Remote sensing analysis of the relationship between sand dune topography and vegetation response to varying precipitation in the Central Great Plains

Tien Vo

Department of Geography

University of Wisconsin-Madison

Advisor: Joseph Mason

I. Abstract

The Central Great Plains is a premier site of sand dune landscapes. These sand dunes are largely covered by native vegetation and as a result, are often used for livestock grazing. The beef industry is an important sector to the region, thus, the maintenance of these landscapes could potentially be important for this region's economy. The Nebraska Sandhills have been shown to be influenced by their environmental conditions in the past. As climate change produces extremes of weather, these sand dunes are vulnerable to activation and transportation by wind or water. The objective of the proposed project is to determine how sand dune topography and precipitation levels affect vegetation growth, a key protector against soil erosion. The project will investigate this relationship in reference to crests and interdunes and during years of drought and heavy rain. To answer our research question, we analyzed NDVI data (used as a proxy for vegetation growth) available for sand dune fields near two Nebraska villages in Google Earth Engine. We hypothesized that crests will experience more of a vegetative reaction to the varying levels of precipitation due to increased exposure to the elements (e.g. wind). However, our results suggest the contrary and, in fact, interdunes had a greater reaction. Our statistical analyses show that this difference between the dune features is significant ($p\text{-value} < 0.05$). Our results affirm the relationship between precipitation and vegetation growth previously established in other studies and imply topography plays a bigger role in sand dune vegetation growth.

II. Introduction

The Central Great Plains is a semiarid ecoregion that spans across the central United States. The region is characterized by the presence of significant loess deposits and sand hills. In fact, within the Central Great Plains is the Nebraska Sandhills, the largest sand dune field in North America (Mason et al. 2020). The Central Great Plains is a prime region for agriculture, with the sand hills often being used as grazing grounds for livestock. These sand hills (interchangeably referred to as "sand dunes" throughout this text) have undergone a tremendous amount of transformation throughout its geologic history. It is this history that present-day scientists can turn towards for information regarding future dune activity.

The sand hills were primarily formed during the Pleistocene Epoch (Mason et al. 2020). During this time period, fluvial incision of the Arikaree and Ogallala groups caused the geologic formations to be more vulnerable to aeolian mobilization. Sand from these formations, along with sand from the Pliocene and Pleistocene, were transported by wind and deposited to create the sand hills. Today, the sand dunes are largely covered and stabilized by vegetation native to the area. Deep-rooted perennial grasess such as little bluestem are the most abundant, but forbs and shrubs can also be found.

The present-day sand hills are, for the most part, inactive as a result of their vegetation cover. However, research and recent history demonstrates that changes in environmental conditions have had a major influence on sand dune activity. Research by Muhs and Holliday (1995) suggests that sand dune mobilization is limited by precipitation, rather than wind. Since the 1900s, severe droughts have negatively affected vegetation growth across the Central Great Plains. Although the Nebraska Sandhills were mostly unaffected, these droughts eventually led to the activation of other sand dunes in the areas (Mason et. al 2020). Studies in Chinese sand dunes suggest that vegetation may be influenced by the same climatic factors that influence dune activity, including wind, precipitation, and temperature (Xu et al. 2017). It's unclear how wind strength affects the sand hills in Nebraska but overall, precipitation and its relationship with vegetation seem to be a major consideration in the stabilization of the dunes.

The climate of the sand hills can be described as sub-humid to semi-arid (Mason et al. 2020). Precipitation has historically ranged from 400 to 650 mm of rain per year, with most rainfall occurring during the summer growing season. Throughout the year, temperatures range from -34°C to 41°C, with 9°C as the annual average. The area is also characterized by winds that are strong enough to lift and transport sand.

Climate change is anticipated to cause extreme weather events, including droughts, to happen more frequently and unpredictably over the Central Great Plains (Hoerling et al. 2014). Since precipitation and vegetation have historically affected dune activity, their unpredictable occurrence due to climate change could affect ecological processes within the Central Great Plains, including the activation, and mobilization of the Nebraska Sandhills.

