DUNE PLANT BIOPHYSICAL TRAITS AND THEIR IMPACTS ON EROSION

A Thesis

by

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ABSTRACT

Increasing frequency and severity of storms has translated into a greater interest in coastal protection, due to fears of storm damage to homes and communities. In the past, communities used man-made structures such as sea walls to mitigate the damage from storms, but recently more natural solutions have come into favor.

We present empirically-derived values for biophysical attributes of commonly-occurring sandy beach and dune plant species, including stem height, density diameter, and strength; number of leaves, their area of cover, and hardness; and quantities of aboveground, belowground, and root biomass. These parameters can be used to further explore the interactions between vegetation, wave attenuation, sediment accumulation and erosion through more realistic experiments, and analytic or numerical models.

We also used wave flume experiments with living vegetation to investigate both the capacity of dune plants to reduce erosion and the specific mechanisms by which this occurs. In particular, our study focused on the relationship between the ratio of above ground biomass to below ground biomass and the resulting differences in levels of erosion. We found that all plant species reduced erosion equally. Dunes with below ground biomass only (BG) experienced more erosion than dunes with whole plants (AGBG), but unvegetated controls experienced about twice as much erosion as either BG or ABGB treatments. Linear regressions singled out high above ground biomass as the primary factor correlated with decreased erosion, and this was corroborated by reduced erosion in the back half of AGBG treatments compared to GB treatments.

Coastal protection strategies, such as dune restoration, are of vital importance to not only the quality of coastal ecosystems, but also for the continued well-being of the disproportionate number of people that live on or near the coasts. Our findings provide needed information for coastal managers and policy makers, while also setting the stage for future research at the intersection of ecological and physical processes on vulnerable coastlines.

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CHAPTER I

INTRODUCTION

Sand dunes provide many valuable ecosystem services. They are a unique habitat that is associated with high biodiversity (Grootjans et al. 2004; Everard et al. 2010). They provide a defensive physical structure that protects coastal areas from flooding and mitigates the effects of storms by dissipating wave energy (French 2001). And, they add to the recreational and aesthetic value of beaches, contributing to coastal tourism (Everard et al. 2010).

With climate change threatening coastal regions worldwide with rising sea levels (Rahmstorf 2007) and increasing frequency and severity of storms (Emanuel 2005), the perceived value of dunes has increased thanks to their protective role. But, in order for dunes to mitigate the negative consequences of storms and sea level rise, they need to be able to resist the erosive forces of moving wind and water. Anecdotal evidence has long suggested a link between vegetation and reduced erosion and more recently this link has been both supported (Danielsen et al. 2005; Barbier et al. 2008) and contested (Kerr and Baird 2007; Feagin et al. 2009) in relation to coastal environments.

The embrace by researchers and the public of the concept that plants can reduce erosion has led to restoration and revegetation projects on coasts throughout the world, thereby necessitating accurate information on dune plants. Coastal managers need this information to make decisions such as what species to plant and to be able to make realistic predictions for the impact of a given project.

We used two different approaches to further the current state of knowledge in this field. Our first approach was to sample dune vegetation in a variety of locations and compile a catalog of the biophysical parameters of dune plants. This catalog is intended as a resource for future studies, providing real world trait values that can be used in modeling studies or to create realistic artificial vegetation for experiments.

Our second approach was an experimental approach to explore the mechanisms that could allow plants to prevent erosion. By testing dunes with above and below ground biomass, dunes with only belowground biomass, and dunes with no vegetation, we were able address the relative importance of above ground versus below ground characteristics in mitigating erosion.

CHAPTER II

BIOPHYSICAL PROPERTIES OF BEACH AND SAND DUNE PLANTS WITH APPLICATION TO WAVE EROSION

Introduction

In recent years, coastal managers have embraced the trend of growing vegetation to stem erosion and mitigate damage on sandy beaches and dunes. Much of the underlying research on this topic has been analytical (Dean and Bender, 2006; Kobayashi et al. 2010), or based on experiments that use artificial representations of vegetation, such as wooden dowels (Kobayashi et al. 2013), or focused on a single species of plant (Silva et al. 2016). A related but separate body of research has been focused on wave attenuation by plant structures in wetlands (Kobayashi et al., 1993; Augustin et al., 2009; Möller and Spencer, 2002; Möller, 2006). Still, the number of controlled experiments using live beach and dune plants has been limited (see Feagin et al. 2015 for a review) and analytical work will continue to be hampered until we know the parameters of real-world plant structures (Irish et al., 2008; Feagin et al. 2011). Researchers have investigated these types of parameters for wetland species (Feagin et al. 2011) and brown macroalgae (Maike and Henry 2014; Paul et al. 2014), but not for beach and dune vegetation.

To fully describe the governing physics of wave attenuation and sedimentary erosion in non-cohesive environments requires information on the biophysical parameters of dune plants. The central objective of the proposed study is to provide measured values for common species that can be used for analytical or modeling exercises by other scientists in order to further our understanding of how plants mitigate coastal erosion. To this end we sampled plants and measured a variety of traits at seven locations in three countries, ranging from tropical to temperate climates.

Methods: Measurement of Field Vegetation

We sampled dune vegetation in the United States, Mexico, and Ireland. In the U.S., we sampled in Galveston, Texas; South Padre Island, Texas; Pea Island, North Carolina; and Moss Landing, California. In Mexico, we sampled in La Mancha, Veracruz and Chuburna, Yucatan. In Ireland, we sampled in Bundoran, Donegal. In each of these locations, we measured above ground biomass, below ground biomass, stem height, stem diameter, number of stems, stem flexibility, number of leaves, and average leaf area of different dune plants. We also measured leaf flexibility in Galveston, South Padre Island, La Mancha, and Chuburna.

At every location, we used a 0.25 m^2 (0.5 x 0.5 m) quadrat to sample the vegetation in ten randomly selected sites where only one species was present. For each plot, we harvested all of the vegetative material within the quadrat and collected roots down to a depth of 0.3 m. This was done by digging a 0.25 m^2 soil pit within the quadrat with a shovel and removing roots by hand. All measurements were later scaled up to 1.0 m^2. The following species were sampled: *Amaranthus greggii* S. Wats, *Ammophila* *arenaria* (L.) Link, *Ammophila breviligulata* Fernald, *Cakile edentula* (Bigel.) Hook., *Cakile maritima* Scop., *Croton punctatus* Jacq., *Ipomoea imperati* (Vahl) Griseb., *Ipomoea pes-caprae* (L.) R. Br., *Leymus mollis* (Trin.) Pilg., *Panicum amarum* Elliott, *Sesuvium portulacastrum* (L.) L., and *Uniola paniculata* L. (Figure 1).

We counted the number of stems and leaves in each plot and measured the stem height and diameter of each plant. We also measured leaf area using ImageJ for 10 random leaves per plot in order to estimate average leaf area. We measured stem flexibility for three stems from each plot, using a method similar to the one used by Sun and Liddle (1993). This was accomplished by clamping the stem to two boards connected with a hinge in the middle. We bent the stems until they broke and recorded the angle. We measured leaf hardness by attaching a metal paperclip to the bottom of a cup so that a small portion of one end of the paperclip pointed down. The cup was positioned on a leaf and slowly filled with sand until the paperclip punctured the leaf. Then the sand was weighed to provide an estimate of the amount of force required to puncture the leaf.

