Dune Restoration and Shoreline Change, Humboldt Bay, California

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Introduction and Purpose

Coastal dunes at Humboldt Bay in northern California have been the focus of early and sustained restoration efforts. For more than two decades, a number of land managers have collaborated to attain ecosystem-level restoration of dune processes through the removal of invasive, overstabilizing, non-native species such as European beachgrass (*Ammophila arenaria*) and iceplant (*Carpobrotus edulis*) (Pickart 2013, Wheeler 2014). To date, over 6 km of shoreline has been restored along the North and South Spits (Fig. 1). Restoration results in increased biodiversity and is associated with population increases in the endangered Menzies' wallflower and beach layia (USFWS 2008, Doudna and Connor 2012, Pickart 2013, Wheeler 2014). Three years of monitoring of foredune morphodynamics at Humboldt Bay National Wildlife Refuge supports the hypothesis that removal of *Ammophila* and the recovery of native vegetation restores physical processes as well, with increased aeolian sediment transport beyond the foredune crest into the disturbance adapted plant communities located behind the foredune (Pickart 2014).

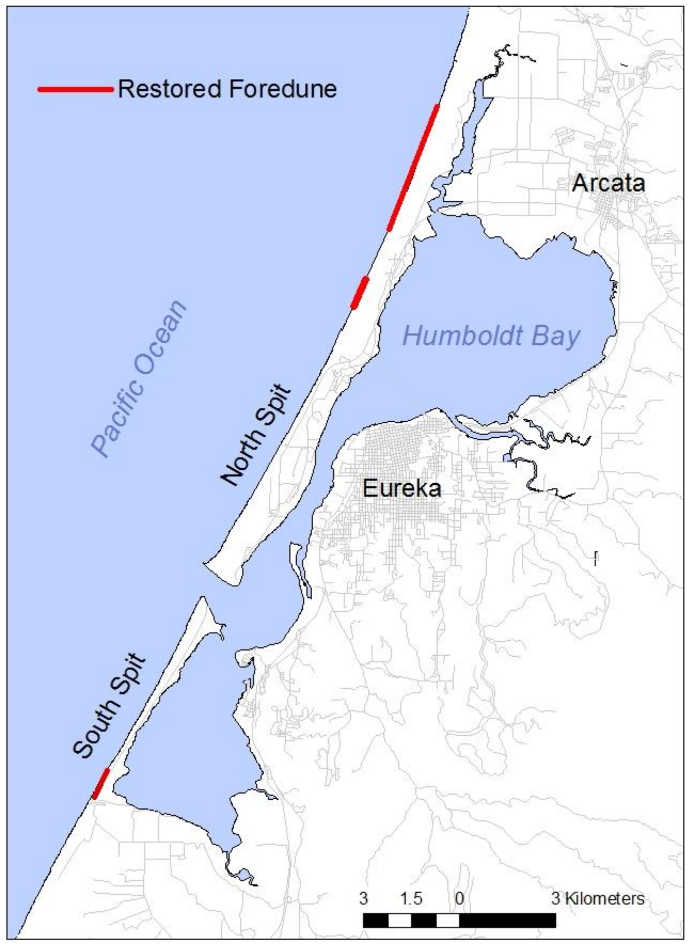

Fig. 1 Map of Humboldt Bay showing location of restored shoreline along the North Spit.

Recently, some public concern has been voiced over these restoration activities based on a perception that restoration lowers the foredune and increases its susceptibility to erosion (Walters 2011). To address concerns about erosion, this study analyzed spatial data obtained from historic air photos and present-day mapping to measure shoreline gain/loss between 1998 and 2012 along a 10.4-km stretch of shoreline on the upper North Spit that encompassed both restored and unrestored areas (Fig. 3). Present-day topographic features such as relict scarps preserved in the dune landscape were mapped on the ground with GPS to assist in interpretation of shoreline change in the context of vegetation and management. This study complements a concurrent study examining the effect of restoration on foredune height and morphology (McDonald 2014).

