had both higher species richness and evenness during this spring sampling interval (32 % higher richness and 352.1 % more evenness than restored dunes). As the annual colonizers did not have to compete with an already established late succession species (*P. amarum*) in non-restored dunes, this availability of space and lack of competition likely accounted for the increase in annual plant presence and diversity for non-restored dunes.

At the 62 weeks fall sampling interval, plant richness and evenness were generally lower and there was less of a difference between restored and non-restored dunes with regards to evenness and richness. During these events, the annuals present in the non-restored dune (principally *A. greggii* and *R. phyllocephala*) and restored dunes (predominantly *Solanum ptycanthum*) mostly disappeared, leading to lower observed diversity. In non-restored dunes, the perennial vine-like plant *S. portulacastrum* made substantial gains over the summer of 2015 (the time between 36 and 62 weeks after restoration) as annual species died back. Anecdotal observations made in 2016 and 2017 (two and three years after restoration) indicated that *S. portulacastrum* continued to dominate non-restored ecosystems after data collection had stopped for this project (Figure 5.11).

Significantly higher vegetation colonization was observed in the dune crest adjacent to *P. amarum* restoration. It is noteworthy that *S. ptycanthum* was observed to be the most abundant colonizer in restored dunes and the areas surrounding where *P. amarum* was restored. *Solanum ptycanthum*, a member of the nightshade family that is not typically found in dunes, differs from most dune plant species in that it produces berries that are dispersed through consumption and excretion of seed material by birds and mammals (Martin, 1951). This species was observed in 20% of plots where *P. amarum* was planted and 0% of plots in non-restored areas (chi test p

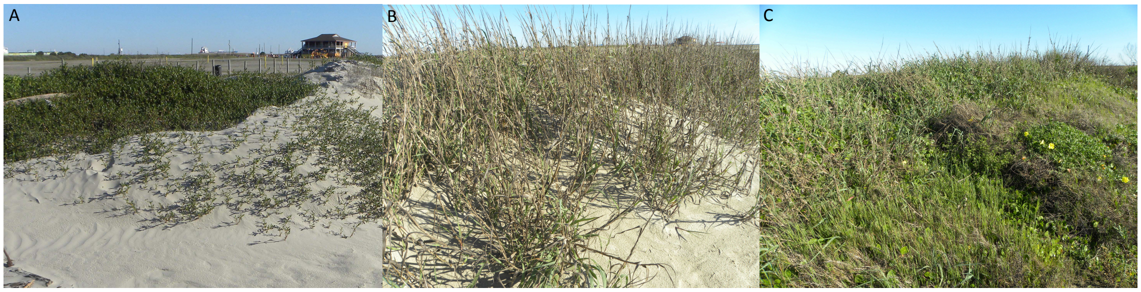

Figure 5.11: At two years and seven months since restoration (March 2017 or 134 weeks), Panel A shows a typical area of a non-restored dune. *S. portulacastrum* is still the dominant species in most areas. Panel B shows what became of the seaward berm (accreting sediment caused it to eventually form into the new dune crest) of a restored dune. *P. amarum* is still the only species present in most of this restored berm area. Lastly, Panel C shows a typical area for a reference dune. Multiple species are visible, including *P. amarum*, *Oenothera drummondii*, *Sporobolus virginicus*, and *Hydrocotyle bonariensis*.

value = 0.11). Additionally, on the dune crest adjacent to *P. amarum* restoration, *S. ptycanthum* was found in 55% of plots compared to 10% on the dune crest adjacent to non-restored areas (chi test p value = 0.007).

This dispersal pattern and the colonization distribution of *S. ptycanthum* in the constructed dunes implies that birds and mammals were drawn to restored dunes, aiding in the recruitment and colonization of animal-dispersed plant species to restored areas. Great Tailed Grackles (*Quiscalus mexicanus*) and House Sparrows (*Passer domesticus*) were often observed perched in *P. amarum* stands while plant material was being collected during sampling events. This observation suggests that a positive feedback mechanism could benefit dune restoration. In other words, plant restoration attracts animals which in turn recruit more plants through dispersal. Such positive feedback mechanisms involving animal-driven plant dispersal could contribute to woody encroachment, plant community succession, and invasive plant species expansion in other ecosystems (Best & Arcese, 2009; Forman & Baudry, 1984; Sarlöv Herlin & Fry, 2000; Simberloff & Von Holle, 1999). To the author's knowledge, it has never been observed in dune restoration.

