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Going With the Flow or Against the Grain? The Promise of Vegetation for Protecting Beaches, Dunes, and Barrier Islands From Erosion

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Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion

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Coastlines have traditionally been engineered to maintain structural stability and to protect property from storm-related damage, but their ability to endure will be challenged over the next century. The use of vegetation to reduce erosion on ocean-facing mainland and barrier island shorelines – including the sand dunes and beaches on these islands – could be part of a more flexible strategy. Although there is growing enthusiasm for using vegetation for this purpose, empirical data supporting this approach are lacking. Here, we identify the potential roles of vegetation in coastal protection, including the capture of sediment, ecological succession, and the building of islands, dunes, and beaches; the development of wave-resistant soils by increasing effective grain size and sedimentary cohesion; the ability of aboveground architecture to attenuate waves and impede through-flow; the capability of roots to bind sediments subjected to wave action; and the alteration of coastline resiliency by plant structures and genetic traits. We conclude that ecological and engineering practices must be combined in order to develop a sustainable, realistic, and integrated coastal protection strategy.

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Low-elevation coastal areas (less than 10 m above sea level) cover only 2% of the world's land area. However, 10% of the world's human population lives along this border between land and sea (McGranahan *et al.* 2007). During the next century, coastal regions are projected to generate 77% of global economic output and contain two-thirds of the world's megacities (Small and Nicholls 2003; Martínez *et al.* 2007). At the same time, these regions are expected to become increasingly vulnerable to sea-level rise and extreme events such as storms (including hurricanes) and tsunamis, while also experiencing changes in flora and fauna associated with global warming and ocean acidification. Thus, human settlements will be subjected to increasing levels of erosion and flooding, damage to infrastructure and ecosystem services, and loss of life (Adger *et al.* 2005). To cope with these hazards, humans are likely to accelerate efforts to stabilize coastal areas.

In a nutshell:

- Vegetation can help to build protective dunes in coastal areas, given enough time and sediment supply
- Aboveground plant architecture can cause waves to break sooner than they otherwise would, but it is currently unknown whether or how their roots can hold dune sand together under the forces of breaking waves
- Native plants are typically adapted to being uprooted or reseeded when storms strike, rather than remaining in place
- Novel management strategies can take advantage of the effects of vegetation and erosion on coastal ecosystems
- Ecologists and engineers must collaborate on erosion prevention and infrastructure protection projects that promote a dynamic view of the coast

Past attempts at such stabilizing measures have relied upon the construction of traditional structures such as jetties and levees. Yet these kinds of protective measures alter sediment transport and accretion processes, often resulting in loss of ecosystems and ecosystem services and, consequently, negatively affecting nearby human communities (Jackson *et al.* 2013). Members of the public are becoming progressively more aware that static structures and policies do not function adequately when challenged by dynamic coastal systems that are changing even more rapidly in the 21st century due to an altered climate, and are beginning to question whether traditional structural measures are the only valid approach.

Concepts such as nature-based solutions (Hanley *et al.* 2014; Ibáñez *et al.* 2014), shelter belts or bioshields (Fosberg and Chapman 1971; Feagin *et al.* 2010a), and ecological restoration and ecological engineering (Borsje *et al.* 2011; Firth *et al.* 2014; van Wesenbeeck *et al.* 2014) are gaining more attention within the coastal management and engineering communities. In particular, there has been growing enthusiasm for the use of vegetation as protection against extreme weather events (eg Danielsen *et al.* 2005; Barbier *et al.* 2008; Tanaka *et al.* 2008; Martínez