Site Description

The North Spit of Humboldt Bay is located within the Eureka littoral cell, which encompasses 64 km of shoreline from Trinidad Head to False Cape near Cape Mendocino to the south. Major features of the littoral cell include the Mad, Little, and Eel Rivers, the entrance to Humboldt Bay, the Eel River submarine canyon, and the coastal dune systems associated with Humboldt Bay and the Eel River estuary (Moffat and Nichol 2013.) The entrance to Humboldt Bay was stabilized between 1891 and 1900 through the placement of jetties at the base of both the North and South Spits (Costa and Glatzel 2002). The entrance to the bay is maintained for safe navigation through annual dredging by the U.S. Army Corps of Engineers. Currently, the Corps removes a minimum of 827,000 m^3 of sand annually, which since 1990 has been deposited outside of the littoral zone in an offshore disposal site (USACE 2012). As a condition of offshore disposal, the Corps of Engineers conducted monitoring of shoreline positions between 1992 and 2005 for a distance of 9.6 km north and south of the jetties. The study concluded that the trend for the lower North Spit was net erosion, and while the amount of erosion was below the Corps threshold criterion for excessive erosion (36.6 m), future disposal is planned to occur within the littoral zone (Moffat and Nichol 2013).

The study area lies along a high energy, dissipative beach-surfzone system (Wright and Short 1984). The wave climate close to shore has a strong seasonal signal. Long period swells (> 10 seconds) with 4.0 – 5.5 m wave heights predominate in winter, while smaller wave heights (1.8-3.7 m) and shorter periods (<10 seconds) occur in summer (Moffat and Nichol 2013). The long-period winter swells approach from west-northwest, while summer waves approach from a more northerly direction (Costa and Glatzel 1982). There is currently no consensus on the rate and direction of littoral transport of sediments, with a number of studies presenting evidence for both north-south and south-north net transport. Based on available evidence, Moffat and Nichol (2013) propose northward, storm-driven transport at deeper depths in winter, and southward, wind-wave driven transport of sediments at shallower depths in summer. A net northward transport may occur during El Niño storms, and net southern transport during milder winters. Both the Eel and Mad Rivers provide sediment to the dunes.

The sand dune system on the upper two thirds of the North Spit of Humboldt Bay consists of a transgressive dune field encroaching on an older, forested and stabilized, Holocene dune phases or phases (Fig. 2) (Cooper 1967, Leroy 1999, Pickart 2013).

Figure 2. A native foredune is shown from the Lanphere Dunes in Segment 2 (top) and an invaded foredune on private land in Segment 8 (bottom). The native foredune, vegetated with the *Elymus mollis* and Dune mat alliances, is punctuated by narrow blowouts and is fronted by a native incipient dune. The invaded foredune (vegetated with *Ammophila arenaria* seminatural stands) has relict foredunes behind the present day foredune, and shows a recent scarp with a sand ramp beginning to form. Both photographs illustrate the newer, more active episode of transgressive dunes encroaching on the older, forested and stabilized episode. Both photographs were taken on Sept. 27, 2013.

On its western margin, the dune system consists of a discontinuous and sometimes poorly-defined foredune punctuated by blowouts. A lower, incipient foredune forms intermittently to the west of the foredune. The presence of the incipient foredune may be linked to interannual climate cycles, or variation in storm frequency/intensity and sediment availability. To the east of the foredune lie deflation basins and/or plains, narrow, long-walled parabolic dunes (Hesp 1990), and larger, more inland trailing ridges that are at least in some cases, relicts of the older stabilized dune episode (Leroy 1999). The trailing ridges separate modern parabolic transgressive dunes that are encroaching on the older, forested dunes.

Foredune morphodynamics are highly influenced by vegetation (Hesp 1991, Hesp et al. 2005). Native vegetation on the foredune in the Study Area includes sea lyme patches (*Elymus mollis* alliance[1]) and dune mat (*Abronia latifolia – Ambrosia chamissonis* alliance) (Sawyer et al.2009). The latter alliance extends inland along vegetated, long-walled parabolic trailing ridges, with later-successional associations occurring on the older, relict trailing ridges. Deflation plains and basins support freshwater wetland vegetation, while the older, stabilized dunes are forested. Following its introduction as a sand stabilizer along the eastern margin of the spit in 1901, *Ammophila* spread both in areas of actively migrating parabolic/transgressive dunes and along the shoreline (Buell et al.1995), creating stretches of continuous, relatively uniform foredune supporting dense European beachgrass swards (*Ammophila arenaria* semi-natural stands) (Fig. 2).