Vegetation plantings could also, by the same process that it traps windblown sediments, trap windblown seed material, further aiding in recruitment of vegetation. These seeds probably do not establish as easily in the *P. amarum* dominated areas (due to competition with an established late succession species) but can in adjacent areas. Additionally, the windbreak provided by *P. amarum* could provide a more stable habitat for colonizing seedlings to germinate. These concepts lend support to the view that positive feedbacks could take place between vegetation plantings (restoration) and natural colonization to adjacent areas. Such positive feedbacks may be a way to take advantage of the natural dynamism of dune systems to enhance the stability provided by vegetation plantings. Planting fewer but denser "wind rows" of *P. amarum* to trap not only sediments but also windblown seeds could be a more efficient way to stabilize dunes than planting "grids" of vegetation. This technique could also require less planting than a grid based system, though its efficiency still needs to investigated.

The last sampling interval included data collection on a wide range of variables which offered a ecosystem "snapshot" for each dune system for comparison to one another and to reference dunes. Linear discriminant function analysis showed that restored dunes grouped together, non-restored dunes grouped together, and both restored and non-restored dunes clustered separately from the reference dunes. This separation was caused by differences between groups across multiple variables. First, reference dunes had relatively higher amounts of fine root biomass, had high plant species diversity and evenness, and *P. amarum* was the most abundant plant. Both restored dunes (those with and without *Sargassum* bales) had relatively higher vegetation coverage, plant heights, and were also dominated by *P. amarum*. Restored dunes without *Sargassum* bales had relatively higher above- and belowground biomasses densities as well. Both restored dunes and the reference dunes had high amounts of soil detritus, which was generally leaf litter associated with *P. amarum* (little *Sargassum* remained in soils by the last sampling period). Non-restored dunes had low values across all variables and were dominated by *S. portulacastrum*. Surprisingly, restored, non-restored, and reference dunes did not vary in terms of the mycorrhizal activity of their root systems. AMF were found in non-restored dune despite the area likely being devoid of mycorrhizal colonizing agents initially. This result is consistent with other studies that how found mycorrhiza can naturally colonize new dunes systems relatively quickly (< one year) (Gemma & Koske, 1997).

After approximately one year, neither the restored nor non-restored dunes resembled the reference dune. Restored dunes were dominated by *P. amarum*, but typically had higher amounts of biomass (with the exception of fine roots) and lacked plant diversity (low richness and evenness) when compared to reference dunes. Non-restored dunes differed from reference dunes in terms of the dominant species and also generally lacked diversity. Perhaps if given enough time, the constructed dunes would begin to resemble an older, natural dune system. However, even after two and a half years, the restored dune had relatively low plant diversity (Figure 5.11). It is possible that the heavy nutrient load (provided by *Sargassum* and restoration of a late successional plant species altered the successional trajectory of the ecosystem. Similar altered trajectories have been observed another study, where rehabilitated dunes had different plant communities and ecosystem structure compared to natural dunes (Landi *et al.*, 2012). Continued long-term monitoring would need to be conducted to determine if the restored dunes built in this experiment ever converged towards natural dunes with regards to ecosystem structure and function.

