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Invasive grasses, climate change, and exposure to storm-wave overtopping in coastal dune ecosystems

ERIC W. SEABLOOM*, PETER RUGGIERO†, SALLY D. HACKER‡, JEREMY MULL§ and PHOEBE ZARNETSKE‡

*Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul, MN 55108, USA, †College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331-2914, USA, ‡Department of Zoology, Oregon State University, Corvallis, OR 97331-2914, USA, §AECOM, Long Beach, CA 90810, USA

Abstract

The world's coastal habitats are critical to human well-being, but are also highly sensitive to human habitat alterations and climate change. In particular, global climate is increasing sea levels and potentially altering storm intensities, which may result in increased risk of flooding in coastal areas. In the Pacific Northwest (USA), coastal dunes that protect the coast from flooding are largely the product of a grass introduced from Europe over a century ago (*Ammophila arenaria*). An introduced congener (*A. breviligulata*) is displacing *A. arenaria* and reducing dune height. Here we quantify the relative exposure to storm-wave induced dune overtopping posed by the *A. breviligulata* invasion in the face of projected multi-decadal changes in sea level and storm intensity. In our models, altered storm intensity was the largest driver of overtopping extent, however the invasion by *A. breviligulata* tripled the number of areas vulnerable to overtopping and posed a fourfold larger exposure than sea-level rise over multi-decadal time scales. Our work demonstrates the importance of a transdisciplinary approach that draws on insights from ecology, geomorphology, and civil engineering to assess the vulnerability of ecosystem services in light of global change.

Keywords: *Ammophila*, climate change, coastal dune, coastal protection, ecosystem service, invasion, sea-level rise

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Introduction

Coastal habitats provide critical ecosystem services for humans as arbiters of resources between the land and ocean (Barbier *et al.*, 2011); in the U.S. alone, 30% of new jobs are generated in coastal counties, 90% of foreign trade passes through ports, and 33% of gross national product is produced in the coastal zone (National Research Council, 1999). More foreign tourists visit U.S. beaches than all national parks combined, and 90% of the dollars generated are spent in coastal states (National Research Council, 1999). Climate change can negatively affect coastal areas through accelerating sea-level rise and associated risk of flooding during intense marine storms (Bindoff *et al.*, 2007; Barbier *et al.*, 2011). These changes combined with population pressures place coastal ecosystems on the front lines of economic and societal impacts from climate change (Barbier *et al.*, 2011). The aftermath of recent hurricanes and the loss of coastal communities due to sea-level rise illustrate the sensitivity of coastal habitats and the importance of understanding the interaction between climate change and human impacts on these ecosystems (Barbier *et al.*, 2011).

Correspondence: Eric W. Seabloom, tel. +612 624 3406, fax +612 624 6777, e-mail: seabloom@umn.edu

Exposure to flood hazards during extreme marine events can be exacerbated by human degradation of marine-terrestrial interface habitats (Barbier *et al.*, 2008). Coastal dunes in the Pacific Northwest region of the USA (PNW) are an excellent example of how human activities can alter vulnerability to flooding. Dunes comprise 45% of the PNW coastline (Cooper, 1958). Historically, these dunes were managed to maintain dune stability through the planting of *Ammophila arenaria* (European beach grass). The switch in dominance from native to exotic dune grass species resulted in ecosystem state changes. Native dune plants formed small hillocks or short parallel ridges depending on sand supply, while the introduced *A. arenaria* facilitated the creation of foredunes, up to 20 meter tall ridges of sand parallel to the shoreline (Cooper, 1958; Hacker *et al.*, 2012). While these foredunes may provide coastal protection services, an unintended consequence of the *Ammophila* invasion is the displacement of native dune species along the Pacific coast including the federally–threatened Western snowy plover (Zarnetske *et al.*, 2010).

Management of coastal dunes in the PNW has been further complicated by the invasion of a second exotic grass from the U.S. Atlantic coast and Great Lakes region, *A. breviligulata* (American beach grass). *A. breviligulata* has displaced *A. arenaria* throughout

Washington and continues to spread south along the Oregon coast (Seabloom & Wiedemann, 1994; Hacker *et al.*, 2012). Foredunes dominated by *A. breviligulata* are lower than foredunes dominated by *A. arenaria* due to the inferior ability of *A. breviligulata* to accumulate sand (Seabloom & Wiedemann, 1994; Hacker *et al.*, 2012; Zarnetske *et al.*, 2012). Given that *A. breviligulata* has viable populations in southern California (Jepson & Hickman, 1993), that it continues to displace *A. arenaria* (Seabloom & Wiedemann, 1994; Hacker *et al.*, 2012), and that it competitively dominates beach grass communities in experimental and model studies across a range of depositional environments (Zarnetske, 2011), it is possible that further invasion by *A. breviligulata* may eventually lower foredune height along the entire Pacific coast. While suggestive, these observations do not establish whether the invasion-induced changes in foredune shape substantially alter exposure to coastal flood hazards currently, or under various climate change scenarios.