Methods

The study area consisted of a 10.4-km stretch of shoreline, including all of the restored foredune on the North Spit, as well as interspersed and adjacent unrestored stretches of foredune (Fig. 3). The juxtaposition of restored and unrestored sections of shoreline allowed for underlying alongshore patterns to be discerned and accounted for. Littoral processes such as sediment transport, wave energy and rip currents commonly vary alongshore, and can result in patterns of erosion (Thornton et al. 2007) that could potentially mask or exaggerate management effects. The region lies along a fold and thrust belt near the southern end of the Cascadia subduction zone (Clarke and Carver 1992), resulting in differential subsidence rates alongshore (Cascadia GeoSciences 2013). In addition, a topographic gradient along the foredune zone from south to north is evident from the 2010 LiDAR, and was confirmed by McDonald (2014).

1.*Leymus mollis* alliance per Sawyer et. al. 2009 (name here reflects recent taxonomic revision).

The study area included the zone between the upper limit of the backshore (western-most limit of dune vegetation through all years and as defined below) east to the most westward positioned deflation plain or zone of deflation basins (Fig. 4). This zone encompassed all shoreline advance and retreat that occurred during the period of study. For the purpose of this study, “shoreline” is defined as the westernmost limit of vegetation that exceeded 30% coverage at a given time period. This threshold was used in part due to the difficulty of determining the exact position of the foredune base or crest on air photos. Since air photos are two dimensional, vegetation cover was used as a proxy for the presence of a foredune crest or stoss slope, or an incipient foredune. Available overlapping printed air photos were examined with a stereoscope to confirm topography when possible. Field checks were conducted in summer 2014 over parts of all management segments to confirm the validity of the 30% threshold in the present-day landscape.

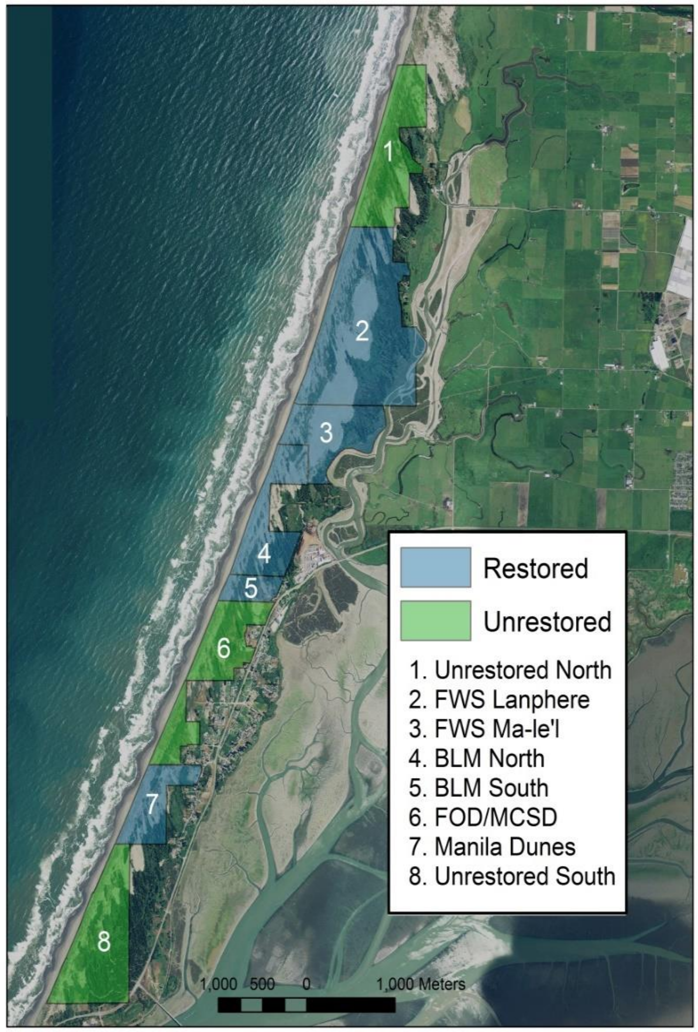

Figure 3. Dune parcels and management.

The study area was stratified into eight segments of different ownership and/or management history (Fig. 3, Table 1). Three of the areas had never been managed, and five were restored at different times between 1992 and 2010. A 250-m stretch of the Lanphere Dunes that had never been invaded was omitted because of its unique history and lack of alongshore replication. Shoreline position (as defined above) was mapped as a linear feature on three sets of imagery: January 1998, January 2000, and summer 2012. Where blowouts occurred, the shoreline was connected up between the blowout walls. The 1998 imagery had some rectification errors, so features were realigned where necessary based on their relationship with modern landmarks such as persistent patches of vegetation.