This potentially altered plant community succession trajectory raises the question: what was the purpose of this dune restoration project? Was it to mimic a natural, late succession dune in terms of diversity and biomass? Biodiversity is valuable because dune plant diversity is linked to diverse and abundant animal and microbial communities (Emery & Rudgers, 2010; McLachlan, 1991; Liu *et al.*, 2009) and has been linked to invasive species resistance in other ecosystems (Stachowicz *et al.*, 1999). The dunes that were restored in this experiment had lower plant diversity than natural reference dunes. However, restored dunes exceeded the natural dunes in terms of above- and belowground biomass, possibly due to the nutrient enrichment provided by *Sargassum*. Above- and belowground growth are aspects of dune vegetation that are linked to erosion reduction and storm protection (see Chapter 3). Is losing diversity worth gains in storm protection? To a certain extent, answering these kinds of questions was beyond the scope of this research project. The main purpose of this TGLO CEPRA dune restoration project was to determine if local coastal stakeholders could remove *Sargassum* from beaches while simultaneously restoring a dune system. To that question, this project was very much a success (see Figure 5.3, Panel E). However, these deeper questions regarding conflicting and competing restoration goals were raised by this dune restoration project and will continue to be raised in future coastal green infrastructure projects. The tradeoffs and potential conflicts between dune restoration goals needs to be further explored, discussed, and researched.

5.4.2 Geomorphological Discussion

Transects taken of each dune system showed that restored dunes accreted more sediment initially but long-term processes outweighed and equalized those initial accretional tendencies. Also, *Sargassum* bales compacted in the weeks following dune construction, as indicated by the disappearance of the dune berm for dunes with *Sargassum* bales. The principle long term process that outweighed these initial tendencies was Tropical Depression Bill and its lasting depositional effects. Tropical Storm Bill deposited a large amount of sediment in front of and on top of the dune systems, which, over the course of a year, redistributed across the beach/dune profile to bring about extensive morphological changes. By the end of a two year period, non-restored dunes showed higher amounts of net accretion than restored dunes. However, the two-year elevation transects were estimated using a krigging-based interpolation of a lower resolution point cloud elevation dataset, potentially introducing some error the last sampling interval's accretion estimate.

When limiting the scope of erosion/accretion to only the seaward dune slope and berm, a slightly different trend emerges (see Figure 5.10, Panel B). Initially (from 0 to 32 weeks after restoration), restored dunes accreted in the restored areas (the berm) and non-restored areas eroded in their equivalent areas. However, during the surge produced by Tropical Storm Depression Bill, restored dunes eroded in the seaward berm/slope and non-restored dunes accreted. This result was surprising as there appeared to be high amounts of erosion in non-restored dunes compared to restored dunes (Figure 5.12). Restored dunes largely appeared to be intact with regards to dune morphology, but roots at the base of the dune berm were exposed (seen in the red box of Panel A, implying that erosion took place). For non-restored dunes, many areas featured a distinctive scarp (marked in red on Figure 5.12, Panel B), a sign of substantial erosion.

Nevertheless, the elevation transects data showed that dunes with vegetation plantings eroded more during the storm surge than the dune without restored vegetation. This finding appears to contradict the results found in the flume experiment detailed in Chapter 3 because restored dunes had higher amounts of aboveground structures and belowground biomass than non-restored dunes yet experienced higher amounts of erosion. However, whereas the flume experiment carefully controlled for dune/beach morphology between vegetated and non-vegetated trials, the inherent complexity and dynamism of *in situ* dunes meant that dune/beach morphology was