Coincident with these beach grass invasions has been a change in the physical forcing conditions that drive coastal processes such as sea-level rise (SLR) and storm-induced wave events. Storm frequency and associated extreme wave heights and periods in the Northeast Pacific have increased over the past several decades (Allan & Komar, 2001, 2006; Graham & Diaz, 2001; Menéndez *et al.*, 2008), mirroring regional trends of increased extreme wind events (Young *et al.*, 2011). While the exact cause of the increasing wave heights in portions of the Northeast Pacific is still uncertain, it is well established that climate change has led to rising global sea levels (Bindoff *et al.*, 2007).

Here we use field data and models to examine how invasion by *A. breviligulata* could alter coastal foredune morphology and associated coastal protective services. We calculate the effects of invasion-induced changes in foredune shape on exposure to coastal flooding due to overtopping of foredunes under a range of sea-level rise and altered storm intensity scenarios. We focus on a 40 year time horizon at multiple sites along the PNW coast. Specifically, we model the exposure to overtopping under three invasion scenarios: Historical Conditions (*A. arenaria* only), Current Conditions (*A. breviligulata* in the north and *A. arenaria* in the south), and Future Conditions (*A. breviligulata* only) under a range of sea-level rise and extreme storm intensity forecasts.

Materials and methods

Field surveys of vegetation

We surveyed vegetation in the major coastal dune areas along the Washington and Oregon coasts in 2006 ($n = 55$), 2007 ($n = 61$), and 2009 ($n = 85$) (Fig. 1; Table S1). Seventy-three of these sites were sampled in at least 2 years (2009 and either 2006 or 2007), and we focus these analyses on the sites with multiple years of data so that vegetation data represent an average taken over a 2 year or 3 year time span (Table S1). These sites span 450 km of the PNW coast from 43.6 to 46.9° north latitude. Sites were selected to provide sample foredunes in seven distinct littoral cells along the Oregon and Washington coasts (Table S1). At each site, we estimated percent areal cover of all species, bare ground, and litter within 20 × 50 cm quadrats located every 5 m along a transect running perpendicularly to the foredune, from the high water line to the back of the foredune. We estimated the relative dominance of *A. breviligulata* by calculating the proportional cover of *A. breviligulata* relative to the total summed cover of *A. breviligulata* and *A. arenaria*. Sites where the proportion of *A. breviligulata* was greater than or equal to 0.5 were classified as dominated by *A. breviligulata*. Transect locations were recorded using a handheld GPS.

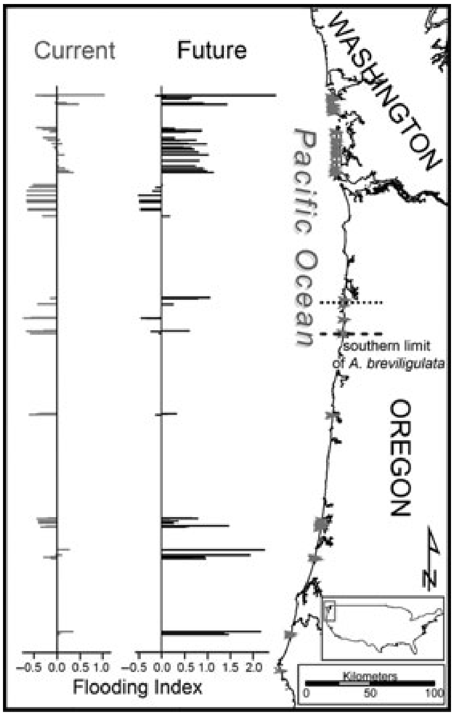

Fig. 1 Transect locations and relative exposure to overtopping under current conditions (Current) and future with combined effects of increased storm intensity, sea-level rise, and *Ammophila breviligulata* invasion (Future). Positive values of the flooding index, I_F, indicate cases where severe storms are expected to overtop coastal foredunes. Dashed line indicates southern limit of *A. breviligulata* at our survey sites (Pacific City, OR). Note that we only detected *A. breviligulata* in sampling quadrats as far south as Cape Lookout, OR (dotted line; Table S1), although it was present outside transects at sites as far south as Pacific City (dashed line).

Quantifying foredune morphometrics

The three most important morphometrics for computing exposure to dune overtopping are the elevation of the foredune crest, the elevation of the foredune toe, and the slope of the fronting beach (Fig. 2). We estimated each of these metrics at all transects using lidar data (Table S1). Lidar provides a dense data set of subaerial topography with both large spatial coverage and high spatial resolution. NASA's Airborne Topographic Mapper (ATM), a scanning laser altimeter, was flown in September 2002. The root-mean-square (rms) vertical error of the ATM has been estimated at 18.5 cm (Sallenger *et al.*, 2003). These data are spatially extensive, synoptic, and of sufficient accuracy to resolve a wide range of beach variability (Brock *et al.*, 1999; Krabill *et al.*, 2000).

