Coastal sand dunes and dune vegetation: Restoration, erosion, and storm protection

Article *in* Shore and Beach · December 2014

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ABSTRACT

Dune restoration projects that integrate re-vegetation efforts have become increasingly popular in coastal communities. Vegetated dunes have high aesthetic value and are likely to be more resilient to wave-induced erosion. Restored vegetation is likely to act as a stabilizing agent in dune systems; however, there is virtually no scientific knowledge on the impact of plants on dune erosion and protective capabilities during storms. Furthermore, vegetative restoration strategies still lack scientific insight from systematic research. The question is: How can we optimize plants in dune ecosystem restoration to maximize the resilience of coastal dunes against erosion from wave and storm surge attack? This paper will review the current state of knowledge about dune restoration and vegetation's role in coastal resilience, discuss the results of our pilot studies, and suggest future trajectories of research on this topic. A special focus is placed on the potential for *Sargassum* (seaweed) and arbuscular mycorrhizal fungi (AMF) to enhance dune restoration. AMF drastically improve plant health in a variety of ways; however, field surveys indicate they are scarce in degraded dunes, warranting the use of AMF inoculations in future dune revegetation efforts. The role of restored vegetation in dune erosion resiliency has not yet been rigorously investigated. Results from a small-scale mobile-bed wave flume experiment with live plants clearly showed that the presence of the plants significantly reduced the volume of dune erosion and the dune scarp retreat rate by over 30%. Shear testing indicated that dune plant roots increase the mechanical strength of non-cohesive sediment. The presence of mature plant roots doubled the amount of time before structural failure occurred and increased the cumulative shear required to break down sediment by 180%. Besides furthering our knowledge of coastal erosion, the results of these and future studies will be of value to coastal managers and policy makers responsible for dune restoration projects. The gained knowledge will be increasingly valuable as we seek natural, sustainable, soft solutions to combat the effects of growing pressure on our coastlines from increasing populations, rising sea levels, and potentially increasing storm frequency and intensity.

ADDITIONAL KEYWORDS: Plant, management, sediment, Arbuscular Mycorrhizal Fungi (AMF), ecology, bioengineer, Texas, Gulf of Mexico

Manuscript submitted 3 July 2014, revised and accepted 29 October 2014.

Coastal dune ecosystems occupy the small but highly dynamic zone at the intersection of ocean and land. Coastal dunes fulfill many different valuable ecosystem functions. They act as protective buffers against storm surge, wave attack, and erosion of the hinterland, and provide a unique habitat for flora and fauna. Coastal dunes also yield substantial economic benefits by reducing damage to built infrastructure during severe storms (USACE 2013).

The ecosystem functions of coastal dunes are integrally linked to both short-term (i.e. severe episodic storms) and long-term (i.e. accretion of windblown sediment, sea level rise) coastal processes. Plants are thought to play a pivotal role in these processes by strengthening the dune sediment with root systems to reduce erosion, dissipating storm wave energy, and helping trap additional wind-blown sediment, which in turn provides continual dune growth. However, substantial knowledge gaps still exist in understanding vegetation's role in the function of coastal dunes, especially with regards to episodic erosional events. This paper will cover these short-term events, review the current state of knowledge about dune restoration and the role of dune vegetation in coastal resilience, discuss our pilot studies in this field of study, and suggest future trajectories of research on this topic.

TEXAS COASTAL DUNE MANAGEMENT AND RESTORATION

This paper will focus on coastal sand dunes along the Texas coast, which exemplifies many of the problems confronting coastlines around the world. Most coastal dunes in Texas naturally vegetate and accrete sediment over time. However, sediment influx reductions caused by the damming of rivers and disruption of longshore transport by groins and jetties have decayed the natural coastal dune building processes in many areas. Developmental

