Differences in the Morphology of Restored and Invaded Foredunes

Humboldt Bay, California

Invaded area of North of Lanphere Dunes (photo credit: Kelsey McDonald)

Restored area of Lanphere Dunes (photo credit: Laurel Goldsmith)

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Abstract

This study used remotely sensed data from a high-resolution (1 m^2) 2010 Digital Elevation Model (DEM) to model the slopes, elevations, and profiles of restored foredunes in comparison with invaded foredunes on the North Spit of Humboldt Bay. Restoration in the study area took place over the last 25 years, and these areas now primarily support native dunegrass (*Elymus mollis* Trin.) and other native dune species. The invaded areas are dominated by non-native European beachgrass (*Ammophila arenaria* L.). Despite recently voiced concerns that restoration might be permanently lowering the foredune, restored and invaded areas showed no significant difference in height ($p=0.748$). However, restored and invaded foredunes did show a significant difference in slope ($p<<0.001$) and slightly different profile shapes; invaded dunes were steeper with a more flat, plateau-like top, and restored areas were more gently sloping with rounded peaks. Dune heights increased from the southern end of the study area to the north, regardless of restoration status, indicating that other factors affect dune heights in the study area. The availability of only one high-resolution DEM limits these observations to a point-in-time characterization, and the applicability of the models is limited to the study area.

Introduction

The Lanphere and Ma-le'l Dunes Units of Humboldt Bay National Wildlife Refuge contain the best remaining example of the native coastal dune ecosystem that once occurred between Monterey, California and Coos Bay, Oregon (Cooper 1967, Buell et al. 1995). European beach grass (*Ammophila arenaria*), which was widely introduced to stabilize sand, has invaded the coastal dune ecosystem and supplanted native vegetation, including native dunegrass (*Elymus mollis*) (Pickart and Sawyer 1998, Buell et al. 1995). Few scattered native dunegrass communities remain in California, Oregon and Washington (Pickart and Sawyer 1998). Several restoration projects along sections of the North Spit of Humboldt Bay have removed *A. arenaria* from the foredunes over the last few decades, and native vegetation has recovered in much of the restored area.

Vegetation plays a critical role in dune formation and impacts dune morphology. Foredunes, defined as dune ridges adjacent and parallel to the shore, are created by aeolian sand deposition within vegetation (Hesp 2002). Tall, dense vegetation like *A. arenaria* tends to capture more sand and form high, peaked dunes (Hesp 2002, Zarnetske et al. 2012). Native *E. mollis* grows to a similar height (or slightly taller) compared to invasive *A. arenaria*, but it grows less densely, with total vegetation cover typically ranging from 25%-75%, compared to *A. arenaria* cover ranging up to 100% (Hacker 2011, Pickart and Sawyer 1998). *Elymus mollis* foredunes often support higher species diversity, presumably due to their more open growth pattern. The more open habit of *E. mollis* is believed to allow more sand transport from the beach over the crest of the foredune and into the diverse dune mat community found there (Pickart 2008). In Oregon and Washington, *A. arenaria* has been observed to create a continuous high foredune ridge where previously a lower or no foredune existed (Wiedemann and Pickart 1996, Buell et al. 1995, Zarnetske et al. 2012). Prior to invasion, native foredunes in the Pacific Northwest were reportedly low and gently sloping (Pickart and Sawyer 1998). The low density and growth habit of *E. mollis* has led to predictions that the biophysical feedback of native *E. mollis* cover would produce a low, gently sloping dune compared to *A. arenaria* (Zarnetske et al.

2012); however, the native portion of the Lanphere Dunes that was never dominated by *A. arenaria* currently contains a high continuous foredune similar to the structure commonly attributed to *A. arenaria* invasion (Pickart and Sawyer 1998).

Over the past 5 years, some members of the public have expressed concerns that the *Ammophila* eradication process could be destabilizing and lowering the foredune near the community of Manila on the North Spit (Walters 2011). Immediately following eradication of *A. arenaria* from the invaded portion of Lanphere Dunes, the slope and elevation of the foredunes was observed to decrease (Pickart 2014), but the foredunes have accumulated sand as native species including *E. mollis* have recolonized the area. The steeper seaward slope of invaded foredunes compared to native dunes has been commonly observed, but their comparative morphology has not previously been systematically measured. To address this information gap, this study was designed to characterize foredunes by restoration status along a 10 km stretch of the North Spit of Humboldt Bay that contains both native and invaded foredunes (Figure 1).