A sample of 100 points was randomly selected along each segment of each year's shoreline using the "sample" tool in ArcMap 10.1. A minimum distance of 2 m between points was maintained to ensure independence of measurements. The "near" tool was used to calculate the positive (progradation) or negative (erosion) distance between the sample points and the shoreline for two time intervals: 1998-2000 and 2000-2012. Two-way analysis of variance (ANOVA) was used to determine whether mean shoreline gain/loss differed between time intervals and among segments, and Student-Newman-Keuls post-hoc multicomparisons were used to locate differences. Linear regression was employed to test for an underlying north-south gradient.

Figure 4. Eastern edge of the Study Area is indicated by the dotted line; arrows show juxtaposition of westernmost deflation basins (Photo Dave Kenworthy 2014).

Table 1. Length, ownership and management history of shoreline segments in Study Area.

Segment	Name	Length (km)	Owner	Management
1	Unrestored North	1.73	Private/USFWS	Unrestored
2	FWS Lanphere	1.91	USFWS	Restored 92-97
3	FWS Ma-le'l	0.44	USFWS	Restored 05-10
4	BLM North	1.45	BLM	Restored 97-04
5	BLM South	0.30	BLM	Restored 05-07
6	FOD/MCSD	1.84	FOD/MCSD	Unrestored
7	Manila Dunes	0.89	MCSD	Restored 92-98/00
8	Unrestored South	1.81	Private	Unrestored

Results

Mean shoreline gain/loss for all management segments by time interval is shown in Figs. 5-6. In the two-way ANOVA, both factors (management segment and time interval) were significant ($p<.001$), as was their interaction. Net shoreline change was negative (erosional) for both time intervals overall. The earlier, two-year interval (1998-2000) experienced almost twice as much mean erosion (-9.8 m) as the later period (-5.2 m). A post-hoc ($\alpha=.05$) multiple comparison (Student-Newman-Keuls) identified six groups of homogeneous means for management segments (Table 2). Manila Dunes had significantly greater erosion than all other sites, while Lanphere Dunes had significantly less. The distribution of means in the north-south oriented horizontal axis of Fig. 5 suggested a possible north-south gradient in erosion, at least in time interval 1. A linear regression of distance gain/loss on Northing confirmed that erosion decreased from south to north for the two time intervals combined (adj. $R^2=.129$, $p<.001$). This association was much stronger for the first time interval ($R^2=.283$) than for the second ($R^2=.024$). Although both time intervals showed net shoreline loss, the amount of erosion/accretion occurring at each sample point in interval 1 was inversely correlated with that of interval 2 ($R=-0.357$, $p<.001$).