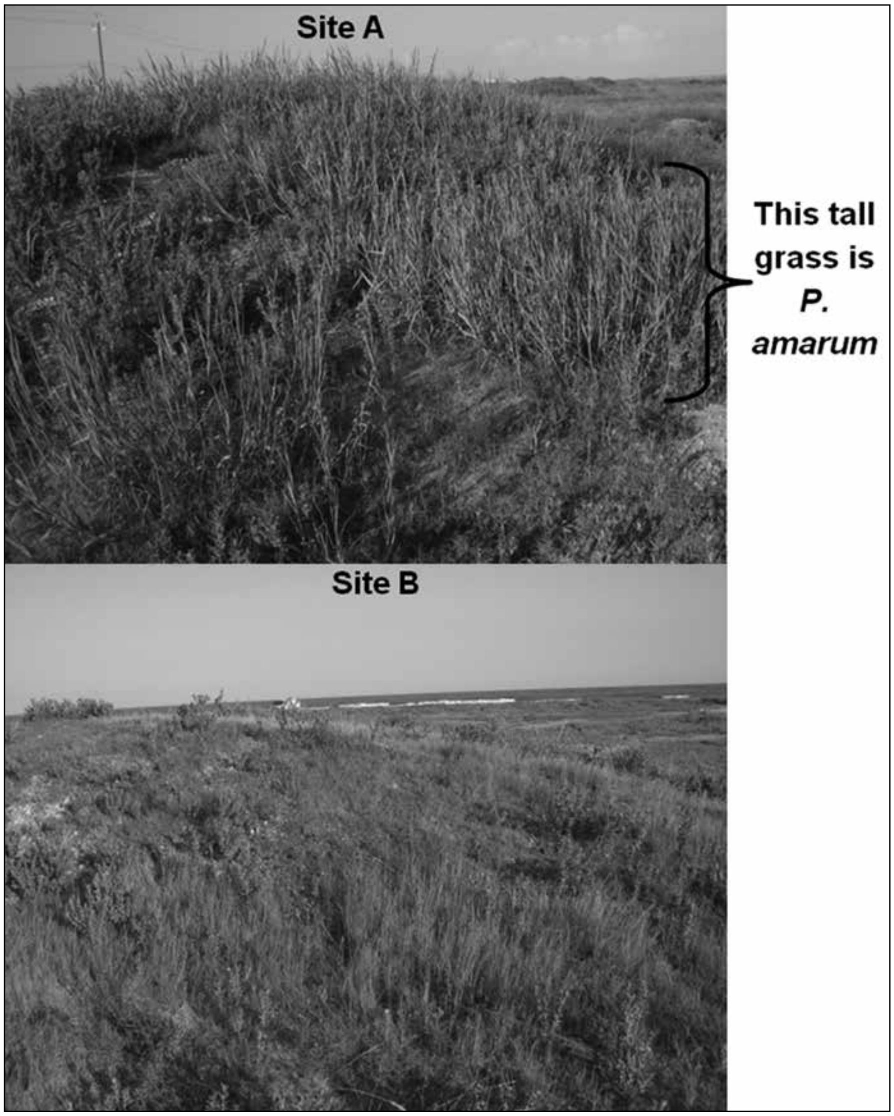


Figure 1. Recent dune construction and restoration protecting the Bluewater Highway along Follet's Island, TX illustrates how dune restoration success is variable. The target species of the restoration efforts was *Panicum amarum*, a hardy coastal dune grass. Site A displays high survival and coverage of the target grass species while Site B (within a few hundred meters of the first) had little to no survival and was either barren or dominated by opportunistic shrubs.

encroachment onto dunes and sea level rise further contribute to the problem. Due to this habitat degradation, many urban communities are engaging in efforts to construct and restore dunes and their associated, crucial ecosystem functions. However, vegetative restoration strategies for coastal dunes still lack scientific insight from systematic research.

The most commonly restored plants along the Texas coast are bitter panicum (*Panicum amarum*), sea oats (*Uniola paniculata*), and marsh hay cordgrass (*Spartina patens*), though numerous other plant species can be utilized (Patterson 2005). The main issue for Texas dune restoration is that dunes consist of dry, nutrient-poor, and often salty sediments. Though many coastal plant species are adapted to the harsh dune environment, transplant survival can be low (Feagin *et al.* 2008; Mendelssohn *et al.* 1991; Miller *et al.* 2001) or highly variable (Figure 1). This is potentially due to the use of stem clippings or tillers with cut root systems as transplant source material. Utilized successfully in other ecosystems (Zahawi and Holl 2009), fully developed plants may enhance restoration success as these plants can better cope with habitat stresses. More reliable and efficient techniques need to be explored to promote consistent restoration success in the unfavorable coastal dune environment.

ARBUSCULAR MYCORRHIZAL FUNGI AND DUNE RESTORATION

Arbuscular mycorrhizal fungi (AMF) are abundant plant endosymbionts. Dune plants and AMF enter into a beneficial relationship that mutually improves survival and fitness. As one of the most common mutualistic organisms in biology, AMF have enormous implications on the primary production and biochemical cycling within many ecosystems. 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 in compensation. They also increase their plant host's salt and drought tolerance, diminish the presence of root parasites, improve soil stability, and reduce erosion (Auge 2001; O'Dea 2007; Tisdall and Oades 1979).

Because of their potential to increase plant fitness, the integration of AMF into restoration ecology is gaining traction (Eviner and 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 and Koske 1997; Smith *et al.* 1998; Sylvia *et al.* 1993; Zhang *et al.* 2011). Coastal sand dunes are great candidates for AMF inoculum usage in habitat restoration for two reasons. First, AMF are exceptionally prevalent in coastal dune plants (Corkidi and Rincon 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 offshore winds blowing beach sediment (devoid of plants or AMF) landward, sand entering coastal dunes ecosystems likely does not contain any AMF spores. Cores taken from non-vegetated areas of Texas coastal dunes have shown this to be the case. From 36 soil samples taken from vegetated and degraded dunes, we found that vegetated dunes have more than 50 times the AMF colonization potential than degraded, unvegetated dunes (an average of 94.4 spores per 100g sediment compared to 1.7 spores per 100g sediment, t-test p-value < 0.001). AMF spores were isolated using a sucrose gradient and centrifugation at 1000 gs. Further research should be aimed at developing efficient means of seeding/inoculating AMF into restored coastal dunes to improve their chance for success.