The objective of this project is to determine the relationship between sand dune topography, precipitation, and vegetation growth. This project investigates how sand dune topography (specifically, dune crests and interdunes) affects vegetation growth during years of drought in contrast to years with heavy rain within recent history (i.e. the last thirty years). We hypothesize that crests will have a greater vegetation response to varying precipitation than interdunes, due to their higher exposure to wind, rain, and sunlight. That is, we hypothesize that crests will experience more vegetation growth during years of heavy rain and less vegetation growth during years of little rain, in comparison to interdunes.

The significance of this research lies in its potential to aid conservation efforts. The beef industry is a major contributor to the economy in Nebraska (Nebraska Beef Council, 2023). By determining where sand dunes are the most vulnerable to activation, mobilization by wind or rain can be prevented and these landscapes can be preserved. As a result, ranchers and farmers who depend on the sand hills for agricultural production can continue to use these landscapes as a natural resource.

III. Methods

The two areas studied in this project were located near the villages of Arnold and Mullen, respectively located in Custer County and Hooker County, Nebraska. The areas were chosen for investigation due to their extensive expanse of sand dunes. The Arnold site is geographically near a loess tableland, while the Mullen site is a large dune field, isolated from other geographic features. LIDAR DEM-based images of the study areas were obtained from the public domain.

Landsat satellites collect moderate-resolution remote sensing data of land (U.S. Geological Survey, n.d.). The data from these satellites can be used to analyze terrestrial changes due to natural causes or human activity. Since the satellites collected data during different time periods, data from Landsat 5, Landsat 7, and Landsat 8 were all used to conduct a part of this research. We used the data of a "dry" and "wet" year from each Landsat satellite. The years of interest and their corresponding Landsat satellite are shown in Figure 1.

Normalized difference vegetation index (NDVI) is an index used to quantitatively measure the presence (or absence) of green vegetation. NDVI data was obtained from the public domain and placed over the Landsat data. NDVI anomaly, defined as "the difference between the average NDVI for a particular month of a given year and the average NDVI for the same month over a specified number of years," (NASA, 2016) was also obtained. The NDVI anomaly value for any particular point was obtained by averaging the months of July and August, the two months where rainfall would likely be at its most heavy.

Landsat	Wet Year	Dry Year
5	1993	2002
7	2009	2012
8	2016	2017

Figure 1. Table of the Landsat satellites and the corresponding wet and dry years that data was gathered from.

Google Earth Engine was used to organize the Landsat and NDVI data into one place. When a user clicks on a random point in the workspace, the Inspector pane shows all the available data for that singular point (dictated by how much data the user previously uploaded to the files directory). Scripts were written to easily extract NDVI data from the Landsat data sets.

NDVI anomaly data was extracted and recorded from both the Arnold and Mullen site using Google Earth Engine. For the Arnold site, thirty points were randomly placed on the crests (n=15) and interdunes (n=15) around the area. For the Mullen site, forty points were randomly placed on the crests (n=20) and interdunes (n=20) around the area.

The National Agriculture Imagery Program (NAIP) imagery program acquires high-quality resolution images of land during the agricultural growing seasons in the United States. NAIP images for the Mullen site were obtained from the NAIP GeoHub site. The same points that were used to obtain NDVI values from the Landsat data sets were also used to obtain NDVI anomaly from the NAIP images in Google Earth Engine. NDVI values obtained from NAIP images were the result of the NDVI difference between 2012 and 2009.

IV. Results

NDVI anomaly values fell between a range of 2 (high vegetation) to -0.8 (low vegetation). NDVI anomaly values corresponding to a specific year and dune feature were averaged for each of the twelve crest and interdune pairings for the Arnold site. A similar process was deployed for the NDVI data collected from the Mullen site. The years 2009 (wet) and 2012 (dry) were used to calculate the difference between the NAIP images for the Mullen site. The NDVI anomaly averages demonstrate a larger vegetative reaction in response to changing precipitation in the interdunes. The results also show there is a bigger NDVI anomaly difference in interdunes, when comparing pairs of wet and dry years.

