Ranchland Resilience:

Climate Change, Desertification, and Cattle Grazing Management

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ABSTRACT

The effects of climate change have a dramatic impact on vulnerable ecosystems and vulnerable populations, specifically the effects of desertification on arid landscapes. In the United States, the majority of ranchlands are dependent on arid ecosystems and the ecological interactions between vegetation, precipitation, and soil. Cattle ranchlands in particular, face higher risk of desertification due to the combined impacts of climate change and cattle pressure. This manuscript explores the intersections between climate change, desertification, and cattle grazing in two sections: 1) The Scientist and 2) The Rancher. By emphasizing the collaboration between scientific knowledge and traditional rancher knowledge I suggest that cattle ranching, and climate scientists should invest in a collaborative, local, and holistic cattle management practice in order to build resilience for both the landscape and its people. The Scientist section explains and applies the theories of ecological dynamics between consumers and resources to the context of vegetated spatial patterns at Chico Basin Ranch, Colorado. First, we explored the regional temporal changes of temperature and precipitation and how they impact the spatial patterns of grassy and bare soil patches, concluding that clear spatial patterns have developed in these grasslands. This may be a result of a climate regime shift in the late 1990s-early 2000s. Second, we additionally explored whether cattle grazing pressure impacts grassland spatial patterns. We hypothesized that if cattle grazing is driving desertification at Chico Basin, then Zones with higher cattle grazing will contain more desertification defined spatial patterns, such as greater distance between grassy and bare soil patches and lower vegetation presence (NDVI). However, our results conclude that cattle movement and hoof disruption of soil crust is more impactful on vegetation than cattle grazing due to the effects of soil crust inhibiting annual vegetation. The scientific knowledge then transitions to rancher knowledge. The Rancher section incorporates the role of ranch management and the rancher perspective into the conversation of desertification. We explore three forms of management, holistic ranch management, community conservation, and regenerative ranching. By honing in on the similarities and differences of each management style, we are able to validate traditional rancher knowledge, advocate for the collaboration between scientists and ranchers, and look forward to how management tools can be adapted to the scientific understanding of ecological processes, while emphasizing the livelihoods and involvement of ranchers.

DEDICATION

Thank you

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For sharing your knowledge and perspective on ranching.

I pay my respect

To the legacy of Ute Peoples who cared, fostered, occupied, and contributed

To the knowledge of arid landscapes and ranchlands.

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PREFACE

This manuscript is a humble attempt at describing the intricacies of desertification, climate change, ranchlands, knowledge, and management. I cannot submit this work without situating myself within the ranching narrative. I am not a rancher, I do not depend on the land for my livelihood, nor am I an expert on the dynamics of spatial distributions. I am a student who seeks to bridge the divide between scientific and traditional rancher knowledge. I believe that intentional environmental communication and collaboration will guide us towards the most reliable and sustainable land management systems. This manuscript attempts to deconstruct the hierarchies of knowledge production in the wake of catastrophic climate change. The environment and people are suffering from both the disproportionate consequences of climate change and the lack of local holistic solutions. While I have not solved the issue of desertification or climate change, I challenge the reader- whether that be a scientist, student, academic, rancher, or learner- to open their minds to the strength of collaboration and to reimagine a new type of conservation that is equitable and adaptable. I hope you find yourself inspired and motivated to share and continue to collaborate in holistic knowledge production.

INTRODUCTION

a. CHANGING LANDSCAPES

We are at a pinnacle point in our climate where landscapes are changing, ecosystems are shifting, and urgency is rising. The natural world is vulnerable, more than ever, to the catastrophic, irreversible impacts of climate change. While conservationists and scientists rush to protect vulnerable ecosystems, they ignore the inherent connection between the natural world and people. The interactions between animals, soil, and vegetation, extend into the human world. People also rely heavily on the health and structure of ecosystems for their livelihoods; therefore, the vulnerability of landscapes and people are directly linked. Solutions to address climate change must engage both scientists and people to build communal resilience.

b. DESERTIFICATION

Climate change impacts are seeping into every vulnerability of ecosystem interaction resulting in a catastrophic mess. Arid landscapes are considered the most vulnerable to climate change in the case of desertification (**Lioubimtseva 2004).** They also have the largest geographic extent spanning 33 million square kilometers with managed grazing lands covering about 30% of global land surface (**Asner 2004).** Arid landscape susceptiveness to desertification is not only due to its expansiveness, but also the pressure of agriculture, grazing, and development. It is important to first distinguish the multiple definitions of desertification. According to the United Nations Convention to Combat Desertification, desertification is considered “land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. It remains potentially the most threatening ecosystem change impacting the socio-economic conditions of billions of people living in the drylands, which account for a significant proportion of the Earth’s land. It is caused by complex interactions of a number of physical, biological, political, social, cultural, and economic factors. Generally, it is a detrimental process that brings about a gradual and an unnoticed reduction in the productive capacity of land over a period of years" (**Kannan, 2014**). I appreciate this definition for calling out the combination of impacts from both ecological and humanitarian factors. What this definition lacks though, is acknowledging the role of historical ranching use and a guide to the spatial pattern of desertification over time (**Bestelemyer 2015**). While desertification is a global issue, its solutions require attention to local vegetation type, specific land topography, grazing pressure, and much more (**Lioubimtseva 2004).** When approaching desertification, we need to scale down to better understand the ecological interactions of soil disruption between long term loss of vegetation, and precipitation **(Bestelemeyer 2015).**

c. VULNERABILITY OF LAND

Each landscape responds to desertification in different ways depending on the severity of land use pressure. The State Change- Land Use Change framework (SC-LUC) gives a more holistic assessment of desertification and management of drylands (**Bestelmeyer 2015**). Part of this process is assessing whether the arid system is experiencing a rangeland regime shift. Regime shifts are when landscapes are susceptible to a complete shift in ecosystem conditions, specifically from grasslands to desert. Regime shifts are highly vulnerable to small shifts in climate, precipitation, land use pressure, and other ecosystem processes (**Bestelmeyer 2015**). According to Bestelmeyer**,** regime shifts require “intensive restoration or management” which ask questions such as, what ecosystem processes are changing? What drives these changes? and how can we mitigate and build resilience to these effects? The SC-LUC framework also pushes scientists and conservationists to acknowledge impacts of socioeconomic factors such as demographics, land tenure politics, and rancher perspectives. Future desertification regime shift research needs to emphasize resilience, state change predictability, and the vulnerabilities of people.