We determined beach and foredune morphometrics from cross-shore profiles extracted from gridded lidar data. On each profile, the horizontal position of the mean high water (MHW NAVD88) shoreline (Fig. 2) was calculated from a linear regression fit to data located within 0.5 m vertically of MHW (Stockdon *et al.*, 2002). The foredune crest (d_c) was identified on the dune closest to the shoreline with a minimum vertical distance of 0.60 m between d_c and the dune heel (d_h) (Cooper, 1958). d_h is the landward edge of the dune at the junction between the back of the dune and remaining backshore. To find the inflection point at the toe of the foredune between the beach face and foredune face (dune toe, d_t), the profile between the MHW shoreline and d_c was approximated by a best-fit cubic function. The inflection point corresponded to the minimum on the best-fit cubic profile subtracted from the original profile. The mean backshore beach slope (tan β) is necessary for computations of the total water level (TWL) and was defined as the elevation difference between MHW and d_t divided by the beach width (horizontal distance between MHW and d_t). To capture the representative geomorphology at each site, parameters were estimated from cross-shore profiles extracted every 10 m in both alongshore directions within 50 m of each vegetation survey location and then averaged together. While the lidar data were collected approximately 4 years before the first vegetation survey, we consider the data to be sufficiently representative of PNW beach and dune conditions for quantifying relative changes in exposure to overtopping at decadal time scales (Hacker *et al.*, 2012; Seabloom & Wiedemann, 1994; Zarnetske, 2011).

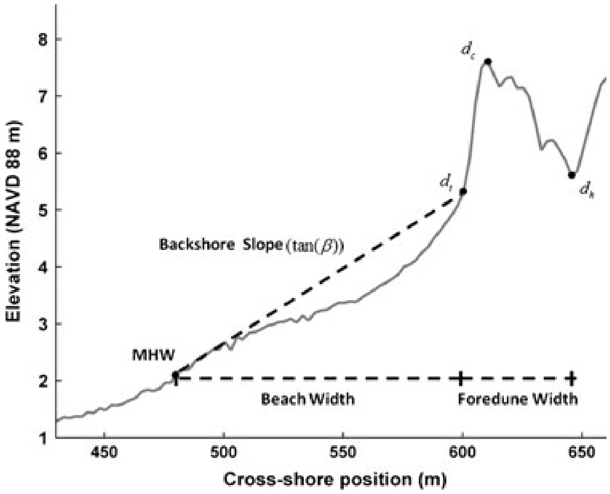

Fig. 2 An example of a lidar-derived cross-shore profile and the beach and foredune geomorphological parameters extracted from the profile. The data have been smoothed and interpolated onto a 2.5 m spaced grid in the cross-shore direction. The d_c elevation indicates the foredune crest and is the most shoreward dune crest with a minimum backshore drop of 0.60 m. The dune heel (d_h) is the lowest swale between the foredune crest and a subsequent dune crest. The dune toe (d_t) is the maximum difference between the profile and the profile detrended with a cubic function. The backshore slope is the slope between d_t and the cross-shore position of MHW.

Estimating exposure to dune overtopping

The frequency and magnitude of dune overtopping and the potential for coastal flooding ultimately depends upon the relative elevation of the TWL achieved on the beach vs. the elevation of the backshore feature of interest (e.g., sand dune crest, shore protection structure) (Sallenger, 2000; Ruggiero *et al.*, 2001). Here the TWL is taken as

$$\mathrm{TML} = \mathrm{MSL} + \eta_A + \eta_{\mathrm{NTR}} + R \qquad (1)$$

where MSL is the local mean sea level (which can be treated as either a constant tidal datum or as a variable with an annual rate of change). η_A is the predictable astronomical tide and η_{NTR} is the non-tidal residual (NTR) water level. The NTR component of the TWL is composed of a complex interplay of processes often dominated by storm surge (atmospheric pressure effect and wind setup) but also including effects of local water density variations and coastal trapped waves. R is the vertical component of wave runup, which includes both wave setup (a super elevation of the mean water level due to wave breaking) and swash oscillations around the wave setup. Here we employ an extreme statistic, $R_2\%$ (Holman, 1986), the two percent exceedance value of wave runup maxima, because it is the highest swash events in a wave runup distribution that are initially responsible for dune overtopping. Simple empirical formulae have been developed for the application of this statistic, for example, Stockdon *et al.* (2006) combined data from 10 nearshore field experiments and derived an expression for $R_2\%$ applicable to natural beaches over a wide range of morphodynamic conditions. Their relationship

$$R_2\% = 1.1\left(.35\tan\beta(H_oL_o)^{1/2} + \frac{[H_oL_o(0.563\tan\beta^2 + 0.004)]^{1/2}}{2}\right) \qquad (2)$$

relates wave runup to deep water incident wave conditions and local beach morphology, where H_0 is the deep-water significant wave height, L_0 is the deep-water wave length given by Airy (linear) wave theory as $(g/2\pi)T^2$ where g is the acceleration of gravity and T is the peak spectral wave period. $R_{2\%}$ is calculated with the local backshore beach slope (tan β), and does not take into account the steeper dune face slope which evolves significantly during a storm event. Therefore, similar to Sallenger (2000), our TWLs can be thought of as the effective TWL that would be achieved in the absence of a backing dune.