To obtain biomass measurements, we sorted the below ground and above ground material from each plot into separate bags. We weighed the samples for wet biomass, and then dried them at 70°C for 48 hours for dry biomass. The differences in plant attributes between grasses (Graminoids) and forbs (non-Graminoids) were then tested using two-tailed, unequal variance t-tests.

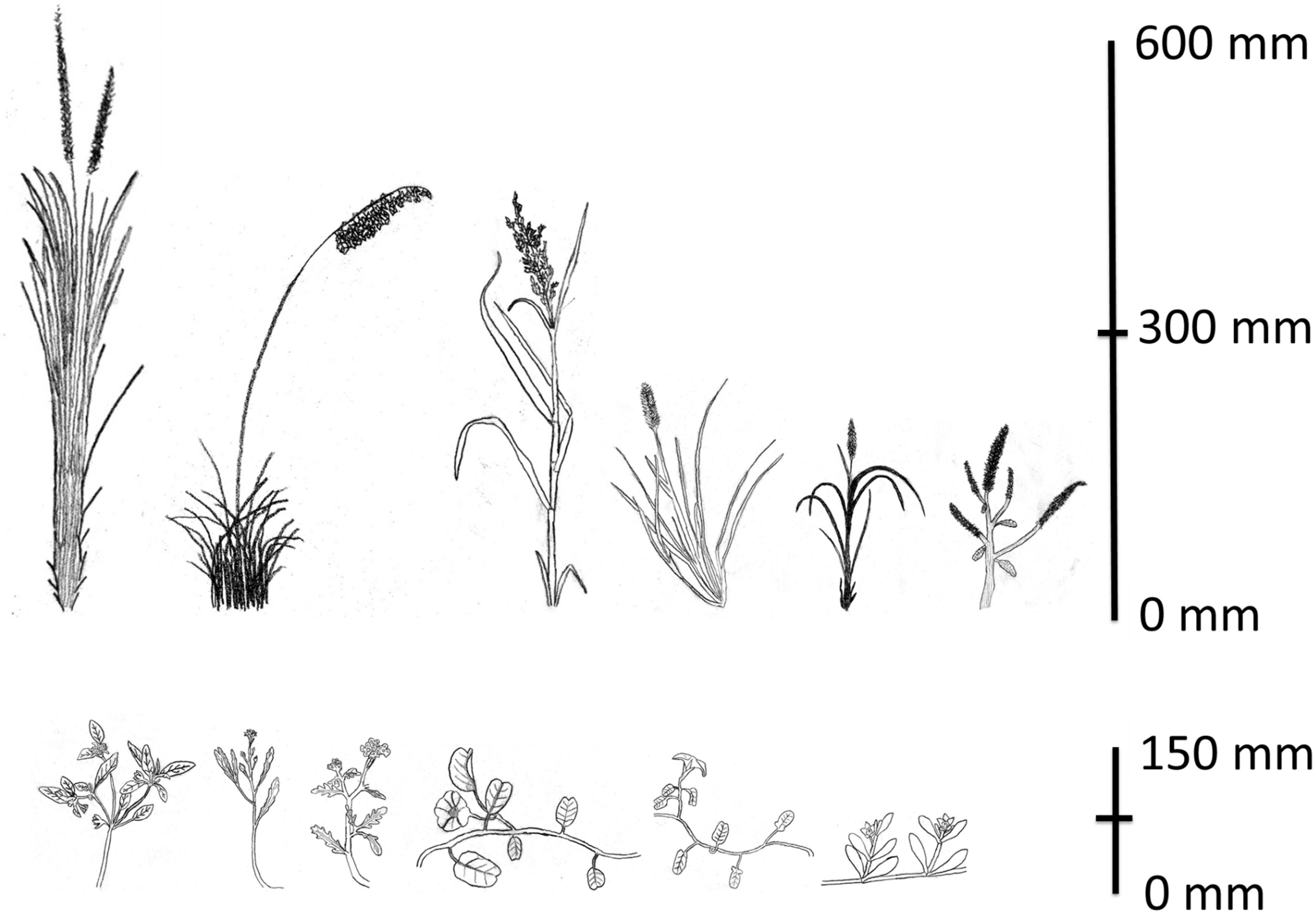

Figure 1. Drawings of sampled dune plants to scale. In order from tallest to shortest stem height: *Ammophila breviligulata*, *Uniola paniculata*, *Panicum amarum*, *Leymus mollis*, *Ammophila arenaria*, *Amaranthus greggii*, *Croton punctatus*, *Cakile edentula*, *Cakile maritima*, *Ipomoea pes-caprae*, *Ipomoea imperati*, and *Sesuvium portulacastrum.*

Results and Discussion

There was an average of 87.31 stems/m^2 in vegetated plots, ranging from a low of 29.3 stems/m^2 for *Leymus mollis* in Moss Landing to a high of 260.0 stems/m^2 for *Ammophila arenaria* in Bundoran (Table 1). Stem height averaged 194.5 mm, while stem diameter averaged 5.24 mm. Stem flexibility, measured as the angle of breakage, averaged 89.69°.

Across all plots, there were 953.65 leaves/m^2 on average, with a low of 96 leaves/m^2 for *Ipomoea pes-caprae* in Galveston and a high of 6388 leaves/m^2 for *Cakile maritima* in Moss Landing. There was also an average of 25.48 leaves per stem, and leaf area averaged 2031.56 mm^2. Leaf hardness, measured as the weight required to puncture the leaf with the end of a paperclip, averaged 105.77 g.

Above ground wet biomass averaged 863.45 g/m^2 and below ground wet biomass averaged 1013.59 g/m^2. Above ground dry biomass averaged 312.87 g/m^2, while below ground dry biomass averaged 171.93 g/m^2.

Table 1. Average dune plant trait values (with std) by species and location. AG = above ground. BG = below ground. Roots column does not include buried stolons.