d. VULNERABILITY OF PEOPLE

While addressing the vulnerability of ranchlands, we cannot ignore the indirect impacts on millions of people that are dependent on these lands (**Reynolds 2007).** If cattle are critical to the basis of ranchlands and human livelihoods are dependent on these successes, we must focus our mitigation efforts on building the resilience of both people and landscapes. The vulnerabilities of these groups of people include being a sparse population, more remote, and a greater distance from policy makers. Their voices are pushed away and lack politically or scientific respect. Ranchers are especially unique to these characteristics because they depend on the productivity of the land and the success of ecological processes at risk of desertification. In the USA, 2.6 million people identify as ranchers on arid landscapes. Ranchers play two significant roles in the urgency of desertification. As victims to its consequences and as mitigators in management. By building up communal resilience of landscapes and people, we are able to invest in a multidisciplinary holistic ranch management style that invites the perspectives of scientists and ranchers.

e. SHARED RESILIENCE

Unpacking the ambiguity of resilience is essential for this conversation. The term resilience has several implications and quantifications depending on the social or ecological context. Resilience was first defined in 1973 as “the amount of disturbance that a system can withstand before it shifts into an alternative stable state” (**Angeler 2016**). The term has transformed into a conservation buzzword that is used without proper application and results. Ecological resilience is measured by the amount of change an ecosystem and its processes can withstand before catastrophic change, while social resilience accounts for the limitations and capacities of political, economic, and social structures (**Angeler 2016**). While this study does not directly quantify the thresholds of resilience on ranchlands and ranchers, I suggest that by implementing adaptive management strategies, ecological and social resilience can be strengthened. My research results suggest that both climate change and cattle presence increase the vulnerability of desertification. However, by investing in knowledge collaboration, conservation easements, and region-specific adaptive management strategies, resilience can be achieved.

f. SETUP

My research is intentionally split into two sections titled The Scientist and The Rancher. The Scientist outlines the ecological concepts and dynamics that support our research at Chico Basin Ranch. We rely on these theories to analyze the interactions between vegetation distribution and cattle grazing spatially. The results and data suggest that a combination of factors is responsible for the spatial distribution of vegetation at Chico Ranch, and suggest a greater understanding of social conditions, which lends to my next section. The Rancher focuses on the role management strategies play in mitigating the effects of climate change and desertification. By amplifying and crediting the voices of ranchers, I suggest the management strategies should rely on the collaboration of both traditional rancher knowledge and scientific conservation knowledge.

Overall, I am insisting that nature and people are not separable, and therefore, efforts to address desertification must pull in a diverse array of perspectives instead of push people out. My goal is to both provide tools for identifying desertification early warning signs and catalyze a conversation where scientists and ranchers can join their efforts and knowledge to build ranchland resilience.

SCIENTIFIC KNOWLEDGE

Before we can discuss the methods and results of Chico Basin Ranch, we must take the time to explain and understand some ecological dynamics. As mentioned previously, it is critical for scientific knowledge and theory to be communicated beyond scientific language. For this study, these theories include consumer resource dynamics. Shifts in the surplus of resources (vegetation/precipitation) or the intensity of consumption (cattle grazing) can impact how resilient a system is towards desertification. Ranchers and scientists need to understand the changes of ecological processes to attune their management style to the demands of the land.

a. CONSUMER RESOURCE DYNAMICS

Consumer resource dynamics between grass and cattle are defined by the rate of vegetation growth and the rate of cattle grazing. As outlined in Figure 1, the rate of vegetation growth is parabolic, meaning vegetation growth increases to a maximum at half carrying capacity then the rate decreases, and becomes zero at carrying capacity. Vegetation carrying capacity is the point where vegetation growth is limited by vegetation competition for available resources. Vegetation competition refers to neighboring plants competing for the same set of resources, therefore, inhibiting vegetative growth. The rate of cattle grazing is dependent on the number of cattle stocked in the system. This shape is described as a type-two functional response where grazing rate increases along vegetation density until it plateaus. At low vegetation density, grazing rate is limited by encounter rate, but at high vegetation density grazing rate is limited by consumption physics (ie. stomach size, metabolism, grazing speed) (Vandermeer 2013). The intersections between vegetation growth rate and cattle grazing rate are called system equilibria (Figure 1A.B.C).

b. MULTIPLE EQUILIBRIA, ATTRACTORS AND REPELLORS

A system equilibrium is when the rate of vegetation growth and the rate of cattle grazing are equal and intersect. These points can either be attractive (stable) equilibria or repelling (unstable) equilibria, depending on the dynamics of ecological processes. Figure 2 outlines the attractive and repelling stable states present in our previous consumer resource model. In the case of most arid ecosystems, one attractive vegetated stable state is characterized by a mixture of grassy patches and bare soil (Figure2C). However, if vegetation density is below a certain threshold (Figure2B), the ecosystem is unable to return to the vegetated stable state and is thus, repelled to an alternative attractive state (Figure2A). Theoretically, this alternative stable state for an arid ecosystem is a desert composed mostly of bare soil. The process of switching from the vegetated state to the desert state is known as desertification. The risk of a system switching stable states is dependent on its resilience. Building stronger ranchland resilience to ecological shocks and changes can better prevent catastrophic bifurcation. The threshold vegetation density that separates the vegetated and desert state is a repelling unstable equilibrium also described as an Allee point. Allee points form where significant intra-specific vegetation-based facilitation is necessary to overcome the adverse environmental conditions. The Allee point itself is defined as the minimum population size above which the facilitation is strong enough to ensure a viable population, but below which the collective habitat modification through facilitation is not strong enough and the population declines to extinction. When an ecosystem has been repelled to an alternative stable state, it requires a significant amount of energy and resources to return back to the original state (Vandermeer 2013). The location of these state equilibria is dependent on ecological inputs and outputs of the environment such as stocking rate and precipitation.

