Understanding Geomorphological Changes of Dunes after Invasive Plant Species Restorations

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ABSTRACT

Coastal sand dunes serve as natural buffers against tides and storms. Invasive plant species with deep roots and rhizomes may over stabilize coastal dunes which can lead to their depletion and in turn eliminate the buffering services they offer. In 2011, the dunes just south of Abbott's Lagoon in Point Reyes National Seashore underwent a series of invasive species plant restorations where *Ammophila arenaria* (European beachgrass) and *Carpobrotus edulis* (ice plant) were removed via mechanical or herbicidal treatment. Using GIS, I attempted to see how the Abbott's Lagoon sand dunes have changed in elevation, slope, and aspect since the restorations started while also trying to see if there was a statistically significant difference between the mechanically and herbicidally treated areas. Since the start of the restorations, the area that was mechanically restored has undergone larger decreases in elevation and slope than the herbicidally treated areas. Over the 8-year difference between the geomorphic data, the mechanically treated phase on average decreased by -0.19m while the next closest herbicidally treated phase decreased by only -0.04m on average. As for the slope change, the mechanically restored phase on average decreased -3.46 degrees between 2010 and 2016 and -4.92 degrees between 2010 and 2018, the largest average decrease compared to the herbicidally treated phases. The mechanically treated area also saw the largest average aspect change between 2010 and 2016, shifting 14.41 degrees clockwise on. The higher deflation and destabilization rates in the mechanically treated area suggest that it is the most effective at removal and prevention of invasive species. While the mechanically treated area was the more effective restoration technique, it is important that the dunes are planted with native vegetation, so they do not become too destabilized and deflated, as that also leads to its erosion and loss of buffering ability.

KEYWORDS

8-year change, 6-year change, Abbott's Lagoon, Mechanical Treatment, Herbicidal Treatment

INTRODUCTION

Invasive plant species have the potential to cause great damage to ecosystems. They may upset the balance of the ecosystem they invade by outcompeting native species, altering environmental conditions and changing resource availability (D'Antonio and Vitousek 1992). In addition to this they may modify existing disturbance regimes or introduce new disturbances that can result in a change of community structure and ecosystem function (Mack and D'Antonio 1998). With the intensity and frequency of climate change related events increasing, many areas are expected to see increases in invasive plants. For example, in Australia, it is predicted that the spread of the non-native woody vine species *Cryptostegia grandiflora* and woody perennial legume *Acacia nilotica* ssp. *indica* will increase due to climate change (Kriticos et al. 2003a: Kriticos et al. 2003b) while in the Southeastern United States it is expected that because of climate change, the invasive plant species kudzu (*Pueraria lobata*), privet (*Ligustrum sinense; L. vulgare*), and cogon grass (*Imperata cylindrica*) are expected to greatly increase in range (Bradley et al. 2010). In response to the spread of invasive plants, many areas affected have undergone restoration projects that try to remove non-native plant species in defined areas.

After a habitat restoration is carried out, there are factors that may determine how successful reinvasion efforts from non-native species are. Post removal of an invasive plant often results in high resource availability, weak competition, and limited native propagules compared to non-native propagules (Gabler and Siemann 2012). This may result in fast reinvasion progress after removal (Kettenring and Adams 2011). Spatiotemporal variation in abiotic factors such as temperature and water availability, propagule pressure, and exotic propagule availability and longevity may also determine how successful reinvasion efforts are (Gabler and Siemann 2012). Additionally, the restoration or management technique play roles in how effective invasive plant removal projects are (Gabler and Siemann 2012).

Coastal dune systems are eolian sand systems composed of narrow strips of land, meters to kilometers wide, that run along the coast and are present at all latitudes (McLachlan 1991). Under natural conditions, dune structures continually change due to wind and wave action, creating morphologically and floristically distinct foredune and back dune communities (NPS 2015). Coastal dunes also serve as natural buffers against tides and surges (Pries 2008). Due to climate change, effects such as increased sea levels, increased precipitation, and more frequent and intense storms are expected to happen (U.S. EPA 2009). Because of these events, the buffering abilities coastal dunes offer need to be preserved. The spread of non-native plant species will greatly alter the resilience of the ecosystem under climate change. Non-native plants that have deep roots and rhizomes, such as *A. arenaria* (European beachgrass) and *C. Edulis* (ice plant), stabilize the sand dunes which in turn slow down the movement of sand and change the sand deposition patterns (NPS 2015). Over stabilized dunes are more susceptible to coastal squeeze (Millington et al. 2010), which is the process in which coastal margins become squeezed between a fixed landward boundary and rising sea levels, leading to the shrinkage of that ecosystem (Schleupner 2008). With the shrinkage of the coastal dune ecosystems, the buffering services we gain that protect against increased sea levels will be eliminated (NPS 2015).

In 2011 an area south of Abbott's Lagoon in Point Reyes National Seashore, located in Marin County north of San Francisco, started to undergo a restoration project to remove invasive European beachgrass and ice plant. Two treatment types were used during the restoration, a mechanical treatment and an herbicidal treatment (Parsons et al. 2020). Monitoring the elevation, slope, and aspect of the sand dunes may aid in evaluating how effective the restorations are and show if the dune's buffering abilities are regenerating or degenerating. In this project I attempt to look at how the Abbott's Lagoon restoration has affected the dunes' elevation, slope, and aspect. In addition to this I will also look to see if treatment type, mechanical or herbicidal, plays a difference in how each structural variable has changed. Lastly, I try to create linear regression models to predict elevation and slope change based on a series of dependent variables. Plant roots help to stabilize sand dunes (Gómez-Pina et al. 2002). If the restoration was successful, there should be more destabilization and the deflation of the sand dunes due to less plant material anchoring the sand down.

METHODS

Study Site and previous restoration efforts

In 2011 a restoration project to remove the invasive European beachgrass and ice plant was undertaken in Point Reyes National Seashore just south of Abbott's Lagoon (38.1147, -122.9536).

The project consisted of 4 phases (Parsons et al 2020). The first phase included mechanically removing beachgrass with bulldozers and burying the biomass under 3 ft. of sand with the addition of hand removal of beachgrass and ice plant (Parsons et al. 2020). Overall, 80 acres of beachgrass and ice plant were removed (Parsons et al 2020). However, the mechanical removal required the hiring of contractors and proved quite expensive so in order to save costs, Phase II consisted of an experimental herbicide treatment (Parsons et al. 2020). During this phase, two herbicide solutions were spot sprayed on European beachgrass in the marked restoration sites (Parsons et al 2020). One solution consisted of 7% glyphosate with 1% imazapyr while the other solution consisted of 2% glyphosate and 1% imazapyr (Parsons et al 2020). The herbicide treatment used here proved successful and overall, 35 acres of European beachgrass was removed and the sites only needed only 16 hours of retreatment in the fall of 2012 (Parsons et al 2020). Due to the success of phase II, a third phase was enacted in the fall of 2012 using a combination of herbicide treatment and mechanical removal (Parsons et al 2020). The solution used in this treatment was composed of 2% glyphosate and 1.5% imazapyr (Parsons et al 2020). This phase removed 30 acres of European beachgrass and some retreatment occurring in 2013 (Parsons et al 2020). Lastly, in 2015, a 4th treatment phase was undertaken to remove invasive beachgrass. This treatment phase also used an herbicidal treatment (Parsons et al 2020).