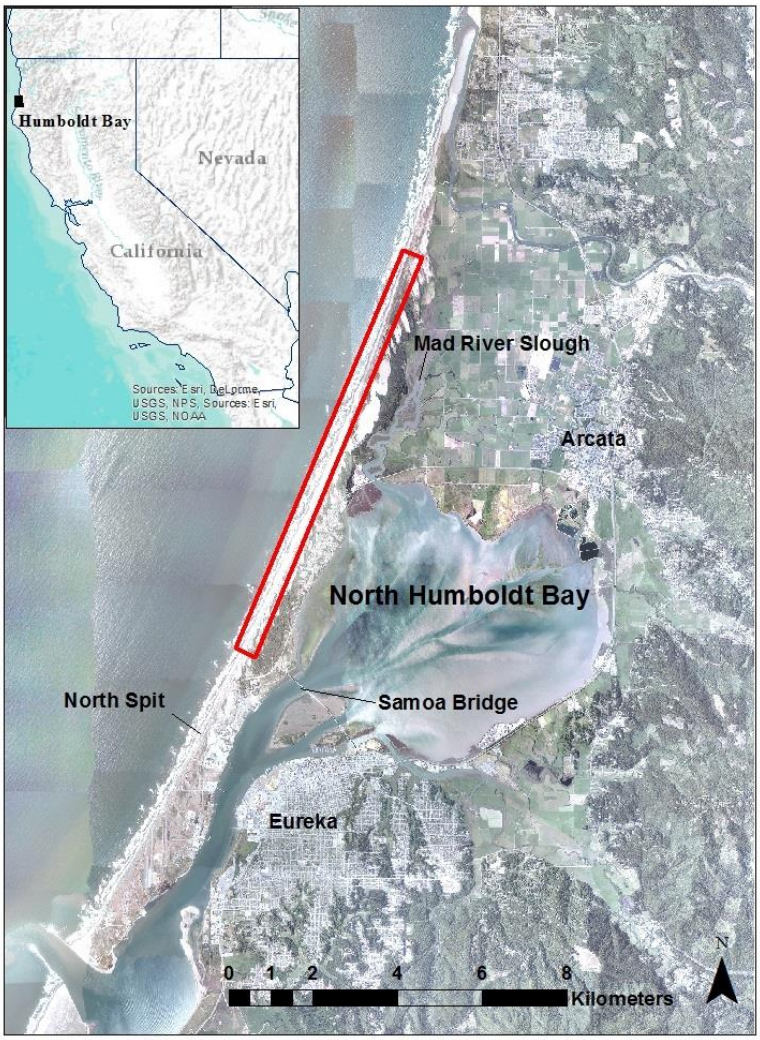

Figure 1. The study area covered the dune system that stretches 10 km from the beginning of the Mad River Slough to the Samoa Bridge on the north spit of Humboldt Bay.

Purpose of the Study

The purpose of this study was to determine the relative heights, slopes, and profile shapes of restored and invaded foredunes. Interpolation of elevation data has been widely used to create individual dune profile transects or show volumetric change over time (Andrews 2002). In this study, interpolation of elevation data from digital transects was used to model the overall shape of the foredunes and extract slopes and maximum heights for data analysis. Because the invasive European beachgrass *A. arenaria* has anecdotally been observed to create a higher, steeper stabilized foredune, the invaded foredunes were hypothesized to be both higher and steeper than restored foredunes vegetated by native species, including *E. mollis*. Determining the differences in the physical structure of these foredunes can shed light on the effects of restoration on dune processes and inform future management decisions.