SARGASSUM (SEAWEED) AS A POTENTIAL RESOURCE

Sargassum natans and *S. 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 and Linton 2013) (Figure 2). Beaches are often raked to remove the unsightly material and encourage tourism, but the issue of what to do with the raked material remains open. 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 and Feagin 2010). Large-scale implementation of *Sargassum* in sand dune restoration could solve two problems at once: boosting tourism to beaches by removing the material, and bolstering dune plant growth in a nutrient starved ecosystem. It should be noted that nutrient enrichment can have complex implications for plant life in oligotrophic coastal environments, depending on differential nutrient uptake ability among plants, secondary limiting resources, biogeomorphic impacts of subsequently altered plant community composition, and changed patterns of herbivory (Armitage *et al.* 2011; Boyer *et al.* 2004, Van den Berg *et al.* 2005). It is not clear whether *Sargassum* amendments will augment plant diversity, yield desirable assemblages of plant species, or be conducive to dune resiliency; these ecosystem effects of *Sargassum* addition to restored dunes should be closely examined.

Figure 2. *Sargassum* landings are typical along the Texas coast in the late spring and early summer. Panel A displays a typical *Sargassum* wrack deposit (10-30 cm high) along a Texas beach (Photo: Rusty Feagin). Panel B shows a heavier landing close to a meter in height (Photo: Galveston Park Board). In the event of heavier landings, communities often rake or frontload *Sargassum* from the shoreline and move it to the back of the beach where it slowly rots. There are no current beneficial-use policies concerning *Sargassum* wrack material.

THE GOAL OF DUNE RESTORATION

Beyond plant survival and growth, it is important to ask: what are the broader restoration and management goals for coastal sand dunes? Are we maintaining critical habitat for wildlife resources or endangered species? Are we aiming for a diverse plant community? Are we trying to sequester carbon or other nutrients? Though these goals are highly relevant to the restoration of numerous habitats, they are not typically the main goal of dune restoration in Texas. Texas has over 350 miles of beaches, but only about 20% are residentially developed; the rest are relatively pristine. The developed coastlines are the main target of dune restoration as these areas are prone to degradation. The primary aim of restoration in these areas is to provide a protective barrier for coastal homes and infrastructure against storms and hurricanes. However, there is virtually no scientific knowledge on the impact of plants on a dune's protective capabilities. It is vital that we begin to explore this topic, as it will provide guidelines for future dune bioengineering, restoration, and management projects along our vulnerable coastlines.

PLANTS AND EROSION

Despite the lack of knowledge of how dune vegetation impacts dune erosion and protective capabilities, reduced erosion caused by plants has been observed in marsh, mangrove, creek bank, and terrestrial ecosystems (Coops *et al.* 1996; Gedan *et al.* 2011; O'Dea 2007; Thampanya *et al.* 2006). In general, there are two ways in which plants impact erosion: water flow modification above-ground and substrate modification below-ground. In other ecosystems, the stems and leaves of plants provide resistance to attacking waves and currents, reducing the amount of erosion occurring in landward sediment (Coops *et al.* 1996; Thampanya *et al.* 2006). Below-ground, plant roots and their associative microbial communities, primarily AMF, interact with surrounding sediment to reduce erosion by improving soil aggregation and shear strength (Burri *et al.* 2011; Fan and Su 2008; Miller and Jastrow 1990; O'Dea 2007). Enhanced soil aggregation influences the general erodibility of sediment in that larger sediment aggregates are more resistant to entrainment by moving water (Figure 3).