Phase	Treatment	Year	Acres	Color
I	Mechanical	2011	80	
II	Herbicidal	2011	35	
III	Mech/Herb	2012	30	
IV	Herbicide	2015	11	
Control	None			

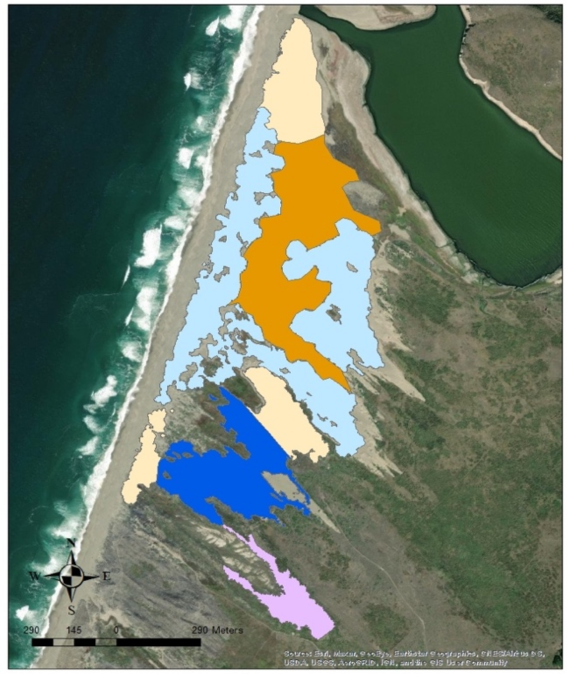


Figure 1. Map and table showing the different phases of the Abbott's Lagoon Restoration.

Lidar data sources

To get the data I needed to find the elevation, slope, and aspect change of the restoration site, I used lidar data of the Abbott's Lagoon area collected from 2010, 2016, and late 2017-2018. The 2010 lidar was collected from the Golden Gate Lidar project and was taken between late July and mid-August of 2010. The 2016 lidar was collected from the West Coast El Nino project between late April and early may of 2016. The 2017-2018 data was collected from the NorCal Wildfire project and was taken early December of 2017 and late April of 2018. Due to most of the NorCal Wildfire project being done in 2018, I assumed that the Abbott's Lagoon coverage was done in 2018. The 2010 Lidar had a point density of 3.33pts/m^2 while the 2016 Lidar had a point density of 11.43 pts/m^2. The 2018 Lidar data had a point density of 16.7 pts/m^2.

Lidar conversion

To convert the lidar point data into a map I could analyze, for each individual lidar set I took the ground categorized points and exported them to ArcMap. In ArcMap I used the LAZ to DEM tool to convert the Lidar point data to a DEM raster file. I made each cell size 1 x 1 meter resolution and used an inverse distance weighted interpolation method to interpolate the cells. I then clipped each DEM to the Abbotts Lagoon Restoration shapefiles I received or created to help make the data processing quicker and more efficient.

Dune structural changes post Abbott's Lagoon restoration

Once I had the Abbott's Lagoon DEMs that showed the elevation for 2010, 2016, and 2018, I was able to find the slope for each DEM in ArcMap using the slope tool and the aspect using the aspect tool. Once I had the elevation, slope, and aspect from 2010, 2016, and 2018, I was able to use the raster calculator to generate maps that show the difference in elevation, slope, and aspect between 2010 and 2018 (8-year), and 2010 and 2016 (6-year). Unfortunately, the 2016 lidar data did not cover the entire extent of the Abbott's Lagoon restoration and because of this I had to exclude Phase IV from the 6-year analysis. Additionally, I chose to treat Phase III, the phase that received a mixed treatment of mechanical and herbicidal removal like it was solely herbicidally treated due to it only being mechanically treated in wetlands and around 25 ft. buffers from ranchlands (Parsons et al. 2020).

Effectiveness in different restoration techniques on dune structure

To quantify how the different treatment methods affected dune structure and to see if one had a greater effect than the other, I created a uniformly spaced grid of sample points in ArcMap that covered the Abbott's Lagoon Restoration site. Each sample point was spaced 10 meters apart from one another. I used the elevation, slope, and aspect maps that I had generated from the previous question and extracted the elevation, slope, and aspect from 2010, 2016, and 2018 to each sample point. I exported all the data into Microsoft Excel where I found the 8- and 6-year differences in elevation, slope, and aspect for each sample point by subtracting the 2018 data from the 2010 data and the 2016 data from the 2010 data. After the differences were calculated, I sorted the points based off treatment type and the elevation of the sample point in 2010 to control for similar environments the dunes were exposed to. The elevation categories I sorted the data into were 5-10m, 10-15m, and 15-20m. These were the only elevation categories I created because these were the only elevations that had sample points in the mechanically treated, herbicidally treated, and control areas present. The treatment types the points were labeled with were either mechanically treated (Phase I), herbicidally treated (Phase II, III, and IV), or control (the native dune land area in between both sides of Phase I). For each elevation class, I ran a Kruskal Wallis and Dunn's test in RStudio (RStudio Team 2021) for the 8- and 6-year changes in elevation, slope and aspect. If the p-values generated from the tests were less than 0.05, the difference in that variable was considered statistically significant.

Linear regression model analysis

To make linear regression models to predict 8- and 6-year elevation change, I used the elevation from 2010 and treatment type as the dependent variables. To make the linear regression models to predict 8- and 6-year slope, I used the slope values from 2010 and the treatment type as the dependent variables. I then log transformed the 8- and 6-year elevation and slope change as well as the elevation and slope from 2010 to better fit the linear regression model assumptions. To log transform the variables that had negative values, I added the largest negative sample value plus 1 to each sample as a constant. This made the minimum value of the range the log of 1. Once this was completed, I ran the regressions in RStudio (RStudio Team 2021).

RESULTS

Geomorphological changes post-restoration

Elevation change

The raster analysis shows that there were phases that both increased and decreased in average elevation over the 8-year period. During this time interval, Phase I, the mechanically treated site, showed the largest average decrease with a decrease of -0.19m. This is followed by Phase III and then Phase IV. Phase II and the control site both showed increases in height over the 8-year period. What is interesting is that all the sites showed an average increase in height from the years 2010 to 2016 and then decreased in height in the 2 years before 2018 (Table 1).

Table 1. 8 and 6 year mean elevation change.

Treatment site	Temporal change (yr.)	Mean elevation change (m)	Min. (m)	Max. (m)
Phase I	8	-0.19 (1.15)	-5.79	5.85
	6	0.44 (2.43)	-7.21	14.52
Phase II	8	0.16 (0.4)	-1.79	2.21
	6	0.30 (1.50)	-8.01	13.91
Phase III	8	-0.04 (0.33)	-3.41	2.33
	6	0.06 (1.23)	-11.21	13.91
Phase IV	8	-0.02 (0.18)	-1.91	1.36
	6	No data	No data	No data
Control	8	0.22 (0.38)	-4.63	2.9
	6	0.27 (1.10)	-4.42	13.82

Phase I had the largest proportion of its area erode and accumulate 2 or more meters in elevation over the 8-year period. Phase I was also where the largest difference in erosion, 5.79m, and accumulation, 5.85m were found during the 8-year time period. The other phases showed that the majority of their elevation changes ranged between 1 m of erosion and 1 m of accumulation (Figure 2b). In the 6-year elevation change, most of the area for all phases looked to only erode or accumulate 5 m (Figure 2a)

a) b)