Study Area and Management History

The study area is owned and/or managed by several different entities, including the U.S. Fish and Wildlife Service (FWS), the Bureau of Land Management (BLM), Friends of the Dunes (a 501(c)3 non-profit), Manila Community Services District, and private landowners (Figure 2). Restoration status varies by management unit (Figure 2). *Ammophila arenaria* is still highly abundant in dense, monospecific stands in a recently acquired FWS parcel north of Lanphere Dunes, as well as in an adjacent, privately owned parcel to the north. U.S. Fish and Wildlife Service eradicated *A. arenaria* from 1.4 km of foredune in the Lanphere Dunes between 1992 and 1997, and then eradicated *A. arenaria* and replanted native *E. mollis* on the Male'l Dunes between 2005 and 2011. The Bureau of Land Management (BLM) eradicated *A. arenaria* and replanted *E. mollis* on their northern property from 1994-2004, and on their southern property from 2003-2008 (BLM). The area to the south of BLM, owned by Friends of the Dunes, is highly invaded. Friends of the Dunes began restoration on the back of the foredunes at the north end of this area in 2008. Restoration on the foredune of the Manila Community Services District parcel took place from 1992-2000 (Miller 1997, Walter, pers. comm. 2014). However, maintenance of this restoration was halted after a 2008 lawsuit (Walters 2011), and in the intervening time, invasive *A. arenaria* reestablished itself along much of the foredune (personal obs. 2014). It is unknown exactly how much of the foredune had been reinvaded as of 2010, but aerial photography from 2010 appears to show a primarily native plant dominated foredune. The southern-most portion of the study area is privately owned and highly invaded. The presence of interspersed stretches of restored and invaded foredunes in the study area provides an opportunity to compare the physical structures of foredunes dominated by invasive *A. arenaria* with restored foredunes dominated by native species including *E. mollis.*

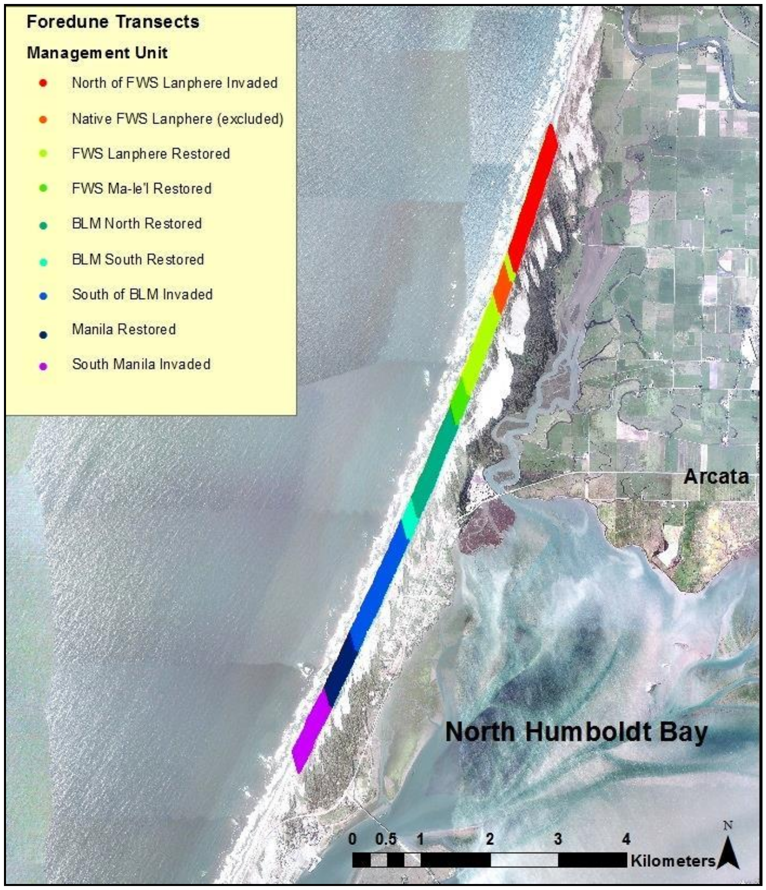

Figure 2. The study area on the North Spit of Humboldt Bay contains several different management units owned by the U.S. Fish and Wildlife Service (FWS), the Bureau of Land Management (BLM), Friends of the Dunes, Manila Community Services District, and private landowners. The unrestored native area of Lanphere was excluded from analysis.