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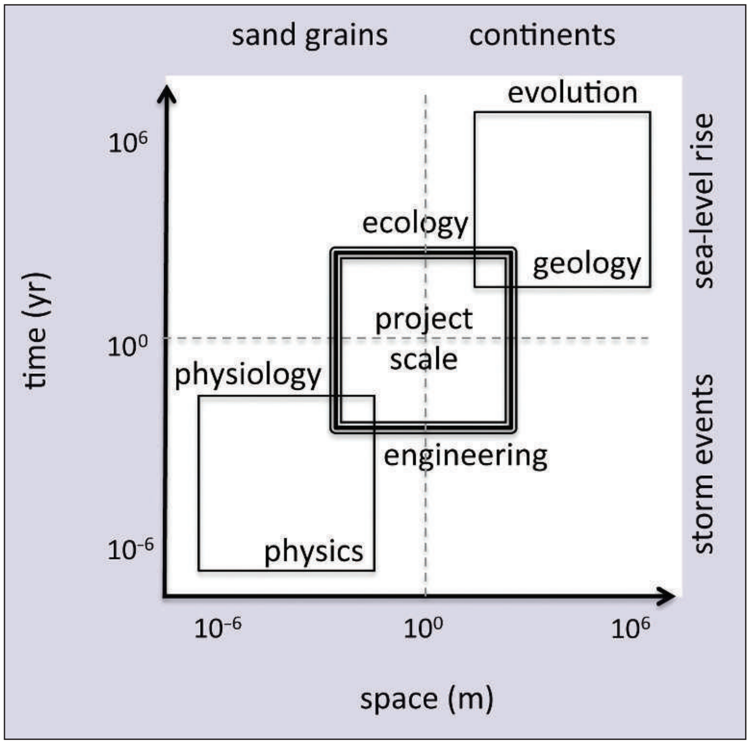

Figure 1. *Coastal processes operate at a variety of temporal and spatial scales, although people most often intervene at the project scale (where the disciplines of ecology and engineering overlap).*

et al. 2011). Nevertheless, field-based and empirical data that quantify the effectiveness of such approaches are generally lacking. Coastal managers are therefore forced to move forward with imperfect or unsupported science, and this is predominantly the case for those dealing with high-energy, ocean-facing shorelines.

In this review, our objective is to synthesize the literature on the effectiveness of vegetation in the protection of ocean-facing shorelines, such as along mainland beaches and barrier islands. We focus on the conceptual and historical bases of using vegetation for protection, and we also explore the physical and ecological mechanisms by which this protection may be provided.

Short-term versus long-term processes

Vegetation must respond to coastal processes on both short-term (seconds to days) and long-term (years to millennia) scales (Figure 1). Short-term disturbances in coastal environments are often dramatic and rapid, and are typified by nearshore scouring, shoreface erosion, flooding and flattening of dunes, barrier breaching and overwash, and deposition of sand at landward locations. Vegetation has been studied in terms of species tolerance to these disturbances as potential stressors (Maun 1994). Research on the ability of vegetation to influence geomorphic (relating to the form or surface features of the Earth) changes during a storm either has generally overlooked the specific and linked vegetative–geomorphic mechanisms that function during these events or has – in the case of laboratory experiments addressing the underlying mechanisms – been limited to the use of inanimate objects such as wooden dowels or cylindrical rods made of flexible foam to mimic plant effects. However, neither of these tactics can mimic the potentially substantial above- and belowground effects of real vegetation (eg Kobayashi *et al.* 2013).

In contrast, long-term processes, such as worldwide sea-level rise and local subsidence, continuously alter topographic elevation, nearshore bathymetry, and littoral and aeolian sediment transport dynamics. Specifically, the exposure of coastal dune vegetation to a shifting substrate has exerted a selective pressure on these plants, resulting in adaptations to burial. Among less tolerant plant species, the response has been a spatial migration by subsequent generations. The functional role of dune vegetation as a management tool for altering the topography of a landscape has been well-documented by ecologists, beginning with Cowles (1899), and it is now well known that the formation of coastal dunes is closely associated with vegetation.

Short- and long-term events act synergistically: short-term processes cause long-term processes to move along a specific trajectory, and long-term processes set the baseline conditions that short-term processes act upon. Moreover, the time and spatial scale of a physical process must match the scale that vegetation can respond to, in order for the vegetation to substantially alter or mitigate the process (Feagin *et al.* 2010b). Furthermore, coastal managers make decisions at the project scale – the spatial and temporal scales at which funding is acquired, expended, and used to physically alter the shoreline – and these decisions often involve different alternatives (leaving the shore alone, using nature-based solutions, or involving traditional engineering practices in construction) to achieve outcomes such as reducing the risk of inland flooding or minimizing changes to ecosystem functions.