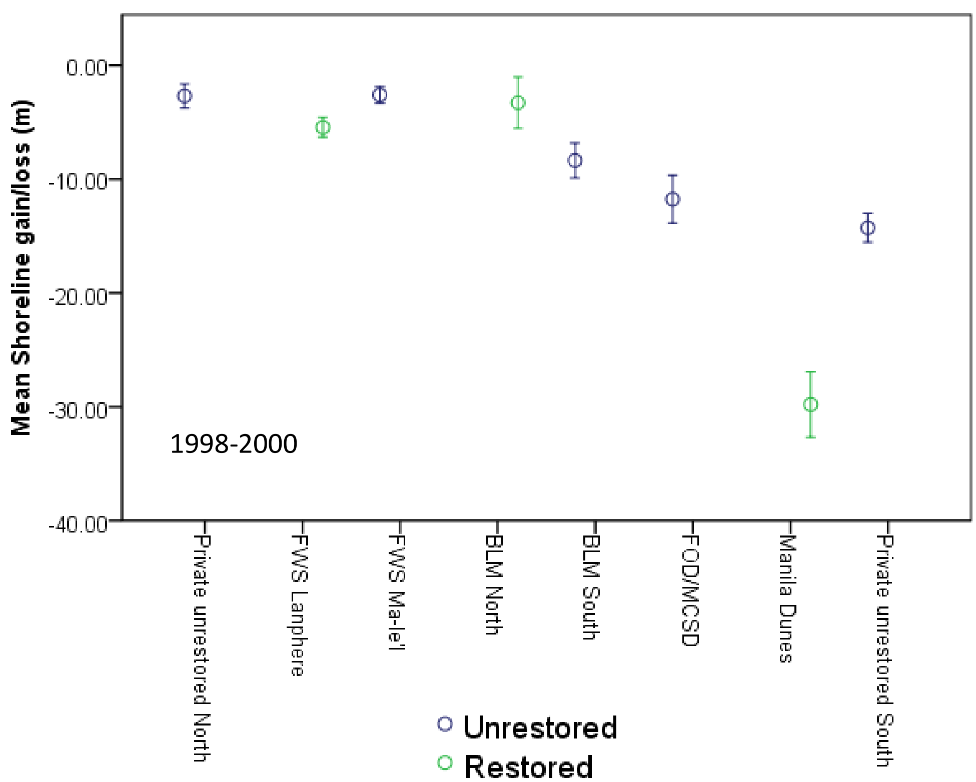

Figure 5. Mean shoreline gain/loss (m) by management segment for time intervals 1998-2000 .Error bars represent 95% Confidence Intervals.

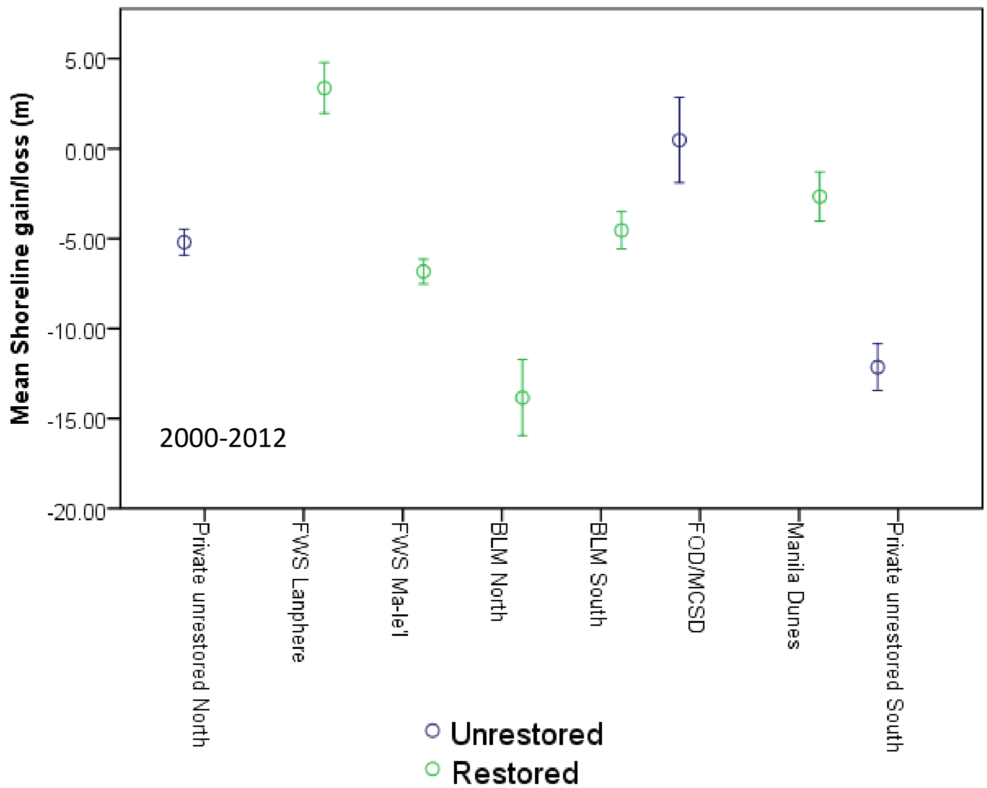

Figure 6. Mean shoreline gain/loss (m) by management segment for time interval 2000-2012. Error bars represent 95% Confidence Intervals.

Table 2. Homogeneous subgroups of management segments over both time intervals 1 and 2. Means for are displayed for shoreline gain/loss (m) by management segment for both years pooled. Means within a homogeneous group are not significantly different from each other (p<.05).