If the estimated TWL exceeds the foredune crest elevation at a particular profile, the profile is in the overtopping (or inundation) regime of the Sallenger (2000) storm impact scale and backshore flooding can occur. Here we normalize the amount of overtopping (TWL − d_c) by the foredune face height to create a non-dimensional coastal flooding index

$$I_\mathrm{f} = \frac{(\mathrm{TWL} - d_\mathrm{c})}{(d_\mathrm{c} - d_\mathrm{t})}, \text{ where positive values indicate overtopping and negative values indicate no overtopping.} \quad (3)$$

Developing invasion and climate change scenarios

Our studies to date suggest that invasion of coastal dune systems by *A. breviligulata* has reduced the height of coastal foredunes previously dominated by *A. arenaria* (Seabloom & Wiedemann, 1994; Hacker *et al*., 2012). Foredune height is directly related to the exposure to overtopping by storm waves. In addition, the earth's changing and variable climate exerts influence on several of the processes that control the probability of coastal flooding. Therefore, the flooding index described above contains parameters that are directly affected by changes in climate (sea-level rise and the possibility of changes in storminess) and changes in foredune shape arising from species invasions. Because the potential for overtopping is a function of water level, offshore wave conditions, and beach morphology, any trends or variability in these parameters, specifically due to climate change and/or species invasions, will directly influence the frequency that backshore properties experience foredune overtopping.

We focus here on a 40 year time horizon, a period relevant to long-term planning and a timeframe over which *A. breviligulata* could possibly dominate the remaining coastal dune areas in Oregon. The displacement of *A. arenaria* by *A. breviligulata* currently spans about 300 km and occurred over a 50 year time period since its introduction in 1935 and there is about 300 km of shoreline that remains uninvaded by *A. breviligulata* in Oregon (sites south of Pacific City where it was found in low density outside the transects; Table S1) (Seabloom & Wiedemann, 1994; Hacker *et al*., 2012).

Effects of A. breviligulata invasion. While there are no foredune morphology and vegetation data for the period of time prior to the introduction of *A. arenaria*, we have been tracking the progressive displacement of *A. arenaria* by *A. breviligulata* for over 20 years allowing us to estimate the effects of this secondary invasion on foredune morphology (Seabloom & Wiedemann, 1994; Hacker *et al*., 2012; Zarnetske *et al*., 2012). Foredune morphology is also strongly affected by sediment supply, and *A. arenaria* is currently rare at sites with rapidly prograding beaches (Hacker *et al*., 2012). We controlled for shoreline change rates (taken here as a proxy for sediment supply) in our estimation of the effects of *A. breviligulata* invasion on foredune height. End point shoreline change rates were calculated by comparing the lidar-derived shoreline positions (2002) with those on aerial photographs or T-sheets from the 1950s to the 1960s (Hacker *et al*., 2012; Ruggiero *et al*., 2012b). We then estimated the effects of *A. breviligulata* invasion on foredune height after controlling for the effects of sediment supply in two ways: (1) we used the entire data set and included shoreline change in the regression model and (2) we calculated the effects of the difference between *A. breviligulata* and *A. arenaria* dominated foredunes only for the range of shoreline change rates for which both species occurred (−1.3 to 1.9 m yr^{-1}). Both methods provided estimates that were within a few cm of each other, and there were no significant interactions between the effects of shoreline change and *A. breviligulata* on foredune height. Here were use the first method (Table 1; Figure S1).

Effects of sea-level rise. A progressive rise in global sea level can be added directly to the TWL model as a time varying MSL. Its addition allows for quantitative predictions of the expected future increase in the extent and magnitude of overtopping of foredunes directly due to the effects of climate change. The elevation of the crest of the foredune governs the average frequency with which it can be reached by the waves during a year, and thus represents its susceptibility to overtopping.

Effects of altered wave climate. Ruggiero *et al.* (2010) used a long time series of measured offshore wave conditions (35 years) to characterize multi-decadal trends in the PNW wave climate. While the averages of all significant wave heights measured during winter months have been increasing at a rate of 0.023 m yr^{-1}, the maximum significant wave heights of the strongest storms have been increasing at substantially higher rates. Any continued trends or variability in wave height or wave period (Allan & Komar, 2006) will directly influence the frequency that backshore properties experience flooding via their control on the wave runup component of the TWL (Eqn 2).