	Stems/m²	Stem Height (mm)	Stem Diam. (mm)	Angle of Breakage (°)	Leaves/m²	Leaves per stem	Leaf hardness (g)	Leaf area (mm²)	AG biomass wet (g/m²)	AG biomass dry (g/m²)	BG biomass wet (g/m²)	BG biomass dry (g/m²)	Roots (g/m²)
Amaranthus greggii													
South Padre Island, TX	226.67 ± 7.68	184.3 ± 9.50	5.8 ± 0.14	99.22 ± 13.53	486 ± 29.75	42.64 ± 33.42	125.87 ± 24.64	185.51 ± 0.83	1727.2 ± 267.20	258 ± 40.60	1216.8 ± 137.20	283.2 ± 26.50	-
Galveston, TX	72 ± 0.71	168.9 ± 5.86	6.9 ± 0.17	81.5 ± 6.50	1125 ± 74.55	72.13 ± 22.80	57.7 ± 13.39	291.22 ± 1.25	1506 ± 150.60	260 ± 8.50	444 ± 53.70	60 ± 5.70	-
Chuburna, Merida	67.2 ± 1.79	154.8 ± 2.60	4.1 ± 0.11	85.33 ± 6.75	481 ± 26.18	33.3 ± 21.53	77.56 ± 15.29	93.63 ± 0.37	-	227.6 ± 24.28	-	24.8 ± 4.56	-
Ammophila arenaria													
Bundoran, Ireland	260 ± 12.88	161.7 ± 95.50	3.06 ± 0.89	35.18 ± 20.72	1516 ± 8.36	1.17 ± 2.90	-	1604.92 ± 6.80	185.4 ± 87.27	-	1139.2 ± 45.07	-	288 ± 13.91
Ammophila breviligulata													
Pea Island, NC	93 ± 11.70	634.88 ± 115.24	3.38 ± 0.77	28.63 ± 16.05	1896 ± 28.56	5.1 ± 0.89	-	832.76 ± 5.74	166 ± 106.71	-	2100 ± 51.54	-	12 ± 0.96
1/Cakile edentula													
Chuburna, Merida	56 ± 1.00	167.9 ± 5.01	3.6 ± 0.06	77 ± 13.72	1083 ± 43.79	79.25 ± 54.58	41.65 ± 11.31	201.36 ± 1.06	-	195.52 ± 9.11	-	8.92 ± 0.58	-
Cakile maritima													
Moss Landing, CA	124 ± 35.51	144.06 ± 4.30	3.81 ± 0.85	80.81 ± 38.77	6388 ± 56.23	17.17 ± 24.19	-	554.3 ± 5.72	625 ± 425.18	-	1504 ± 111.73	-	0.64 ± 0.05
Croton punctatus													
South Padre Island, TX	128 ± 0.00	168.8 ± 5.33	4.6 ± 0.04	-	200 ± 6.61	12.5 ± 6.61	112.8 ± 11.10	402.68 ± 1.32	828 ± 0.00	184 ± 0.00	500 ± 0.00	176 ± 0.00	-
La Mancha, Veracruz	90.7 ± 2.08	144.4 ± 2.86	5.66 ± 0.14	133.5 ± 10.86	384 ± 10.43	24.17 ± 6.69	77.2 ± 13.25	396.89 ± 1.24	-	263.2 ± 27.87	-	214 ± 56.45	-
Ipomoea imperati													
Galveston, TX	68 ± 1.50	93.5 ± 4.23	3.5 ± 0.18	93.67 ± 10.41	136 ± 6.49	8.2 ± 3.51	55.45 ± 14.42	1324.71 ± 9.38	969.2 ± 124.10	285.2 ± 29.30	474 ± 45.44	109.2 ± 23.80	-
Ipomoea pes-caprae													
South Padre Island, TX	88 ± 0.71	149.1 ± 3.21	6 ± 0.09	134.17 ± 8.84	96 ± 3.32	6.17 ± 2.59	149.8 ± 21.63	3557.71 ± 17.69	1402 ± 68.60	212 ± 17.00	536 ± 49.50	180 ± 35.40	-
Galveston, TX	52 ± 0.96	178.1 ± 3.46	7 ± 0.11	110.17 ± 12.60	156 ± 4.21	10.44 ± 4.66	77.9 ± 17.92	3306.12 ± 17.70	1730 ± 90.30	372 ± 26.50	717.2 ± 94.20	300 ± 44.50	-
Chuburna, Merida	40 ± 0.84	11.53 ± 3.20	6.2 ± 0.14	102.28 ± 8.80	213 ± 5.96	14.36 ± 4.76	66.03 ± 19.02	2019.29 ± 9.70	-	237.6 ± 25.39	-	96.4 ± 25.23	-
La Mancha, Veracruz	46 ± 0.35	135.9 ± 3.81	6.9 ± 0.35	136.17 ± 7.23	185 ± 4.72	11.71 ± 3.24	119.53 ± 22.98	2468.62 ± 10.59	-	244.8 ± 12.06	-	197.2 ± 32.04	-
Leymus mollis													
Bundoran, Ireland	32.8 ± 3.56	232.89 ± 261.61	8.89 ± 2.57	37.36 ± 22.17	796 ± 3.03	4.85 ± 1.44	-	13012.62 ± 46.00	291.4 ± 289.87	-	1414.4 ± 77.30	-	452.8 ± 25.77
Moss Landing, CA	29.3 ± 1.53	141.82 ± 90.53	4.86 ± 1.39	83.41 ± 38.12	936 ± 22.13	10.64 ± 1.47	-	6262.05 ± 28.37	151.67 ± 104.20	-	2026.72 ± 28.87	-	186.72 ± 8.50
Panicum amarum													
Pea Island, NC	33.3 ± 2.08	432.4 ± 168.55	5.36 ± 1.41	63.6 ± 21.91	1496 ± 18.04	14.96 ± 5.49	-	4568.24 ± 14.33	240 ± 196.98	-	586.72 ± 5.77	-	96 ± 5.29
Galveston, TX	76.8 ± 1.92	316.7 ± 10.73	5.9 ± 0.12	91.93 ± 8.84	110 ± 2.47	6.39 ± 1.61	253.32 ± 27.42	1633.82 ± 9.38	1036.8 ± 165.00	291.2 ± 44.20	811.2 ± 95.30	380.8 ± 61.30	-
Sesuvium portulacastrum													
South Padre Island, TX	126.5 ± 3.18	101.3 ± 2.99	5.9 ± 0.12	110.15 ± 15.64	368 ± 17.57	23.25 ± 10.05	110.34 ± 26.16	269.12 ± 1.21	1452.4 ± 227.60	228 ± 33.60	795.6 ± 65.80	239.2 ± 24.90	-
Galveston, TX	83.2 ± 2.77	82.5 ± 1.90	4.2 ± 0.10	128.2 ± 13.34	1087 ± 77.39	80.34 ± 92.24	118.44 ± 36.64	190.14 ± 0.92	1202.4 ± 288.40	245.6 ± 75.60	504 ± 96.30	164.8 ± 46.90	-
Chuburna, Merida	60.8 ± 0.84	130 ± 4.35	4.7 ± 0.08	97.53 ± 11.93	1038 ± 27.14	67.03 ± 24.10	62.92 ± 18.79	199.93 ± 0.64	-	681.6 ± 105.13	-	146 ± 23.27	-
La Mancha, Veracruz	81.78 ± 1.54	106.6 ± 3.28	6.3 ± 0.08	128.3 ± 14.58	522 ± 21.16	34.54 ± 17.65	185.8 ± 36.54	183.1 ± 0.51	-	819.6 ± 75.91	-	170.4 ± 29.87	-
Uniola paniculata													
Pea Island, NC	72 ± 14.73	431.38 ± 412.02	3.83 ± 1.23	35 ± 17.98	1236 ± 24.08	5.72 ± 1.57	-	3167.15 ± 15.41	301.67 ± 133.45	-	2293.28 ± 58.59	-	144 ± 9.64
Combined Average	87.31 ± 56.95	194.50 ± 137.88	5.24 ± 1.46	89.69 ± 33.58	953.65 ± 1296.18	25.48 ± 25.42	105.77 ± 55.19	2031.56 ± 2915.05	863.45 ± 591.34	312.87 ± 178.06	1013.59 ± 631.59	171.93 ± 100.18	176.03 ± 160.19

The average stem height of grasses was more than double the stem height of forbs ($p=0.02$) (see Figure 1; tallest five species are grasses, the rest are forbs), but forb stems were nearly twice as flexible as grass stems ($p<0.001$). Forbs also had about four times as many leaves per stem as grasses ($p=0.001$), but there was no significant difference in the number of leaves/m^2. In addition, grasses had more than quadruple the leaf area of forbs on average ($p=0.074$). Forbs had more than three times more above ground wet biomass than grasses ($p<0.001$), but grasses had nearly twice as much below ground wet biomass ($p=0.029$). We did not have enough measurements to compare dry biomass between grasses and forbs.