In view of the interactions among physical and ecological processes, we first examine plants as modifiers of the environment before the arrival of a major storm, in order to understand the role of vegetation in forming the cross-shore profile of a high-energy shoreline. We then explore the role of vegetation as direct protection during an episodic storm event, when waves and flowing water are intersecting this profile. We close by identifying plant functional traits that enable survival during storms and evaluate post-storm recovery, when longer-term processes once again dominate.

Plants as modifiers of geomorphic features before a storm

Sand dunes can form in the absence of plants, particularly in interior and coastal deserts (Hesp 1989). However, on a sandy coast, vegetation typically increases dune height and volume when sediment supply is sufficient (Figure 2).

Plants and other material (eg wrack) act as barriers to wind flow (Durán and Moore 2013), reducing the local wind velocity behind and below the canopy surface, thereby allowing sand to accumulate. Embryonic dunes begin to grow, merge, and develop into dune ridges over longer periods of time. Emergent properties evolve beyond those of individual plants, and in this sense, plant communities and geomorphic sequences operate as complex systems (Stallins and Parker 2003).

Organisms and their interactions can shape, and are shaped by, geomorphic processes (Murray *et al.* 2008). Both the general form and the physiology of vegetation are linked with the movement of sediments. Grasses, for example, typically accumulate sediment more efficiently than do forbs or woody species because of their flexible stems, which allow them to lie flat on the ground during high winds, and the nodes on their stems from which they can grow roots after burial in sand (Gilbert and Ripley 2010). Dune-builders generally have similar responses to sand accretion, but there is geographic variation in individual species among coastal dune systems. For instance, sediment accretion actually stimulates growth in *Ammophila breviligulata* and *Uniola paniculata* in North America, and *Ammophila arenaria* in Europe, thus facilitating further sediment deposition in a dune-building feedback loop. This process is less effective in other grass species (eg *Spartina patens*) or may occur in later successional stages, where burial is not as common (eg *Andropogon* spp). Forbs and woody species are more erect than grasses and are not usually associated with dune-building in temperate climates. These types of plants are more vulnerable to damage by wind, particularly to the severe dehydration and necrosis of leaf tissue that may result from abrasion of the cuticle by wind-borne sand. Yet in tropical climates – such as on the dunes along the southern Gulf of Mexico – typical dune-building species take the form of short shrubs, in which growth is stimulated by sand burial (Martínez and Moreno-Casasola 1996).

Figure 2. *Individual ramets begin to trap sediment and add elevation (foreground), which will lead to dune formation in the presence of continued sediment supply (background). Vegetation will continuously grow and increase dune height. Matagorda Peninsula, Texas.*

As the topography of a high-energy shoreline becomes higher in elevation and more complex, new plant types arrive, each with distinctive functional traits enabling them to avoid moisture stress (eg leaf rolling, soft down or fine short hairs on the leaves and stems, succulence), withstand low nutrient availability, and develop root symbioses with vesicular–arbuscular mychorrhizal fungi (AMF; Maun 1994). AMF are crucial to the functioning of coastal dune ecosystems, improving plant drought tolerance, enhancing nutrient acquisition, and reducing salt stress. Once the landscape has been modified by dune plant species and AMF, the development of shrub thickets, maritime forests, or other climax communities can occur (Wolner *et al.* 2013).

In sum, vegetation alters the geomorphic features of high-energy shorelines, which subsequently alter the distribution patterns of wind-borne salt spray and floodwaters affecting landward locations. Vegetation creates topographic protection, given adequate time and sediment supply.

Plants as modifiers of soil stability before a storm

Coastal sand dunes form a protective barrier that erodes under storm conditions. The processes of beach erosion during intense episodes such as hurricanes have been widely studied and can be characterized reasonably well, because the sediment being transported is predominantly non-cohesive material (Silva *et al.* 2012). Although more cohesive clay soils do form beaches and dunes, their erosive properties are less well-characterized.

Gravity and intergranular friction are the only forces maintaining the profile of unvegetated dunes made of purely granular material. During a storm, wave energy is dissipated primarily through turbulence initiated by wave breaking, and the high fluid stress acts to carry along granular material, which is redistributed throughout the nearshore zone. Assuming equal densities, coarse grains are more difficult to mobilize than fine grains because of their greater mass.