Invasion and climate change scenarios. We calculated the non-dimensional flooding index (I_F) for three invasion

Table 1 Results of linear regression used to estimate change in foredune height resulting from invasion by *Ammophila breviligulata*. Full model contained all interactions terms, but there were no significant interactions (based on AIC)

Response	Parameter	Estimate	SE	*t*	*P*
Dune height ($\log_{10}$ m)	Intercept	0.702	0.031	22.776	<0.001
	Shoreline change (m yr^{-1})	−0.098	0.041	−2.368	0.021
	A. breviligulata dominant (T or F)	−0.145	0.057	−2.549	0.013

scenarios (Historical, Current, and Future), 3 wave period scenarios (Decreasing, Current Conditions, and Increasing), 3 wave height scenarios (Decreasing, Current Conditions, and Increasing), and 3 sea-level scenarios (No Change, Slow Rise, and Rapid Rise) for a total of 81 combinations. We calculated all 81 flooding scenarios at each of the 73 sites for a total of 5,913 risk forecasts.

The invasion scenarios represented three states: 1. Historical Conditions (all dunes dominated by *A. arenaria*), 2. Current Conditions (*A. breviligulata* dominates most areas in Washington and northern Oregon), and 3. Future Conditions (all dunes dominated by *A. breviligulata*).

For the storm intensity scenarios, we used an event selection approach in which we deterministically selected the relevant parameters in Eqns 1 and 2 associated with a major winter storm approximately equal to the 100 year return level event (1% probability of occurrence in any given year). We chose this approach and this 'design' event because they have been used to determine coastal erosion hazard zones by the Oregon Department of Geology and Mineral Industries (DOGAMI) (Allan & Priest, 2001), however, we note here that the event selection approach can be relatively conservative.

We first prescribed the hydrodynamic conditions associated with the 100 year storm assuming the present-day extreme wave and water-level climate (H_o = 14.5 m, T = 17 s, η_{NTR} = 1.0 m, and η_A = 0.4 m above MHW). The significant wave height (H_o) associated with this extreme event is taken from Ruggiero *et al.*'s (2010) application of the peak over threshold (POT) method of extreme value theory (Coles, 2001). The wave period (T), astronomical tide (η_A), and storm surge (η_{NTR}) associated with this extreme wave height are roughly based on the storm of record in the PNW, a severe storm that occurred on March 2–4, 1999 (Allan & Komar, 2002).

By applying non-stationary extreme value theory to the wave height time series, Ruggiero *et al.* (2010) found that the 100 year return level wave height (H_o) was increasing at a rate of approximately 0.05 m yr^{-1} (again using the POT approach). We note that the results of studies like that of Ruggiero *et al.* (2010), relying solely on buoy measurements, have recently been called into question after careful analyses of modifications of the wave measurement hardware as well as the analysis procedures since the start of the observations have demonstrated heterogeneities in the records (Gemmrich *et al.*, 2011). Accounting for these changes, trends for the corrected data are smaller than the apparent trends obtained from the uncorrected data. However, Young *et al.*, (2011) used a 23 year database (1985–2008) of satellite altimeter measurements to investigate global changes in oceanic wind speed and wave height. They find a general global trend of increasing wind speed and to a lesser degree wave height. For both winds and waves, the rate of increase is greater for extreme events as compared to the mean condition. For extreme wave heights (99th-percentile), there is a clear statistically significant trend of increasing wave height at high latitudes including off the U.S. west coast. At the location of the buoy analyzed by Ruggiero *et al.* (2010), extreme wave heights have been increasing at a rate of approximately 0.045 m yr^{-1}. Because of the significant uncertainty in understanding past let alone predicting future wave climates, we developed scenarios reflecting increasing storm intensity and decreasing storm intensity. These scenarios can be thought of as the 100 year wave height after approximately two to three decades of the increasing or decreasing trend in storm intensity. Note that due to the large uncertainty in projecting future wave climates, we do not allow the trends to increase for the full 40 year time horizon of the invasion and SLR scenarios. Specifically, we use the following three scenarios (wave height, wave period): Decreased Intensity (13.0 m, 14 s), Current Conditions (14.5 m, 17 s), and Increased Intensity (16.0 m, 20 s). All scenarios have an astronomical tidal level of 0.4 m above MHW and storm surge of 1.0 m.

Baron (2011) compiled published semi-empirical SLR estimates that relate sea level to global mean temperature (Rahmstorf, 2010) and developed a suite of possible projections through time for the IPCC SRES scenario A1B. These global SLR projections were adjusted for the local rate of vertical land movement, or uplift, which varies considerably in the PNW (Burgette *et al.*, 2009). Here we examine three sea level scenarios taken at 2050: Current Conditions (0 m), Slow Rise (0.21 m), and Rapid Rise (0.47 m).