Methods

A 1 m resolution 2010 Digital Elevation Model (DEM) from the 2009-2011 CA Coastal Conservancy Coastal Lidar Project provided elevation and slope data for this study. The "slope tool" in ArcMap 10.1 (ESRI 2012) generated a 1 m slope raster from the 2010 DEM. The study area was restricted to the northern portion of the spit where both restored and invaded foredunes occur, and where encroaching development and consequent impacts on natural processes are limited (Figure 2). In order to address the impact of restoration on dune structure, the relatively undisturbed section of native foredunes on the north end of Lanphere Dunes Unit was excluded from the analysis of restored and invaded foredunes. A 20 m buffer excluded the transition area between management units. The restored and invaded stretches are evenly distributed from north to south within the study area, with no significant correlation between dominant vegetation and northings ($r<<0.001$, $p=0.906$). The study area was confined to the foredune area from a 6 m elevation contour along the beach to 70 m southeast along transects parallel with prevailing wind. The inland edge of the study area (70 m southeast along the transects, which corresponds to approximately 40 m from the 6 m contour) was chosen because this is the typical area occupied by foredune grasses *A. arenaria* and *E. mollis*, as shown by previous GPS mapping of the extent of *E. mollis* and *A. arenaria* between Manila and the Bair parcel of Lanphere Dunes Unit (McDonald 2014, unpublished data).

A smoothed 6 m elevation contour line along the shore of the North Spit served as a baseline approximating the seaward edge of the foredune. The "create random points" tool distributed 844 points along the 6 m contour within the limits of study area between UTM y-coordinates 4520600 and 4529550 (from near the Samoa Bridge north to the north end of the Mad River Slough), excluding the unrestored native area and 20 m buffers between management areas. These points served as the start of 844 digital profile transects roughly parallel to the prevailing north-northwest winds. Each transect consisted of 49 points located 1 m apart in the x-direction (a diagonal distance of 3.85 m) for a total of 41,356 points (Figure 3). 421 transects were located in the invaded areas, and 423 transects were located in the restored areas. Elevations and slopes were extracted from the DEM and slope rasters in ArcMap at each point.

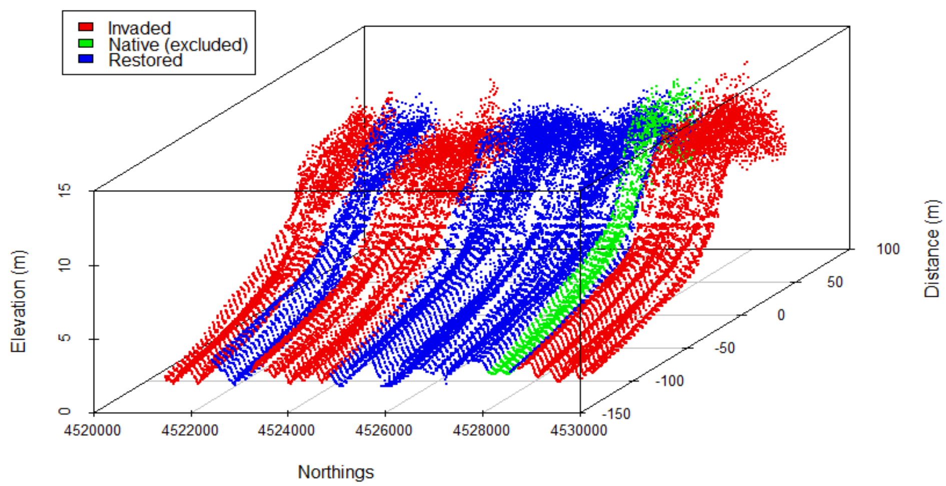

Figure 3. Random profile transects showing elevations extracted from the DEM, plotted from south to north colored according to restoration status. Positive distances are indicated for meters inland southeast along the transect from a 6 m elevation contour at the base of the foredune, and negative distances approach the ocean as they increase in magnitude.