		Subset					
Management Segment	N	1	2	3	4	5	6
Manila Dunes	200	-16.2258					
Private unrestored south	200		-13.2101				
BLM North	200			-8.5660			
BLM South	200				-6.4504		
FOD/MCSD	200				-5.6435	-5.6435	
FWS Ma-le'l	200				-4.7188	-4.7188	
Private unrestored north	200					-3.9466	
FWS Lanphere	200						-1.0348

Discussion

Net erosion occurred over the entire Study Area during the period 1998-2012, with greater losses in the period 1998-2000 compared with 2000-2012. These results are consistent with a previous study conducted by the Army Corps of Engineers that revealed a trend of shoreline erosion along the North Spit and accretion on the South Spit between 1997 and 2005. However, their study was limited to the lower 9.6 km of the North Spit, overlapping a distance of only 1.6 km with the 10.4-km-long site of this study. Notably, the area studied by the Corps included only 0.3 km of restored shoreline

The significant interaction between time interval and management segment was caused by the differing erosion trends of the segments in each time interval (Figs 7-8). Although erosion was 50% lower in the second time interval, the location of erosion with respect to management segment differed from interval 1, and was to some extent, inversely correlated, suggesting shoreline equilibration over time.

It seems likely that the greater erosion measured in the first time interval was due at least in part to the 1997/98 El Niño, which, together with the 1998/99 La Niña, caused excessive erosion over much of the Pacific Northwest (Allan and Komar 2002, Ruggiero et al. 2005). In other parts of California and Oregon, dune and bluff erosion during these El Niño/La Niña winters was observed to be highly localized within a given stretch of shoreline (Allan and Komar 2002). A similar pattern of localized erosion is evident from the record of aerial and ground photographs for the North Spit, and this pattern does not correspond to management. In terms of length of shoreline affected, erosion was greater in the southern half of the spit during the first time interval, whereas the majority of restoration during that interval was located in the northern half (Fig. 7). However, the parcel with the greatest amount of erosion in the first interval was Manila Dunes, a restored site in the south. Significant vertical scarping occurred at this site during the La Niña winter of 1998/99. Restoration was not yet completed over the entire length of the site, and the scarp encompassed both restored and unrestored areas (Fig. 9). During the second time interval, this area eroded very little compared to the *Ammophila*-dominated, unrestored foredunes immediately to the south. Similar localized scarping can be seen along the unrestored, *Ammophila*-dominated Ma-le'l shoreline in the winter of 1995/96 (Fig. 10), and along a stretch of native foredune on the restored Lanphere shoreline following the winter of 2005/06 (Fig. 11).

Over the period of this study, the pattern of erosion and accretion do not correspond with management, but rather with a general north-south trend of increasing erosion, stronger in the first time interval, superimposed with localized pockets of greater erosion. The north-south trend may reflect a gradient of decreasing sediment