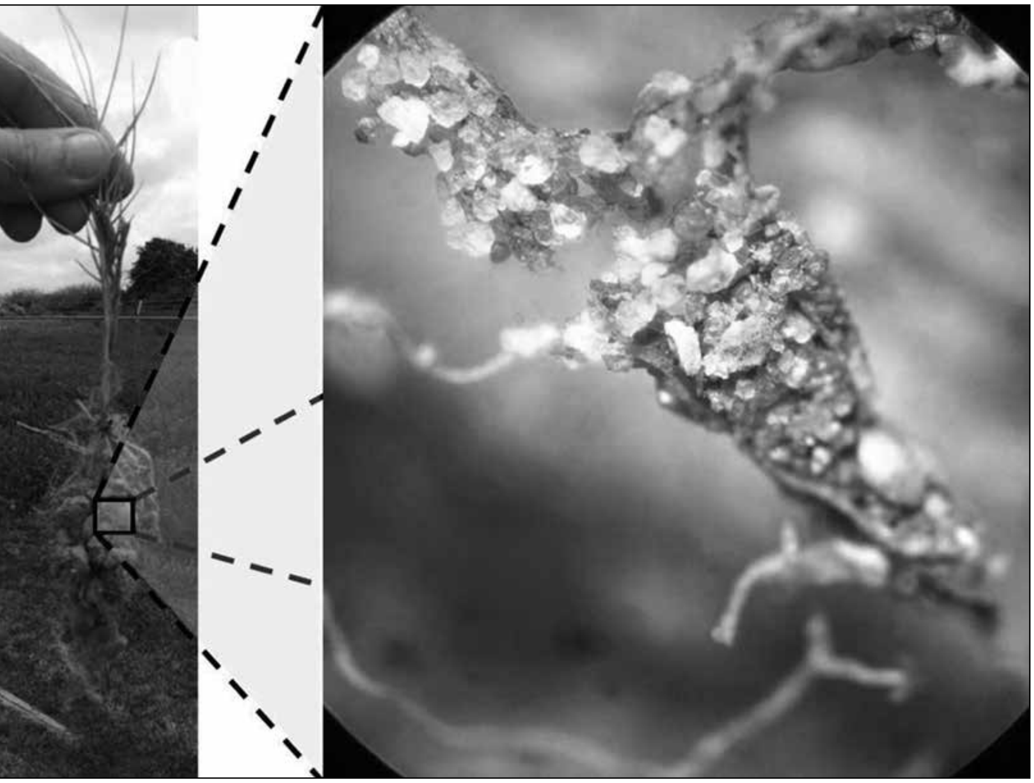


Figure 3. The roots of *Sporobolus virginicus*, a dune grass, are pictured magnified at 45X. Fine root hairs and AMF hyphae (the root-like structures of a fungus) enwrap sediment grains and bind them into larger aggregates. Adhesive soil glycoproteins produced by plants and AMF further contribute to aggregate binding. Larger aggregrates have a smaller effective surface area, making them less likely to become entrained by moving water which may lead to reduced erosion.

Figure 4 depicts the potential above- and below-ground roles of dune vegetation in a wave collision scenario. 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 interact with wave uprush and downrush events in the swash zone, potentially reducing the amount of energy eroding landward sediments (Figure 4, Panel A). Sediment aggregation caused by plant roots could further reduce erosion. As the front face of a dune erodes, a dune scarp forms (Figure 4, Panel B). As waves erode the base of the scarp, gravity pulls on the overhanging sand, inducing shearing stress across the dune sediment. At a criti-