The maximum heights and the mean seaward slopes of foredune transects in invaded and restored areas were compared using oneway tests, t-tests and boxplots in R statistical software (2013). Generalized Additive Models (GAMs) were created to depict the typical profile for restored versus invaded dunes. Mean seaward slopes of each transect were calculated between the 6 m contour baseline and 25 m southeast along the transect towards the foredune peak. Because the ArcMap slope tool calculates slope based on the elevations of the surrounding cells, the slope analysis used means from every other transect to eliminate the possibility of using slope data calculated from overlapping areas. Restored and invaded profile models were cross-validated by subsetting 50% of the transects (Wood 2011, Graham 2014).

Results

Oneway tests on the means (not assuming equal variances) of the maximum transect heights showed that the heights of invaded and restored foredunes are not significantly different (p=0.748) (Table 1). However, dunes dominated by invasive *A. arenaria* had significantly steeper mean slopes (p<< 0.001) from the base of the foredune (at the 6 m contour) to the area where the dune peak begins to level out (25 m back along the transects) according to a t-test (Table 1, Figure 4).

Table 1. Oneway tests and t-tests on the means showed that maximum elevations of restored and invaded foredunes were not significantly different, but the slope of invaded dunes was significantly higher than the slope of restored dunes.

	Invaded mean /median		Restored mean /median		P-value	Outcome
Max Height (m)	10.78	10.65	10.75	10.77	0.748	Not significantly different
Slope (percent rise)	16.54	16.68	13.94	14.28	<<0.001***	Significantly different

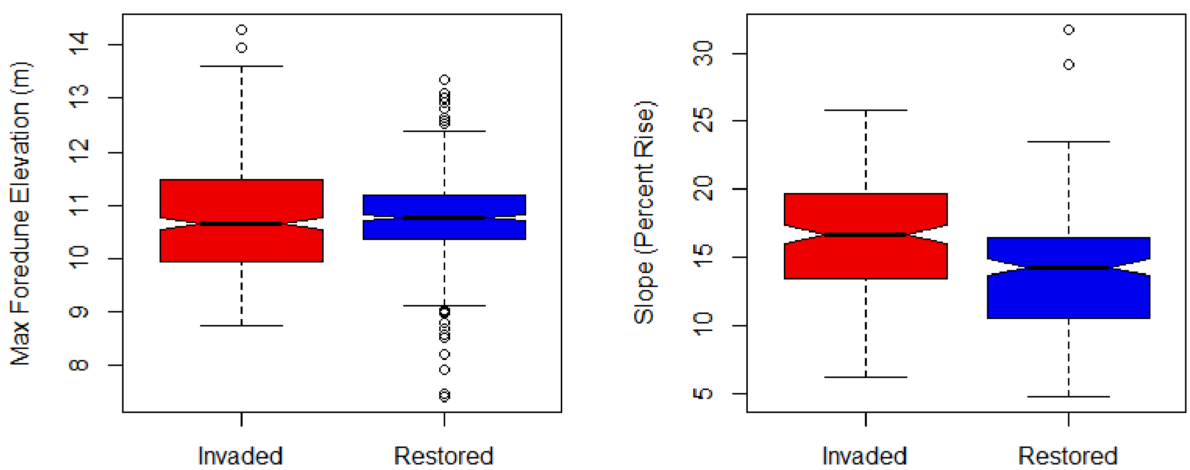

Figure 4. Maximum foredune elevations (m) were not significantly different (left), but invaded primary foredunes had significantly steeper slopes (right).

Modeling foredune transects in native and invaded areas in R with GAMs showed the typical foredune profile shapes of restored and invaded areas (Fig. 5) The foredune model extends approximately 70 m back along transects from the baseline at the 6 m shoreline contour (distance 0 m). Model residuals were normally distributed for the foredune area. Despite a wide variation between transects, models had a high level of precision because of the large number of transects (n=844), and showed a slight difference in the typical shapes of restored and invaded dunes (Figures 5-6). Restoration status was a highly significant predictor of profile shape (p<<0.001). Cross-validating the GAM profile models by repeatedly subsetting 50% of the transects for training and 50 percent for testing demonstrated low model sensitivity by generating models that were consistent with the overall GAMs.