These results indicate that dune vegetation falls into two discernable groups despite high variability in biophysical traits. In terms of above ground traits, grasses tend to have taller, more rigid stems with larger leaves than forbs, but fewer leaves per stem. Forbs tend to have shorter, more flexible stems with smaller leaves than grasses, but more leaves per stem. Forbs also have higher above ground wet biomass, likely a result of higher water content in the stems and leaves, and lower belowground wet biomass. This information provides a direction for future research into how these two strategies compare with regard to their effects on wave attenuation and erosion.

Conclusions

The quantification of the biophysical properties of common beach and dune plants provides an important resource for future coastal engineering studies. These plant attribute values can be used to design artificial vegetation to be used in more realistic experiments in the lab. These values also can be used in process-based models to further our understanding of how vegetation impacts wave attenuation, sediment accumulation, and erosion. A more realistic understanding of how vegetation interacts with processes of wave attenuation and erosion will allow managers to implement fact-based, result-driven coastal protection and restoration projects.

CHAPTER III

CAN DUNE VEGETATION REDUCE EROSION? THE EFFECT OF ABOVEGROUND VERSUS BELOWGROUND PLANT STRUCTURES

Introduction

The increasing frequency of highly damaging storms has led to a reinvigorated interest in coastal protection (Borsje et. al 2011, Feagin et al. 2015). One coastal protection strategy historically has gained popularity and proponents: that coastal vegetation may lessen the effects of storms and decrease erosion (Stockton and Gillette 1990; Castillo et al. 1997; French 2001). Sand dunes are the first physical line of defense for coastal communities (De Ronde et al. 2003), and restoration efforts to vegetated dunes are common (Day et al. 2007; Rosati and Stone 2009; Hong and Lee 2014). Unfortunately, there is a general lack of research on how dune plants can protect exposed sediments, with the exception of a handful of studies (Kobayashi et al. 2010, Kobayashi et al. 2013, Silva et al. 2016). It is unknown how different plant structures affect both wave attenuation and soil erosion, and which species provide the greatest protection. A deeper understanding of the mechanisms by which dune plants slow erosion and reduce the impact of storms could greatly assist coastal managers and policy makers.

There are three common explanations for any reduction in erosion that is caused by vegetation, but each of these lines of work has never been applied to dune plants. The first is that the physical aboveground properties of plants (e.g. leaves and stems) attenuate the power of waves in submerged wetlands (Shi et al. 1995; Möller et al. 1999). The second is that the leaves and stems of plants slow down the flow of water over the soil in submerged wetlands (Leonard and Luther 1995; Nepf and Koch 1999). The third explanation is that the roots of plants impede erosion in terrestrial environments (Gyssels et al. 2005; Saifuddin and Osman 2014); though this has been shown to not apply to wetland edges (Feagin et al. 2009). These various explanations are not exclusive, meaning that erosion can be reduced by the combination of some or all of these factors. Moreover, a vague understanding of the mechanisms by which plants reduce erosion has prevented us from knowing whether or not any effect actually translates to protection in the case of a natural disaster caliber event (Feagin et al. 2010).

In this study, we discerned the relative importance of aboveground versus belowground biomass in mitigating dune erosion, and quantified the effects of four common dune plant species. We discuss the importance of other plant traits (e.g. stem height, stem circumference, number of leaves) and their usefulness for predicting a given plant's capacity for reducing erosion. We expect the results to fill the gap in current understanding regarding dune plant characteristics and their effect on erosion, while also providing tools for coastal managers and policy makers to apply in real-world projects.

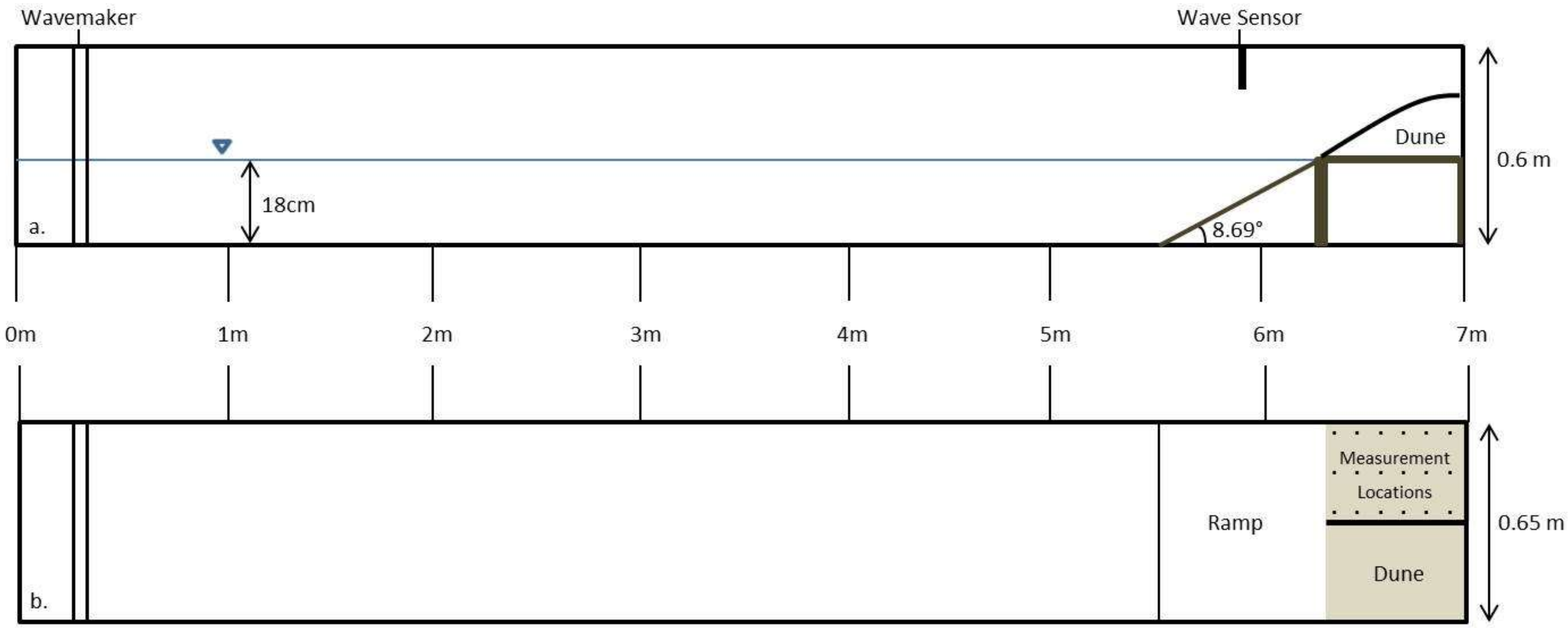

Figure 2. Wave flume diagram (not to scale). a. Side view b. Top view.

Methods

Wave Flume Specifications and Wave Generation

We used a 7 m long, 0.65 m wide, and 0.6 m tall wave flume to measure the effect of dune plants on erosion, and specifically the effects of belowground versus aboveground biomass (Figure 2). Previous studies have successfully used wave flume experiments to observe the impacts of waves on beach erosion (Kajima et al. 1982; Silva et al. 2016) and mud erosion (Maa and Mehta 1987). The water level was maintained at a depth of 0.18 m. A 1.2 m ramp with a slope of 0.15 was placed at one end of the flume leading up to a 0.18 m high raised platform. Two simulated embryonic dunes were placed side by side within wooden boxes with one side open to wave attack, atop the raised platform.

