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# Erosion of Coastal Foredunes: A Review on the Effect of Dune Vegetation

*by Duncan B. Bryant, Mary A. Bryant, and Alison S. Grzegorzewski*

**PURPOSE:** The purpose of this Coastal and Hydraulics Engineering Technical Note (CHETN) is to identify the potential roles of vegetation in mitigating coastal dune erosion during storm events by presenting a review of current literature.

**INTRODUCTION:** Out of the 3 million square miles of land in the United States, less than 10% comprise the coastal shoreline counties. However, 39% of the nation's population resides in these coastal shoreline counties, a population density six times greater than inland counties. From 2010 to 2020, the projected population increase in these coastal areas is 10 million, an 8% increase (National Oceanic and Atmospheric Administration [NOAA] 2013). Due to their proximity to open water, these communities are the most vulnerable to the direct effects of coastal hazards resulting from tropical and extratropical cyclones. Unfortunately, as the human population has historically encroached into coastal areas, many coastal dune systems are in advanced stages of degradation and may have been completely removed in the process of creating aesthetic, nonrestricting ocean views or providing living spaces. A consequence of this reduction and removal of coastal dune topography is that the potential for storm surge damage has increased noticeably in the coastal zone (Martínez et al. 2004).

Following Hurricane Sandy in 2012, efforts to include dunes in coastal planning were renewed after communities fronted by these systems, such as Sea Girt, NJ (Walling et al. 2014), and Rockaway Peninsula in Queens, NY (City of New York 2013), sustained fewer damages as a direct result of reduced wave impacts, overland surge propagation, and/or severe scour (U.S. Army Corps of Engineers [USACE] 2013). Furthermore, natural or man-made dunes with established vegetation were observed to erode less than unvegetated dunes comprised simply of mounded sand (City of New York 2013). While management guidelines for constructing dunes identify vegetation as necessary to trap and accrete sediment, the potential for vegetation to mitigate dune erosion during severe events remains unaddressed due to a paucity of data. The effect of vegetation on dune erosion and overwash has not been studied comprehensively, instead relying largely on anecdotal evidence, post hoc observational studies, and analogous studies of other land features (Feagin et al. 2009, 2015).

This CHETN begins with an introduction to coastal dune systems, with the following section detailing the dune erosion regimes defined by Sallenger (2000). Next, nonwoody species of dune vegetation prevalent to the Atlantic and Gulf of Mexico coasts are presented. Finally, a review of research efforts exploring the effects of vegetation on dune erosion is provided.

**COASTAL DUNE SYSTEMS:** Coastal sand dunes are found along the coast, above the high water mark, and landward of the sandy beach. Three essential requirements must be met for dune formation on a beach: (1) a prevailing onshore wind above the critical wind velocity for transporting the sediment, (2) a continuous supply of sand, and (3) an obstacle to reduce the velocity of the wind to encourage deposition and prevent remobilization of the sediment (Maun 2009). Coastal dunes can be classified into four types or complexes: foredunes, relict foredune plains, parabolic dunes, and transgressive (mobile) dunefields (Hesp 1991). The focus herein will be on foredunes.

Often referred to as the primary dune system, the foredune system is supplied with sand directly from the beach and is highly dynamic. The foredune system consists of incipient “embryo” dunes (if present) and the foredune ridge (Figure 1). The seaward dune face is referred to as the stoss slope while the landward face is called the lee slope. Summarizing Hesp (2002), embryo dunes are new or developing foredunes formed by sand deposition around an obstacle, such as flotsam, driftwood, individual plants, or plant clumps. Often resembling unconnected mounds of sand found at the base or backshore of existing foredunes, embryo dunes are typically a few centimeters (cm) to 1 to 2 meters (m) high and 10–20 m wide. These embryo dunes are short-lived when developed around nonliving obstructions or annual plant species and require support by perennial plants in order to persist. On stable or eroding beaches, these embryo dunes are considered transient, developing over several months or even years before being removed by large storms. However, in cases of beach progradation, these embryo dunes can grow and merge over time, eventually becoming the youngest foredune ridge. The foredune ridge is formed in the backshore, landward from the limit of storm wave action, and is oriented shore-parallel irrespective of the prevailing wind direction. Initially stabilized by the pioneer vegetation that colonized the embryo dunes, intermediate, woody vegetation may replace these pioneer communities with time, resulting in distinct vegetation types between embryo dunes and foredune ridges. Established foredunes are usually 5–20 m high and 30–50 m wide, although they can also range from very low, scattered dunes less than a meter in height to dune complexes reaching 30–35 m in height. These highest dunes are rare and are typically a result of human interference inflating the foredune height through nourishment and the installation of sand fencing. The morphological development of the dune system primarily depends on the habit of the colonizing plant species, wind velocity, and rates of aeolian sand accretion and erosion although wind direction, human disturbance, and incidence of swash inundation, storm wave erosion, and overwash impact subsequent dune evolution. A comprehensive review on foredune morphology, disturbances, and management practices is available in Swann et al. (2015).