Plants can alter the physical properties of a dune in two distinct ways: with their root network and by altering the composition of the sediment itself (Figure 3; the role of individual roots will be discussed in the next section). A plant community can add organic matter (including humic material) directly to the soil and also increase its clay content by trapping relatively fine inorganic sedimentary particles. These two processes can reduce erosion over the long term by increasing particle cohesion (Wischmeier and Smith 1978; Feagin *et al.* 2009). Plants also reduce soil desiccation by generating shaded microclimates, and soil moisture generally increases particle cohesion (Pollen *et al.* 2004) with variable effects on erosion (Bendoni *et al.* 2014).

Moreover, AMF play an active role in soil aggregation and erosion control. Increased soil stability has been attrib-

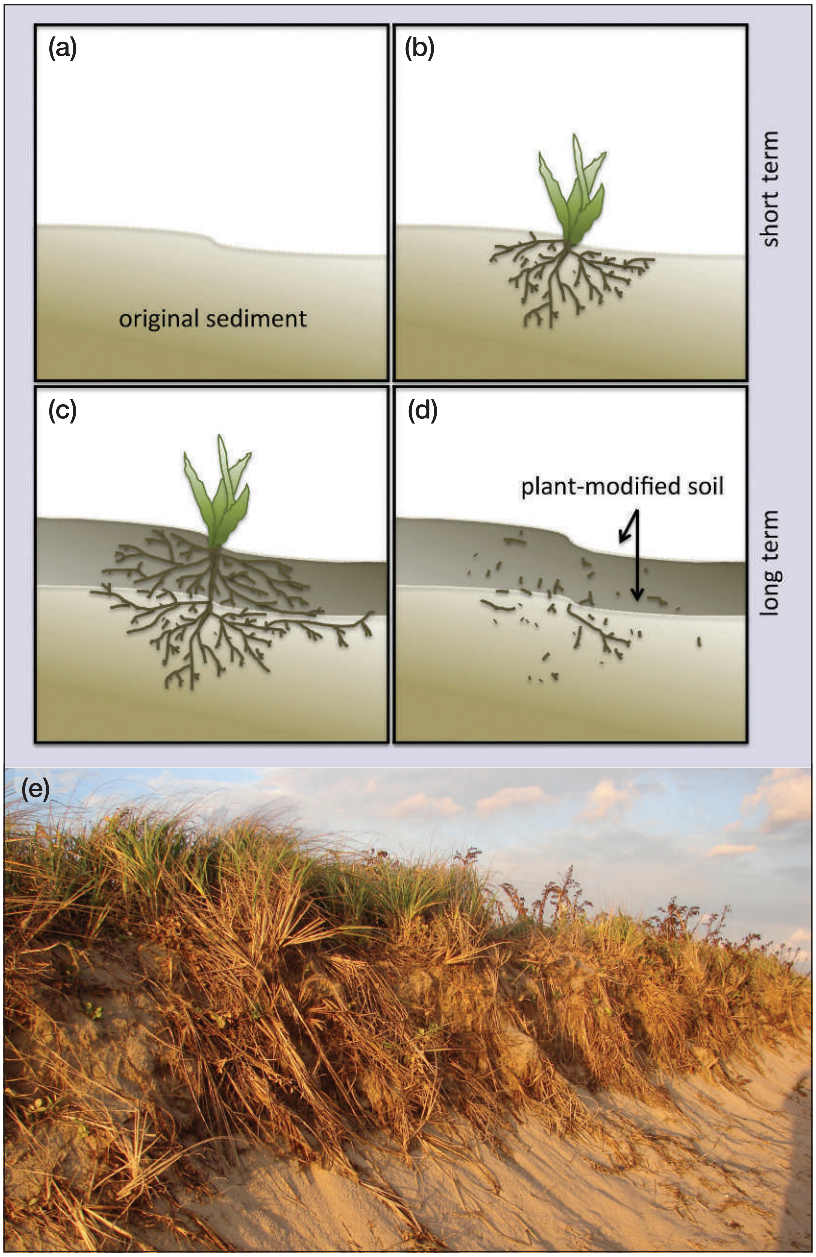

Figure 3. *Plants alter the physical structure of the sediment with their roots in an immediate sense and also by "re-engineering" sediment properties over time. Possible states, or experimental units for research, include: (a) original sediment only, (b) original sediment and plant roots, (c) plant-modified sediment and plant roots, and (d) plant-modified sediment only. (e) Cross section of a dune near Matunuck, Rhode Island, exhibiting aboveground portions, belowground roots, and two different soil structures.*