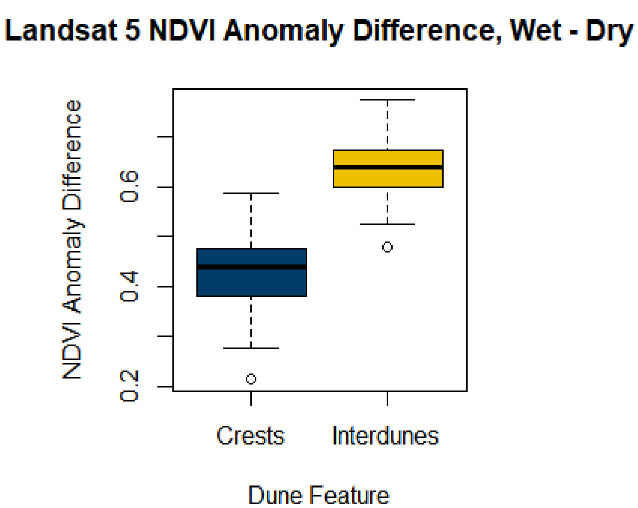
	Wet			**Dry**		
	1993	2009	2016	2002	2012	2017
Crests NDVI Anomaly Average	0.183323198	0.085314468	0.010005803	-0.24570611	-0.382202623	-0.153988942
Interdunes NDVI Anomaly Average	0.246110795	0.115647105	0.027029533	-0.390742188	-0.479729121	-0.230949953

Figure 2. Crest and interdune NDVI anomaly averages across (n=30) points throughout the Arnold site during wet and dry years between 1993 to 2017.

Box plots were graphed for each Landsat wet and dry year pairs (i.e. 1993 vs. 2002; 2009 vs. 2012; 2016 vs. 2017, respectively) for both the Arnold and Mullen site. A box plot was also graphed for the Mullen site with NAIP data from 2009 (wet) and 2012 (dry). The box plots show the NDVI anomaly difference between each wet and dry year pair. All of the box plots show that between both sites and image resolutions (in the case of the Mullen site), interdunes have a higher average NDVI anomaly difference.

	Wet			**Dry**		
	1993	2009	2016	2002	2012	2017
Crests NDVI Anomaly Average	0.098475001	0.263514599	0.084180986	-0.204079486	-0.314377369	-0.046839239
Interdunes NDVI Anomaly Average	0.128153711	0.29932907	0.094288425	-0.231661436	-0.337557757	-0.068211184

Figure 3. Crest and interdune NDVI anomaly averages across (n=30) points throughout the Mullen site during wet and dry years between 1993 to 2017.



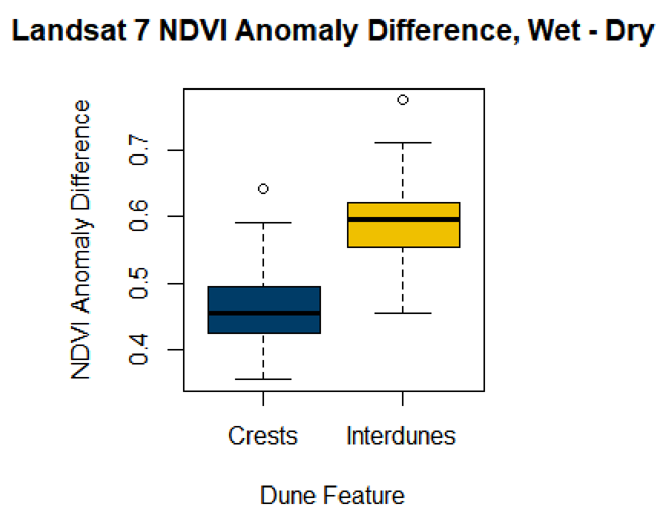
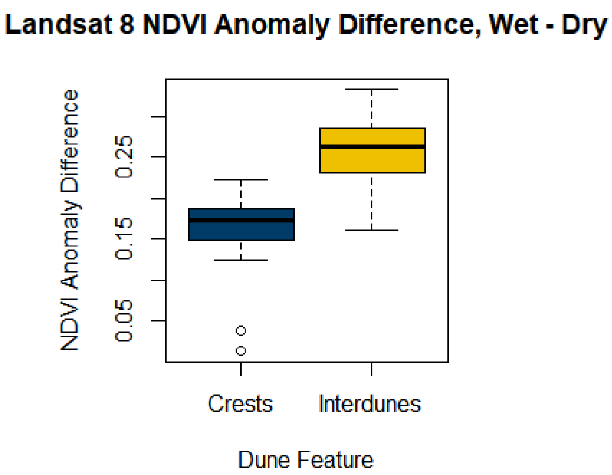