i. Stocking Rate

We can investigate the changes of stable states through a progression of various cattle stocking rates (Figure 3). Cattle stocking rate is defined by the number of cattle put in the system and therefore, impacts the intensity of cattle grazing. It also defines the starting grazing rate shown in the previous consumer resource dynamics models. Within this progression of consumer resources, the system has two stable attractive equilibria, a bare soil desert equilibrium at 0,0 (Figure3.A) and a vegetated equilibrium (Figure3.C) where the grazing rate plateau intersects with the vegetation growth. The two attractive equilibria are separated by a threshold (Figure3B) that divides the basins of attraction for the vegetated and non-vegetated equilibria. At a low stocking rate (Fgiure3.a) the desert equilibrium remains a repellor and the new carrying capacity moves slightly towards lower vegetation density (Figure3. a. B). As the stocking rate increases (Figure 3.abc) the vegetated equilibrium and the repellor move closer together until they fuse into a single point (Figure 3.D) at the top of the parabola. This means that rate of consumption exceeds the rate of vegetation growth at any vegetation density, fusing the attractor-repellor point and making the non-vegetated state the only possible equilibrium. We call this point catastrophic bifurcation (Figure3.D). The movement of attractive and catastrophic bifurcation can also be visualized by a stability landscape (Figure 4). This figure uses the stability of gravity to represent the sway of attraction and repulsion between the basins of attraction and repulsion of two alternative stable states.

ii. Precipitation

While cattle grazing may contribute to catastrophic bifurcation in arid ecosystems, interactions between precipitation and vegetation growth are also noteworthy. Studies have found that vegetation can support local precipitation. Vegetation supplies moisture to the atmosphere through evapotranspiration, which condenses into clouds and produces rain. It has been estimated that between 30-70% of rainwater in arid ecosystems originated as evapotranspiration (Rietkerk 2004). Vegetation also, quite obviously, needs rain to grow. The disparities in how much rain can vegetation produce and how much rain the vegetation needs can produce a system with multiple equilibria (Figure 5). Following Rietkerk, we postulate that the amount of rain increases linearly with vegetation density on the landscape – we conceptualize this as the supply function for rain. However, vegetation increases non-linearly with rain as a step-function– we conceptualize this as the demand function for rain. Similar to our progression of cattle grazing, precipitation function also contains three equilibria: vegetative attractor (Figure5.C), repellor (Figure5.B), and desertified attractor (Figure5.A). In the case of the first desertification attractor, at a low vegetation cover, there is more demand for precipitation than the supply. Here the landscape is barren, and the moisture is low. As there is no appreciable vegetation, no water is recycled by vegetation. However, at an intermediate vegetation density the supply and demand are again perfectly balanced forming an unstable equilibrium --- a repellor. When the vegetation density is above the repellor the supply of rain is larger than the demand and the landscape can progressively become fully vegetated. The progression of precipitation levels changes the supply and demand dynamics between each equilibrium, swaying the system towards catastrophic bifurcation (Figure5.D). It is also important to note that precipitation is connected to evapotranspiration, therefore, an increase in temperature can, increase evapotranspiration, and decrease the amount of precipitation received by vegetation.

c. CATASTROPHIC BIFURCATION

Both the impacts of cattle stocking rate and precipitation rate impact the proximity between attractive and repelling equilibria, which can potentially lead to catastrophic bifurcation. The dynamics of catastrophic bifurcation point, in relation to both attractive stable states, has more depth on a vertical axis (Figure 6). The area where green and yellow stable states overlap in vegetation density signify the potential for two alternative stable states. Here, point D is the catastrophic bifurcation point where the systems can shift abruptly from one stable state (Figure6.C) to another (Figure6.A) depending on the set of environmental conditions. Managing cattle stock *and* monitoring precipitation input is highly important as it determines how close the attractor (Figure6.C) and repellor point (Figure6.B) are from one another. High cattle stocking or low precipitation levels can result equilibria B and C merging together at catastrophic bifurcation (Figure6.D), shifting the grassy arid ecosystem into desertification. The bifurcation plot underscores the path-dependency of the system. As environmental conditions slightly shift, such as increased grazing or decreased precipitation, the system gravitates away from one stable equilibria to another. Once the system reaches the alternate equilibrium its conditions are stabilized by a new set of feedbacks. Therefore, in order to return back to the original stable state, the system requires a significant amount of shift to surpass the multiple equilibria overlap and overcome catastrophic bifurcation again (D).

d. SPATIAL PATTERNS

The tipping point between two stable states can be catalyzed by small and large shifts in environmental conditions depending on its vulnerability. This includes changes in cattle stocking, intensity of grazing, amount of precipitation, change in temperature, or a combination of these factors. Creating visual scales to identify the ecosystem's proximity to desertification is critical for mitigation strategies. Spatial vegetative patterns can suggest the level of precipitation input, or the level of grazing pressure, where the system would be unable to maintain vegetation in the absence of the positive feedback (Ritkerk 2004). Recent research has discovered ways to associate vegetative spatial patterns with ecosystem degradation level and the proximity to tipping point (Kefi 2014) (Figure 7). A prosperous stable vegetative state is characterized by full vegetation coverage (Figure7.F). A transition to an alternative stable state is characterized by a progression of specific vegetation patterns. First, approximately equally spaced circular areas of bare soil appear (Figure7.E), sometimes called "fairy rings". With decreasing precipitation or increasing grazing pressure these turn into a labyrinth maze pattern between grassy patches/bare soil (Figure7.D). With a further decrease in precipitation or an increase in grazing pressure the labyrinth disintegrates into equally spaced patches of vegetation in a matrix of bare soil. The higher proportion of bare soil indicates motion towards catastrophic bifurcation (Figure7.D). The appearance of spatial patterning can be interpreted as signaling the development of the latent alternative decertified equilibrium. Likewise, the stage of progression of the spatial pattern from fairy rings, to labyrinths, to vegetation spots can be seen as indicative of the proximity to the catastrophic bifurcation.