We built embryonic dunes that would be typical of a back beach environment (i.e. the most shoreward location of vegetation clumps, lying on top of relatively small mounds of sand) as based on our observations along the Gulf Coast of Texas and Mexico. We chose to focus on embryonic dunes because we were able to replicate them at a 1:1 scale, they fit in the wave flume, and they typically have only one plant species per dune. Our dunes were 60 cm long, 30 cm wide, and 20 cm tall at the crest. The mean sediment grain size was 2 phi with a standard deviation of 0.803 phi, indicating that the dunes consisted of mostly medium sand and fine sand and were moderately sorted. Waves hit the dunes as they would on a typical beach, with sand transported forward or backward. No scour was obvious either on the fore, aft, or side walls during the experiment. All plant, sediment, and wave conditions were simulated at a 1:1 scale.

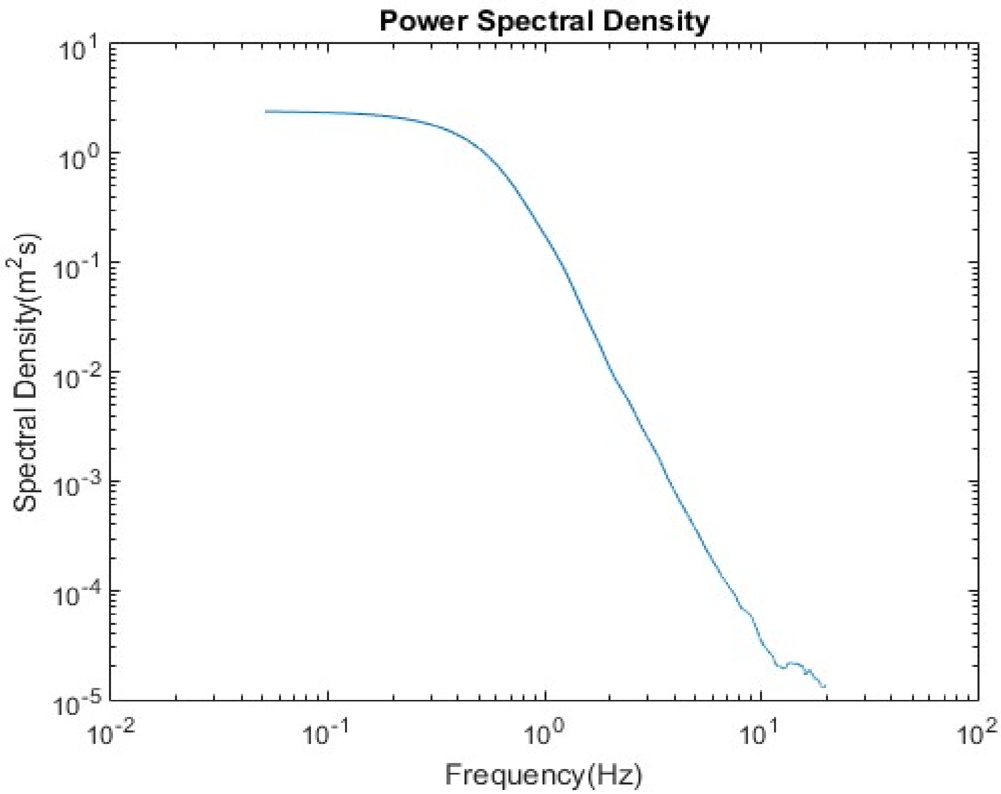

Figure 3. Combined wave power spectral density.

In order to identify whether these conditions were representative and identify how long an event with such swash motion would take to reach an equilibrium slope state, we simulated a much longer series of waves that ran for 8,310 sec. During this long trial, the vast majority of erosion occurred during the first 1,050 sec, indicating that the length of our trials was sufficient to record the amount of erosion caused by the waves (Figure 4).

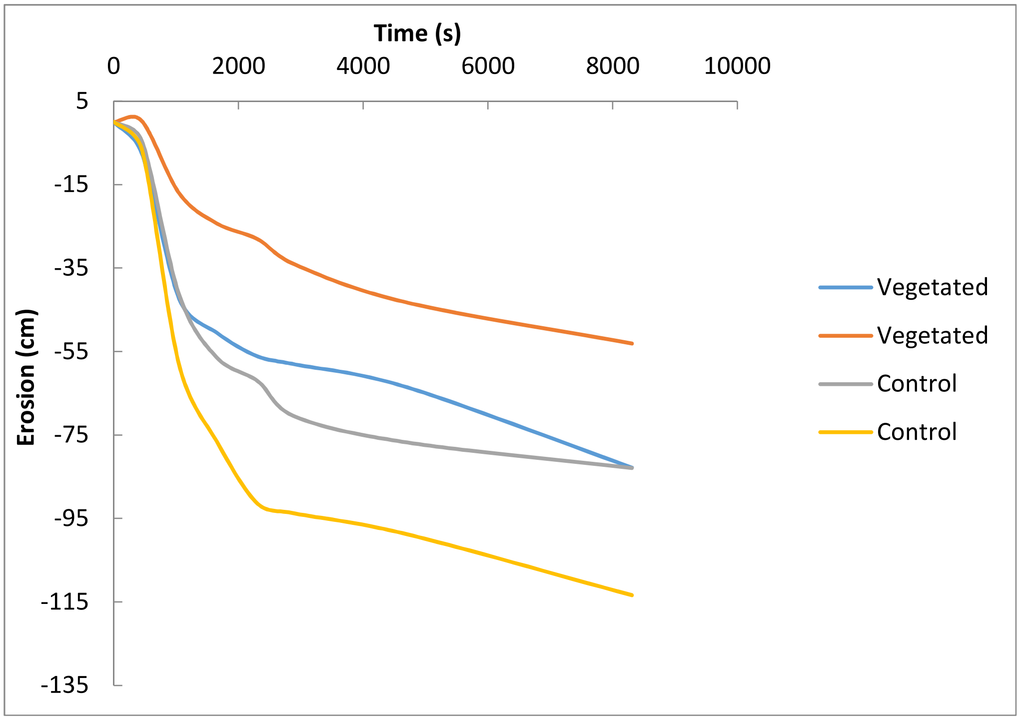

Figure 4. Long trial results. The majority of erosion occurred initial portion of the trial.

Vegetation Treatments and Measurements

We planted the dunes with a rhizomatous grass, *Spartina patens*, a bunch grass, *Panicum amarum*, and two stoloniferous forbs, *Sesuvium portulacastrum* and *Ipomoea pes-caprae*. The plants were allowed to grow for three months in the dunes to allow the roots and soil to set. Throughout the growing period, the plants were watered every two days and fertilized once.