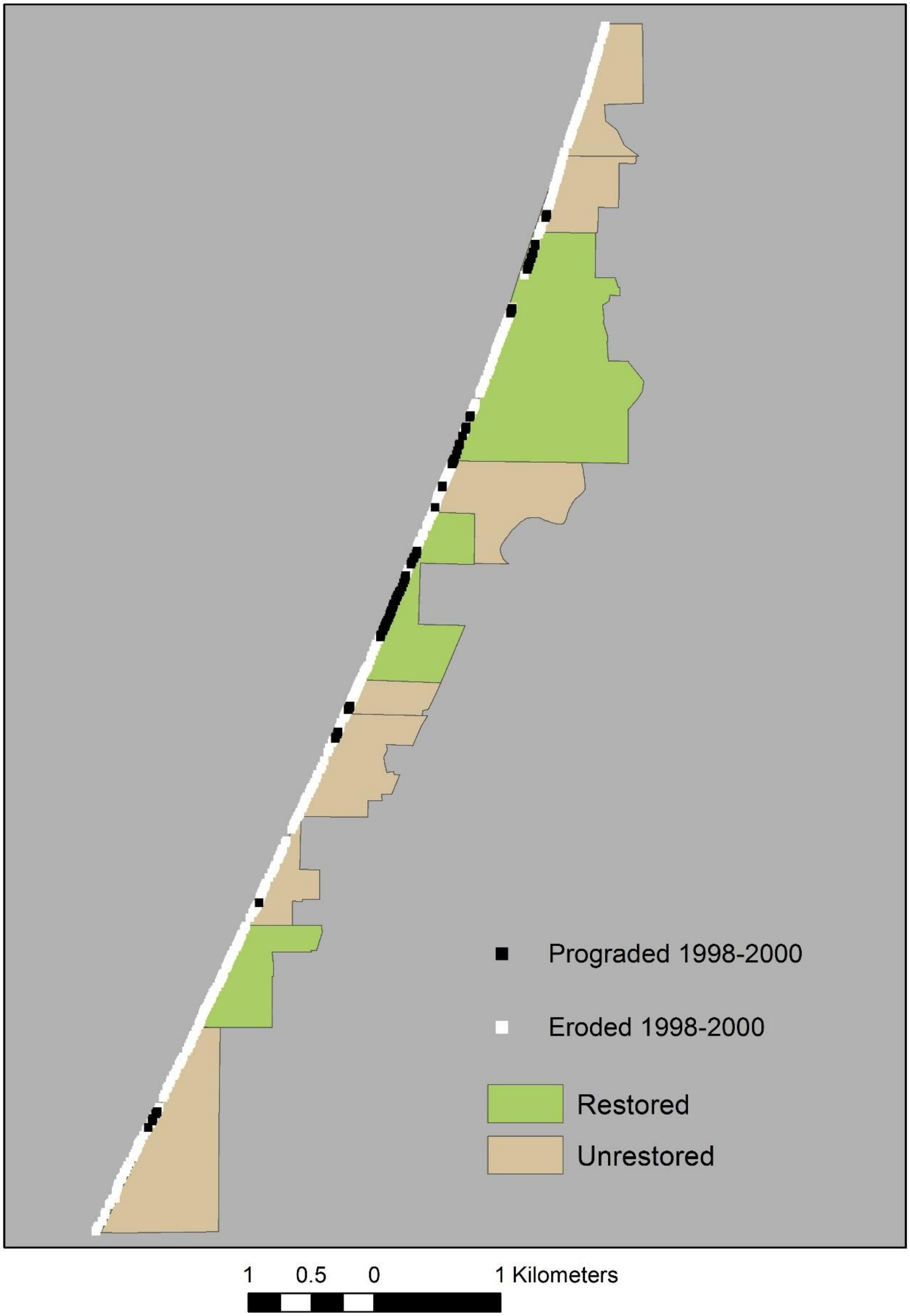

Figure 7. Areas of net shoreline gain (progradation) and loss (erosion) by management type for time interval 1998-2000.