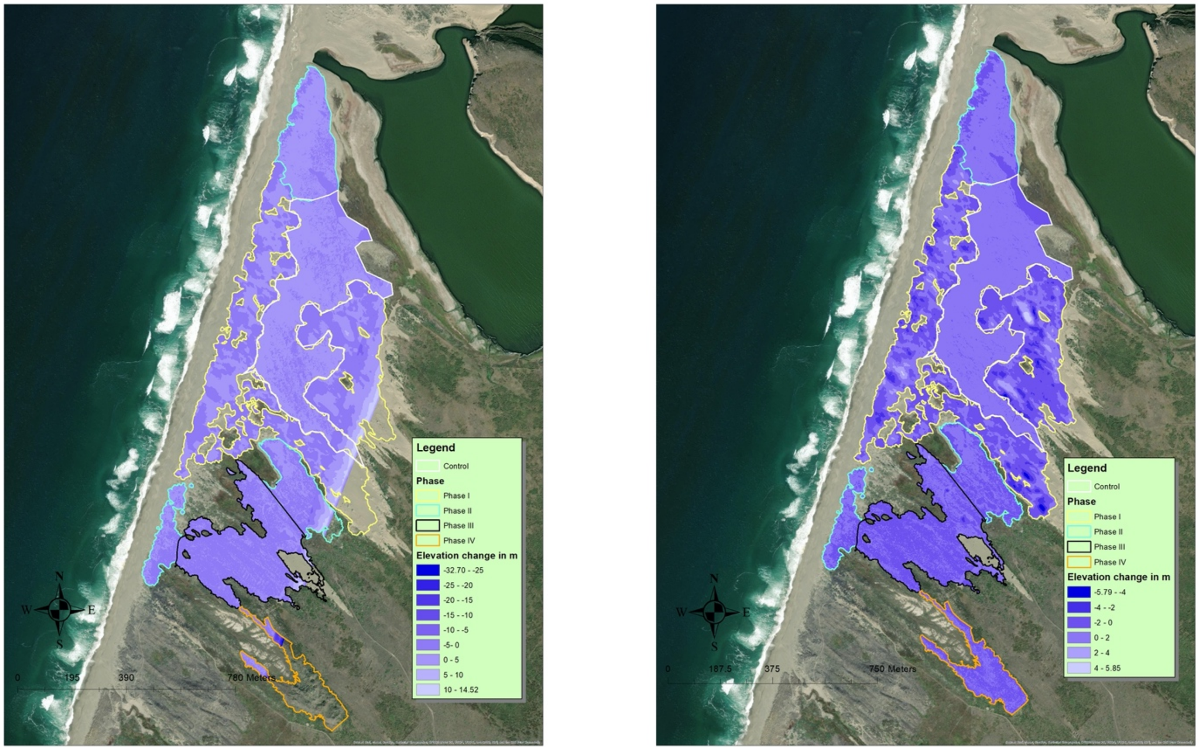


Figure 2. 6- and 8-year elevation changes. Elevation change from 2010 to 2016 (a) and elevation change from 2010 to 2018 (b).

Slope Change

Similar to elevation, the slope analysis showed that there were phases that both increased and decreased in slope. Over the 8 years since the start of the restoration, Phase I showed the greatest average decrease in slope per sample location with an average decrease of -4.98 degrees. Phase I was the only treatment site that experienced an average decrease in slope for each time interval, 6 year and 8 year, as well. Phase II experienced the second largest average decrease in slope over the 8-year period, followed by Phase IV. Phase III and the control site both experienced an average increase in slope. For the 6-year slope change, all the other phases increased on average (Table 2).

Table 2. 8 and 6 year mean slope change.

Treatment site	Temporal change (yr.)	Mean slope change (deg)	Min. (deg)	Max. (deg)
Phase I	8	-4.92 (6.37)	-43.47	34.47
	6	-3.46 (7.93)	-42.85	61.80
Phase II	8	-0.56 (4.74)	-28.63	36.14
	6	0.14 (6.06)	-29.57	64.15
Phase III	8	0.05 (4.42)	-29.92	31.53
	6	0.47 (5.02)	-28.72	63.86
Phase IV	8	0.10 (4.42)	-19.48	28.05
	6	No data	No data	No data
Control	8	6.64 (4.73)	-0.01	43.69
	6	0.32 (3.77)	-26.55	0.01

During the 8-year change, the Phase I treatment site showed the largest proportion of its area that underwent a decrease in slope of more than -15 degrees. The other sites for the most part underwent slope changes of positive or negative 15 degrees. Excluding the control site, the herbicide treatment plots have a higher area of slope increase to site size ratio than Phase I, the mechanically treated site (Figure 3d). The slope in Phase I decreased more from 2010 to 2016 than it did from 2010 to 2018 (Figure 3c and 3d).

c) d)

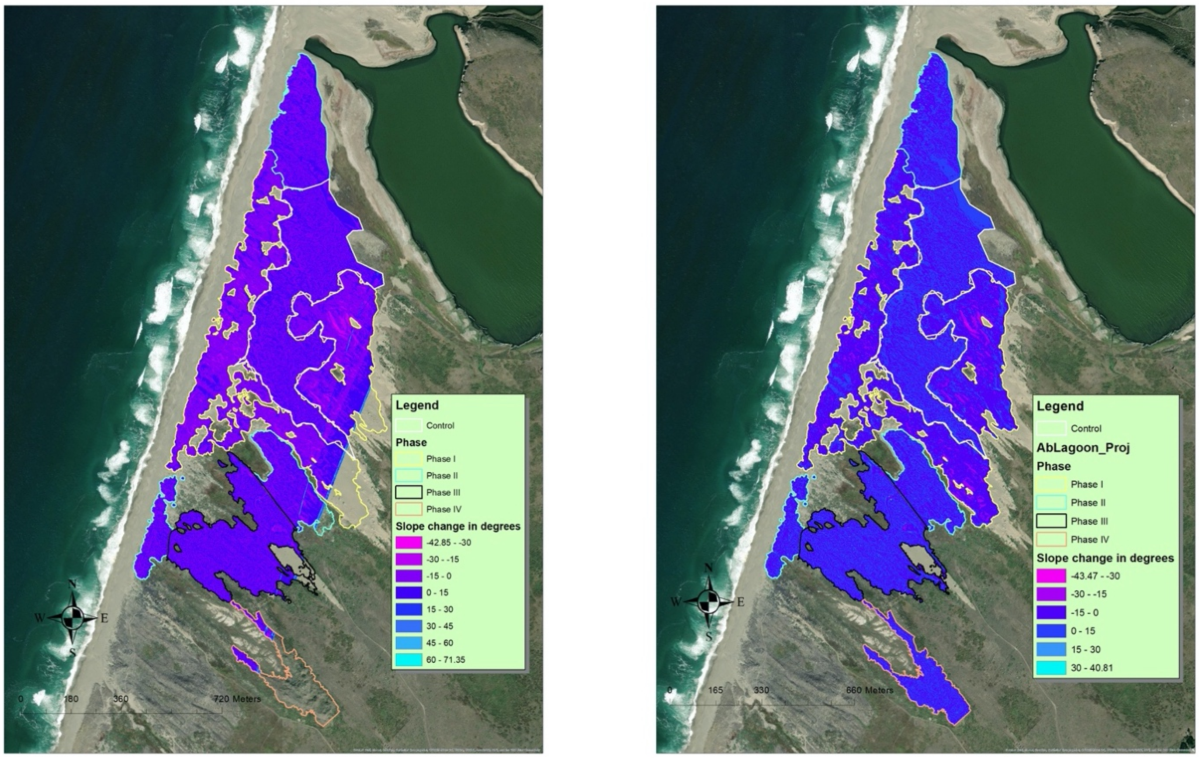


Figure 3. 6- and 8-year slope change. Slope change from 2010 to 2016 (c) and slope change from 2010 to 2018 (d).