We had a total of nine treatments: controls with no vegetation and each of the four species with either (a) the aboveground and belowground portions of the plant (AGBG), or (b) the belowground only (BG). To create dunes with only belowground biomass, we cut the aboveground portion of the plants off immediately before they were put in the flume. This was intended to maintain the same below ground environment as in the dunes with full plants, but with no above ground biomass. Control treatments had no vegetation, but otherwise were built to the same specifications and watered similar to the vegetated treatments. There were a total of 54 replicates with unequal numbers across the treatments: 10 controls, 5 *Panicum amarum* AGBG, 5 *Panicum amarum* BG, 5 *Sesuvium portulacastrum* AGBG, 5 *Sesuvium portulacastrum* BG, 7 *Ipomoea pes-caprae* AGBG, 7 *Ipomoea pes-caprae* BG, 7 *Spartina patens* AGBG, and 7 *Spartina patens* BG.

Before each trial in the wave flume, the aboveground vegetation was measured, including the stem height, stem circumference, and number of leaves (Table 2). Stem height was measured as the distance from the base of the plant to the highest point on the plant. Stem circumference was measured 1 cm above the base. The total number of leaves was summed for each dune replicate. After each trial, we clipped all aboveground plant material, weighed and dried it for 48 hours at 70°C to obtain wet and dry biomass quantities. We then excavated the sand within each replicate and sieved the belowground material (roots and rhizomes) with a 2 mm mesh sieve, and found the wet and dry

Table 2. Plant trait measurements (with std).

	Avg. Stem Height (mm)	Avg. Stem Diameter (mm)	leaves/m²	AG Biomass Wet (g/m²)	AG Biomass Dry (g/m²)	BG Biomass Wet (g/m²)	BG Biomass Dry (g/m²)
Ipomoea pes-caprae							
	15.50	1.58	377.78	188.89	61.11	94.44	50.00
	22.83	1.83	433.33	911.11	394.44	138.89	83.33
	20.83	1.62	388.89	266.67	83.33	150.00	77.78
	29.67	1.92	622.22	877.78	350.00	166.67	111.11
	30.83	2.10	944.44	2033.33	822.22	244.44	105.56
	21.17	1.75	411.11	272.22	88.89	394.44	122.22
	20.67	1.75	327.78	166.67	72.22	316.67	72.22
	24.00	2.03	588.89	1044.44	316.67	166.67	127.78
	25.83	1.55	344.44	1061.11	466.67	133.33	50.00
	15.33	1.80	188.89	316.67	116.67	577.78	161.11
	23.17	1.97	511.11	505.56	188.89	594.44	200.00
	21.00	1.73	388.89	916.67	277.78	83.33	55.56
average	22.57 ± 4.72	1.80 ± 0.18	460.65 ± 191.77	713.43 ± 543.47	269.91 ± 223.25	255.09 ± 179.12	101.39 ± 46.37
Sesuvium portulacastrum							
	9.67	0.97	3522.22	300.00	138.89	94.44	38.89
	11.25	1.07	4300.00	277.78	111.11	77.78	27.78
	7.50	1.22	2883.33	244.44	105.56	94.44	55.56
	10.00	1.05	3066.67	327.78	94.44	66.67	27.78
	7.17	1.00	3733.33	316.67	105.56	83.33	44.44
	10.83	1.23	3755.56	244.44	88.89	111.11	66.67
	10.17	1.28	3094.44	416.67	177.78	105.56	61.11
	13.00	1.15	4177.78	261.11	105.56	83.33	38.89
	9.67	1.07	3055.56	372.22	144.44	88.89	38.89
average	9.92 ± 1.79	1.12 ± 0.11	3509.88 ± 518.27	306.79 ± 58.78	119.14 ± 28.75	89.51 ± 13.73	44.44 ± 13.89
Panicum amarum							
	59.67	1.27	488.89	177.78	72.22	111.11	61.11
	47.83	1.35	561.11	233.33	116.67	150.00	105.56
	50.00	1.63	644.44	172.22	100.00	200.00	144.44
	64.00	1.67	733.33	416.67	211.11	205.56	155.56
	65.83	1.47	694.44	305.56	183.33	155.56	111.11
	41.67	1.40	577.78	338.89	144.44	150.00	111.11
	59.67	1.43	761.11	405.56	183.33	200.00	150.00
	62.00	1.67	861.11	344.44	177.78	188.89	138.89
	54.67	1.60	622.22	188.89	100.00	161.11	116.67
average	56.15 ± 8.16	1.50 ± 0.15	660.49 ± 114.41	287.04 ± 96.70	143.21 ± 48.09	169.14 ± 31.56	121.60 ± 29.46
Spartina patens							
	56.50	0.77	1211.11	188.89	144.44	166.67	122.22
	62.67	0.82	1066.67	138.89	122.22	133.33	122.22
	55.67	0.67	661.11	105.56	100.00	394.44	133.33
	53.67	0.77	866.67	261.11	133.33	555.56	133.33
	54.67	0.75	511.11	94.44	88.89	166.67	61.11
	62.17	0.68	1383.33	183.33	161.11	911.11	244.44
	61.33	0.82	1022.22	116.67	105.56	344.44	116.67
	49.50	0.97	944.44	138.89	127.78	411.11	133.33
	53.00	0.72	594.44	88.89	77.78	138.89	50.00
	50.33	0.87	694.44	127.78	116.67	327.78	150.00
	64.83	0.77	1183.33	177.78	133.33	150.00	111.11
average	56.76 ± 5.23	0.78 ± 0.09	921.72 ± 282.00	147.47 ± 51.30	119.19 ± 24.64	336.36 ± 236.65	125.25 ± 50.08
Combined Average	36.34 ± 21.07	1.31 ± 0.43	1297.56 ± 1236.06	378.73 ± 368.53	168.56 ± 137.59	221.68 ± 177.66	99.73 ± 49.05

biomass for these portions as well. These measurements allowed us to compare individual plant traits with respect to the amount of erosion experienced by each dune.

Erosion Measurements and Statistical Analysis

Due to the vegetation cover, we measured sediment erosion using fiberglass rods. This approach avoided the difficulties that laser scanning methods would encounter. A Plexiglas sheet above the dunes was drilled with 18 holes spread evenly over each replicate. Rods were inserted through each hole until the ends touched the sand, taking care to avoid or push aside vegetative structures. The length of the portion of rod that remained above the Plexiglas sheet was measured. We measured before and after each trial. Erosion was calculated for each replicate as the sum of the differences between pre- and post-trial measurements for all 18 rods. We additionally weighed the replicates before, and later after, each trial.

We conducted separate one-way ANOVAs for each of the two wave conditions, across the nine treatments, since this was the most efficient set-up for comparing individual treatments with the controls. We tested differences among treatments using post-hoc contrasts and then used linear regression analysis to identify correlations between erosion and measured plant characteristics.

Results

In general, we found that erosion was higher when vegetation was absent. The contrasts between control, AGBG, and BG for wave one and wave two showed more erosion in controls than AGBG (wave 1: $p=0.0011$, wave 2: $p<0.0001$) or BG (wave 1: $p=0.0040$, wave 2: $p<0.0001$) (Table 3). There was no difference in erosion between AGBG and BG after wave 1 ($p=0.5836$), however, after wave 2 there was more erosion in BG than in AGBG ($p= 0.0662$). Contrasts between AGBG and BG were more significant in the back portion of the box ($p=0.0521$) than in the front half ($p=0.4441$) (Table 4), with more erosion occurring in the back half of BG treatments than occurred in the back half of AGBG treatments.

Table 3. Significance values for control, whole and cut comparisons for wave 1 and wave 2.