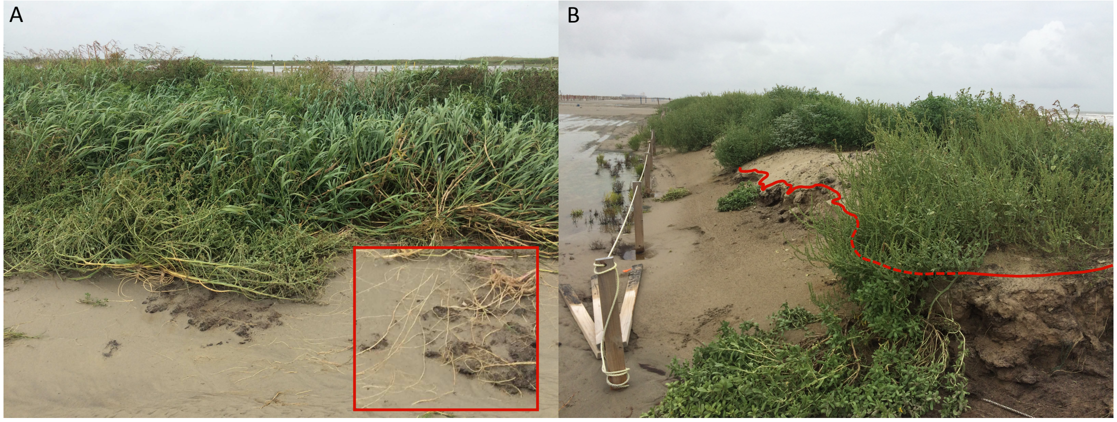

Figure 5.12: Evidence of damage and erosion that occurred to a restored dune system (A) and a non-restored dune system (B) during Tropical Depression Bill. The red box zooms in on exposed root systems in Panel A and the red line traces a scarp that has formed in the non-restored dune.

not the same for restored vs. non-restored dunes. This lack of morphological control is apparent when considering the X axis of the plots in Figure 5.9. Due to errors made by the dune construction team, dune systems without restoration tended to be further from the shoreline than those with restoration, potentially altering storm conditions for the different dune systems. Restored dunes could have been exposed to more severe wave conditions because there was less beach in front of the dune to dissipative wave energy.

Additionally, accretion gains could be counteracted by erosion during small storm events. Dense vegetation promoted accretion in the seaward berm area because windblown sediments were trapped toward the seaward side of the dune rather than penetrating landward into the dune profile. This process created a steeper dune profile that was closer to the water for restored dunes. This more seaward and steeper berm profile then eroded more during the minor storm event of Tropical Depression Bill. Varying dune morphologies have been demonstrated to show different erosional tendencies when attacked by waves and surge in wave flume studies (Figlus *et al.*, 2011). In other words, dense vegetation causes accretion but primarily in seaward areas where this accreted sediment is most vulnerable to erosion during small storms. Thus, the minor storm event had an equalizing effect on the restored and non-restored dune system's net accretion and erosion.

From the current perspective of Texas coastal policy makers, the main point of vegetation planting during dune construction is the stabilization of sediment (Patterson, 2005). However, over the course of two years, dune stability with regards to accretion/erosion was roughly the same when comparing planted vs. non-planted systems. This result raises the question: is vegetation planting actually useful for stabilizing sediments when natural colonization of vegetation occurs so rapidly? These results are probably dependent on the fact that the East End of Galveston Island, TX (where the dune was located) is an accreting area. Additionally, the small storm surge caused by Tropical Depression Bill deposited large amounts of sediment into the dune and beach system, aiding in additional accretion. If these dunes had been constructed in a more erosive environment, such as the center of Galveston Island, TX (Paine, 2012), perhaps vegetation planting would have made more of a difference with regards to dune stability compared to natural colonization.

5.5 Concluding Statements

The effects of vegetation plantings and *Sargassum* bale usage on dune succession and biogeomorphology were evaluated over time. Planted dunes showed higher amounts of vegetation coverage at all sampling intervals compared to non-planted dunes though the magnitude of the difference decreased as time progressed. Plant species richness and evenness were generally lower while vegetation coverage and biomass were generally higher in restored dunes compared to non-restored and reference dunes. These results bring to light the potential for conflicting goals with regards to dune restoration. Higher above- and belowground biomass could increase erosion resistance to storms but higher diversity could boost ecosystem resistance to other forms of disturbance (such as invasive species or drought).

Vegetation planting also appears to improve the colonization of plants into adjacent areas potentially through positive feedbacks involving animal driven dispersal and/or the trapping of windblown seed materials. Dune vegetation plantings increased sediment accretion initially as well, but these tendencies were overwhelmed by the depositional effects of a tropical depression and long-term processes. Natural vegetation colonization stabilized sediments better than anticipated. After two years, net accretion/erosion rates were similar for restored and non-restored dunes. Ultimately, using a combination of vegetation planting and natural colonization could be an efficient way to restore a diverse plant community and a stable dune ecosystem.