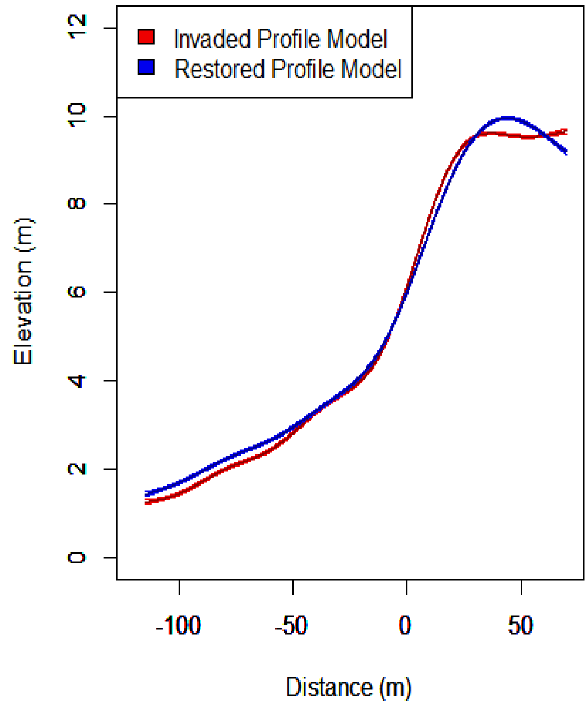

Figure 5. GAMs for foredune profiles in invaded and restored areas plotted with 95% confidence intervals showed different shapes for invaded and native foredunes, with a rounded peak in native foredunes and plateau-like shape in invaded foredunes.

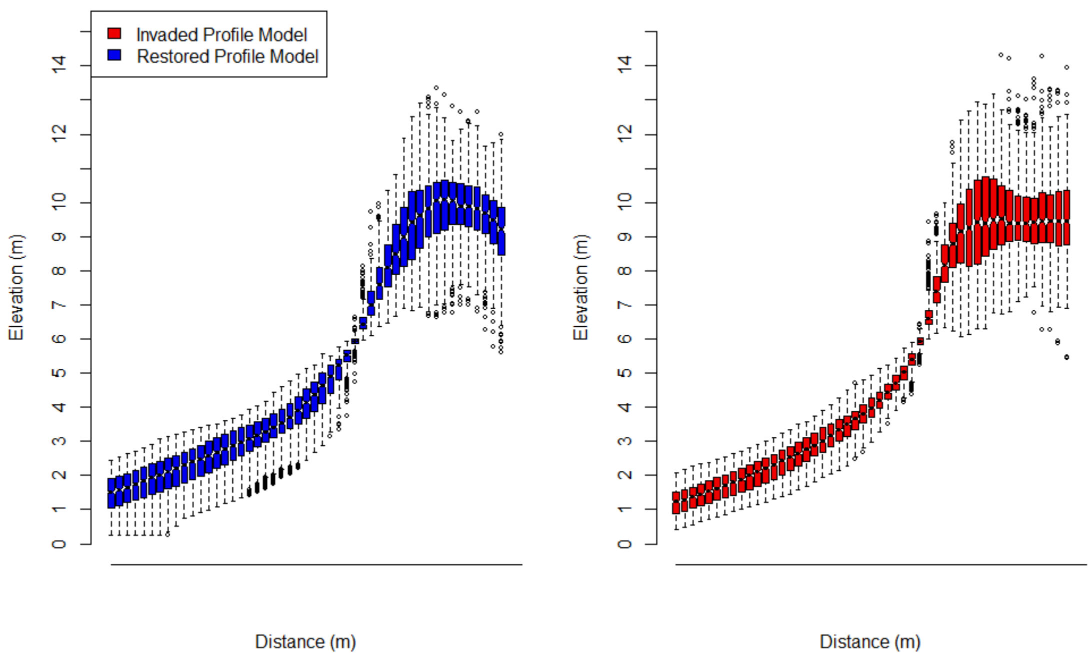

Figure 6. Boxplots around median profile elevations for restored (left) and invaded dunes (right) show a wide variation in profile shape, but most data points are tightly clustered.