uted to the secretion of water-stable adhesive compounds and the physical entanglement of soil particles by AMF hyphae, which bind fine grains into larger assemblages (Figure 4; Daynes *et al.* 2013; Sigren *et al.* 2014). The formation of larger soil aggregates effectively increases erosion resistance because coarser, heavier particles are more difficult to mobilize. The presence of AMF on plants has been shown to reduce erosion from wind and rain in sandy soils (Burri *et al.* 2011), but their impact on wave-induced erosion on high-energy shorelines has not been studied.

Plant-induced sedimentary changes can increase grain-to-grain cohesion and transform a dune from a collection of individual grains to a larger mass of grains, bound together, increasing the effective grain diameter and thus reducing erosion. Moreover, resistance to soil shearing should increase and, in a storm impact regime, the binding forces should reduce slumping after scarp formation.

■ Plants as structures that alter hydrodynamics during a storm

Both above- and belowground plant structures likely alter wave energy and flow during storms. When a storm hits, the impact regime (the type of erosion at a specific location along the beach-dune gradient) determines the portions of plant structures that are reached by the waves (Figure 5). Possible scenarios include wave collision, overwash, and inundation (Sallenger 2000), which are based on relative water levels (surge and wave runup) with respect to the beach, dune, or barrier height. In the collision regime, waves break and exert their energy on the dune face. Large amounts of sediment can be mobilized and redistributed along the beach profile and a prominent dune scarp may continuously progress landward. The overwash regime entails intermittent wave overtopping of the dune crest, which may lead to rapid crest erosion that alters both the seaward and landward sides of the dune (Figlus *et al.* 2011). During the inundation regime, dunes are eroded via a constant flow of water over the crest, with erosion mostly occurring on the landward face.

The limited amount of empirical research on this topic for high-energy shorelines clearly indicates that erosion is reduced when using dowels (Kobayashi *et al.* 2010, 2013) or when vegetation is placed in wave flumes under collision regimes (Odériz Martínez *et al.* 2014). Nonetheless, the specific mechanisms (above- versus belowground structures, uprooting versus scour versus attenuation, etc) that alter the hydrodynamics or sediment transport have not been defined; we must therefore extrapolate from other landforms where work has been conducted (riverine slopes, herbaceous salt marshes) in order to create a hypothesized understanding of their protective role. Still, in contrast to these other landforms, beaches, dunes, and barrier island ridges are unique in that they have coarse and granular sands, as well as steep substrate slopes maintained by gravity (when not vegetated), and in that they are affected only when wave energy and water levels are extreme, during storms.

Aboveground plant structures alter hydrodynamic forces, although this finding has been limited to seagrasses and wetland plants that are fully or partially submerged, and to flat surfaces with fine, cohesive sediment (eg Blackmar *et al.* 2014). Aboveground portions of plants add surface roughness to the landscape, increasing the friction encountered by water particles (Nepf and Koch 1999). Stems and leaves alter turbulence and flow patterns, and therefore patterns of scouring, erosion, and sediment accretion (Bouma *et al.* 2008). Enhanced friction reduces the wave energy that would otherwise propagate landward, although it can also cause waves to break farther seaward. Such plant-induced wave transformation is dependent on such factors as wave height, period, and speed; water level (Möller and Spencer 2002); and vegetative architecture (Tanaka *et al.* 2008), density, and width (Koch *et al.* 2009). In wetlands, wave attenuation and enhancement processes occur at the scale of an individual plant, with cumulative effects potentially influencing broad areas of coast during large storm surges (Sheng *et al.* 2012; Zhang *et al.* 2012; Lapetina and Sheng 2014). This capacity to attenuate wave energy may be reduced when the cross-shore width or height of an ecosystem is altered due to human settlement, particularly in the case of dunes. However, it is not clear whether this effect is largely attributable to the change in plant architecture or geomorphic structure (Feagin *et al.* 2010b).