While storm surge is important, we have little empirical grounding for estimating expected changes. Because of the uncertainty, we did not incorporate storm surge in our full modeling scenarios. Instead, we conducted a sensitivity analysis to determine how altered storm surge would affect flooding by holding the extreme wave height and wave period constant at current conditions (14.5 m, 17 s) and calculating the effect of changes in storm surge (0.75, 1.0, and 1.25 m), sea-level rise (0, 0.21, and 0.47 m), and invasion (Past, Current, and Future Conditions) on overtopping exposure for a total of 27 scenarios. As with the full analysis, overtopping exposure was calculated for all 27 scenarios at all 73 sites for a total of 1971 scenarios in this sensitivity analysis. In our sensitivity analyses, storm surge accounts for 2.4% of the total variance in overtopping exposure, four times less than invasion and similar to sea-level rise.

Statistical analyses

Processing of lidar data and flooding simulations were conducted in Matlab version R2008a (The MathWorks. Natick, MA, USA). All statistical analyses were performed using R version 2.12.0 (R Foundation for Statistical Computing, Vienna, Austria, 2010). We used ANOVA to calculate the sum of squares associated with each forcing factor (invasion, wave height, wave period, and sea-level rise) and all of the second order interactions. Many factors were highly significant due to the large number of replicate scenarios. While we present the *P* values, we focus the interpretation on the percent of variance accounted for by each of the factors. We included shoreline change rate as a factor in all models, given its strong correlation with foredune height (Hacker *et al.*, 2012) and hence overtopping exposure.

Results

We conducted field surveys of vegetation composition at 73 locations along the PNW coast in 2006–2009

(Fig. 1; Table S1). At each site, we calculated beach and foredune morphometrics from cross-shore profiles extracted from gridded, airborne lidar (light detection and ranging) data. Beach and foredune morphometric data were combined in a total water level model (Eqns 1 and 2) to calculate whether foredunes would be overtopped during extreme storm events (Ruggiero *et al.*, 2001). Backshore flooding can occur by a variety of mechanisms once a foredune is overtopped (Sallenger, 2000) but is ultimately a function of the volume of overtopping (Cox & Machemel, 1986). While in this study we do not explicitly calculate overtopping volumes, we take the elevation of storm-induced total water levels (TWL) relative to dune crest height as a first order estimate of the exposure of an area to coastal flood hazards. Our non-dimensional flooding index (I_F) takes on positive values when waves would overtop foredunes and potentially flood backdune areas (Eqn 3).

Our study sites encompassed a wide array of physical and ecological conditions. Multi-decadal shoreline change rates ranged from −2.6 (erosion) to 11.5 (progradation) m yr^{-1} (mean = 1.4 ± 2.0 SEM), foredune height (d_h) ranged from 1.4 to 13.7 m above the foredune toe (mean = 4.9 ± 2.8 SEM), cover of *A. arenaria* ranged from 0 to 93%, cover of *A. breviligulata* ranged from 0% to 95%, and proportion of *A. breviligulata* (cover of *A. breviligulata* divided by total *Ammophila* cover) ranged from 0% to 100%.

In our surveys, foredune height declined with increasing shoreline change rate and dominance by *A. breviligulata* (Fig. 3). Across all sites, dunes that were less than 50% *A. breviligulata* had a mean height of 5.9 (0.48 SEM) m while sites that were 50% or more *A. breviligulata* had a mean height of 3.3 (0.31 SEM) m. Part of this difference was due to differences in shoreline change rates among *A. breviligulata* and *A. arenaria* dominated sites. We estimated the direct effects of *A. breviligulata* on foredune height by calculating the difference between *A. breviligulata* and *A. arenaria* dominated foredunes after accounting for shoreline change (Table 1), and we calculated foredune heights for our invasion scenarios by adding or subtracting the estimated change in foredune height parameter (-0.145 $\log_{10}$ m) to determine heights for *A. breviligulata* foredunes if they were dominated by *A. arenaria* and vice versa.

Wave period was the primary driver of changes in exposure to flooding (I_F) in our climate change scenarios, accounting for 16% of the total variability (Table 2; Fig. 4). Invasion accounted for an additional 8% of the variability in exposure to flooding. Sea-level rise and wave height accounted for 1.7% and 1.4% of the variability in flooding exposure, respectively. While invasion had a smaller effect than wave period, invasion-induced changes in foredune height had significant effects on the number of sites vulnerable to flooding. *A. breviligulata* invasion tripled the number of cases which were vulnerable to flooding (i.e., sites with a positive flooding index) from 13% with only *A. arenaria* to 40% in the future scenario with all foredunes dominated by *A. breviligulata*.

