Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats

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Much of America's coastline is threatened by overdevelopment and coastal erosion, driven by global sea-level rise, a problem that is attracting the attention of researchers around the world. Although we have now acknowledged the impending risks, little is known about the response of spatially dependent dune plant communities to the loss or restriction of their habitat. In order to study this development, a spatially explicit model of sand dune plant succession on Galveston Island, Texas, was created, using sea-level rise as the primary mechanism causing local erosion. Simulations of sea-level rise scenarios developed by the Intergovernmental Panel on Climate Change demonstrated that beach erosion constrained plants to a narrow area, resulting in a breakdown of the successional process. The loss of late-succession plants along coastlines, their dependent faunal species, and possible solutions are discussed. This model and example serves as a harbinger of the future for many of the US's sandy beaches and coastal communities.

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Coastal erosion is a problem common to shorelines around the world, impacting about 70% of the Earth's sandy beach environments (Bird 1985). The causes of erosion can be of local (eg a decrease in sediment supply) or global importance (eg a worldwide change in sea level). Beach erosion in a sediment-rich environment will result in a landward displacement of coastal environments (including dunes; Martinez and Psuty 2004) as long as there are no barriers (eg cliffs) to restrict such migration. Where there are barriers, including those commonly introduced by human activities (Nordstrom 2004), erosion reduces the area available for plant and animal communities (Feagin 2005). In some places, coastal development confines the natural community to such a narrow stretch of beach that plants are no longer able to disperse or grow.

In order to study this development, a spatially explicit model of species dynamics within a sand dune plant community on Galveston Island, Texas, was created. Average rates of shoreline loss on Galveston Island exceed several meters per year. Local processes such as subsidence and reduced along-shore sediment transport have contributed to historic coastal retreat in this region (Morton *et al.* 2004), although current subsidence rates are minimal (USGS 2002). Erosion rates are already accelerating as a result of sea-level rise (Holgate and Woodworth 2004) induced by atmospheric warming (Titus *et al.* 1991; Twilley *et al.* 2001), a problem of global dimensions (IPCC 2001). Galveston Island is an ideal site for the study of accelerated erosion rates, as it has historically attained the relative sea-level rise rates that are expected to affect much of the receding coastlines of the US over the next century.

The Gulf Coast of the city of Galveston is protected from storm surge by a seawall (Figure 1a) constructed in response to the damage caused by a 1900 hurricane that still stands as the US's worst natural disaster (Pilkey and Frasier 2003). Although the seawall and the groins that front it protect the properties immediately landward, these structures have caused greater down-drift erosion by disrupting the natural sediment transport system, resulting in the need for other shoreline protection measures such as geotextile tubes (Figure 1b). Along most of Galveston Island, extensive development and the presence of non-native lawn vegetation behind the beach presents a landward barrier that blocks the migration of native habitat (Figure 1c).

Although it is recognized that continued erosion restricts the plant community's habitat within a narrow zone, it is not yet understood what the ecological ramifications to the plant community may be in terms of successional dynamics among species and functional groups. Moreover, there has been little research on the impact of a narrowing habitat upon community pattern formation in plant succession in general. Because of the impending habitat loss of dune plant communities in this area, this issue is ideally suited to investigation through simulation modeling.

Methods

Study area

A detailed description of the study area and baseline model, minus the sea-level parameters, can be found in Feagin *et al.* (2005). The sand dune plant community, upon which the model was based, was contained in a research plot (Figure

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Figure 1. *Four views of the rapidly eroding sand dune plant habitat on Galveston Island, Texas. (a) Transitory dunes in front of the seawall, just visible beyond the lip of the wall; (b) habitat in front of geotextile tubes during a natural storm event (here, Hurricane Lily, the eye of which passed over Louisiana, 400 km to the east); and (c) the maintenance of non-native lawn vegetation, leaving a tenuous 2 m strip of habitat. (d) Under natural circumstances, the native plant community in the research plot can "move" with the dunes and the back-and-forth migration of the beach.*