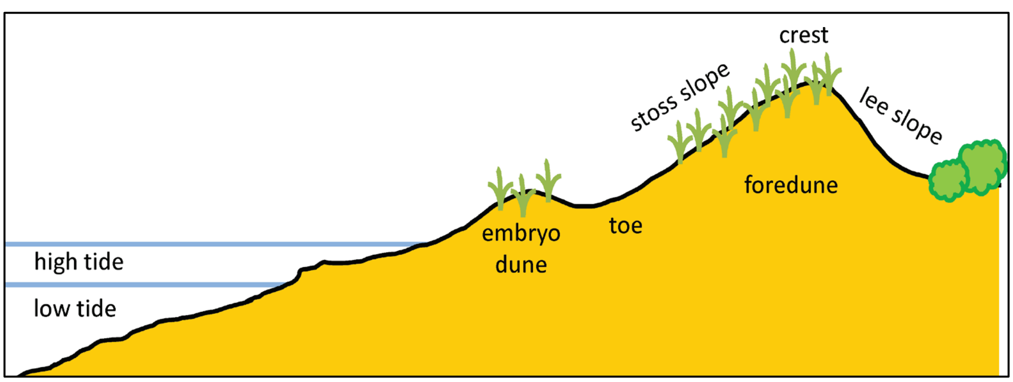


Figure 1. Diagram of coastal dune system.

**DUNE EROSION:** The erosion of dunes during a storm event is dependent on several factors, namely storm forcing parameters (e.g., storm surge and waves) and dune geometry, although sedimentary and biophysical characteristics also contribute (Bridges et al. 2015). Sallenger (2000) developed a well-known classification of storm impact by scaling the magnitude of storm parameters relative to dune geometry. By considering the elevation of total storm water level (i.e., vertical water elevation due to astronomical tides, storm surge, wave setup, and runup) relative to the elevation of the foredune, four regimes to characterize and forecast the dune response were proposed: the swash regime, the collision regime, the overwash regime, and the inundation regime.

The collision and overwash regimes without vegetation have been studied extensively in large-scale experiments (e.g., Kraus and Smith 1994; van Thiel de Vries 2008; van Rijn 2009; Tomasicchio et al. 2011; Figlus et al. 2011). These regimes directly impact the dune areas (e.g., stoss slope, dune crest, and lee slope) inhabited by vegetation (Figure 2).The collision regime occurs when the total storm water level exceeds the elevation of the dune toe but is lower than the dune crest. During the collision regime, swash impacts the dune face, forcing net erosion and a steepening or scarping of the stoss slope. Summarizing Hesp (2002) and Hesp and Martínez (2007), the degree of scarping, characterized by the volumetric loss of sediment, affects the level of vegetation disturbance and subsequent foredune recovery. Slight scarping (10% to 20% of the removal of the dune volume) may lead to slight dieback or death of some plant species due to salinity intolerance or inability to survive in the swash zone. Moderate scarping (20% to 40% volumetric loss) results in the dieback of plants on the scarp frontline due to the impacts of salt spray, burial, and slumping. Plants with extensive root systems may survive the collapse of the surrounding substrate by remaining anchored or reestablishing at the base of the scarp when the slump blocks slide or fall from the scarp crest. Severe scarping (greater than 40% volumetric loss) may result in foredune destabilization and have devastating effects on the vegetation population, leading to blowouts, long-term foredune degradation, and dune retreat.