Northings were the best predictor of dune heights, according to a linear model (r^2=0.24; p<<0.001), and and dune heights showed no significant correlation with restoration status (p= 0.876) (Figure 7). The isolated patch of undisturbed native dunes that was excluded from the analysis of restored and invaded foredunes was significantly higher than the restored and invaded dunes in the study area, according to a linear model controlling for the linear latitudinal elevation gradient (p<<0.001). The roughly sinusoidal GAM based on northings showed a complex repeating pattern of spatial autocorrelation in foredune elevation (Figure 7).

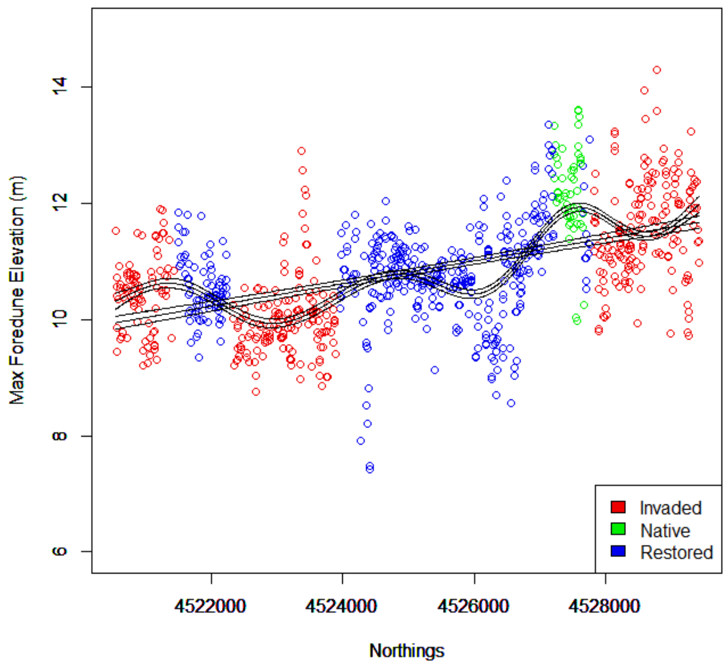

Figure 7. The maximum foredune elevations were linearly correlated with northings (r^2=0.24; p<<0.001) with higher foredunes to the north, and had no linear relationship to restoration (p= 0.876). The undulating GAM showed a more complex pattern based on northings. 95% confidence intervals are shown on both the linear model and the GAM.

Discussion

Although statistical testing and models supported the hypothesis that foredunes invaded by *A. arenaria* in the study area are steeper (p<<0.001), they did not support the hypothesis that they are taller than restored foredunes in the study area (p=0.748). The removal of *A. arenaria* did not result in foredunes that are significantly different in height from the surrounding invaded foredunes. The initial erosion and lowering of the dunes after restoration was photodocumented (Pickart 2014); however, they appear to have regrown to an equivalent height as of 2010. The restoration process did not completely remove the foredune structure built up by *A. arenaria*, so this study cannot address the question of the relative capacity of *E. mollis* and *A. arenaria* to build foredunes where they did not previously exist. The relatively undisturbed native section of Lanphere Dunes was excluded from analyses addressing the differences between restored and invaded areas. The excluded undisturbed native area was significantly higher than the restored and invaded foredunes according to a linear model controlling for the latitudinal elevation gradient (p<<0.001), but this site is unreplicated and the effect of vegetation is confounded by abiotic effects. This small native area provides insufficient evidence to determine relative dune-building capacity of *A. arenaria* and *E. mollis*; however, it shows that native plants can build relatively high dunes in certain circumstances.

The invaded dunes are not significantly taller overall, but their significantly steeper slope might be contributing to the misperception that they are higher than the more gradually sloping native dunes. *Ammophila arenaria*'s dense growth pattern and thick web of rhizomes might allow the foredunes to build up at a steeper angle. In contrast, native *E. mollis* might be allowing sand to move farther from the base of the foredune so that dunes build up gradually to a similar height with a peak further back from the shore. Although dune shapes vary widely, it is common to see invaded dunes in the study area with closely set double peaks of similar heights that would make the averaged shape of the dune plateau-like (personal obs. 2014). Native dunes in the study area often have a single, rounded primary foredune peak (personal obs. 2014). These shapes are reflected in the profile models, which are significantly affected by restoration status (p<<0.001) (Figures 5-6).