Contrasts	Wave 1	Wave 2
Control Vs Whole	0.0011	< 0.0001
Control Vs Cut	0.0040	< 0.0001
Whole Vs Cut	0.5836	0.0662

Table 4. Significance values for whole vs. cut contrasts compared between back and front of dune (after wave 2).

Contrasts	Back	Front
Whole Vs Cut	0.0521	0.4441
Ipomoea-Whole Vs Ipomoea-Cut	0.0393	< 0.0001
Sesuvium-Whole Vs Sesuvium-Cut	0.8090	0.3228
Panicum-Whole Vs Panicum-Cut	0.0081	0.2158
Spartina-Whole Vs Spartina-Cut	0.0450	0.2045

After wave 1, there was significantly more erosion in controls than in AGBG for *Ipomoea* (p= 0.0227), *Spartina* (p= 0.0012), and *Sesuvium* (p= 0.0110). BG treatments of *Sesuvium* experienced less erosion than controls as well (p= 0.0005). In addition, *Ipomoea* and *Panicum* both showed significantly greater erosion in AGBG than in BG treatments (p=0.0227 and p=0.0337, respectively) (Figure 5).

After wave 2, there was significantly more erosion in controls than in AGBG treatments for all four species (p<0.0001). Controls experienced significantly more erosion than BG treatments for all plants as well (p<0.0001). ABGB treatments of *Ipomoea* and *Panicum* both saw lower levels of erosion than BG treatments (p<0.0001 and p= 0.0092, respectively) (Figure 5).

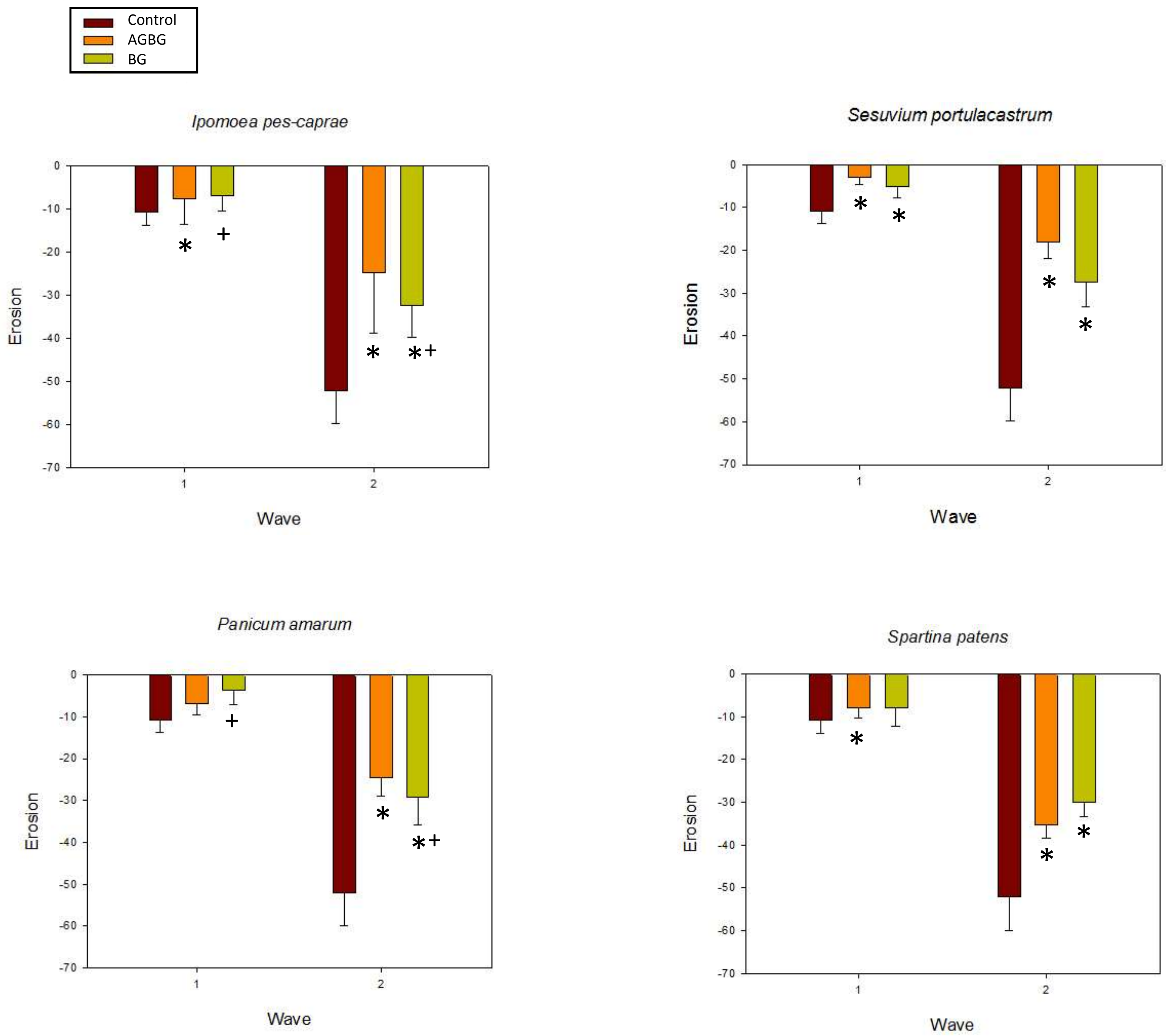

Figure 5. Cumulative amount of erosion (cm) in AGBG, BG, and control treatments after wave 1 and 2 for four plant species.

* indicates a significant difference from the control ($p < 0.05$).

+ indicates that BG is significantly different from AGBG ($p < 0.05$).

Linear regressions indicated that erosion is significantly reduced for all species with increasing number of leaves (R^2=0.207, p=0.034), above ground biomass (R^2=0.329, p=0.005), and total biomass (R^2=0.487, p=0.002) (Table 4). In terms of individual species, *Ipomoea* and *Panicum* both had a significant inverse relationship between erosion and above ground biomass (R^2=0.734, p=0.029 and R^2 = 0.874, p = 0.02, respectively), while *Sesuvium* showed no significant correlations between measured plant traits and erosion. *Spartina*, on the other hand, had a significant inverse correlation between erosion and stem height (R^2 = 0.657, p = 0.05). For both cut and whole plants, there were no significant correlations between below ground biomass and erosion (Table 5).

Table 5. R^2 and associated significance values from linear regressions of above and below ground plant characteristics with erosion. Significant correlations in red.