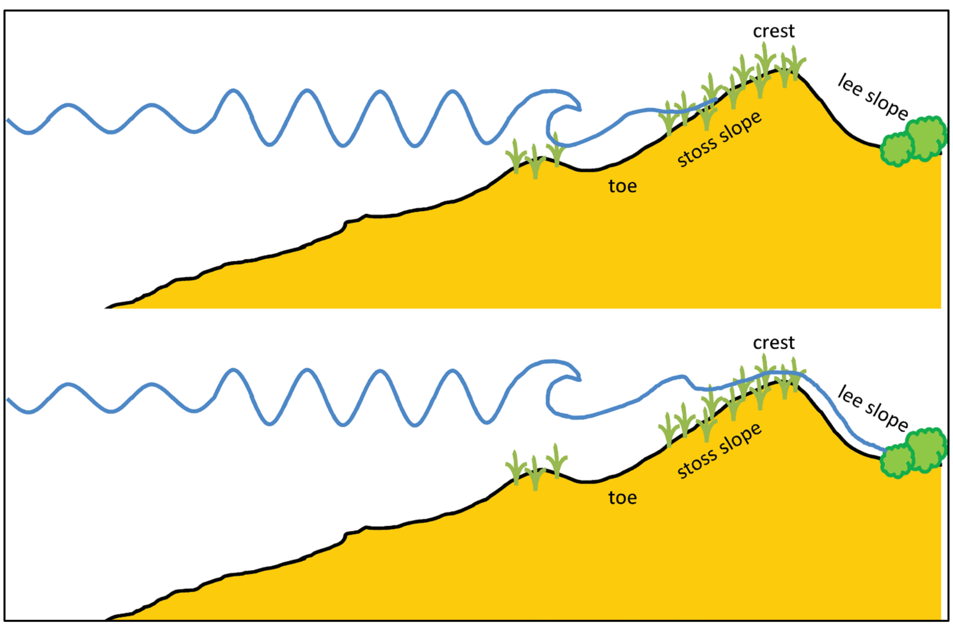


Figure 2. Collision (top) and overwash (bottom) regimes of Sallenger (2000).

As the storm progresses, the total storm water level may continue to increase until runup intermittently overwashes the dune. Note that dune geometry is evolving during storms, especially those of long duration, such that the dune crest may have been lowered as to initiate overwash of the dune crest or overtopping. Overtopping can lead to rapid erosion of the dune face and crest whereby the eroded sediments are deposited landward. During severe storm events such as tropical storms, hurricanes, and northeasters, a breaching, complete removal, or submerging of the dune is possible, leading to inundation and inland flooding. A comprehensive literature review on coastal overwash can be referenced in Donnelly et al. (2006).

The framework proposed by Sallenger (2000) considers only one dimension, the cross-shore extent. However, the exact location of dune erosion and overwash is dependent on variabilities in the alongshore storm forcing and dune line geometry, such as low-lying areas or existing gaps between foredunes. The alongshore response of the dune system is partly reinforced through a complex biogeomorphic feedback with vegetation (Stallins and Parker 2003). For example, dunes with low overwash frequencies are higher topographically and stabilized by rich plant communities. In contrast, dunes regularly overwashed have disturbance-dependent, sparse, or absent vegetation cover, which locally promotes lower crest elevations and increases the susceptibility of these previously overwashed regions to future overwash events (Bird 2008; Hesp and Martínez 2007; Houser 2013).

**DUNE VEGETATION:** Vegetation is paramount for trapping aeolian transport in order to actively build and sustain dune growth. At least three dune plant functional types, based on responses to sediment burial, have been described: dune builders, burial-tolerant stabilizers, and burial-intolerant stabilizers. Both dune builders and burial-tolerant stabilizers demonstrate positive growth responses to burial. However, burial-tolerant stabilizers have decumbent growth forms and do not promote dune development whereas dune builders encourage the development of steep foredunes due to their upright growth habit. The third group, burial-intolerant stabilizers, demonstrates negative responses to burial and is found in more protected inland areas (Stallins 2005). The discussion in this section focuses on the dune-builder functional type.