Figure 4. NDVI anomaly difference between crests and interdunes for years 1993 versus 2002, Arnold site

Figure 5. NDVI anomaly difference between crests and interdunes for years 2009 versus 2012, Arnold site



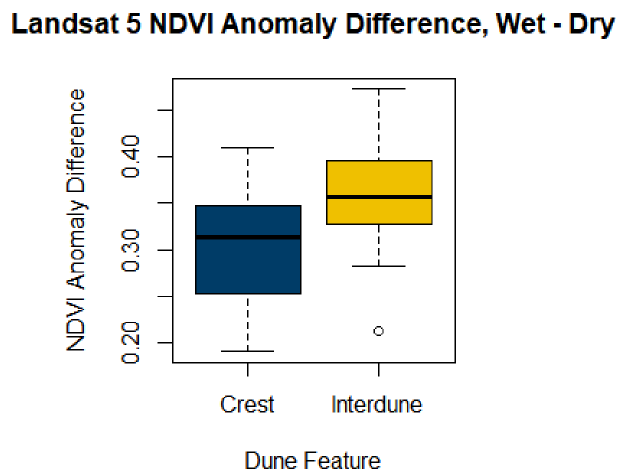
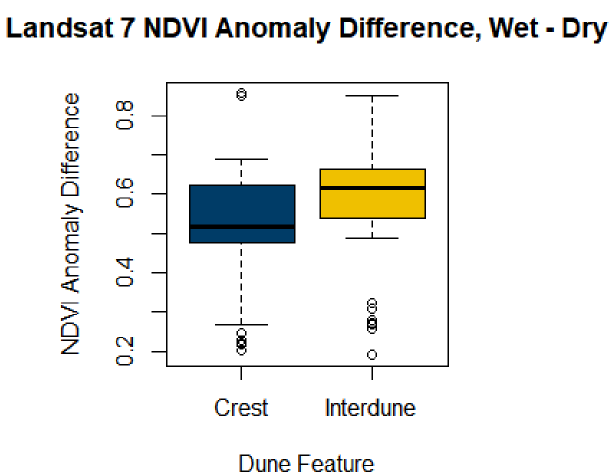


Figure 6. NDVI anomaly difference between crests and interdunes for years 2016 versus 2017, Arnold site

Figure 7. NDVI anomaly difference between crests and interdunes for years 1993 versus 2002, Mullen site



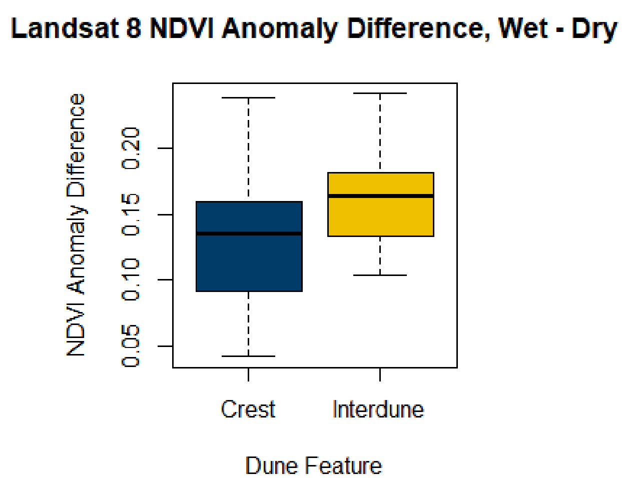


Figure 8. NDVI anomaly difference between crests and interdunes for years 2009 versus 2012, Mullen site

Figure 9. NDVI anomaly difference between crests and interdunes for years 2016 versus 2017, Mullen site