It is worth noting that vegetation on slopes develops patterns through a slightly modified mechanism called the "runoff-run-on system" that results in vegetation stripes that are oriented perpendicular to slope. Here the vegetation stripe upslope infiltrates runoff and depletes moisture downslope. The depleted moisture does not allow for new vegetation to grow and this results in a bare soil patch. The bare soil patch then serves as a water harvesting area, generating runoff for the vegetation stripe below. Again, mathematical models show that the presence of spatial patterns coincide with the development of the latent desertified equilibrium. As the system progresses towards the catastrophic bifurcation the wavelength of the pattern between grassy patches and bare soil increases.

The spatial distribution of grassy patches and barren soil should not be confused with vegetative failure or certain catastrophic bifurcation. While some studies believe that spatial patterns signify risk of regime change or ecosystem collapse, others point out the level of uncertainty in this conclusion (Dunkerley 2018) Changes in precipitation and temperature may cause interactions between soil, vegetation, and water to condense into smaller areas for better vegetative production, instead of the whole system suffering from inadequate resources (Dunkerley 2018). The spatial changes in ranchlands represents the systems attempt to adapt to new sets of ecological inputs and outputs. Whether or not the landscapes fall into catastrophic bifurcation is determined by the strength of resilience. Overall, future research should fully understand the differing effects climatic conditions have on ecological processes and the limits of resilience.

e. PATTERN PERIODICITY

As mentioned previously, when an arid ecosystem approaches catastrophic bifurcation the spatial distribution of vegetation transitions either (1) from labyrinth to spots and then to a complete barren landscape, or (2) through a series of striped patterns with increasing wavelengths. We can measure these changes by focusing on the patchy spatial distribution of NDVI (normalized difference vegetation index) values in aerial photographs (the further the distance between grassy patches and bare soil, the closer the system is to desertification). Spatial distribution of NDVI values signify whether these patches are close or farther from one another, with high NDVI representing grassy patches and low NDVI representing bare patches. Levels of NDVI can be plotted against distance on transects to show the organization of spatial patterns in the system and its proximity to desertification (Kefi 2004) (Figure 8). The transect patterns of NDVI are processed by Fourier analysis to decompose the complex spatial pattern into a series of sine and cosine waves that collectively reproduce the pattern. The outcome of the Fourier Analysis is a combination of different wavelengths and amplitudes associated with each wavelength. The amplitude of the wave signifies the NDVI difference between grassy patches and bare soil, while the wavelength indicates how close these differences of NDVI are from each other.

The wave in figure 8 represents the product of combining multiple, smaller waves. Each smaller wave represents a different interaction or mechanism which impacts the organization of patchiness. Figure 9 a) extracts the spectral density frequency of each smaller wave to determine which wave is most dominant/strongest in the system. The frequency indicates the inverse of a wavelength; thus, a lower frequency means a longer wavelength and a higher proximity to desertification. Figure 9, graph 2, places each wavelength on top of one another to provide comparison for how three individual waves compile together to form a cumulative wave in Figure 8. Analyzing and tracking the spatial distribution of arid ecosystems gives us a spectrum of early warning signs to look out for.

Scientific knowledge provides a foundation for explaining why and how our ecosystems are changing. It connects the interactions between cattle, grass, and water, to observable and measurable patterns. While these scientific theories are useful, their application varies depending on the context, conditions, and management of an arid landscape. This next section applies these theories to the conditions and ecological interactions of Chico Basin Ranch.

THE SCIENTIST

a. CHICO BASIN RANCH

Chico Basin Ranch is located 40 minutes Southeast of Colorado Springs, CO, and spans over 90,000 acres of shortgrass arid ecosystems with five spring fed lakes, many natural springs, and two creeks. Chico Basin is the headquarters of the larger Ranchlands ownership. Chico's primary enterprise focused on raising Beefmaster cattle and calves, while also diversifying profit in guest programs, hunting, fishing, leather product manufacturing, education programs (K-12), college research involvement, ranch management training programs, and conservation **(Chico 2021)**. The land of the Chico Basin Ranch is owned by the State Land Board and has been managed by Ranchlands since 2002. It is important to note that the data collection, results and analysis of Chico Basin Ranch represents only one acre of land. The aim of this research is to begin asking the question of whether cattle grazing, climate change, or a combination of these factors are pushing Chico ranch towards catastrophic bifurcation and desertification.

b. SPATIAL AND TEMPORAL PATTERNS

Although this research was conducted in 2020, the spatial patterns of Chico Ranch have developed over long periods of time. We used Google Earth aerial photographs of our area of interest in 1999, 2003, 2015, 2017, and 2019 (Figure 1). These selected images project a vertical oriented stripe pattern which consists of vegetated patches; particularly from 2015-2019. This does not mean the system is at immediate risk of desertification, but it does signify that the changes in vegetative patterns is directly linked to temperature and precipitation patterns discussed later.

c. TEMPERATURE AND PRECIPITATION PATTERNS

Temporal patterns of temperature and precipitation should also be considered in the context of Chico Basin as a result of climate change. Therefore, we analyzed the changes in yearly precipitation levels and average temperature between 1948 and 2019 at a weather station located near Colorado Springs Airport (38 miles northwest of Chico) (National Historical Climatology Network) Figure 2a shows dips in precipitation levels which are correlated to natural drought periods around Chico Basin. No strong linear trend in precipitation levels was identified, however, according to our analysis, Chico is currently experiencing a long drought. While precipitation levels show no obvious trend, the average temperature experienced a statistically significant increase (R^2=0.194, n=72, and p= 0.0001) starting in the mid 1990s (Figure2.b). Temperature increases by itself may be significant, but increased temperature also increases evapotranspiration. Although precipitation does not show a significant increase/decrease, increased evapotranspiration can negatively impact the water balance making the environment more arid and less resilient to external pressures, such as grazing. By analyzing patterns of precipitation and temperature, it is evident that impacts of increased temperature due to climate change are impacting the land of Chico Basin Ranch as seen in Figure 1. The development of spatial patterns in 2015 support the theory that high temperatures result in high evapotranspiration and lower water input into vegetation. The periodic patterns of grassy and bare soil patches are a result of ranchland's resiliency and adaptiveness to ecological changes.