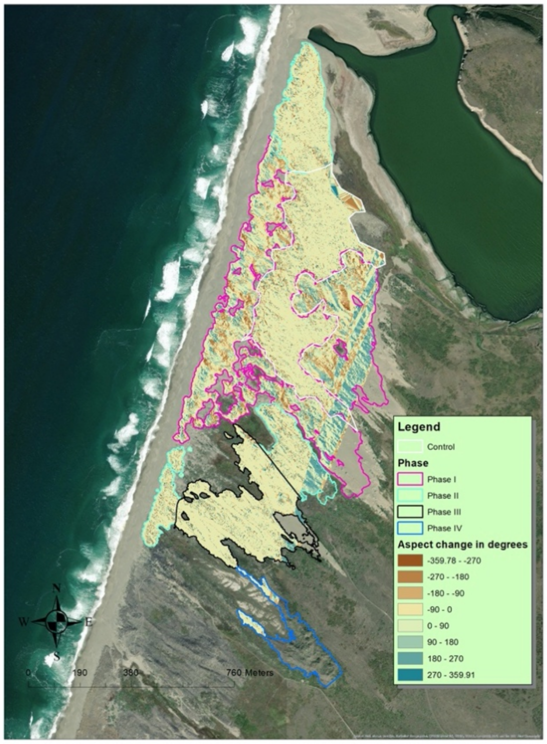
Aspect Change

The control site showed the largest mean aspect change over the 8-year period. During this time interval, the aspect on average shifted 7.22 degrees counterclockwise. This is followed by the Phase I, Phase II, Phase III, and then Phase IV. For the 6-year change, Phase I saw the largest average shift, changing 14.41 degrees clockwise. The second largest average aspect shift occurred in Phase II followed by Phase III and lastly the control (Table 3). It's intriguing that the control site went from seeing the lowest average aspect change over the 6-year time difference to seeing the largest average aspect change over the 8-year time difference. Something that is also interesting is that every phase, including the control site, had a sample point where the maximum change was just about 360 degrees clockwise and counterclockwise. This is also true for the 6-year change in aspect. In both the 8- and 6-year change, Phase I was the phase where the highest proportion of its area changed more than 90 degrees in either direction (Figures 4e and 4f).

Table 3. 8 and 6 year mean aspect change.

Treatment site	Temporal change (yr.)	Mean aspect change (deg)	Min. (deg)	Max. (deg)
Phase I	8	3.07 (136.21)	-359.56	359.15
	6	14.41 (137.55)	-359.69	359.02
Phase II	8	-2.40 (101.13)	-359.18	359.36
	6	7.74 (106.56)	-358.93	359.36
Phase III	8	-1.36 (89.78)	-359.22	359.69
	6	4.62 (93.12)	-359.26	359.91
Phase IV	8	-1.16 (60.22)	-359.17	359.00
	6	No data	No data	No data
Control	8	-7.22 (99.66)	-359.51	359.66
	6	0.16 (101.11)	-359.78	359.40

e)



f)

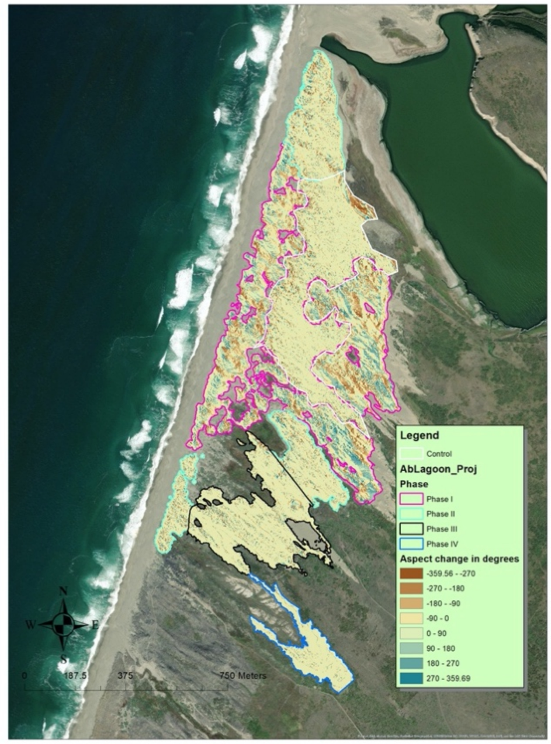


Figure 4. 6-year and 8-year aspect change. Aspect change from 2010 to 2016 (e) and aspect change from 2010 to 2018 (f).

Treatment type comparisons

After running Kruskal Wallis tests for treatment type vs. changes in elevation, slope, and aspect, most of the p-values came back < 0.05. The 8- and 6-year aspect change were the only variables with insignificant p-values in the 5-10m starting elevation. In the 10-15m elevation, all the variables measured resulted in significant p-values. In the 15-20m starting elevation, the 8-year aspect change, 6-year slope change, and 6-year elevation change resulted in an insignificant p-value. For all the variables with p-values < 0.05, the null hypothesis that that treatment type did not play a role in affecting any of the structural aspects is rejected.

5-10m starting elevation

In the 5-10m starting elevation category, only the 8- and 6-year aspects received a p-value greater than 0.05. All the 8- and 6-year elevation and slope variables resulted in p-values less than 0.05 (Table 4). According to the Dunn's Post Hoc test, the difference between the mechanically treated and the control site were significant. As for the herbicidally treated areas, only the two slope variables showed significance against the control. There was a significant difference between the mechanically treated and herbicidally treated areas for all 8- and 6-year elevation and slope (Table 5).

Table 4: 5-10m starting elevation mean changes and p-values.

Variable	Control	Herbicidal	Mechanical	P-value
8 yr. Elevation change (m)	0.25 (0.75)	0.29 (0.39)	0.17 (1.04)	1.13×10^{-10}*
6 yr. Elevation change (m)	0.25 (0.52)	0.18 (0.29)	0.28 (1.39)	9.80×10^{-6}*
8 yr. Slope change (deg)	0.293 (3.18)	-0.59 (4.21)	-4.53 (5.70)	$< 2.2 \times 10^{-16}$*
6 yr. Slope change (deg)	0.14 (3.02)	-0.31 (3.18)	-4.50 (5.85)	$< 2.2 \times 10^{-16}$*
8 yr. Aspect change (deg)	-14.07 (113.35)	-4.04 (78.25)	-11.34 (111.74)	0.17
6 yr. Aspect change (deg)	-1.82 (104.87)	-5.27 (66.71)	-3.06 (116.99)	0.81

*Note: * denotes the variable is statistically significant*

Table 5: 5-10m starting elevation Dunn's Test P-values.

Variable	Mech - Control	Herb - Control	Mech - Herb
8 yr. Elevation	2.25×10^{-6}*	0.287	2.09×10^{-9}*
6 yr. Elevation	2.26×10^{-5}*	1	2.61×10^{-3}*
8 yr. Slope	3.07×10^{-145}*	1.42×10^{-3}*	8.14×10^{-73}*
6 yr. Slope	1.1×10^{-140}*	4.7×10^{-2}*	1.98×10^{-88}*

*Note: * denotes the variable is statistically significant*

10-15m starting elevation

After running Kruskal Wallis tests for the temporal changes in elevation, slope, and aspect in the 10-15m elevation categories, all the p-values came back significant (Table 6). The Dunn's test show that there was a significant difference for all the variables in the mechanically treated area vs. the control area. There was only a significant difference in the herbicidally treated areas for the 8-year elevation and slope change and the 6-year elevation change. There was a significant difference between the mechanically and herbicidally restored areas for all the variables except the 8-year aspect (Table 7).

Table 6: 10-15m starting elevation mean changes and p-values.

Variable	Control	Herbicidal	Mechanical	P-value
8 yr. Elevation change (m)	0.20 (0.26)	-0.03 (0.44)	-0.40 (1.05)	$< 2.2 \times 10^{-16}$*
6 yr. Elevation change (m)	0.60 (0.05)	-0.01 (0.40)	0.39 (2.84)	$< 2.2 \times 10$ $^{\wedge-16}$*
8 yr. Slope change (deg)	0.57 (3.93)	-0.37 (4.82)	-4.71 (6.08)	$< 2.2 \times 10^{-16}$*
6 yr. Slope change (deg)	0.64 (4.09)	0.16 (4.72)	0.58 (8.28)	$< 2.2 \times 10^{-16}$*
8 yr. Aspect change (deg)	-8.58 (98.10)	2.80 (91.80)	14.91 (120.81)	5.08×10^{-5}*
6 yr. Aspect change (deg)	34.80 (123.27)	2.67 (90.21)	0.79 (90.41)	8.75×10^{-12}*

*Note: * denotes that the variable was statistically significant*

Table 7: 10-15m starting elevation Dunn's Test P-values.