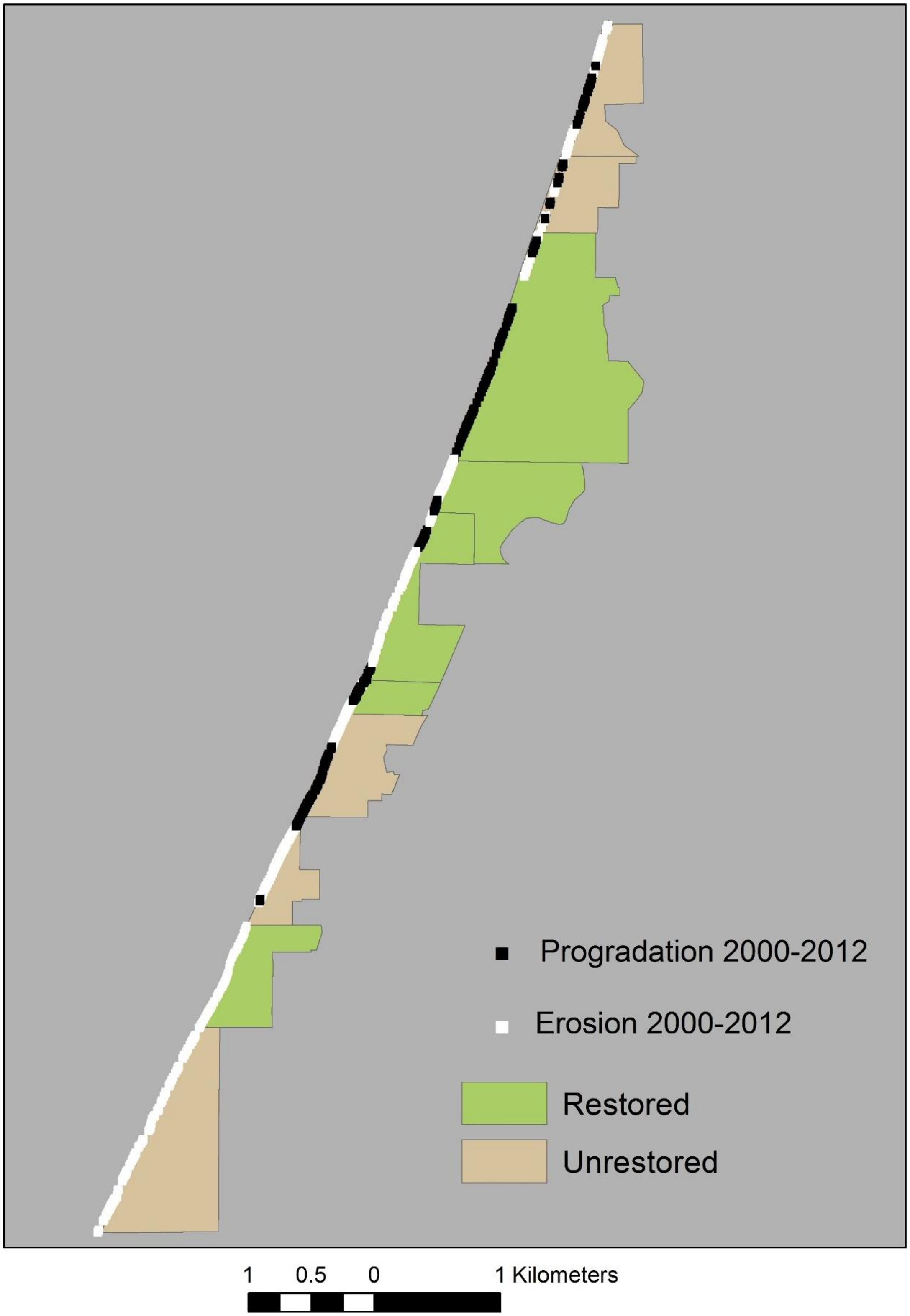

Figure 8. Areas of net shoreline gain (progradation) and loss (erosion) by management type for time interval 2000-2012.

Figure 9. Scarping and collapse of foredune at Manila Dunes from winter 1998/99 in restored (above) and unrestored, Ammophila dominated foredune (below). Date of photographs June 16, 1999. (Photos: Kyle Wear).

Figure 10. A section of unrestored, *Ammophila*-dominated foredune on the Ma-le'l Dunes Unit following a scarping event in winter 1995/1996.

Figure 11. A section of native foredune on the Lanphere Dunes Unit following a scarping event in winter 2005/06.

supply, which would be consistent with the north-south decrease in foredune height (McDonald 2014). Sediment supply may also be affected by the removal of dredge material from Humboldt Bay to the deepwater disposal site since 1990, bypassing potential longshore transport from the mouth of the bay northward. An alongshore gradient could also potentially be associated with the documented 1.2 mm/year differential in subsidence rates between the mouth of the Mad River slough in North Bay and the mouth of the Bay (Cascadia Geosciences 2013). The superimposed pattern of localized erosion could be caused by variation in alongshore processes such as rip currents, which have been shown to create beach megacusps and associated dune erosion at a Monterey, California dune system (Thornton et al. 2007). Additional study is needed to determine whether rip currents drive patterns of alongshore erosion on the North Spit.

Although this study did not examine enough imagery dates to quantify a relationship between ENSO (El Niño Southern Oscillation) cycles and net shoreline erosion, research elsewhere on the West Coast has demonstrated that ENSO is a strong driver of shoreline erosion (Revell et al. 2002, Storlazzi and Griggs 2000). The increased wave heights and sea levels associated with higher intensity El Niño winters are more likely to generate storm surges and wave energy able to undercut the foredune. ENSO may also play a role in the cycle of incipient foredune building and erosion observed on the North Spit, but more research is needed to examine this relationship.

Conclusions

For the time interval covered in this study, no relationship was found between restoration activities and shoreline/dune erosion. Susceptibility to erosion appeared to be distributed along a general north-south gradient reflecting background processes such as sediment supply or subsidence, superimposed with a more intermittent pattern that may be related to alongshore processes such as rip currents. An overall trend of shoreline loss was observed, similar to that documented by the Corps of Engineers in their study of beach erosion to the south from 1992-2005. While it is possible that erosion is exacerbated by removal of sediments from the littoral zone by the offshore disposal of dredged material from Humboldt Bay, it is clear that this erosional trend will continue over the long-term, regardless of sediment management, as sea level rise accelerates. Landward translation of the foredune occurs with sea level rise (Davidson-Arnott 2005), and maintaining non-native vegetation such as European beachgrass cannot prevent this migration from occurring. However, the presence of overstabilizing vegetation could potentially interfere with the process of translation by preventing sediment from reaching and overtopping the foredune crest, resulting in sediment bypassing of the beach-foredune sand-sharing system. Ongoing monitoring at

Humboldt Bay National Wildlife Refuge will hopefully shed light on this complex system and its drivers.

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