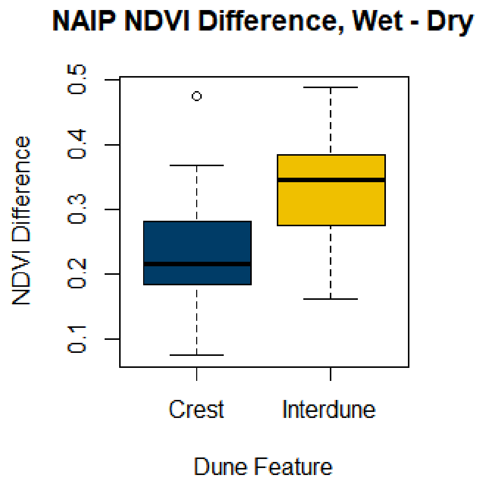


Figure 10. NDVI difference between crests and interdunes for years 2009 versus 2012, NAIP images for Mullen site

Paired t-tests were conducted for each Landsat wet and dry year pairs (i.e. 1993 vs. 2002; 2009 vs. 2012; 2016 vs. 2017, respectively) for both the Arnold and Mullen site and the NAIP images available for the Mullen site (2009 vs. 2012). All of the t-tests returned a p-value smaller than 0.05, indicating that the difference between each dry and wet year pairs were significant. In other words, the difference in vegetative reaction to varying levels of precipitation between crests and interdunes is significant.

	Landsat 5	**Landsat 7**	**Landsat 8**	**NAIP**
Arnold site	2.848e-13	1.204e-08	1.635e-10	
Mullen site	2.103e-06	0.04398	0.0001254	5.539e-07

Figure 11. P-values returned after conducting Bartlett's test for homogeneity of variances for each wet and dry year pairs, Arnold and Mullen site

V. Discussion

The results from this study do not support the hypothesis initially stated in this text. Crests were expected to have a greater vegetative reaction in response to “dry” and “wet” years, however, interdunes consistently had a greater reaction. When precipitation was low, interdunes had less vegetation growth and when precipitation was high, interdunes had more growth in response. Regardless of the dune feature, the results overall signify a positive relationship between precipitation and vegetation growth in the sand hills, a relationship that is consistent with the literature (Mason et al. 2020).

The study was limited by the number of points that were used for analysis. Both the Arnold and Mullen site could have benefited from more points during the data collection process, especially because cloud cover obscured the NDVI data for a number of Landsat points during 2012 for the Mullen site. No data was recorded for those points, and thus, those points did not contribute to the data analysis.

The study demonstrates a strong relationship between precipitation and vegetation growth in the sand hills. However, to advance the relationship between topography, precipitation, and vegetation growth, phenology could be incorporated in this study. Vegetation growth is a biological cycle that can be highly dependent on climatic factors such as temperature and precipitation. As climate change worsens, phenology will play a bigger role in vegetation growth. This study focused specifically on the crest and interdunes of a dune, but the entire sand dune structure could also be investigated, including the lee and stoss side of a dune. The stoss side could especially reveal interesting things about the role of wind in these landscapes. Since the sand hills are frequently used as grazing grounds for livestock, grazing management and their effects on vegetation growth could also be explored.

VI. Conclusion

In this project, we investigated the relationship between sand dune topography, precipitation levels, and vegetation growth in the Nebraska sand hills. We found that the interdunes had a larger vegetative reaction in response to low and high precipitation, in comparison to crests. Our results imply that the characteristics of the interdunes, compared to the crests of the sand hills, make them more "vulnerable" to climatic variables such as precipitation. The findings from this study have implications for current grazing management practices implemented by ranchers in Nebraska, as well as understanding how a combination of biotic and abiotic variables influence ecological processes in the sand hills.

VII. Acknowledgements

I would like to thank my advisor, Dr. Joseph Mason, for his expertise, guidance, and support on this project. I would also like to thank Taylor McDowell for her insight around the lab. Lastly, I would like to thank the McNair Scholars Program for providing me with a community of like-minded scholars with whom I can grow as a researcher.

This research was made possible thanks to financial support from TRIO grant #P217A180158 and NSF EAR-1920625.

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