Variable	Mech - Control	Herb - Control	Mech - Herb
8 yr. Elevation	6.40×10^{-70}*	4.41×10^{-9}*	2.37×10^{-15}*
6 yr. Elevation	3.98×10^{-28}*	2.79×10^{-8}*	9.34×10^{-3}*
8 yr. Slope	1.15×10^{-83}*	4.15×10^{-3}*	2×10^{-35}*
6 yr. Slope	8.66×10^{-45}*	0.207	6.28×10^{-22}*
8 yr. Aspect	2.79×10^{-5}*	0.1645	0.381
6 yr. Aspect	1.33×10^{-10}*	1	2.10×10^{-5}*

*Note: * denotes the variable is statistically significant*

15-20m starting elevation

The 6-year elevation change, 6-year slope change, and the 8-year aspect were the variables in the 15-20m elevation category that resulted in p-values less than 0.05 (Table 8). Of the three variables that did show significance between the treatment types, the Dunn's test showed significance between the mechanically treated areas and the control site for all variables, significance between the herbicidally treated area and control for only the 8-year elevation change, and significance between the mechanically treated areas and herbicidally treated areas for all variables (Table 9).

Table 8: 15-20m starting elevation means and p-values in meters and degrees.

Variable	Control	Herbicidal	Mechanical	P-values
8 yr. Elevation change (m)	0.11 (0.50)	-0.02 (0.20)	-0.81 (1.21)	$< 2.2 \times 10^{-16}$*
6 yr. Elevation change (m)	0.39 (1.63)	0.59 (0.03)	0.58 (0.14)	0.57
8 yr. Slope change (deg)	1.59 (5.99)	-0.36 (3.79)	-7.66 (6.35)	$< 2.2 \times 10^{-16}$*
6 yr. Slope change (deg)	1.74 (7.44)	-0.60 (5.99)	0.80 (11.87)	0.19
8 yr. Aspect change (deg)	-21.67 (113.35)	-4.79 (74.55)	15.03 (134.89)	0.06
6 yr. Aspect change (deg)	-3.12 (117.54)	15.97 (89.54)	47.02 (127.10)	1.56×10^{-5}*

*Note: * denotes the variable is statistically significant*

Table 9: 15- 20m starting elevation Dunn's Test P-values.

Variable	Mech - Control	Herb - Control	Mech - Herb
8 yr. Elevation	5.62×10^{-20}*	5.60×10^{-4}*	3.82×10^{-37}*
8 yr. Slope	2.57×10^{-19}*	0.395	4.35×10^{-17}*
6 yr. Aspect	2.79×10^{-4}*	0.153	2.14×10^{-4}*

*Note: * denotes the variable is statistically significant*

Linear Regression Analysis

8-year elevation

The linear regression model that was produced to predict the 8-year elevation change had a p-value of < 2.16 x10^-16. The R squared statistic was 0.1108 meaning that model accounted for 11.08% of the variance of the data. The y intercept of the mechanical treatment 0.837 and lower than the y intercept of the herbicidal treatment, which was 0.878. The entirety of the model is expressed below:

Mechanical treatment.

8 yr. elevation change = 2010 elevation* (-0.066) + 0.837

Herbicidal Treatment.

8 yr. elevation change = 2010 elevation* (-0.066) + 0.878

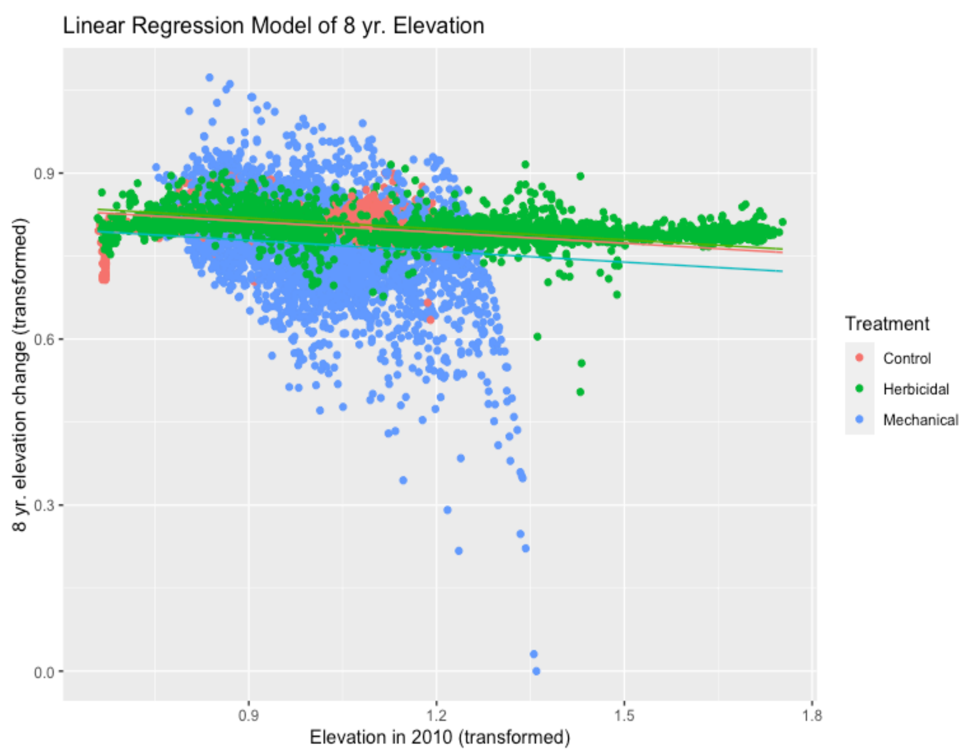


Figure 5. 8-year elevation change linear regression model.

8-year slope

The 8-year slope regression model received a p-value of $< 2.16 \times 10^{-16}$ while the R squared was 0.3336. The y-intercept of the mechanically treated slope line is 1.555 and was less than the y- intercept of the herbicidally treated slope line, which was 1.629. The equations for the mechanically and herbicidally treated models are below.

Mechanically treated.

8 yr. Slope change = 2010 Slope * (-0.088) + 1.555

Herbicidally treated.

8 yr. Slope change = 2010 Slope * (-0.088) + 1.629

Figure 6. 8-year slope change linear regression model.

6-year elevation

The 6-year elevation linear regression model looks to be the least accurate of the models. The p-value was significant at 5.612×10^{-12}, but the R squared was only 0.0077. The y -intercept for the mechanically treated model was 1.421 and was slightly greater than the y-intercept of the herbicidally treated model, which was 4.416. The mechanically and herbicidally treated equations are below.

Mechanically treated.

6-year elevation change = 2010 Elevation* (-0.010) + 1.421

Herbicidally treated.

6-year elevation change = 2010 Elevation* (-0.010) + 1.416

Figure 7. 6-year elevation change linear regression model.

6-year slope

The linear regression model for the 6-year slope resulted in a p-value of $< 2.16 \times 10^{-16}$. The R squared value was 0.2277. The y-intercept for the mechanically treated line was 1.560 while the y-intercept for the herbicidally treated line was 1.622. The mechanically and herbicidally treated equations are below.

Mechanically treated.

6-year slope change = 2010 Slope* (-0.094) + 1.560

Herbicidally treated.