d. METHODS

i. Study Site Within Chico Basin Ranch

To investigate the impacts of cattle on vegetation, we focused on an Area of Interest (AOI) in the pasture immediately east of the airstrip, extending 3 meters north from a water stock tank. The total area of the AOI was about 3 hectares, split into three one-hectare Zones. Each Zone represents either high, intermediate, or low cattle grazing presence under the assumption that cattle grazing is greatest the closer the Zone is to the water tank. Zone 1 represents high cattle grazing pressure and is closest to the water tank, Zone 2 represents intermediate cattle grazing pressure, and Zone 3 represents low cattle grazing impact as is furthest to the water tank (Figure 3).

ii. Drone and Arcmap

Our drone NDVI data was collected from September 28 - October 14 of 2020, during the grass dormant season and a prolonged drought season. First, we used a custom-built octocopter drone carrying a Micasense RedEdge multispectral drone to obtain multispectral images of the AOI. The drone was flown at the elevation of 35m with 85% image overlap. The images were processed using Pix4D photogrammetry program into multispectral orthomosaics and the red and NIR bands were used to calculate the NDVI index raster as NDVI=(NIR-red)/(NIR+red). Second, using *Arcmap* we created twenty-four transects to investigate NDVI patterns. Four horizontal transects and four vertical transects per Zone. Each transect was labeled by its Zone and vertical or horizontal orientation ie. (z1_v2). NDVI values were generated every 10 cm along each transect to analyze the periodicity of bare soil and grassy patch patterns (Figure 4).

iii. R- Studio Spectral Density, ANOVA, & Chi-Square

Using spectral analysis in R-*studio*, we analyzed the transect NDVI points for each Zone. After smoothing the data (averaging every 5 points using a rowing window algorithm), we plotted the NDVI values along the distance for each transect showing the NDVI spatial fluctuations for each Zone. Then we used Fast Fourier Transform code in R-Studio and pulled out peak frequencies and spectral density values for each Zone to determine the dominant wavelength and spatial pattern. We also ran an ANOVA test twice, once to determine the statistical significance differences in the NDVI values between the Zones, and again to measure the statistical significance of percent vegetation cover among the Zones. Both of these tests assess whether vegetation changes amongst all three zones, therefore their results should be consistent.

iv. Percent Vegetation and Cattle Hooves

Percent vegetation and presence of cow hoof prints were collected by a quadrat analysis in Mid-November. To do this, we randomly threw a quadrat frame (50 by 50 cm) across each zone 20 times (total of 60 quadrats). Vegetation percent was measured by counting how many quadrat string intercepts lay over vegetation (x/16). Each quadrat was also described by the absence (value of 0) or presence (value of 1) of cattle hoof prints. The presence of cattle hoof prints was determined by any sign of soil disruption, edges, or rounding. We did not consider how recent the markings were made. The absence and presence of hoof markings was run through a chi-square test to determine statistical significance between cattle presence in each Zone. Note that while the NDVI drone data was taken in late September/early October, vegetation quadrats were measured in Mid-November. With this under consideration we anticipate some discrepancy between vegetative precedent and NDVI data.

v. Research Questions and Hypotheses

The purpose of this study is to determine whether climate change, cattle grazing, or a combination is the dominant mechanism behind spatial patterns at Chico ranch. Our null hypothesis states that if cattle grazing is the primary cause of pattern formation in the vegetation, we expect longer wavelengths at the Zone closest to the water tank (Zone1), meaning there is a prominent spatial pattern and labyrinth between grassy patches and bare soil. We would also expect lower NDVI and a greater amount of hoof prints closer to the water tank indicating a greater grazing presence and vegetation reduction. We also acknowledge that the increase in temperature observed in our temporal analysis suggests an increase in evapotranspiration and a decrease in moisture input. While we did not investigate spatial pattern changes as a function of climate change, we hypothesize that the changes of temperature and evapotranspiration will influence our results and data.

e. RESULTS

i. Drone NDVI

The drone data reveal substantial spatial variability of NDVI values both within and between the Zones. To better visualize the spatial variability in vegetation cover we categorized NDVI into three color ranges: bare soil (yellow), grassy patches (orange), and annual vegetation (red) (Figure 3). Most of the annual vegetation was found around the water tank in Zone 1. We hypothesize that this is a result of a recent rain event in early September, two weeks before data were collected. Unlike grassy patches, annual vegetation reacts significantly to changes in precipitation, therefore we would expect an increase in NDVI with precipitation events. Zone 2 and 3 contained a mixture of patches of grass and bare ground. We also note a tiger stripe pattern of grassy patches and bare soil present at Zone 3, indicating the presence of spatial organization. In contrast Zone 1, closest to the water tank did not display any strong patterning.

ii. Visual Analysis of NDVI Over Transect Distance

NDVI points for all twenty-four transects were plotted on R-studio. Each graph displayed the relationship between NDVI and distance for each horizontal and vertical transect. We chose to focus on vertical transects (north-south) instead of horizontal transects (East-West,) because the tiger-stripe pattern in Zone 3 was oriented perpendicular to the transects. Out of the 12 vertical transects, Transect 3 displayed the strongest pattern in all three Zones, therefore we use Transect 3 for our remaining spatial pattern analysis (Figure 6) (Appendix).