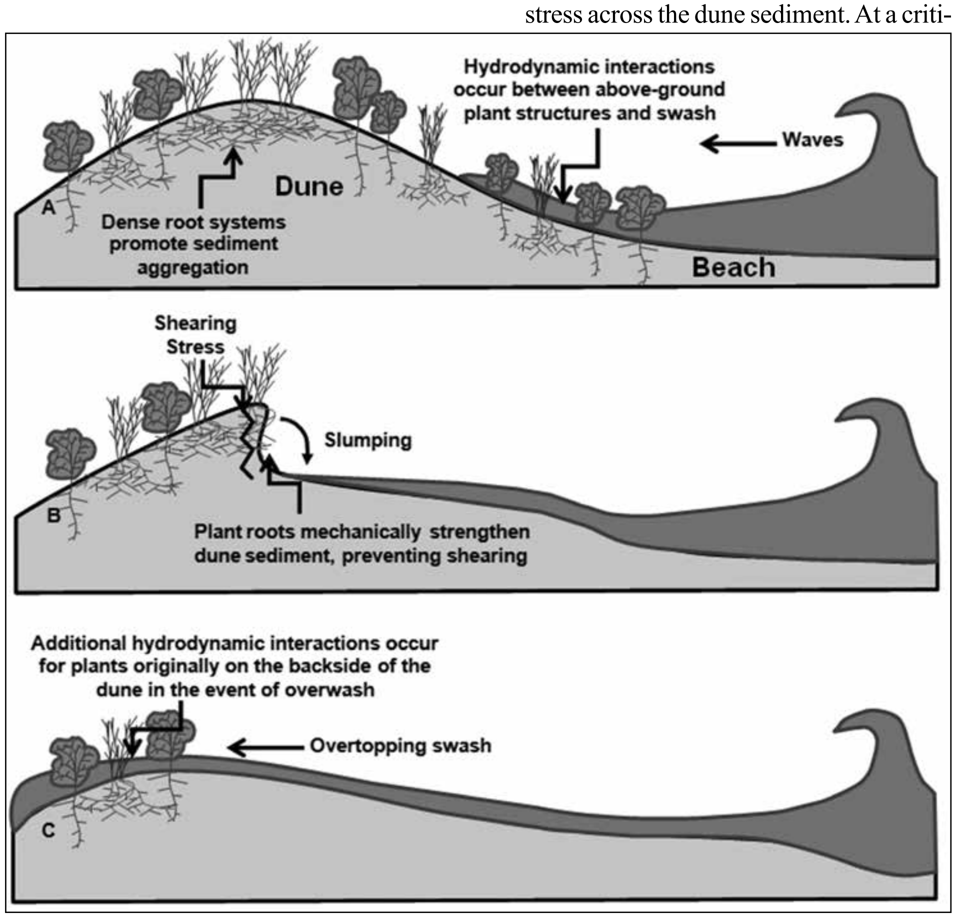


Figure 4. Under storm conditions, a dune ecosystem can be affected by hydrodynamic forcing in multiple ways. Initially, plants and sediment on the fore-dune and seaward facing dune slope interact with the waves and increased water levels (Panel A). In Panel B, a dune scarp is depicted which may occur after a significant seaward portion of the dune has been eroded, effectively exposing above- and below-ground plant portions to the hydrodynamic forcing conditions. Panel C illustrates an overtopping scenario where the plants and substrate on the back-dune are now subjected to hydrodynamic forcing conditions and overwash sediment.

cal overhang mass, the scarp will break off and slump into the oncoming waves. Plant roots theorectically prolong this process as the tensile strength of roots resists the shearing stress. If a wave collision regime is extreme, the entire dune ridge can eventually be overtopped by waves (Figure 4, Panel C). Waves now carry sediments over the crest of the dune where above-ground portions of plants in the back-dune can further modify hydrodynamics and sediment transport. None of these effects have been quantified or rigorously investigated.

PILOT STUDY RESULTS

Shear testing of vegetated and non-vegetated substrate samples was carried out in the laboratory and indicates that dune plant roots contribute to the mechanical strength of noncohesive dune sediment. For these tests, the substrate was subjected to shear in the direction of root growth corresponding to a vertical plane (i.e. dune scarp) in a real dune. *Sporobolus virginicus*, a perennial dune grass, was grown in sand and tested at different levels of maturity (plants with varying levels of root density) to determine the impact of root accumulation on sediment shear strength. Figure 5 compares the results of the constant velocity shear tests for the case of no plant roots to two cases with immature (6 weeks) and more mature (9 weeks) plant roots, respectively. The ultimate shear strength of the substrate without roots (i.e. peak of the black dashed curve) was found to be around 2,500 N/m^2 and occurred 7 seconds into the test. The ultimate shear strength of the substrate with immature roots (peak of gray solid line) was about the same, but occurred 3 seconds later at 10 seconds into the test. Substrate with a mature root system (black solid line) showed significantly increased ultimate shear strength with a peak at 3,500 N/m^2 11 seconds into the test. In addition, the presence of roots improved the shear strength of the substrate beyond its peak value which is indicated by the increased area under the curve (cumulative shear). In sum, the presence of plant roots delayed the amount of time before structural failure occurred and increased the cumulative shear required to break down the sediment. Figure 6 shows the result of a regression analysis relating the dry root biomass to the cumulative shear strength using data from each conducted trial. The trend line (R^2=0.835) clearly indicates an increase in substrate shear strength with increase in root biomass (i.e. maturity of the plant-root system).

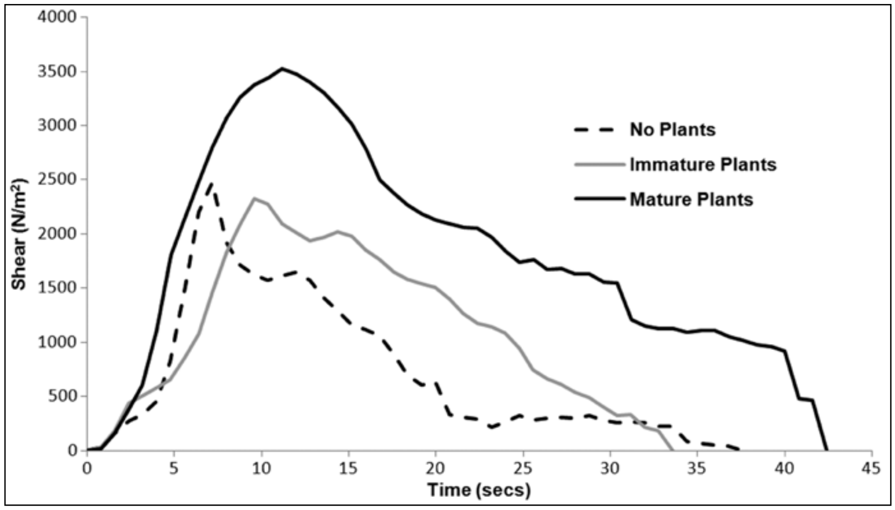
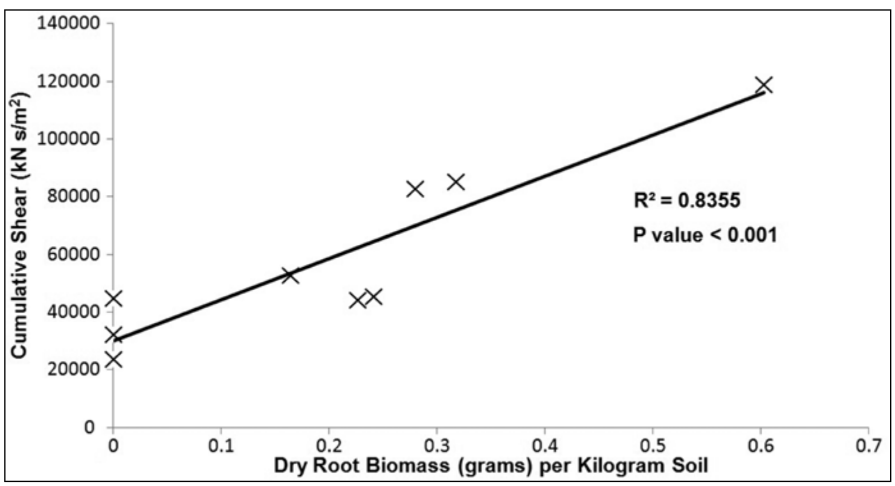