6-year slope change = 2010 Slope* (-0.094) + 1.622

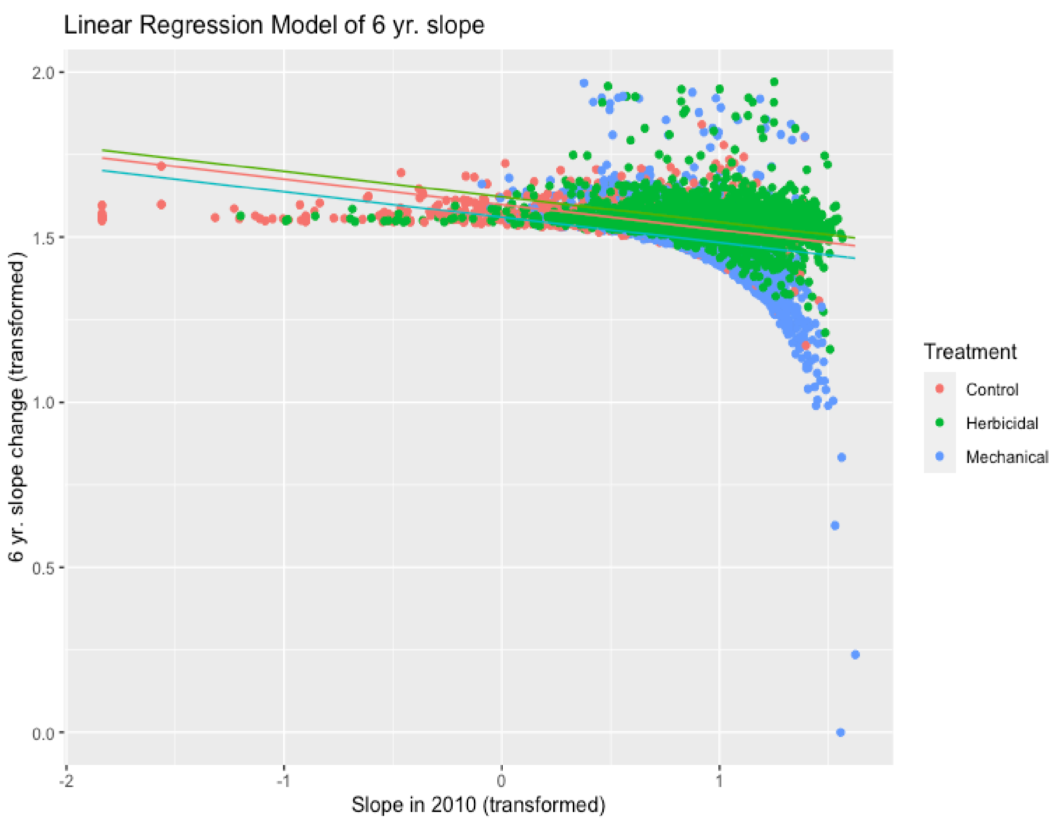


Figure 8. 6-year slope change linear regression model.

DISCUSSION

Monitoring the changes in geomorphology of the dunes in the Abbott's Lagoon restoration can be used to assess the success of the restoration treatments and to see if there are significant differences between the restoration treatments. Some of the phases of the restoration treatment had noticeable mean changes in elevation, aspect, and slope between the 6-year (2010-2016) and the 8-year (2010 to 2018) change. Some phases did not exhibit very drastic changes. The mechanically treated areas exhibited larger negative slope and elevation differences from the control area compared to the herbicidally treated areas. Based on these findings, the mechanically restored areas overall showed the most significant response due to the restoration and when possible, should be the preferred treatment method.

Abbott's Lagoon dune structure change

The dunes in the Abbott's Lagoon restoration showed deflation and destabilization with respect to treatment phase. Phase I clearly differed from the other phases in destabilizing the sand dunes. Phase I received the largest mean decrease for the 8-year elevation with a mean decrease of -0.19m, 8-year slope with a mean decrease of -4.92 degrees, 6-year slope with a mean decrease of -4.36 degrees, and 6-year aspect with a mean change of 14.42 degrees clockwise. 6-year slope and aspect were the only variables where Phase I did not receive the largest mean decrease and change. Phase I also only received the largest mean increase in the 6-year elevation change with an average increase of 0.44m. While Phase I did receive the maximum elevation increase in both the 8- and 6-year change, 5.84m and 14.52m respectively, it also received the largest decrease in elevation for those two variables as well, -5.79m and -7.21m respectively. Phase I also received the majority proportions of its area decrease 2 or more meters than any of the other phases. For both temporal changes in slope, Phase I never received the largest decrease, but it also never received the largest increase. Looking at the Abbott's Lagoon dune changes as whole without respect to phase or treatment type, my results did differ from dune geomorphological studies that looked at just the natural movement of sand over time and not changes post-restoration. Sand dunes in Jockey's ridge in North Carolina saw the majority of its area decrease 5 m or less between 1995 and 1998 and between 1999 and 2001 with the maximum decrease and increase being 10m and

15m respectively (Mitasova et al. 2005). The deflation of the Jockey's Ridge sand dunes was said to be due to a reduction in sand sources from expanding vegetation withing the park and its immediate neighborhood (Mitasova et al. 2005). Sand dunes in Kanyakumari on the southwest coast of India decreased only up to roughly 3 m from 2000 to 2011 (Kaliraj et al. 2017). The elevation decrease in this study was due to wind winnowing during monsoons (Kaliraj et al. 2017). My results lie in between these two studies and show that the majority of the Abbott's Lagoon dunes increased or decreased up to 2 m over an 8-year period of time with the largest decrease being -5.79m and largest increase being 5.85m. As for the 6-year period, the majority of the Abbott's Lagoon dunes eroded or aggregated 5 meters with the largest decrease being 11.52 m and the largest increase being 14.52m. Compared to the Jockey's Ridge dunes, the Abbott's Lagoon dunes look to be moving at a slower rate while compared to the Kanyakumari dunes, the Abbott's Lagoon dunes look to be decreasing at a faster rate.

The National Park service (NPS) was originally disappointed with the restoration results since it led to decreases in native plant cover, native plant biodiversity, and an issue where the soil in Phase I was too harsh for native plants to grow in (Parsons et al. 2020). The removal of plants can result in the eco-geomorphic couplings between the sand and vegetation to fail which can then result in erosion (Jackson et al. 2013). The average decreases in the 8-year change in elevation and slope in Phase I reflect this. Some of the herbicidally treated phases also showed an average decrease in elevation and slope over the 8-year time difference but not as prominent as Phase I as Phases III and IV only decreased -0.04m and -0.02m respectively and Phase II on average decreased by -0.56 degrees in slope. Due to the erosion that can result from vegetation removal, the National Research Council (NRC) stated that ecological engineering is likely suitable to manage coastlines but only for larger time scales (Jackson et al. 2013, NRC 2012). Due to annual vegetation surveys done by the NPS, the vegetative community of the Abbott's Lagoon dunes is being tracked. From the surveys, it was found that the native plant coverage and native plant richness has been increasing and in 2019 was been the highest it has been since the restoration started in both the mechanically and herbicidally restored phases (Parsons et al. 2020). The fact that areas that were not able to be revegetated early on post-restoration but are now being revegetated suggests that the Abbott's Lagoon restoration is following the NRC statement.