Flexible aboveground structures that bend easily with the water flow do not dissipate as much energy as rigid structures, given the same surface area (Feagin *et al.* 2011), yet the flexible portions also transfer less energy down the stem shaft and into the roots. Depending on the vegetation density and rigidity or stiffness of the connection between above- and belowground components, the energy transferred may lead to plant uprooting and an increase in erosion. Conversely, exposed root systems may also provide additional hydrodynamic resistance and energy dissipation if portions of the root system are still anchored (eg clonal species in particular), although this represents change for the root system from belowground to aboveground. Kobayashi *et al.* (2013) identified both cases in the same system, demonstrating that above- and belowground components need to be considered together.

Terrestrial belowground root structures may increase soil cohesion through their tensile strength and their ability to create suction through a water pressure gradient (Wu 2013), but this evidence has been restricted to studies on cohesive sediment. While much of the research on roots and erosion has been conducted in the context of shallow landslides and slope stability analyses (Schmidt *et al.* 2001), and because the marine literature has focused primarily on boundary layer hydraulics (Houwing 1999), riverbanks and salt marshes may provide the best analogs for high-energy (ocean-facing) coasts.

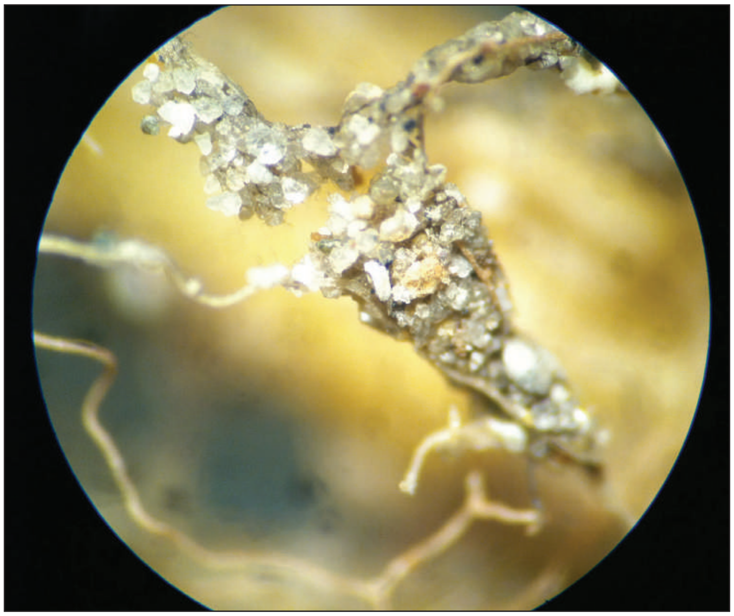

Figure 4. *Binding of sand grains by vesicular–arbuscular mychorrhizal fungi, surrounding the roots of* Sporobolus virginicus *(magnified at ×45). After Sigren* et al. *(2014).*