1d) adjacent to Pirates Beach on Galveston Island, at latitude 29.21 and longitude –94.92. The climate at this location is subtropical, characterized by hot summers and mild winters. The community extends along a 50 m beach–sand dune gradient, stretching from the summer berm on the open beach to the edge of the upland/coastal prairie community behind the dune ridge. The sand dune plant community, depicted in Figure 1d, can be described in terms of its three successional stages: colonizers, soil binders, and competitors. Multiple years of plant succession in this community have been documented since 1998, when Tropical Storm Francis destroyed the plant cover and subsurface growth, removing the soil and leaving only bare sand. The model was calibrated based on spatial patterns observed over a 5-year period at this location, with the beach accreting at an average rate and growing conditions that were typical for the subtropical, humid coastal dunes of Texas.

Baseline model description

The sand dune plant community was modeled using two-dimensional cellular automata, and written and implemented in Mathematica (Wolfram 1996). A two-dimensional lattice, composed of 100 x 100 individual sites, was created. Each site represented a 0.5 x 0.5 m (0.25 m^2) quadrat in the research plot. The top of the lattice represented the landward boundary of the sand dune plant community while the bottom of the lattice represented the seaward boundary.

Each site had four possible states, consisting of bareground (0), colonizer plants (1), soil binder plants (2), or competitive plants (3). Because sand dune succession is based on facilitation by adjacent plants, as well as the amelioration of environmental constraints by previous successional stages, each state represented one step in the successional sequence. For example, a site could start as bareground and move through the three subsequent successional stages if an adequate number of other plants were growing in adjacent locations. The relative effect of a site upon an adjacent site, through facilitation, was based on proximity, as detailed in Feagin *et al.* (2005).

During each time step, all sites were simultaneously updated based on the adjacent sites, with time steps representing 6 months. The model was run for a total of

6 years, as this is the frequency of catastrophic disturbances expected at the research site (Morton *et al.* 1983). Such disturbances often result in the retrogressing of the site back to its initial bareground state.

An environmental stress gradient was also constructed, where stress values (–1) were distributed along the gradient, with 100% of the sites undergoing stress at the seaward edge and 0% at the landward edge. Sites could retrogress to earlier stages of succession if the summation of adjacent sites was reduced by adding stress. The baseline model produced plant patterns which approximated the research plot data, as described in Feagin *et al.* (2005).

Sea-level rise calculations

One estimate for the global rate of sea-level rise is around 0.20 cm yr^{-1} over the past 100 years. However, the historical local rate may differ greatly as the relative rise is a function of several components, including eustatic (eg global sea-level rise due to deglaciation, or thermal expansion of water at higher temperatures), isostatic (eg land elevation changes caused by plate tectonics, or rebound of land after deglaciation), and subsidence effects (caused by withdrawal of water, oil, and gas, or compaction of sediments; Douglas 1991). The local rate of relative rise at the research plot was 0.65 cm yr^{-1} between 1909 and 1999, as recorded by the Galveston tide gauge (Permanent Service for Mean Sea Level; www.pole.ac.uk/psmsl). During most of this period, the area experienced dramatic land subsidence, at a rate of 0.32 cm yr^{-1}, due to oil and groundwater extraction (USGS 2002; www.hg.subsidence.org). If we subtract 0.32 from 0.65, this yields 0.33 cm yr^{-1} as the rate of eustatic rise at the research plot. This number exceeds the global eustatic rate, but there are two possible explanations for this: (1) thermal expansion in the warm Gulf of Mexico (Miller and Douglas 2004), which agrees quite well with Leatherman's (1984) calculations for this area, and/or (2) a slight, natural isostatic change at a much larger regional scale than that of the USGS (2002) data.

Sea-level rise is a dominant force driving widespread coastal erosion (Leatherman *et al.* 2000; Zhang *et al.* 2004). Since the terrain of the Gulf Coast is quite flat, a small rise in water level can result in a severe loss of land. Historical erosion rates exceed 3.3 m yr^{-1} at the research plot location (Gibeaut *et al.* 2003; www.beg.utexas.edu/coastal/hazard_atlas1.htm). If we partition this erosion rate into a linear function of its known subsidence and eustatic components, then 1.68 m yr^{-1} of this erosion was due to eustatic rise.