Treatment type's role in dune structure change

The results from the Kruskal Wallis tests also showed that the mechanically treated area resulted in the more deflation and destabilization of sand compared to the herbicidally treated and control areas. Of the 18 variables tested, the mechanically treated areas showed either the largest deflation, smallest inflation, or largest change in 9 of them. The 8-year elevation in the mechanically treated area for the 5-10m starting elevation category on average increased 0.17m but was the smallest average increase compared to the herbicidally treated area and the control. The 8-year elevation change in the mechanically treated 10-15m and 15-20m starting elevations on average decreased -0.4m and -0.81m respect. As for the 8-year slope change, the mechanically treated areas saw the largest average decrease in the 5-10m, 10-15m, and 15-20m starting elevations with average decreases of -4.53, -4.71, and -7.66 degrees respectively. The mechanically treated area experienced the largest average decrease in the 6-year slope category in the 5-10m starting elevation with a mean decrease of -4.5 degrees. Lastly the mechanically treated area saw the largest mean aspect change in the 8-year 10-15m and the 6 year 15-20m starting elevations changing 14.91 degrees and 47.02 degrees clockwise respectively. For all the variables that were statistically significant, there was significance found between the mechanically treated and the control area. These same variables also showed significance between the mechanically and herbicidally treated areas in all but the 8-year aspect change in the 10-15m and 15-20m starting elevation categories. On the other hand, of the variables that were significant, only roughly half of them showed significance between the herbicidally treated areas and the control.

One reason why the mechanically restored area may have allowed for more deflation of sand is due to the herbicidally treated areas having less bare ground cover and more native and non-native vegetative cover than either the mechanically restored area or the control area post restoration (Parsons et al. 2020). In the subsequent years after the restoration up until 2018, when the most recent elevation data for this project was taken, the mechanically restored areas had a bare ground cover that ranged from 87.7% to 98.9% while the herbicidally treated areas had a bare ground cover ranging from 6.5% to 15.1% (Parsons et al. 2020). Up until 2018, the mechanically restored sites did not have non-native vegetation growing while in the herbicidally treated areas, the non-native vegetation cover ranged between 12.8% and 19.7% from 2013 to 2016, then increased to 58.3% in 2017 and went back down to 36.4 % in 2018 (Parsons et al. 2020).

Additionally, in some of the herbicidally treated areas, after the herbicide treatment was applied, the dead biomass was left above the sand, acting like a mat that may have inhibited the sand's ability to move (Parsons et al. 2020). With more bare ground cover and less non-native vegetation cover type, the sand in the mechanically treated areas is freer to move around due to the wind and waves, thus resulting in larger changes in elevation, slope and aspect compared to the herbicidally treated areas.

Elevation and slope change regression

From the linear regression models, the mechanical treatment y-intercept was lower than the herbicidally treated y-intercept for 8-year elevation and slope as well as 6-year slope. All the slopes of the linear models were negative as well. The mechanically treated 8-year elevation y-intercept was 0.837 while the herbicidally treated y-intercept was 0.878. For the 8-year slope regression, the mechanically treated y-intercept was 1.555 while the herbicidally treated y-intercept was 1.629. Lastly, the mechanically treated y-intercept for the 6-year slope change was 1.560 while the y-intercept for the herbicidally treated areas was 1.622. For these variables just mentioned, the mechanically treated areas saw larger decreases in elevation and slope due to the smaller y-intercept as well and the negative slope of the line. The larger decrease in elevation and slope of the mechanically restored dunes is showing that these dunes are becoming more destabilized and deflated, meaning the mechanical restoration technique is more effective, as with less plant material, the more freely the sand can move (Gómez-Pina et al. 2002). This conclusion is also supported by the fact that post restoration, the mechanically restored area was covered in lower rates of invasive species than the herbicidally treated areas (Parsons et al. 2020). This deflation and destabilization from the removal of invasive species is good for the dune's viability, as with more invasive plants present, the more over stabilized the dunes become and the more susceptible to coastal squeeze they become (Millington et al. 2010).

It is important to note that the Abbott's Lagoon dunes should not become too destabilized or deflated. Plant roots contribute to the mechanical strength of non-cohesive dune sediment (Segrin et al. 2014). With small amounts of vegetation covering the dunes, they become susceptible to loss from erosion (Gómez-Pina et al. 2002). Although the mechanical treatment looked to be the most effective at the removal of invasive species due to more erosion, flattening, and the NPS vegetation surveys, Phase I is currently primarily open bare ground. The deflation of the bare ground mechanically treated area in Abbott's Lagoon follows other studies that have been done regarding coastal dune restorations. In a coastal dune restoration done in Rome, Italy off the coast of the Tyrrhenian sea, dunes that were not planted with vegetation and were bare decreased to 47% of its initial height over a 5-year period (De Lillis et al. 2014). To prevent the deflation and destabilization of the dunes in Phase I from becoming too extreme, efforts should once again be taken to relegate the area with native species. Now that Phase I has recently started to increase in native vegetation coverage and native species richness (Parsons et al. 2020), this may be a more conceivable task.

Limitations

This study was able to monitor the Abbott's Lagoon dunes post invasive species restoration and determined that the mechanically restored area was the most efficient treatment to destabilize and deflate the dunes from the European Beachgrass and Ice plant. It is important to note that I had many data points in my sample grid. I ended up with a little over 8,100 sample points. With the number of sample points I had, there is a higher likelihood that some of the p-values came back significant due to the sheer number of samples I had. There was also the fact that the lidar data had to be interpolated. The 2010 lidar data had a lower resolution (3.33 points/meter squared) than the 2016 and 2018 lidar data (11.43 and 16.7 points/meter squared respectively). Due to the 2010 lidar being lower resolution, more of the elevation that readings in my 1m x 1m DEM had to be interpolated, possibly leading to a less accurate DEM and therefore less accurate slope and aspect values as well. With lidar data sets having high and similar resolutions, more accurate DEMs may be interpolated. For the linear regression models, even after I log transformed my data, the residuals were not completely normal, meaning that these models could be improved with more robust statistical models.

Future steps

One of the challenges I faced was using many sample points. I thought spacing each sample point 10m apart would result in a sufficient number of sample points. Instead, this spacing still resulted in roughly 10,000 points. Resampling the area but spacing the sample points even further apart so that there are only a couple hundred points and then seeing if any of the p-values change from being significant to insignificant may be interesting to see. Many dune studies such as Kaliraj et al. 2017 and De Lillis et al. 2004 separate the dunes into categories based off the dunes' distance to the water. It is possible that separating the dunes into categories based off distance to the water instead of starting elevation could produce different results regarding significance between treatment types and may be intriguing to carry out. Foredune and back dune communities are exposed to differing amounts of wind and wave action. Looking at how the dune structure differs between the foredune and back dune areas after the restoration treatments may also be worth analyzing in the future. Research regarding if there is any herbicidal residue being washed into the ocean is something important regarding wildlife and ocean chemistry that would be interesting to look at as well.

Management Implications

This research presents an alternate way of determining what type of treatment method is the most effective at restoring coastal sand dunes and can be used alongside vegetation survey data to analyze how dunes are responding to restorations or the progression of time. With vegetation, geomorphological, and restoration practice data, better decisions regarding how to go about managing coastal sand dunes, such as deciding what type of restoration practice to use, where restorations should happen, and where to vegetate areas, can be made in the future. Looking at the elevation slope and aspect change post Abbott's Lagoon dune restoration, I was able to observe that through larger average decreases in elevation, slope, and larger average changes in aspect, the mechanically treated Phase I was the more effective restoration practice as compared to the herbicidal practice. The larger average decreases in elevation and slope, as well as the little vegetative coverage as observed by the NPS, also show that Phase I is destabilizing and deflating faster than the herbicidally treated. Continually analyzing how dune elevation and other structural components have changed over time is important in making sure that the dunes do not become too over stabilized or destabilized or deflated, as both can lead to erosion thus compromising their buffering abilities.

ACKNOWLEDGEMENTS

I would like to thank the ESPM 175 teaching team Tina, Leslie, and Kyle for all the help and guidance I've received throughout the thesis. Thank you to my thesis mentor Professor Matthew Potts of the ESPM department at U.C. Berkeley for giving me advice on how to go about completing certain aspects of my thesis as well as help in R. Lastly, thank you to Lorraine Parsons with the National Park Service for giving me access to shapefiles, vegetation surveys, and information regarding the Abbott's Lagoon restoration.