Plants in the Family *Poaceae*, characterized as flowering grasses, have adapted to the harsh conditions present on coastal foredunes. These plants endure salt spray, occasional submersion, porous and poor soils, sand burial, and extended droughts. Along the Gulf and Atlantic Coast of the United States, three grass species, *Uniola paniculata, Ammophila breviligulata,* and *Panicum amarum,* are among the pioneer species of coastal foredunes. Foredunes along the Pacific Coast are often colonized by *Leymus mollis*, *Poa macrantha,* and *Poa douglasii*, also of the Family *Poaceae.* Each species is found to be specialized for different portions of the coastal United States, with *Ammophila breviligulata* and its European counterpart, *Ammophila arenaria*, invasively spreading along the Pacific Coast. The species listed above are not all inclusive as local conditions, such as frequent inundation or higher water tables, promote other species such as *Spartina patens* or *Croton punctatus*. Additionally, annuals such as *Cakile edentula*, which can also tolerate burial and salt spray, are not considered (Maun 2009). The following section focuses on the Atlantic and Gulf of Mexico nonwoody perennial species, as tropical and extratropical storms often erode coastal dunes and threaten human developments in these regions.

*Uniola paniculata* (sea oats) is the primary species found growing on the embryo dune and foredunes of the Gulf of Mexico and Southern Atlantic Coast (Figure 3). *Uniola paniculata* is reported by the U.S. Department of Agriculture (USDA) to grow up to 2 m tall with leaves reaching 60 cm long and less than 2.5 cm in width. Seed heads, also known as panicles, are large and become a yellow-brown, straw color in late summer (Amos and Amos 1997). Despite the distinct panicles, *U. paniculata* does not produce many seeds and spreads more effectively by underground rhizomes resulting in dense mounds or stands of vegetation (Wagner 1964). *U. paniculata* serves to trap wind-blown sands that eventually mound, leading to dune formation (Johnson and Barbour 1990). Burial by sand stimulates growth and is essential to the plant biology. This species is both an excellent pioneering species due to its ability to rapidly colonize and establish itself and an excellent climax species due to its high tolerance to seawater and salt spray. The root system is characterized by the Smithsonian Marine Station at Fort Pierce, FL, as "extensive," and the USDA describes the plant in its fact sheet (Shadow 2007) as having a "massive root system." Hester and Mendelssohn (1989) showed the belowground biomass is nearly equal to the total aboveground biomass and nearly double the live aboveground biomass. The distribution of the belowground biomass is dependent on local growing conditions. Hester and Mendelssohn (1989) demonstrated that sea oats have a large proportion of roots (> 50%) in the top 30 cm of soil, with a smaller proportion of deeper roots penetrating to zone of capillary rise from the water table. Stalter (1974) reported average root depths between 12.7 and 38.1 cm along coastal South Carolina, with a maximum root depth of 213 cm.

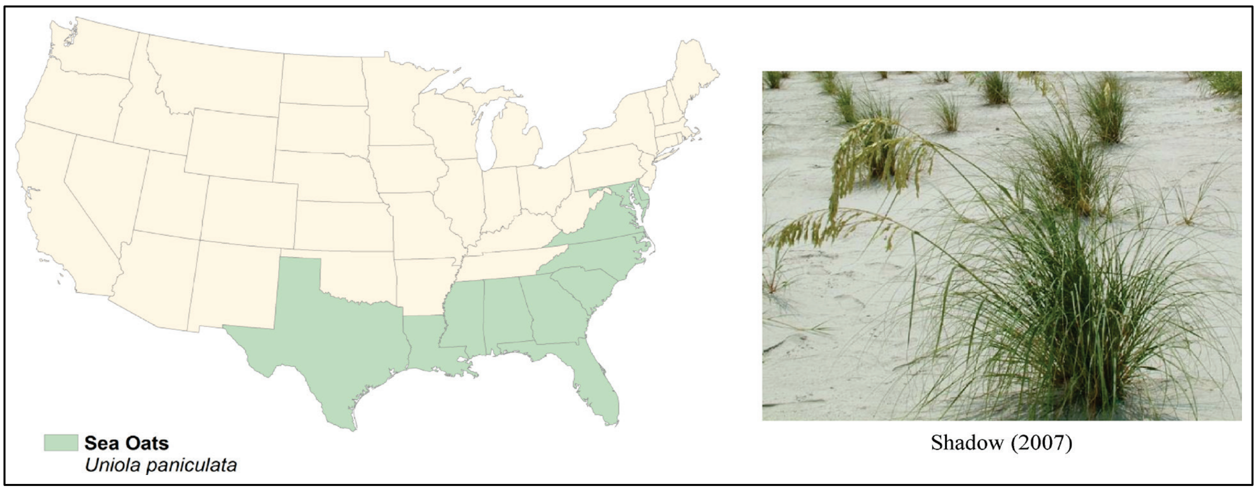


Figure 3. Reported coastal range and photo of *Uniola paniculata* (sea oats).