Figure 5 (above). *Sporobolus virginicus* roots growing in dune sediment at different levels of maturity were tested under constant velocity shearing conditions. Three cores per treatment group were averaged to produce each curve. Sediment was maintained at 15% moisture content during shear testing as dunes under wave and surge attack are in a saturated state (shearing of dry sediment would therefore be inappropriate). Sediment with more mature plants (higher density of plant roots) yielded a higher ultimate shear strength at a later time in the test indicated by the peak of the black solid curve.

Figure 6 (below). Plant roots increase the total amount of stress required to breakdown dune sediment. Cumulative shear (the area under the curves of Figure 5) is plotted on the vertical axis and root density (dry root biomass, per kilogram dune sediment) is plotted on the horizontal axis. The plant mediated increase in mechanical stress necessary to compromise dune sediment could be vital in preventing dune scarps from collapsing into oncoming waves, allowing the dune to erode more slowly.



Small-scale mobile-bed wave flume testing with regular waves demonstrated that plants reduce wave-induced erosion, increasing a dune's protective ability by prolonging the amount of time it acts as a storm buffer. In our pilot wave flume tests, dune plants were transplanted onto a dune within a small wave tank (dimensions: 750 cm long, 40 cm wide, 40 cm tall). *Sporobolus virginicus* was grown in a greenhouse for three months to allow the development of mature root systems. The vegetation and substrate was then transplanted onto the seaward facing slope of the dune and subjected to attack by regular waves (wave height: 5 cm, wave period: 0.7 seconds, water depth: 26 cm). Bathymetric profile measurements of the entire beach and dune

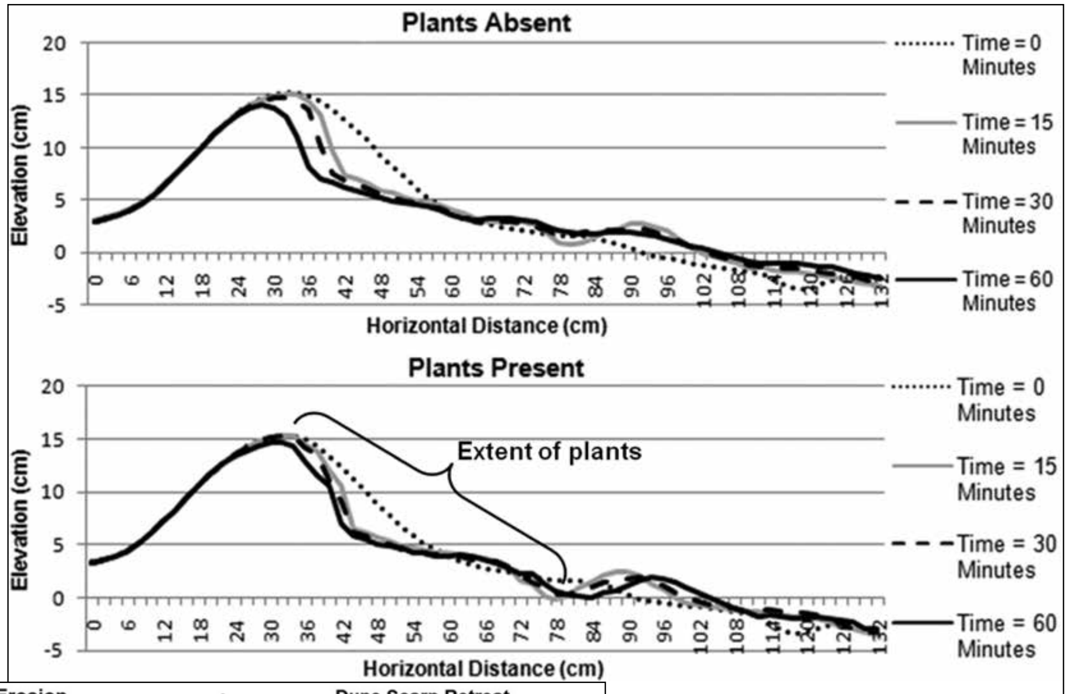


Figure 7. Measured beach profile evolution from pilot, small-scale wave flume testing. The bathymetric profiles were determined from three 60-minute tests without plants and three tests with plants. Four profiles were taken for each test at t = 0, 15, 30, and 60 minutes into the test. *Sporobulus virginicus* was transplanted in the area between 30 cm and 80 cm along the cross-shore axis.