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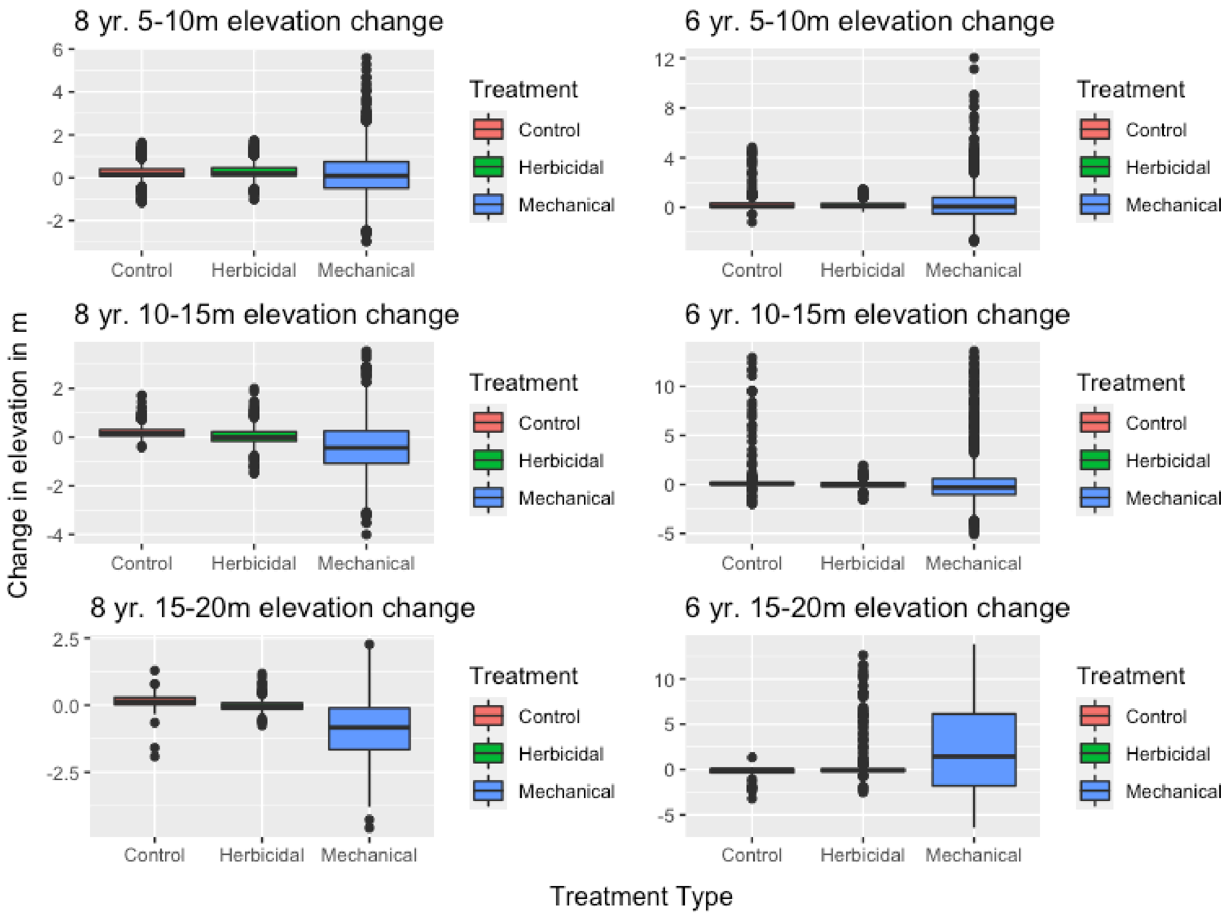
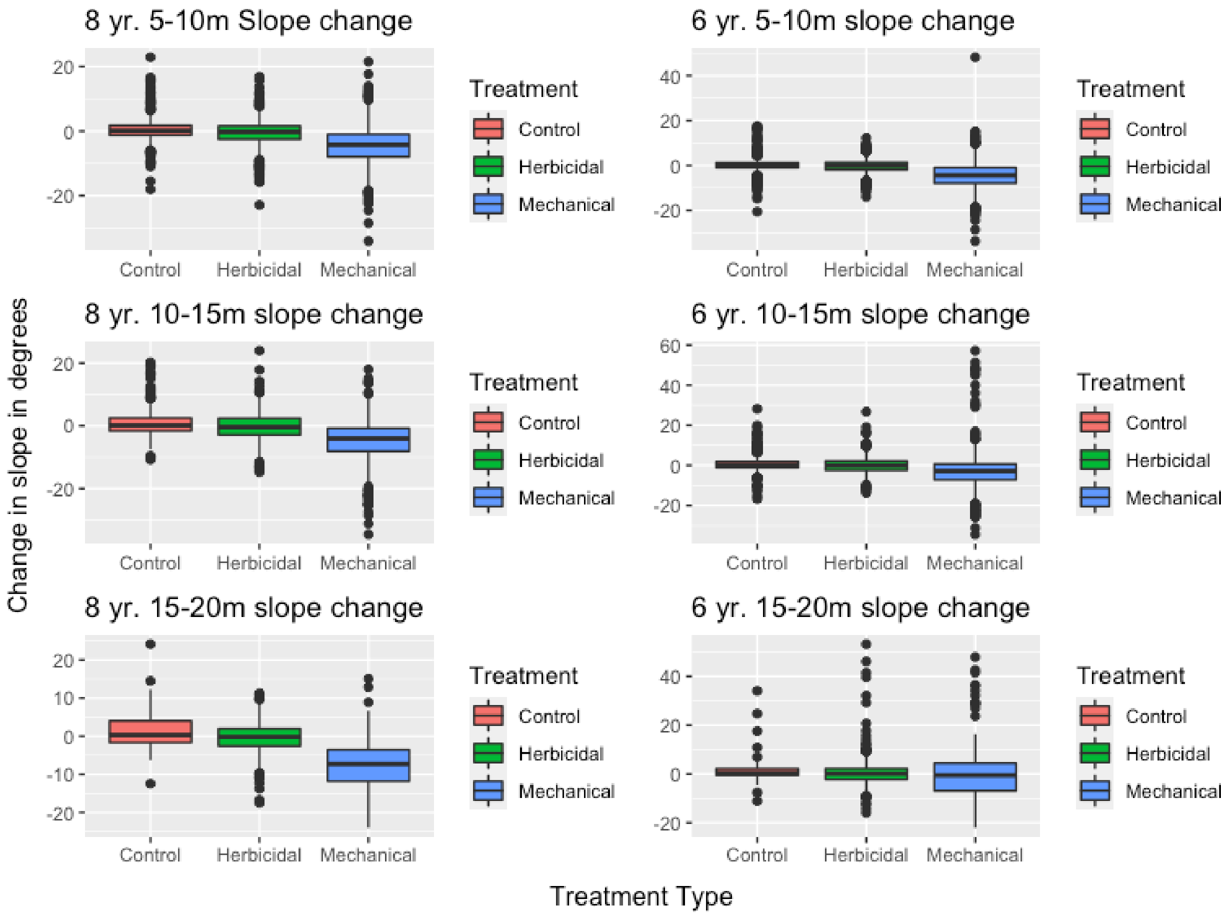

8 yr. 5-10m elevation change
6 yr. 5-10m elevation change
8 yr. 10-15m elevation change
6 yr. 10-15m elevation change
8 yr. 15-20m elevation change
6 yr. 15-20m elevation change
Treatment
Control
Herbicidal
Mechanical
Change in elevation in m
Treatment Type

Appendix A2: Boxplots showing slope changes per starting elevation category



Appendix A3: Boxplots showing change in aspect per starting elevation category