*Ammophila breviligulata (*American beachgrass) is a frontier grass species for the North Atlantic States, Great Lakes States, and Pacific States (Figure 4). The USDA factsheet (USDA 2006) reports *A. breviligulata* growing to a height of 60 to 90 cm and a yearly horizontal spreading rate of 2 to 3 m via rhizomes. As with *U. paniculata*, *A. breviligulata* is adapted to sand burial. Seliskar (2003) measured the properties of *A. breviligulata* along the dune ridge lines at Assateague Island National Seashore, Maryland. The results report an average belowground biomass for buried shoots of 322.8 grams per $m^2$ ($g/m^2$) and 14.1 $g/m^2$ for root and rhizome biomass. The aboveground biomass averaged 315.2 $g/m^2$ with an average of plant density 353.6 stems per $m^2$. *A. breviligulata* is present along the Pacific Coastal States as an invasive species, where it outcompetes the native *Elymus mollis* (American dune grass) (Washington State Department of Ecology 2016).

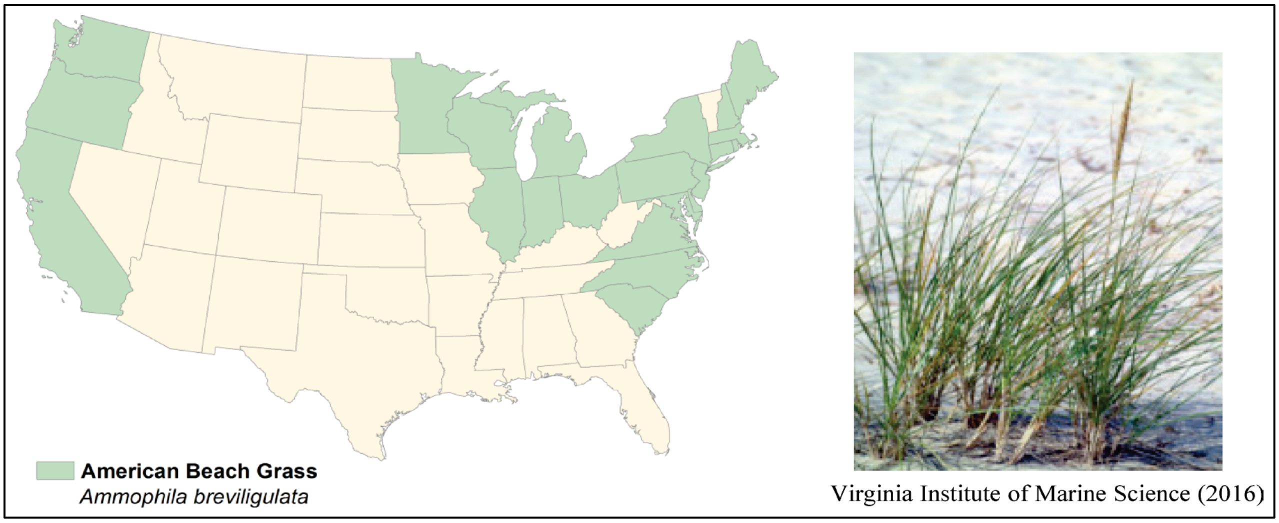


Figure 4. Reported coastal range and photo of *Ammophila breviligulata* (American beach grass).

Last, *Panicum amarum* (bitter Panicum or bitter panicgrass) is a grass species found from coastal Texas to New England (Figure 5). Like *U. paniculata* and *A. breviligulata, P. amarum* is deep rooted (up to 1.8 m) and is cited by the USDA for its ability to reduce coastal dune erosion (Lamphere 2006). *P. amarum* is reported as an excellent frontier species, efficiently trapping sand leading to dune growth (Dahl and Woodard 1977; Lamphere 2006). Typically, *P. amarum* grows between 1.2 and 2.4 m tall, with leaves under 1.25 cm wide. As with the other frontier grass species, *P. amarum* spreads by rhizomes or seeds. Laboratory results from Willis and Hester (2008) show that transplanted *P. amarum* had on average 40 g of belowground biomass and 6 g of aboveground after 14 weeks of growing in a controlled laboratory.