Above Ground Characteristics										
	combined		*I. pes-caprae*		*S. portulacastrum*		*P. amarum*		*S. patens*	
	R^2	p-value	R^2	p-value	R^2	p-value	R^2	p-value	R^2	p-value
stem height	0.158	0.067	0.356	0.211	0.473	0.199	0.347	0.296	0.657	0.05
stem circumference	0.157	0.068	0.508	0.112	0.524	0.167	0.475	0.198	0.155	0.44
stem volume	0	0.969	0.414	0.168	0.154	0.513	0.759	0.055	0.051	0.668
#leaves	0.207	0.034	0.389	0.186	0.648	0.1	0.716	0.071	0.139	0.466
above ground biomass	0.329	0.005	0.734	0.029	0.423	0.234	0.874	0.02	0.051	0.667
total biomass	0.487	0.002	0.807	0.085	0.876	0.124	0.893	0.107	0.673	0.187
Below Ground Characteristics										
	combined		*I. pes-caprae*		*S. portulacastrum*		*P. amarum*		*S. patens*	
	R^2	p-value	R^2	p-value	R^2	p-value	R^2	p-value	R^2	p-value
AGBG below ground biomass	0.098	0.155	0.003	0.92	0.384	0.265	0.482	0.193	0.433	0.155
BG below ground biomass	0.001	0.897	0.34	0.224	0.491	0.188	0.038	0.754	0.212	0.358

Discussion

Vegetation reduced sedimentary erosion from the dunes during the initial stages of a simulated storm, when intercepted with swash. Sediments eroded significantly less when both aboveground and belowground portions of plants were present (AGBG), and this also held true for when only belowground portions were present (BG), as compared to the control with no vegetation present. Additionally, sediments eroded somewhat differently between AGBG versus BG only, with more erosion occurring when aboveground portions were absent. No obvious differences existed among the various species, however, and they all reduced erosion by a factor of approximately two as compared to the control, suggesting that any species is better than none, and that all of the plants in this study were relatively equal in their capacity to prevent erosion.

For three reasons, the results suggest that wave attenuation by aboveground portions of plants is the primary mechanism that reduces erosion on the dunes. First, only aboveground structures, along with total biomass, were significantly correlated with a reduction in erosion. Belowground metrics alone had no correlation with erosion. Second, although AGBG and BG only treatments were marginally statistically different, the magnitude of the differences was on average small (AGBG = -26.0318 mm and BG = -29.9227 mm; compared to Control = -52.11 mm). Third, there was significantly reduced erosion in the back half of AGBG dunes compared to the back half of BG dunes, with less difference between the fronts of the dunes (Table 2). This seems to suggest that it is attenuation of waves that alters erosion and scour immediately behind the stems. Additionally, it is possible that the small difference between AGBG and BG is in part due to the fact that below ground biomass became exposed as erosion progressed. This exposed plant material may have then acted in the same capacity as above ground biomass and reduced further erosion in BG treatments.

Our linear regressions suggest that it may be difficult to make generalizations across species about which above ground plant structures are more important in preventing erosion. For example, high aboveground biomass was very strongly correlated with decreased erosion for *Ipomoea pes-caprae* and *Panicum amarum*, but was not significantly correlated for *Sesuvium portulacastrum* or *Spartina patens*. We did not find any traits that correlated significantly with erosion for *Sesuvium portulacastrum*, but for *Spartina patens*, increased stem height was strongly correlated with decreased erosion. Aboveground biomass and total biomass appear to be the strongest predictors of erosion across all species, as indicated by the linear regressions including all four plants. However, biomass is only a more easily measured proxy for plant surface area, which is likely the characteristic that truly corresponds to wave attenuation and erosion reduction.

It is important to note that our experiments concerned only swash, and the results may have varied if we had simulated other stronger forces. Our results relate directly to typical day to day forces as well as semi-frequent high tide events that act on embryonic dunes. During intense storms, wave collision and overtopping are likely to reduce the impact of vegetation.

It is also possible that the embryonic dunes in our experiments retained more moisture than natural dunes due to the high frequency of waves. Increased moisture can enhance the likelihood of slumping and decrease infiltration, both of which could lead to higher erosion rates. In the vegetated treatments, however, this may have been counteracted by root matric suction and the increased infiltration associated with plants. This could have contributed to the large differences in erosion rates between our vegetated dunes and the unvegetated controls.

Although no other studies have investigated the relative roles of above ground versus below ground biomass in reducing dune erosion, our results, in terms of the overall impact of vegetation on erosion, are very consistent with previous research. Kobayashi et al. (2013) using wooden dowels to represent dune vegetation in a wave flume experiment, reported erosion reductions by about a factor of two, a similar magnitude to our findings. Sigren et al. (2014) also tested vegetated and unvegetated dunes in a wave flume and found that erosion was reduced by a factor of 1.5 in vegetated dunes. More recently, Silva et al. (2016) conducted wave flume experiments with live vegetation, two different dune profiles, and a variety of wave conditions, and found that erosion was reduced by a factor ranging from about 1.4 to 1.6 when vegetation was present. In addition to providing support for the claim that dune vegetation reduces erosion, our findings go further by also addressing the mechanisms responsible for this effect. We have shown that above ground plant biomass, through interception and attenuation of waves, is the primary driver of erosion reduction by dune vegetation.

The results of this study will help to provide a framework for policy makers and coastal managers who are concerned with increasing storm frequency and severity.

Efforts to build new dunes or restore dunes will benefit from knowledge of the biophysical mechanisms by which dune plants can reduce storm damage or slow erosion.

Conclusions

Our results indicate that vegetation does reduce sediment erosion from sand dunes, and that both above ground and below ground biomass play a role. Nevertheless, it is likely that above ground biomass is the primary driver of erosion reduction and that this is due to wave attenuation. This claim is substantiated by the observed decrease in erosion in the back of AGBG dunes compared with the back of BG dunes, as well as the inverse correlation between erosion and above ground biomass.

In spite of differences in biophysical traits between the four species, all plants reduced erosion to a similar degree, suggesting that, in terms of erosion prevention, any vegetation is better than none. This information should help to free policy makers and coastal managers to emphasize other important factors such as biodiversity and native status when choosing plants for dune restoration. In other words, there is no need for any given region to use exotic or potentially invasive plants for erosion protection since native plants are likely to be just as effective.

CHAPTER IV

CONCLUSION

Beaches and coastal regions are worth protecting for their aesthetic, economic, and environmental value. They contain unique habitats with high biodiversity, and attract high levels of tourism. But the proximity to the ocean and high vulnerability to storms means that coastlines are constantly at risk of damage.

Coastal managers and policy makers have long been attempting to solve this issue. In many places, hard structures such as seawalls and jetties have been engineered to hold back the ocean, or to change patterns of erosion. However, these structures can have unintended consequences and are not very adaptable once built. This has led to more natural solutions such as bringing in sand to replenish beaches or build up dunes. These strategies are helpful in the short term, but do not truly solve anything since they lead to a cycle of erosion followed by sand replenishment.

For these reasons, coastal managers and policy makers have increasingly turned to dune revegetation projects, driven by the idea that dune vegetation protects dunes by mitigating erosion. These projects have continued to gain in popularity despite a general lack of research into the interactions between plants, waves, sediment accumulation, and erosion in beach and dune environments. In order for these restoration efforts to be successful, coastal managers and policy makers need to be equipped with accurate information and expectations.

A few recent studies have indicated that plants probably do reduce erosion, but none have shed light on the mechanisms through which erosion reduction is achieved. In the research presented here, we have shown that decreased erosion is mostly due to wave attenuation by above ground plant biomass, and that it does not seem to matter how above ground biomass is distributed in terms of leaves versus stems, etc. However, erosion is still reduced when only below-ground biomass is present. Additionally, none of the plant species we studied were particularly better or worse than the others in terms of preventing erosion.

Future research could expound on these results by further exploring the relationship between above ground biomass and erosion. For example, is there an optimal amount of biomass for preventing erosion that could be applied in dune restoration projects? Our catalog of dune plant biophysical parameters will be useful for researchers attempting to answer questions like this through experimental or modeling approaches.

Together, the results of our wave flume experiment and our catalog of dune plant traits should provide a valuable asset for coastal managers and policy makers as well as for coastal ecologists and engineers.

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