Discussion

Coastal foredune systems provide critical ecosystem services in the form of reducing the exposure to flooding and storm damage (Sallenger, 2000; Barbier *et al.*, 2008). The vulnerability posed by flooding is likely to change globally through the interactive effects of sea-level rise resulting from human changes to global climate and possibly shifting storm intensities (Bindoff

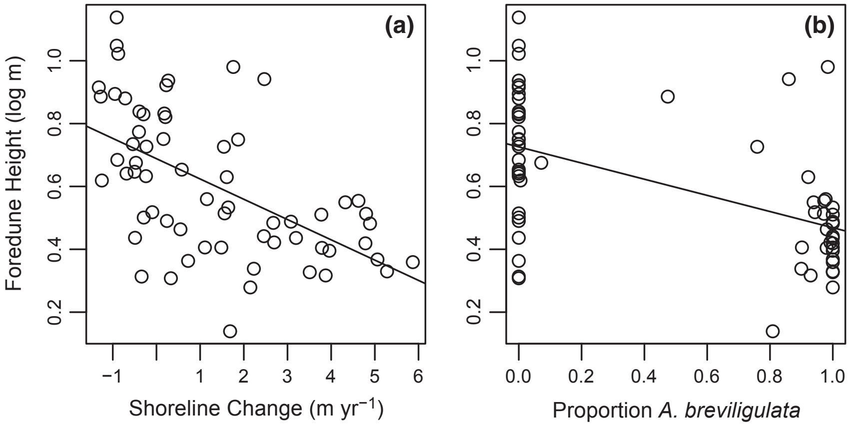

Fig. 3 Effect of shoreline change (a) and dominance by *Ammophila breviligulata* (b) on height of foredunes $\{\log_{10}(\mathrm{m})\}$ on the coast of Oregon and Washington (USA). Note that treating the proportion of *A. breviligulata* (Panel b) as binary variable rather than continuous does not affect the results.

Table 2 Analysis of Variance showing effects of climate change and invasion on the non dimensional flooding index. Climate change scenarios include the effects of sea-level rise (current conditions, slow change, and rapid change) and altered wave height and period (decreased, current conditions, and increased). Climate change effects are crossed with three invasion scenarios: Historical (*Ammophila arenaria* only), Current Conditions (*A. breviligulata* in the north and *A. arenaria* in the south), and Future (*A. breviligulata* only)

Source	d.f.	SS	MS	*F*	*P*	Percent of variance
Wave period	1	147.9	147.9	1345.0	<0.001	16.1
Invasion state	2	72.4	36.2	329.1	<0.001	7.9
Sea-level rise	1	15.9	15.9	144.4	<0.001	1.7
Shoreline change × Invasion	2	14.5	7.3	66.1	<0.001	1.6
Wave height	1	12.8	12.8	116.1	<0.001	1.4
Invasion × Wave period	2	2.8	1.4	12.5	<0.001	0.3
Shoreline change	1	2.3	2.3	20.8	<0.001	0.2
Shoreline change × Wave period	1	0.8	0.8	7.1	0.008	0.1
Shoreline change × Sea-level rise	1	0.5	0.5	4.2	0.041	0.1
Invasion × Sea-level rise	2	0.3	0.1	1.3	0.263	0.0
Wave period × Wave height	1	0.3	0.3	2.4	0.121	0.0
Invasion × Wave height	2	0.2	0.1	1.1	0.340	0.0
Shoreline change × Wave height	1	0.1	0.1	0.6	0.433	0.0
Wave period × Sea-level rise	1	0.0	0.0	0.0	1.000	0.0
Wave height × Sea-level rise	1	0.0	0.0	0.0	1.000	0.0
Residuals	5892	648.0	0.1			70.5
Total	5912	918.6				

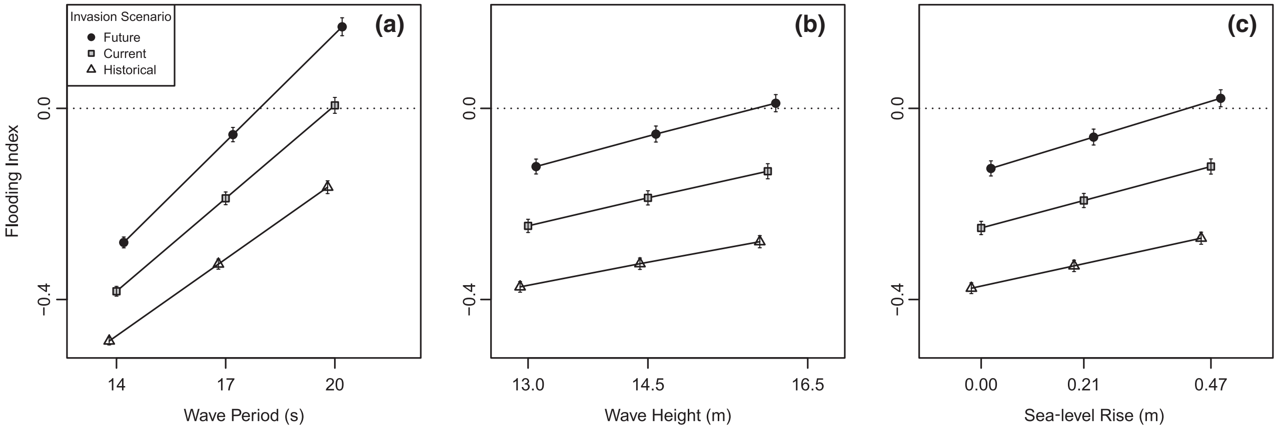

Fig. 4 Effects of wave period (a), wave height (b), and sea-level rise (c) on the flooding index under different beach grass invasion scenarios. Positive flooding risk values indicate conditions in which foredunes will be overtopped during storms. Storm intensity scenarios represent the effects of both wave height and wave period. Invasion scenarios represent the following: Historical (*Ammophila arenaria* only), Current (*A. breviligulata* in the north and *A. arenaria* in the south), and Future (*A. breviligulata* only). Flooding Index values are averaged across all transects and all sea-level rise scenarios. Error bars represent 1 SEM.