For riverbanks, the ability of roots to provide reinforce-

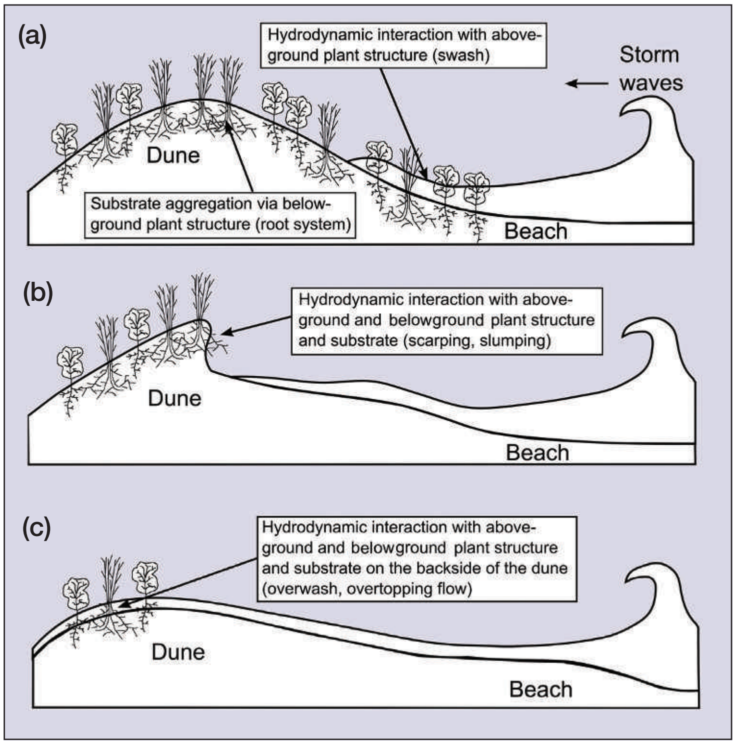

Figure 5. *Above- and belowground plant–substrate–wave interaction scenarios during storms: (a) swash interaction, (b) dune scarping/slumping during collision regime, and (c) overwash and inundation regimes. While the flow direction in (a) and (b) reverses between uprush and downrush, the flow during (c) is unidirectional.*

ment is dependent on the soil shear strength and bulk density (Pollen *et al.* 2004), both of which would be much different in a soil composed of sand grains. For salt marshes in areas with highly cohesive sediments, the roots of salt-marsh plants have little to no effect on erosion under wave action (Feagin *et al.* 2009) and while over sufficient time these roots reduce the frequency of smaller erosion events, they also increase the magnitude of larger erosion events (Francalanci *et al.* 2013). The larger, albeit less frequent, episodes of mass failure of a riverbank are a result of the roots binding sediment until aggregated root clumps break off.

For high-energy shorelines, the applicability of traditional vegetation–geotechnical models will likely be limited, particularly given the granularity of the sandy sediment. An additional aspect to consider is that many beach and dune plants rely on the uprooting of their rhizomes for dispersal, although the importance of this physiological trait for erosion has not been examined. Exploration of these topics must begin with empirical studies.

■ Plants as modifiers of recovery after a storm

The unique set of functional traits of each plant species affects the mode of recovery from extreme events (MacGillivray *et al.* 1995), and therefore influences the long-term resiliency of the dune-building process. Dispersal by early successional plant species – often annuals in temperate latitudes, but usually perennials in the tropics – allows re-colonization of bare areas through the spread of seeds and rhizomes that can withstand saline conditions (Gornish and Miller 2010). Such species are tolerant to disturbances and often spread to new areas after a storm. Annual plants, such as the endangered *Amaranthus pumilus*, require a lack of substrate stability to maintain their niche, and travel long distances to these locations through dispersal of their small seeds. Many perennial beach and dune plants, such as *U paniculata*, *Panicum amarum*, or *Leymus mollis*, respond to extreme events by uprooting and spreading via rhizomes and nodes; the seeds of both the Western Gulf variety of *U paniculata* and *P amarum* are not viable, and yet these species persist and dominate dune tops as a result of this trait (Feagin 2013). In the tropics, *Cakile lanceolata* seeds are adapted to being carried on ocean currents, and the pan-tropical creepers *Canavalia rosea* and *Ipomoea pes-caprae* are also widely dispersed by ocean currents (Devall 1992; Mendoza-González *et al.* 2014). In general, the growth of coastal dune psammophytes (plants that thrive in sandy habitats) at all latitudes is stimulated by disturbance events, such as burial in sand (Maun 1994). That is, disturbance as a result of an extreme event is not a threat to most native dune species, but rather a chance to extend their distribution.

Notably, since the nineteenth century, stiff and tall plant structures, typically woody species not adapted to the dynamism of coastal ecosystems, have been selected and introduced specifically for the purpose of stabilizing sandy substrates, attenuating waves, and reducing water-flow speeds (Feagin *et al.* 2010a). Both *Tamarix gallica* and *Casuarina equisetifolia* were introduced by coastal managers in many areas to provide a hard protective structure that was assumed to be better than the herbaceous species they replaced on beaches and sand dunes. Yet in the case of *C equisetifolia* in India, sedimentary accretion and elevation were reduced, and critical habitat for many animals (eg nesting sea turtles) was lost (Mukherjee *et al.* 2010).