The first part of the analysis investigates NDVI values of Transect 3 in all three Zones. Figure 7 compares the NDVI vs. distance graphs over the Transect 3 distance in all three Zones to visually estimate the wavelength and amplitude. Wavelength indicates the distance between grassy and bare soil patches. Amplitude indicates the difference in NDVI between grassy and bare soil patches. Zone 3 displays a clear pattern with wavelength of approximately 20m where the wave clearly repeats itself five times in the transect. The NDVI amplitude of the waves in Zone 3 was .24. Zone 2 displays a pattern with a wavelength of approximately 60m with an NDVI amplitude of .23. The wave repeats itself approximately 1.5 times in the Zone and thus it is unclear whether it can be classified as a repeating pattern. Zone 1 displays a wavelength of approximately 70m with an NDVI amplitude of .27. The "wave" in Zone 1 takes up most of the full length of the 100m transect and hence it is unclear whether it is repeating or not.

Based on these graphs, it appears that Zone 1 visually has the longest wavelength and highest amplitude, meaning grassy and bare soil patches are further away from one another. These results support our hypothesis that Zones with high cattle presence will have greater wavelengths, though it challenges our hypothesis that Zones with high cattle presence will have lower amplitude and NDVI values. Despite these results, we acknowledge that our conclusions are limited by the transect distance. We recommend that future research extends the length of transects to better determine the repetition of wavelengths and the validity of spatial patterns. The next analysis determines the number of statistically significant wavelengths and the most dominant wavelengths within all three Zones.

iii. FFT Analysis of NDVI Over Transect Distance

To perform a quantitative analysis of the Transect 3 spatial patterns we ran a Fast Fourier Transform (FFT) analysis and associated spectral densities to distinguish what wavelengths were most dominant in the oscillations between NDVI and distance. The spectral density graph shows that most of the statistically significant wavelengths were present at low frequencies indicating larger wavelengths in all Zones. Figure 8 shows the spectral density graphs of Transect 3 for all three Zones. Zone 3 has a dominant peak at a frequency of 0.0648 m^{-1}, corresponding to a wavelength of 15m, which is congruent with the estimated wavelength of 20m based on the visual analysis in Figure 7. The analysis also identifies other statistically significant wavelengths besides the dominant peak. These additional wavelengths were 4.7m and 3.2 m. Zone 2 has a frequency of 0.00925 m^{-1}, corresponding to a wavelength of 108m, which is longer than the full length of the transect and thus should not necessarily count as a repeating pattern. The other statistically significant wavelengths were at 12.5m, 8m, 5m, 3m, and 2.5m. Zone 1 has an identical frequency and wavelength in Zone 2 and hence we cannot consider its wavelength as a repeating pattern. The other statistically significant wavelength was at 11m.

These graphs suggest that large wavelengths with the greatest NDVI difference are the most dominant in each Zone. All other vertical transect analyses are outlined in the Appendix, congruent to Transect 3. To conclude this spectral and spatial analysis, we overlapped each dominant Zone wavelength on a NDVI distance graph to contrast the varying amplitudes and wavelengths of each Zone (Figure 9)

iv. Spectral Density Histograms

Given that the analysis of wavelengths that are associated with the highest spectral density produced an inconclusive result due to the limitation of the transect distance. Therefore, we focused on an aggregate analysis of all statistically significant wavelengths that were represented by distinct peaks in the spectrum in all of the 24 transects across the three zones (with 8 transects per zone). In this analysis we did not weigh the peaks by their spectral density, instead we focused on the question of what are the most frequent statistically significant wavelengths in each Zone?

To better visualize the distribution of all statistically significant wavelengths, we generated three histograms with 2m bins, one histogram for each Zone (Figure 10). This means that all wavelengths are binned together every 2 meters. While a spectral density analysis informs us on which wavelengths are most dominant, a histogram analysis informs us on the distribution of all wavelengths. The distribution of statistically significant wavelengths can tell us how many wavelengths are influencing the overall spatial patterns of each Zone. The 2m histogram in Figure 10 shows that the Zone 1 and Zone 2 wavelength distribution spans from 0-10m, while Zone 3 wavelength distribution extends to 20m. This suggests that the spatial patterns in Zone 3 contain a higher variety of wavelengths, which could be due to the land adapting and transitioning away from high cattle presence. Furthermore, the 2m bin histogram suggests that the most common wavelengths, corresponding to the dominant peak in the corresponding histogram, were 11m (Zone 1), 5m (Zone 2), and 3m (Zone 3) by visual interpretation. Based on the histogram, the peak wavelength result supports our null hypothesis which states that Zones with the higher cattle grazing presence (Zone 1) will have a larger wavelength than Zones further away.

v. ANOVA Transect NDVI

From mid-September to early October, we investigated the changes and differences between NDVI across each transect and Zone. To simplify this process, we averaged the NDVI values of each horizontal transect in all three Zones giving us one NDVI value for each transect: four values per Zone, twelve values totals. These values were analyzed using an ANOVA test. The results showed that the highest NDVI values with (mean NDVI=0.23) were found in Zone 1, followed by Zone 2 (mean NDVI=0.22), and the lowest NDVI values were found in Zone 3 (mean NDVI=0.21). ANOVA showed that the differences in the mean NDVI values among the Zones were statistically significant as revealed by a high F-value (F 2.9=11.1) and low p-value (p=0.000723). We followed up the test with post-hoc Bonferroni-corrected significance tests that indicated that the difference between Zone 1 and Zone 2 was statistically significant while the difference between Zone 2 and 3 was not. This result was highly surprising because it showed that the system had highs NDVI in the zone with the highest cattle impact. This directly contradicts our hypothesis that the cattle have negative impact on vegetation cover due to their consumption of biomass.

vi. ANOVA Vegetated Percent

Additionally, in mid-November we went into the field twenty quadrats were displaced randomly in each of the three Zones, to compare the vegetative percent among the Zones. Photographs were taken of each quadrat to estimate percent vegetation cover and give visual context to the analysis (Figure 11). The images also give context to what the grassy patches, labyrinths, and bare soil look like at Chico Basin Ranch. The statistical significance of the vegetative percentages was run through an ANOVA test for each Zone. The results showed that the three Zones did not differ in the percent vegetation cover as indicated by a low F-value (2.59) and a p-value greater than 0.05 (p=0.286), undermining our hypothesis that vegetation percent should increase from Zone 1 to Zone 2 to Zone 3.