To simulate the impacts of sea-level rise on coastal retreat, we extrapolated the historical erosion rate into the future, and assumed that the Bruun Rule (essentially a ratio of the sea level rise rate, a, to the profile migration, or erosion, rate, s) provides a reasonable first approximation of cross-shore profile response of water-level change (Leatherman *et al.* 2000; Zhang *et al.* 2004). We then projected future sea-level rise scenarios and their impacts upon coastal erosion rates at specific locations.

However, the Bruun Rule could not be used independently, as it does not accommodate alongshore variability in profile response (eg Stive 2004). To address this variability, we used historical erosion rate data, available in a spatially explicit layer at 50 m increments in the longshore direction (Gibeaut *et al.* 2003), and the historical eustatic rise rate from the tidal gauge data, and applied the Bruun Rule every 50 m along the beach in order to derive the profile response ratio. We then assumed that the ratio represented a constant function describing the cross-shore equilibrium profile at each location, and back-calculated the expected erosion rate for the projected sea-level rise scenarios.

For example, the historical data yields:

$$\frac{s}{a} = \frac{1.68\ \text{m yr}^{-1}}{0.0033\ \text{m yr}^{-1}} = 509$$

as the ratio at our research plot, the value that we then used for simulations at the plot site. If we assume eustatic sea-level rises at 1.00 cm yr^{-1}, then we calculate:

$$\frac{s}{a} = \frac{x}{0.01\ \text{m yr}^{-1}} = 509$$

with the projected erosion rate at that spatial location as $x = 5.09$ m yr^{-1}. We repeated this calculation every 50 m in the longshore direction, using the local values for the Bruun ratio.

This method assumes that the rate and direction of longshore sediment transport does not change when the sea-level rises, yet it accounts for morphologically different cross-shore profiles at spatial locations in the longshore direction. Our method assumes sediment transport in the erosion term, s, by using the Gibeaut *et al.* (2003) dataset at each longshore location. As a reasonable first approximation in our model, the proportion of s that could be due to a negative or positive sediment transport term (often known as q in coastal engineering literature) will proportionately change with the rise, a, based on the empirically derived relationship at each spatial location separately. Another assumption is that sediment particle sizes remain constant, also subsumed in the relatively high Bruun rule ratios that can be found on Galveston's high clay content beaches. The method also assumes that the cause of historical, long-term erosion is sea-level rise, with beach profiles recovering from transitory storm effects; this accords with the most recent evidence (Zhang *et al.* 2002).

Simulations

Simulations expanded upon the baseline model by (1) testing hypotheses about plant community response to erosion induced by climate change, and (2) adding new parameters