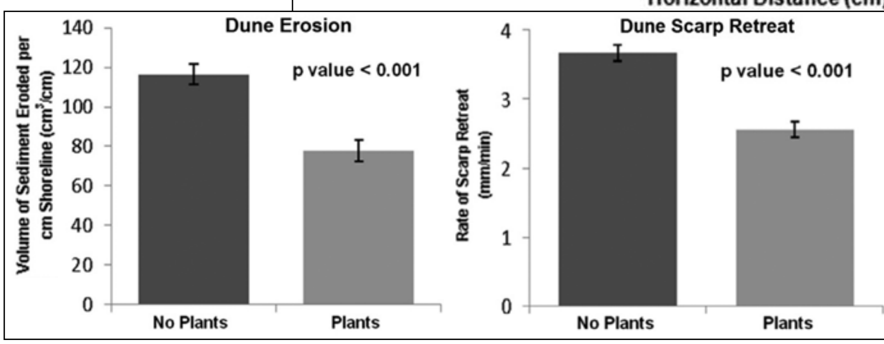


Figure 8. The presence of *Sporobulus virginicus* on the dune face reduced the total amount of eroded dune volume by 33%. It is likely that this erosion reduction was due to a combination of above-ground and below-ground plant interactions. The presence of *Sporobulus virginicus* on the dune face also reduced the rate of dune scarp retreat by 30%. This is a crucial aspect of a sand dune's protective capabilities. If a storm surge collision regime is severe enough, a dune scarp will retreat to a point where the dune may be breached, leaving coastal infrastructure and homes vulnerable to wave and surge attack. If plants can prolong the amount of time before a dune is breached, damage to coastal communities would likely be reduced.

system were taken to monitor erosion with and without plants (Figure 7). When plants were present on the dune face, only 78.0 cm^3 of sediment per unit length of shoreline eroded compared to 116.5 cm^3 of sediment per unit length of shoreline when plants were absent, an erosion reduction of 33% (Figure 8).The rate of dune scarp retreat was lower for the case with plants (2.6 mm/min) compared to the case without plants (3.7 mm/min), a decrease of 30% (Figure 8).

RESEARCH OUTLOOK

Many additional questions stem from the fact that different species of plants impact erosional processes in different ways. The root systems of some plant species improve soil aggregation, shear strength, and reduce erosion better than others (Burri *et al.* 2011; De Baets *et al.* 2008). Also, plant species differing in leaf distributions, flexibilities, stem densities, and plant heights alter wave hydrodynamics in unequal ways (Bouma *et al.* 2005; Leonard and Luther 1995; Ysebaert *et al.* 2011). Dune and beach ecosystems along the Texas coast harbor dozens of plant species with distinct above- and below-ground characteristics. Do different species of plants variably impact erosion in dunes? What features of plants are most important for dune erosion control? Can we restore plant communities in ways that increase dune protective potential? We will conduct additional wave flume tests on different species of dune plants while also analyzing plant biological features to create a broadly applicable model to dune bioengineering in the future. We will focus on native dune plant species in our studies. Although exotic plant species could provide a short-term gain in dune stability, these benefits are outweighed by the broader ecological impacts of species invasions.

Figure 9 illustrates the current state of our hypothesized conceptual model, relating different dune plant biological parameters to soil aggregation, soil shear strength, wave energy dissipation and ultimately dune resilience (+ for positive correlation, - for negative correlation). Though these interactions have not been empirically tested in terms of their impact on coastal dune protection capabilities, predictions can be made from literature. Miller and Jastow (1990) and De Baets