Similarly, the introduced, herbaceous *A arenaria* (or *A breviligulata*, depending on location) re-engineered formerly low, hummocky dunes dominated by *U paniculata* into taller, ridge-like dunes that subsequently reduced overwash and landscape diversity, through the use of a guerilla (spreading across larger distances) versus phalanx (clumping within a given spot) root-binding strategy (Stallins and Parker 2003). Over decades, a monoculture of the invader species can emerge, altering the topography, reducing habitat diversity, and leaving the ecosystem less resilient to disturbance (Seabloom and Wiedemann 1994; Hertling and Lubke 2000).

In spite of the above results, research has not fully addressed how woody versus herbaceous species differen-

Table 1. Management considerations for the use of vegetation species as protection on high-energy shorelines

Choose plants as modifiers of geomorphic features based on their ability to:
- Accrete sand/build elevation
- Develop high dunes versus low hummocks
- Fit within a heterogeneous array of different successional stages, with effects on landscape form

Choose plants as modifiers of soil stability based on their ability to:
- Add soil organic matter and increase water content, reduce soil bulk density
- Promote mycorrhizae, increase effective grain size of non-cohesive particles
- Promote clay and cohesive particle accumulation
- Incorporate layering of algal and other beach wrack

Choose plants as structures that alter storm hydrodynamics based on their ability to:
- Attenuate waves and alter water velocities according to: stem height, diameter, flexibility; leaf area; overall plant architecture; aboveground biomass
- Reinforce, abrade, or loosen soils according to: root diameter, configuration, and density; belowground biomass; aboveground-to-belowground biomass ratio

Choose plants as modifiers of storm recovery based on their ability to:
- Physiologically respond to storm erosion according to: damages to plant structures or compensatory stimulation of growth; sexual (seeding) versus asexual (uprooting of rhizomes) modes of reproductive spread
- Provide protection for humans via their physiognomic form; potential to also become invasive, alter habitat diversity, and increase or decrease long-term ecosystem resilience

tially accumulate sand, and whether generalizations can be made regarding their protective role with regard to erosion. Moreover, the scientific community has yet to identify whether the roots of any species of coastal plant respond physiologically to sediment removal (as opposed to sediment addition).

Table 2. Dichotomies in coastal management

	Timescale	
	Short (seconds to days)	*Long (years to decades)*
Phenomena to manage	Extreme events	Sea-level change
Human desire	Stability	Dynamism
Physical process	Wind and wave erosion	Littoral/aeolian transport, accretion
Biological process	Structure (friction, cohesion)	Function (succession, dispersal)
Management goal	Resistant	Resilient
Project implementation	Hard solution	Soft solution

Conclusion

Novel management strategies can take advantage of the interactions between vegetation and physical erosion processes, but they will need to be tailored to realistic scales of action. Ecologists must listen carefully to local citizens, real estate agents, homeowners associations, and politicians, as they are the stakeholders and decision makers for the majority of coastal lands. The decisions made by these stakeholders are most often made based on political and economic considerations, and are exercised at the scale of individual parcels of land. Managers typically have project action plans that extend only one to a few years into the future, with the implementation of these actions occurring on parcels that range in size from several meters to several thousand meters. The good news is that when ecologists can guide specific management actions (Table 1), vegetation can be used to control sediments at these spatial and temporal scales.

The resilience of managed coastal systems and their resistance to disturbance will be stretched to new limits over the next century. In the past, coastlines have traditionally been managed for resistance (structural stability) rather than for resilience (functional dynamism), with fear of extreme events being weighted over the importance of maintaining long-term sustainability (Table 2). Accordingly, when implementing coastal projects, some low-cost, nature-based solutions such as planting vegetation have been ignored, in favor of more expensive, hard-structure solutions. To maximize sustainability, coastal ecologists and engineers must find a better balance between human needs and natural system requirements, and work together to develop a comprehensive strategy for integrated coastal protection.

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