The increase in foredune height from south to north points to geological processes or historical events as the main causes of differing dune heights in the study area. The latitudinal gradient in elevation might reflect differing rates of sedimentation or the higher rates of subsidence on the southern end of Humboldt Bay (Williams et al. 2013). The undulating pattern in maximum dune heights over the study area might reflect natural patterns of sediment accumulation and erosion, or other abiotic factors (Figure 7). The morphology of foredunes depends on sand supply, vegetation cover and species composition, the rate of aeolian sand accretion and erosion, waves and wind forces, storm erosion, dune scarping and overwash processes, long term accretion or erosion of the beach, sea level, and the extent of human impact (Hesp 2002). A wide variety of stochastic events could be affecting the variation in foredune heights and shapes.

Although restored and invaded transects were evenly distributed from north to south to eliminate covariance with the linear elevation gradient (r<<0.001, p=0.906), location and restoration status are inherently confounded in this study. Models reflect the typical shapes, heights, and slopes within the study area at the time of LiDAR (Light Detection and Ranging) data collection. *Ammophila arenaria*'s dense growth might be the primary cause of the steep slope in invaded areas, but scarping and other circumstantial events might also be contributing to the differing shapes seen among native and invaded areas. Dunes continuously build, erode, and sometimes wash away over time, and the heights and profile shapes seen in this report might reflect the stages of the dunes' development in 2010 as well as any influence of geological processes, management history, or vegetation.

The use of elevation data from a DEM created from airborne LiDAR represents a source of error; however, the resolution of the 2009 - 2011 CA Coastal Conservancy Coastal Lidar Project: Hydro-flattened Bare Earth DEM is suitable for the scale of this study (Andrews 2002). The metadata for the DEM reported 50 cm horizontal root mean square error (rmse) and 9 cm vertical rmse, with at least 95% of the positions having an error less than or equal to 18 cm when compared to GPS survey grade points in generally flat, non-vegetated areas (CA Coastal

Conservancy 2012). The vegetation on the dunes could be negatively affecting the vertical accuracy of the model, especially where the vegetation density is particularly high and LiDAR might not be able to penetrate to the earth. This source of error would be more likely to overestimate the height of invaded dunes because they tend to be more densely vegetated. The max height and slope data are dependent upon the designated limits of the study area. The profile model shapes are dependent upon the placing of the baseline at the 6 m elevation contour, which approximates the elevation of the beginning of the foredunes. Profile model shapes could shift with different baseline designations. The profile models seen in this report are specific to the study area and the year the elevation data was collected (2010), and they are not intended to be extrapolated beyond these bounds.

Conclusion

The availability of remotely sensed high-resolution elevation data provided a way to conduct the extensive sampling needed to create models of a large, complex dune system. Creating randomly-spaced digital transects using GIS can be a powerful tool for topographical modeling. Manually collecting data with highly accurate RTK (Real Time Kinematic) GPS units to plot individual profile transects can provide valuable, precise information about change over time on individual transects. However, these methods are far more labor intensive and prohibitively costly for modeling on the scale of this study. Foredunes exist at a larger scale than humans can easily perceive from the ground, and their complex shapes and variability make them difficult to generalize. Creating models based on the vast data available from the remotely sensed DEM showed the overall shapes of restored and invaded foredunes within the study area in 2010, and demonstrated that they are not significantly different in height. The finding that restoration status is not a significant predictor of dune height is valuable for informing management decisions, especially in light of concerns voiced from community members that removing *A. arenaria* might be permanently lowering the height of the dunes. Additional high resolution LiDAR data is needed to verify the trend of these patterns over time, and to show how the dunes change over time, particularly after restoration. Expanding this study to other areas with invaded and restored or native foredunes could determine whether the results of this site study are typical for dunes vegetated by invasive *A. arenaria* and native *E. mollis*.

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