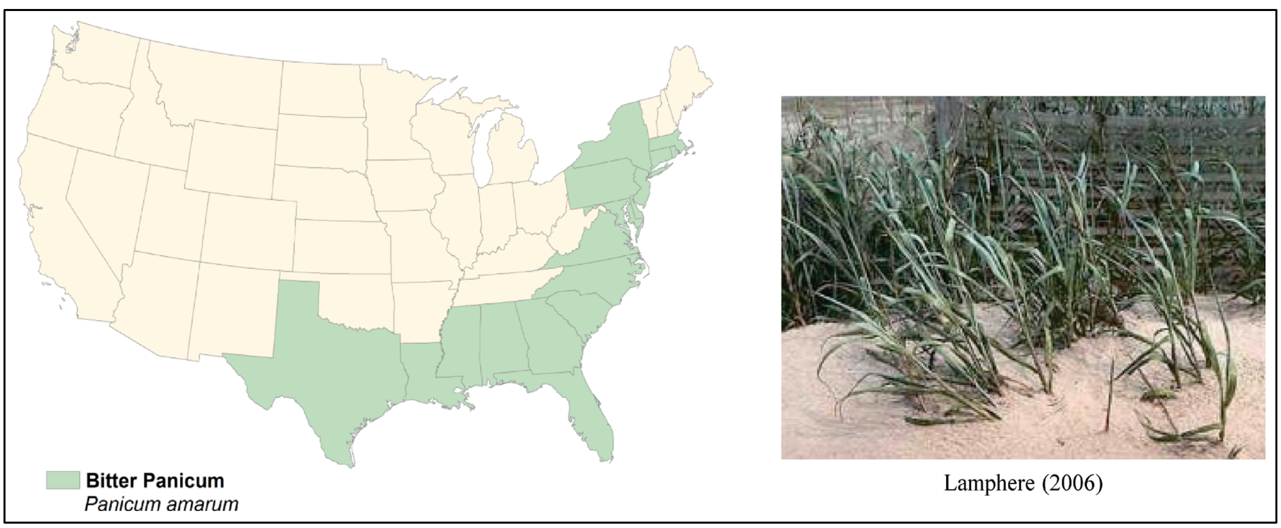


Figure 5. Reported coastal range and photo of *Panicum amarum* (bitter Panicum or bitter panicgrass).

All three of the species described above are effective at establishing and growing coastal foredunes. Additionally, they are characterized by their abundance of belowground biomass, both roots and rhizomes. In established dunes, the roots associated with these species are often in a symbiotic association with arbuscular mycorrhizal (AM) fungi. Arbuscular is defined as "branching, tree like structures involved in exchanging material between fungus and plant" (Koske and Polson 1984). The AM fungus provides nutrient absorption benefits to the plants in exchange for carbohydrates via hyphae. These branching filaments of the fungus extend beyond the roots into the substrate, improving plant drought tolerance and nutrient acquisition while reducing salt stress (Feagin et al. 2015). Koske and Polson (1984) found AM fungi to be present in dune plants, including *U. paniculata* and *A. breviligulata*, from Maine to Georgia. Tisdall and Oades (1982) describe three distinct phases of AM fungi aggregate formation. First, AM fungi hyphae entangle the soil particles. Then, the AM fungi and roots bind the soil into microaggregates (< 0.25 millimeter [mm]). Finally, the microaggregates are bound further into macroaggregates (> 0.25 mm). Under controlled laboratory experiments, AM fungi were found to create up to 412 aggregates per kilogram of sand, with 38% to 78% of the sand being in aggregate form (Forster and Nicolson 1981). Additionally, Sutton and Sheppard (1976) found in controlled laboratory experiments that AM fungi tripled aggregate formation and the percentage of sand adhered to roots versus when no fungi were present. This aggregation of sand reduces wind erosion (Koske and Polson 1984) and stabilizes the dune sand (Forster and Nicolson 1981). However, the value these plants and their associated AM fungi have in reducing coastal dune erosion has not been fully characterized and may reveal a service not currently accounted for in coastal planning.