et al., 2007; Rahmstorf, 2010; Young *et al.*, 2011). In many areas, manipulation of vegetation also can alter exposure to flooding (Barbier *et al.*, 2011). In our study system, we found that the further invasion of *A. breviligulata* likely will lower foredune heights and compound the exposure to coastal flooding posed by intense marine storms.

Relative to storm intensity and invasion, sea-level rise had minor effects on flooding in this system. The seemingly modest vulnerability posed by sea-level rise in our work should not be interpreted as downplaying the threat of increasing sea levels. Ultimately, the inexorable increase in sea level will flood many coastal areas. For example, by 2100 sea-levels may rise by over 1.0 m (Rahmstorf, 2010; Baron, 2011), while here we only examined increases up to 0.5 m because we focused on shorter (multi-decadal) time horizons.

The world's coastlines are critical to our economies and quality of life; however, they are also highly sensitive to the impacts of climate change. While a great deal of attention has focused on the slow and steady flooding caused by sea-level rise, our analyses suggest that there is much more immediate risk posed by potential changes in storm intensity and vegetation. In our simulations, storm intensity (wave height and period) accounted for about 10 times more of the variability in flooding exposure than did sea-level rise. Much of this difference is due to our lack of knowledge about future wave conditions, so our scenarios included both an increase and decrease in storm intensity. However, it is clear that storm intensity potentially poses an important and more imminent threat than does sea-level rise at time horizons of a few decades (Ruggiero, 2012a). This is particularly worrisome given our current inability to accurately forecast future wave conditions.

While there is great concern about costs of invasive species, they may also impart important benefits or services such as pollination or pest control (Schlaepfer *et al.*, 2011). The dual nature of these species can create a dilemma for mangers. The U.S. West Coast dune system described here is an example of this type of conundrum. Climate change is increasing the need for the protection services of foredunes, but conservation mandates the removal of beach grasses and the foredunes they created in some areas along the coast to favor recovery of threatened and endangered species (Zarnetske *et al.*, 2010). Furthermore, the uncontrolled invasion by *A. breviligulata* is associated with large declines in foredune height and plant diversity creating a particularly suboptimal state for both management of flooding risk and conservation of native ecosystems (Seabloom & Wiedemann, 1994; Zarnetske *et al.*, 2010; Hacker *et al.*, 2012).

Humans have a long history of using vegetation to create barriers for coastal protection (Barbier *et al.*, 2011). Studies of the effects of coastal habitat modifications on flooding risk largely have focused on the direct removal of coastal vegetation, such as mangroves or kelp forests or eelgrass beds (Barbier *et al.*, 2008). While it is proposed that vegetation can directly mitigate flooding risk via frictional dissipation, it may more often indirectly lower this risk through the accumulation of sediments such as is seen in salt marshes and sand dunes (Feagin *et al.*, 2009; Gedan *et al.*, 2011). Our work reveals that species invasions are another pathway by which risk of flooding from even extreme storm events can be altered through human-induced changes to coastal vegetation. In our system, the introduction of the first exotic grass, *A. arenaria,* dramatically increased coastal foredune heights (Cooper, 1958; Hacker *et al.*, 2012), however the lowered foredunes associated with the subsequent spread of the secondary invader, *A. breviligulata*, should serve as a cautionary tale about the risks of species introductions. In addition, the work presented here suggests that a clear assessment of climate change effects on ecosystem services requires research and analytical approaches that integrate ecology, geomorphology, and civil engineering so as to explicitly recognize the linkages between the biotic and abiotic forces that shape our world.

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Author contributions

EWS, SDH, and PLZ planned and executed the field surveys of the vegetation. PR and JM analyzed the lidar data to produce dune morphology maps, developed climate change scenarios, and calculated exposure to dune overtopping. EWS analyzed the data. All authors contributed to the writing of the manuscript.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Foredune heights are predictions for three different invasions scenarios based on difference between current *A. arenaria* and *A. breviligulata* after accounting for shoreline change rates.

Table S1. Study sites included in foredune risk analysis. The year column indicates sampling years. Note that while *Ammophila breviligulata* only occurred in our quadrats at far south as Cape Lookout it occurred near the transects as far south as Pacific City, Oregon, USA.