The results of our vegetated percent and NDVI analysis are puzzling. While vegetative percent data suggests that the percent of vegetation and bare soil does not change throughout the three Zones, our transect NDVI data analysis reveals that Zone 1, with the highest cattle presence, has the greatest NDVI values. The inconsistent results can be due to two reasons. One, it suggests that there may be another mechanism or interaction influencing the vegetative patterns besides cattle grazing. This could be cattle movement, precipitation levels, type of vegetation, or management style. Secondly, it could be a result of our differing data collection times. Drone and NDVI data were measured in early September while vegetative percent data was measured in late October. Our field observations also note that NDVI data taken in September was 10 days after a recent rain event, while data in October was 40 days after the rain event. We also noted in September that Zone 1 vegetation consisted of mostly annual forbes while Zone 3 did not contain annual vegetation and mostly seasonal bunchgrasses. Both of these hypotheses suggest that a combination of recent precipitation events and alternative impacts of cattle may have affected the inconsistent results. One possible explanation is that cattle presence also entails high hoof impact, breaking down soil crusts, allowing for both seedling dispersal and growth with the precede of recent rain events. However, as soon as the precipitation passed over, the annual vegetation died out.

vii. Chi-Squared Hooves

The purpose of this analysis is to test our assumption of cattle grazing distribution. The layout of our study and interpretation of data in the scientific position relies on the assumption that the impact of cattle on the ranchland decreases with increasing distance from the water tank. Assuming that Zone 1 represents high cattle presence, Zone 2 represents intermediate cattle presence, and Zone 3 represents low cattle presence. While this assumption is reasonable, it needs to be independently tested. To do this, we used the presence of cattle hoof markings as our sign of cattle grazing and movement presence. During our vegetative quadrat collection, we simultaneously document the presence or absence of hooves within the 60 quadrats. As expected, the proportion of quadrats with hoof-prints decreased with increasing distance from the water tank. Zone 1 had the highest proportion of 55%, Zone 2 had 40%, and Zone 3 had 5%. The proportion of quadrants with hoof prints for each Zone was compared to one another using a chi-square test for statistical significance. The results showed the difference in proportion of quadrats with hoof prints were statistically significant between Zone 1 and Zone 3 (chi-square= 0.899, df=1, two tail p=0.0017), while the differences between Zone 1 and Zone 2 and the difference between Zone 2 and Zone 3 were not statistically significant. This implies that the impact of cattle decreases with increasing distance from the water tank.

While the main intention of the research was to determine whether cattle grazing consumption impacts vegetative patterns, we did not largely focus on alternative ways cattle presence may impact interactions. Based on our results, we suspect that cattle movement may be as critically impacting as grazing. Cattle hoof prints plow through the arid crusts of bare soil, interrupting the dynamics between bare soil and grassy patches. Grassy patches no longer benefit from the runoff precipitation of bare soil and thus bare soil becomes habitable for the seedling establishment of annual vegetation.

viii. Conclusion

Observing the changes of spatial distribution amongst vegetation is the best step towards anticipating catastrophic bifurcation and ultimately, desertification. In this manuscript we have suggested ways to monitor the dynamics between grassy patches and bare soil through the case study of Chico Basin Ranch. This includes comparing the changes in distance between grassy and bare patches, the difference in NDVI, and the presence of cattle hooves in Zones with different levels of cattle presence. Determining the dominant mechanism, or combination, behind these changes is the next great goal for scientists. In our research, we hypothesized that if cattle presence were the main contributor to altering spatial patterns, we would expect lower NDVI, lower vegetative percent, high hooves presence and larger distances between grassy patches and bare soil in areas with high cattle presence (Zone 1). In reality, our data suggests that areas with high cattle presence have a higher NDVI, no significant change in vegetative percent, high hooves presence, and a large distance between grassy/bare patches. The mixed results reveal that cattle grazing may affect the spatial distribution and distance between grass and bare patches, but its impact on NDVI and vegetation presence is more complex than anticipated. This suggests that cattle movement and hoof presence is more impactful on vegetation patterns than cattle grazing. We must also consider the impact increased temperature has on potentially increased evapotranspiration, making the ecosystem more vulnerable to the additional pressure of cattle grazing. In conclusion, further research should focus not only on the impacts of cattle on ranchlands, but also the larger inputs and outputs of other natural dynamics including precipitation and soil dynamics.

This next section brings a new variable into consideration: the rancher. Cattle consumption, movement, and management are dependent on the knowledge of ranchers and the management style they implement on the land. By understanding and acknowledging the rancher perspective and various management strategies, we can build more resilience of people and the land against desertification.

THE RANCHER

The Rancher section focuses on importance of various management strategies and the role of the rancher. It is critical that we invite the perspective of ranchers into the conflict of cattle ranching as they are ones who manage and depend on the land the most. Management strategies are highly dependent on observing how vegetation, precipitation, animals, and ecological processes change over time. Land management strategies can make or break the resilience of a landscape; therefore, it is highly important to understand the range of benefits and consequences of cattle ranching. This section will dive into the foundation of holistic cattle ranching, highlight the importance of traditional rancher knowledge through several interviews, and suggest examples of successful collaborative ranching styles used today.

a. HOLISTIC RANCH MANAGEMENT

i. Introduction

The discourse on cattle ranching has fluctuated over time. In the 2000s, ecologists critiqued cattle ranching for infringing on natural ecosystems, while in 2010, a deeper investigation evolved at the hands of white Zimbabwean ecologist Allan Savory. Savory coined a new way of raising cattle which simultaneously protects the land against desertification: Holistic Ranch Management. This management style uses cattle as a tool to promote “regeneration of soils, increased productivity and biological diversity, as well as economic and social well-being” (**Savory 2020**). The strategy of Holistic Management is to mimic the presence of wild herds that previously roamed the landscape. By closely monitoring grazing movement and vegetation response, ranchers are able to adapt different rest and grazing periods for different vegetation types. As land rests, cattle are able to facilitate regular water cycles, mineral cycles, and other ecosystem dynamics. Furthermore, Savory states that the presence of cattle dung, urine, and hoof disruption on soil facilitate positive soil nutrient cycling and activity. Holistic Management is now formalized into the development of the Savory Institute, where their research actively informs "policy discussion on issues such as climate change, land stewardship, and food security" (**Savory 2020)**. The benefits of Holistic Management can be considered in the context of vegetation, precipitation, and people.