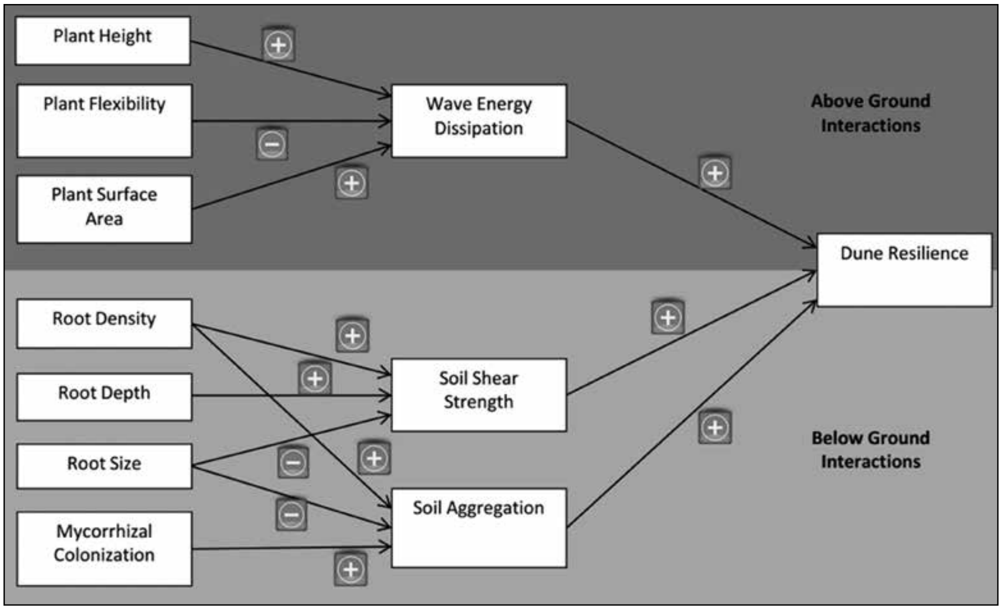


Figure 9. Hypothesized model of below-ground and above-ground interactions between vegetation parameters and dune resilience (+ for positive correlation, - for negative correlation). Ultimately, an understanding of these interactions would create a broadly applicable framework for coastal dune bioengineering. Coastal communities throughout Texas and around the world could make relatively simple measurements of local dune plant characteristics and use that information to inform restoration practices.

et al. (2008) showed that higher root densities contributed to greater soil shear strength and aggregation. Miller and Jastow (1990) illustrated that finer roots and increased mycorrhizal colonization improved soil aggregation. Genet *et al.* (2005) explained that finer roots also proportionately increased shear strength more than coarse roots due to higher cellulose content. Flexible plants offer little resistance to wave forcing and therefore contribute little to wave energy dissipation (Bouma *et al.* 2005). Lastly, increased plant surface area also increases hydrodynamic drag and decreases the energy carried by attacking waves (Augustin *et al.* 2009). Such an interaction model has the potential to impact coastal margin health at an immense scale as it applies to dune systems beyond Texas and lays the groundwork for numerous continuation studies for biologists and engineers globally.

As previously addressed, a variety of dune restoration techniques also need to be explored as the potential benefits of dune vegetation in erosion control and coastal protection depend on the successful restoration of plants to the harsh dune environment. Therefore, we are going to conduct experiments that integrate *Sargassum* bales, AMF inoculation, and *Panicum amarum* transplantation on a recently constructed dune in Galveston, TX. The survival and vitality of fully-developed potted plants vs. cut transplanted tillers will also be compared in this experiment. To understand the long-term implications of restoring vegetation to a dune system, we will track the erosion/accretion of restored and non-restored sections of the dune over multiple years. These experiments will inform guidelines for dune restoration, bioengineering, and management, ultimately providing tools to improve dune ecosystems as barriers to storms and increasing the resilience of both urban and natural coastal communities.

SUMMARY

A multitude of problems confront coastlines globally: population and development growth, rising sea level, and increasing vulnerability to more frequent and intense storms. Effective dune management and restoration could play pivotal roles in mitigating these problems. However, substantial knowledge gaps exist with regards to efficient vegetative restoration techniques and vegetation's role in dune resilience. *Sargassum* and AMF may increase dune restoration success along the Texas coast, but empirical testing is needed to assess them. Though the impact of plants on erosion and wave attenuation has been analyzed in a variety of other ecosystems, their role in coastal sand dunes remain largely unstudied. Our pilot wave flume experiments suggest that plants have great potential to reduce dune erosion under wave and surge attack.

Additional flume and laboratory experimentation with regular and also irregular waves will determine the impact of different kinds of vegetation on dune erosion within a controlled setting. By also testing the underlying biological and physical mechanics which relate to dune erosion reduction, a widely applicable framework for coastal dune bioengineering will be created. Field experimentation on a constructed dune will determine effective means of restoring vegetation with AMF and removing *Sargassum* from beaches for beneficial use. Subsequent monitoring of the dune will illuminate the role of vegetative restoration in dune accretion and erosion during storms *in situ*, further contributing to coastal dune restoration and management. Once we better understand the role of vegetation in coastal dune resilience, we may be able to optimize the protective capabilities of restored dunes. While this may not prevent dune destruction during the most severe storm attacks, it may reduce the impact of more frequent minor storms and events that continue to erode away the base of coastal dunes, as well as improve mitigation approaches following severe storms. The gained knowledge will be increasingly valuable as we seek natural, sustainable, and soft solutions to the plethora of issues challenging our coasts.

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