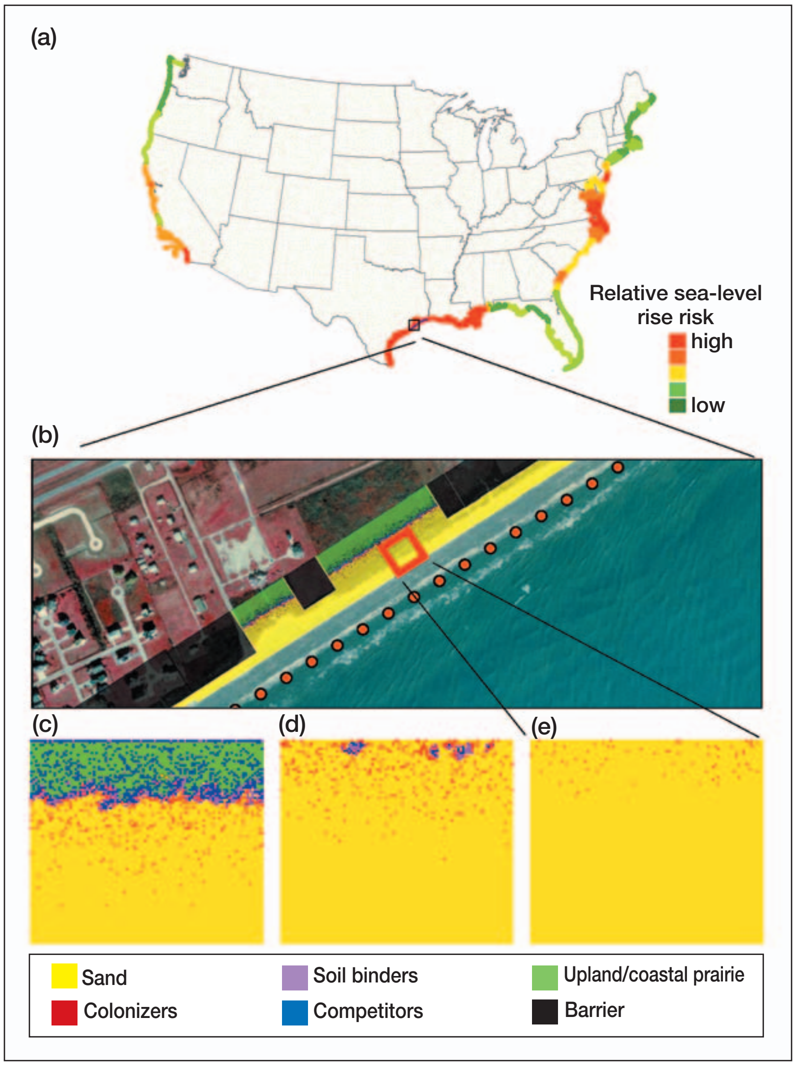

Figure 2. *Sea-level rise, the risks, and impacts to the sand dune plant community at multiple scales. (a) The risk of relative sea-level rise at the scale of the continental US (adapted source data from Thieler and Hammar-Klose 2000). At the Galveston Island landscape scale (b), the model was run and geo-referenced within a GIS. Here, we show the results for the most accelerated rate of sea-level rise, with the circles representing the spatial locations mentioned in the text. At the plant community scale, simulations were executed under the three IPCC scenarios: the (c) low, (d) moderate, and (e) high rise scenarios. Plant community scale maps have the ocean at the bottom, a barrier at the top, and are 35 x 35 m.*

to the model to incorporate longshore morphological characteristics at a broader scale with the help of a Geographic Information System (GIS). Simulations tested the effect of sea-level rise on the plant patterns by moving the stress gradient in the landward direction along the cross-shore profile. The rate at which the rising sea, and the associated stress gradient, moved landward was represented in three well-known Intergovernmental Panel on Climate Change simulation scenarios (IPCC 2001): a low rise scenario (0.09 m by 2100), a moderate rise scenario (0.48 m by 2100), and a high rise scenario (0.88 m by 2100). We modeled each scenario according to the method outlined in the previous section.

Several changes were also made to facilitate investigations into plant community responses to longshore morphology. First, the scale of inquiry was broadened and 1500 x 100 m strips were demarcated along the coastline on an aerial photograph within a geographic information system (GIS). A grid was created, showing locations where dune growth was restricted by barriers such seawalls, geotextile tubes, manicured lawn vegetation, or housing developments. The grid was then fed into the model and run as a 3000 x 200 site lattice, with each site representing 0.5 x 0.5 m in the GIS. The historical erosion rate data were also fed into the model with values explicitly known at 50 m increments in the longshore direction. In addition to the previous four states (0, 1, 2, 3), sites could now also be categorized as an upland plant community (4) or a barrier to dune development (5). Model output was then geo-referenced within the GIS, producing maps that detailed plant community responses to the much broader-scaled phenomena of longshore coastal morphology.

Results and discussion

Coastal erosion due to sea-level rise, in concert with human-erected barriers, confined simulated plants to a small zone at the rear of the research plot, altering the sand dune plant community's characteristic patterns. Although littoral drift, sediment dynamics, and beach composition may differentially affect the risks to sand dune habitat at a continental scale (Figure 2a), the landscape-scale GIS output demonstrates little deviation in the plant community's development as a result of the longshore morphology response to sea-level rise, for 50 m increments (Figure 2b). Yet the spatial limitations enforced by the barriers led to a differential placement of the community in the longshore direction, leaving some areas completely barren of dune habitat and others with remnant dune populations.