6. CONCLUSION AND OUTLOOK

Storms inflict massive economic and social damage to coastal communities worldwide. Engineering with nature serves as a means to mitigate storm damage while gaining additional beneficial ecosystem services. Coastal dunes restoration and construction could be integrated into a coastal hazard mitigation strategy along with building regulations, conventional structures, flood insurance policy, and land use control as well as other coastal ecosystem restoration projects. However, several knowledge gaps existed for coastal sand dunes acting in this capacity. For one, the cost efficiency of dunes in terms of storm damage mitigation had not been established. The multivariate analysis conducted in Chapter 2 showed that dunes, including small dunes that are breached by a severe hurricane, are highly valuable and can be cost effective. This novel methodology featured the use of real flood damage data (FEMA claims) sustained during Hurricane Ike and a dune size quantification technique using LiDAR and aerial photography. Dune storm damage mitigation value was largely dependent on the pre-storm state (*i.e.* a combination of ecological, built, and geographic variables) of a coastal area and this pre-storm state can inform strategic hazard mitigation planning. Additional analysis of other dune systems and storms are still needed to determine if these findings extend to other storm scenarios.

Other knowledge gaps, explored in Chapter 3, existed regarding the role of dune vegetation and erosion resistance during storm surges. This role could be important for both the long term stability of dune systems during consecutive small storms or for erosion and breach during large episodic events (*e.g* a hurricane). Both above- and belowground features were important in reducing erosion in a wave flume experiment which featured multiple species of plants. Aboveground aspects of plants, particularly the surface area of plant structures in the swash zone, reduce both flow and turbulent velocities and dissipate wave energy more efficiently in the swash zone. Belowground, fine roots increase shear resistance, reducing collapse and slumping of the dune scarp. Better understanding these roles can inform dune restoration and management practices. For example, optimizing the amount of plant structures and root biomass density in dunes should decrease erosion during storms. However, these interactions between plants, water, and soil need to be explored at larger scales.

Though dunes were found to be cost effective with regards to storm damage mitigation in Chapter 2 and plant features were important in dune erosion mitigation during storms in Chapter 3, restoration success is variable for coastal sand dunes, largely because there have been few quantitative studies to develop effective restoration techniques. Chapter 4 evaluated the effect of multiple restoration techniques on transplant growth and survival of *P. amarum*. Rooted (potted) plants had higher survival rates and accumulated more biomass compared to sprigs, but this difference between rooted plants and sprigs decreased over time. Native mycorrhizal inoculations increased plant biomass compared to commercial and control treatments though this difference also converged after several months. Compacted *Sargassum* bales tended to slightly decrease plant growth compared to dunes with less dense and more dispersed *Sargassum* material. Using rooted plants and a native mycorrhizal inoculum to quickly increase biomass in a new dune system could be an effective means to stabilize vulnerable dune sediments.

Biogeomorphological trajectories of coastal dunes in the context of dune restoration also remain largely unexplored for the Texas Coast. The effect of vegetation planting/restoration compared to natural vegetation colonization on plant coverage, plant species diversity, and dune geomorphology was evaluated in Chapter 5. Planting vegetation increased vegetation coverage and accretion initially but decreased plant diversity. A large deposition of sediment occurred during Tropical Depression Bill in June of 2015, which subsequently promoted accretion in both planted dunes and non-planted dunes. After two years, the net accretion of restored dunes was similar to non-planted dunes. Potentially, utilizing a combination of vegetation planting and natural colonization in coastal dune restoration could be an efficient way to restore a stable, diverse plant community.

The research detailed in this dissertation has shown that dunes possess large storm protection value, that vegetation is important for wave energy dissipation and dune stability during a storm surge collision, and that the usage of rooted plants and mycorrhizal inoculums can provide an effective means to restore dune vegetation and stabilize sediments. This research contributes to the growing body of knowledge concerning engineering with nature, and will promote the design and planning of sustainable and resilient coastal communities.

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