**DUNE EROSION WITH VEGETATION:** Based on analogous studies of other landforms, the physical and ecological mechanisms by which aboveground and belowground vegetation structure may provide protection against dune erosion is discussed by Feagin et al. (2015). The stems and leaves of seagrasses and wetland plants alter hydrodynamic forces and reduce wave energy, a function thought to extend to dune vegetation. Based on studies of fringing wetlands and riverbanks, the root system of dune vegetation is thought to bind sandy soil albeit the properties of sand grains are vastly different than cohesive sediments. A few field studies have qualitatively demonstrated the role of vegetation in slowing dune erosion and overwash (Donnelly et al. 2006), but the resistance contributed by the vegetation was not measured.

Laboratory studies of dune vegetation and wave-induced erosion are extremely limited. Kobayashi et al. (2013) conducted a small-scale experiment to examine the effects of woody plants, represented by buried dowels, on dune erosion and overwash. The following five dune configurations were subjected to the same incident wave condition: a high dune with absent, narrow, and wide vegetation and a low dune with absent and wide vegetation. The narrow vegetation was installed only along the lee slope of the high dune and did not reduce the water overtopping and sediment overwash rate compared to the bare dune. However, when the vegetation was expanded to the stoss slope, the vegetation reduced scarping, delayed the initiation of wave overtopping, and reduced overwash and overtopping rates. A decrease in wave overtopping and overwash was also observed for the low dune with wide vegetation. The stoss vegetation slowed the wave uprush but increased offshore sand transport from the eroded dune. These data were used by Ayat and Kobayashi (2015) to expand the cross-shore numerical model CSHORE to include the drag force acting on cylinders. Ayat and Kobayashi (2015) then conducted additional experiments to examine and model the effects of density and toppling of the cylinders on dune erosion. The effectiveness of the dowels in reducing overwash diminished after toppling and when the ratio of cylinder spacing to diameter exceeded seven.

Figlus et al. (2014) and Silva et al. (2016) conducted small-scale experiments investigating the effect of live vegetation on dune erosion. The vegetation, *Sporobolus virginicus* for Figuls et al. (2014) and *I. pes-caprae* for Silva et al. (2016), were grown in greenhouses and transplanted into the model dune for testing after a certain number of growing weeks. In both studies, dune erosion was reduced in the presence of vegetation cover. Whereas Figlus et al. (2014) observed the greatest reduction in total eroded volume (30% for regular waves and 8% for irregular waves) for the most mature and densely planted vegetation, Silva et al. (2016) found no direct relationship between vegetation density and volume eroded, with results being qualitative to some extent. Testing of substrate samples with no roots, 6-week-old, and 9-week-old plant roots showed an increase in the ultimate shear strength of the substrate with more mature root systems (Figlus et al. 2014). Both Figlus et al. (2014) and Silva et al. (2016) emphasize accounting for belowground biomass in future efforts focusing on dune erosion.

**CONCLUSION:** As coastal communities experience greater pressures due to ever-expanding population, sea level rise, and a possible change in storm frequency and/or intensity, sustainable nature-based coastal protection measures are of growing interest. One of these considered features is coastal dunes, which prevent or delay flooding of inland areas by acting as a physical barrier against waves and storm surge (Hanley et al. 2014). Guidance on constructing dune systems advises planting vegetation for promoting dune growth and stabilization against windblown sand transport but does not consider the potential of vegetation to reduce dune erosion. Feagin et al. (2015) explore the physical and ecological mechanism by which this protection may be provided but emphasizes that empirical data addressing the underlying mechanisms are lacking.

Recent laboratory studies indicate that dune erosion is reduced by wooden dowels (Kobayashi et al. 2013) and when live vegetation is exposed to the collision regime (Figlus et al. 2014; Silva et al. 2016). These studies have noticeable limitations. Kobayashi et al. (2013) employed a highly simplified model of plant geometry by essentially neglecting root systems. By transplanting vegetation, Figlus et al. (2014) and Silva et al. (2016) limited root structure to the immediate potting substrate and encountered the scale-problem of real-size plants in a scaled dune. These research efforts demonstrate the level of difficulty in mimicking the aboveground and belowground structure of real vegetation, and their effects, in a laboratory setting. However, knowing whether, and to what degree, vegetation affects the dune response to storms will be invaluable as efforts are pursued to improve coastal resiliency by incorporating natural features into the coastal planning process.

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