Strong differences in community pattern development resulted in the cross-shore direction under the three IPCC scenarios. The low rise scenario (Figure 2c) allowed the plant community to develop fully in 5 years within the research plot area. Dunes were covered by all stages of succession, including coastal prairie and upland plants.

Under the moderate rise scenario (Figure 2d), plants did not grow in the lower section of the gradient due to high stress levels. There was a random distribution of colonizers across the mid-section of the gradient, yet the community did not develop further due to the high level of stress and the lack of permanence in the distribution of the annual colonizers. In the upper section of the gradient, only a few embryonic dunes had formed, around which the later successional species could coalesce. In these areas, the plant distribution was not random, as each successional stage depended on prior amelioration of the location by the colonizers in order to survive.

The high rise scenario resulted in a complete breakdown of the successional process, as only colonizers were randomly distributed and located in the upper section of the gradient in the research plot area (Figure 2e). The random distribution of the annual colonizers, their ephemeral nature, and their restriction to the thin strip of habitat did not provide the ameliorative force (eg windblocks, islands of fertility, elevated dune structures) that was needed for the community to progress to advanced stages of succession. In terms of the spatial and temporal mechanics of any one focal site, the summation of its adjacent positively valued sites (facilitative plants) and its adjacent negatively valued sites (stress) produced a number that did not exceed the threshold for its graduation to the next stage of succession. Without strong and spatially explicit facilitation to counterbalance the stress induced by sea-level rise, each adjacent site had no lasting temporal effect upon this focal site. The successional process became decoupled; the dynamics within the sites at the upper part of the gradient became spatially isolated and temporally ephemeral. In the lower part of the gradient, it was impossible for even the colonizers to survive the stress.

The model produced graphical output which matched quite well with what has already been seen along the Gulf Coast (Figures 1a–c) and the East Coast of the US (Roman and Nordstrom 1988); late-succession sand dune species are being lost because embryonic dunes are not able to form in front of the barriers (Gibeaut *et al.* 2003), leaving isolated "islands" of plant communities (Figure 2b) that are spatially removed from other communities, sometimes by considerable distances.

In the short term, money and time must be spent to restore these communities. In many cases, late-succession species such as beach panic (*Panicum amarum*) have very low rates of seed viability, and must therefore be planted during restoration efforts in order for them to appear (Feagin 2005). The loss of such species is already occurring on Galveston Island, where sea oats (*Uniola paniculata*) has disappeared due to a combination of human-induced disturbance and climate change (Greipsson 2002). In the long term, it may be critical to maintain propagule dispersal sites with planning done at a landscape scale in order to maintain populations along the East Coast of the US and in areas of large-scale development, even for early succession species such as the endangered sea-beach amaranth (*Amaranthus pumilus*).

The maintenance of the late-succession species is critical, as they are usually the most important species in the building of dunes, binding of sediments, and reduction of erosion. Moreover, these perennial species provide cover on the dunes throughout the year; if lost, erosion rates are certain to increase. Dependent animal species, such as the endangered Kemp's ridley sea turtle (*Lepidochelys kempii*) and the endangered Choctawatchee beach mouse (*Peromyscus polionotus*), will be lost without them. Although our simulations are restricted to the conditions at Galveston Island, the basis for the model suggests that similar scenarios, with different retreat rates, will occur in the near future, in most dune systems along developed coastlines experiencing sea-level transgression.

Considerable planning needs to be done in order to decide how we want our coasts to look, as well as to preserve the species that inhabit them. A small increase in sea-level rise can result in a large amount of coastal erosion. It may soon be necessary to reassess the importance of sand dune plant communities, in the same way that coastal wetlands were re-evaluated by the last generation of coastal zone statutes and laws. As it is our duty to maintain these coastal plant communities alongside our private developments and shoreline protection structures, we must publicly consider the impacts of squeezing the sand dune plant habitat between the land and the sea.

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