Vegetation

As discussed previously, vegetation growth can be resilient towards a threshold level of herbivory consumption. Vegetation resilience is impacts by factors such as the intensity of grazing, the extend of areas grazed, time spent grazing, and how much time vegetation has to rest from grazing. However, with the additional stress of temperature and climate change, impacts of cattle grazing are exacerbated. Temperature increase can result in an invasion of nonnative grasses and buildup of high fuel plants, putting the ecosystem both at risk to fire and the pushout of important native grasses (**Savory 2020)**. Savory Institute claims that these issues were historically mitigated by the heavy grazing from wildebeests (Africa) or other large herbivores such as buffalo (North America), to suggest that herbivory pressure can increase the diversification of the land's vegetation (**Brunson 2008**). Grazing is also shown to have positive effects within native plant communities. Cattle grazing reduces plant competition in short ranges, promoting seedling dispersion and establishment in bare soil openings (**McNaughten 1985**). The more species packing, niche overlapping, and interactions between grazing, dung nutrients, hoof erosion, and plant facilitation/competition, the more resilient the vegetation is towards other stressors, such as climate change (**McNaughten 1985**).

Water and Precipitation

Cattle grazing also impacts the dynamics of precipitation, transpiration, and evaporation. Precipitation levels often dictate the productivity and state of an ecosystem, specifically, where it lays on the scale of desertification (**McNaughten 1985**). In this case, Holistic Management involves constant observation of weather patterns and their effects on different species of vegetation. By doing this, ranchers can allocate cattle in more resilient crops to allow drought sensitive vegetation time to rest (**Savory 2020**). Grazing can also regulate vegetation transpiration surface exposure by reducing vegetation they also reduce avenues for water to be lost through leaf pores. This means that the plants can invest more water and energy into survival and growth instead of leaf density (**McNaughten 1985**). While cattle grazing can positively impact hydraulic processes, we will be also discussing ways it can hinder it.

People

Although holistic ranch management emphasizes the ecological relationships between cattle and vegetation, it also acknowledges the role and resilience of ranchers and people. Practicing Holistic Ranch Management with conservation initiatives has become an increasingly popular and advantageous management style for ranchers (**Savory 2020)**. Workshopping rotational grazing, educational programs, and wilderness conservation initiatives has diversified the income of many ranchers (**Brunson 2008**). Under Holistic Management, ranchers act as ecosystem engineers**,** a dynamic role that is responsible for adapting ranch rotations depending on changing precipitation and conditions. By giving more agency to ranchers, people are invited back to the questions of conservation and are in turn, more invested in the well-being of their surrounding environment (**Brunson 2008**). Overall, Holistic Ranch Management prioritizes both ecological and socioeconomic benefits for the environment and people.

ii. Holistic Management Critique

While at first glance, Savory's Holistic Management strategy promises both ecological and social benefits to cattle ranching, some criticize its road to success. Papers have questioned how well cattle mimic the previous presence of grazing herds in Africa and that these results are not globally translatable to reversing desertification in North America (**Fliescher 1994**) (**Nordberg 2016**). While Holistic Management has proven to have positive impacts on some aspects of vegetation and ecosystem processes, it some cases it can also have negative impacts on vegetation, water cycles, and people.

Vegetation and Soil

When discussing the negative impacts cattle have on vegetation, we can categorize them as the alteration of species composition, disruption of ecosystem functions, and an alteration of ecosystem structure (**Fleischner 1994**). Cattle grazing can lead to active selection and over consumption of specific vegetation, causing an unequal distribution and proportion of vegetation types. Grazing movement and rotations can also contribute to the spread of exotic nonnative species through fur and dung (**Freilich 2020**). The severity of these impacts is highly dependent on the fragility and resilience of the ecosystem and habitual makeup (**Fleischner 1994**). Holistic Management also assumes that vegetation is highly dependent on grazing and would die if not grazed (**Fleischner 1994**). Whether or not a landscape thrives under grazing is dependent on the type of vegetation on the system, which will ultimately alter the way Holistic Management strategy is managed (**Carter 2014**). Vegetation impacts are highly related to the health of soil. Arid ecosystems often have cryptogamic or microbiotic soil crusts, which are fragile "symbioses of cyanobacteria, lichens, and mosses from a variety of taxes" (**Rahmanian 2018**). The purpose of these crusts is nutrient cycling, nitrogen fixation, and absorbing dew during dry periods

(**Carter 2014**). Therefore, the presence of constant cattle grazing, and movement breaks up the storage of cryptobiotic soil and decreases the macrobiotic species richness (**Fleischner 1994**). Once these crusts are trampled it takes a significant amount of time to recover and redistribute its benefits (**Carter 2014**).

The discourse around soil disruption benefits and consequences is at the crux of cattle ranch management practices. Soil disruption has the potential to positively increase seedling dispersal and vegetation expanse, while it can also negatively decrease the benefits of precipitation runoff and soil nutrients. The Scientist section alludes to the impact of cattle hoof disruption of soil crusts in the context of Chico Basin Ranch. Our data suggests that cattle movement does break up soil crust, both permitting the establishment of annual vegetation and increasing the spatial patterns of vegetation. We suggest that both the benefits and consequences of soil disruption should be considered in implemented periodic cattle disturbance specific to the resiliency of vegetation types.

Water and Riparian Systems

Cattle movement and soil disruption can have compounding effects on ranchlands that contain riparian systems. As mentioned, cattle presence can increase soil disruption and compaction, resulting in more surface runoff, and potential for massive flooding (**Fleischner 1994**). Cattle can specifically affect four general components of riparian systems: streamside vegetation, stream channel morphology, shape and quality of water column, and structure of streambank soil. Grazing on plant seedlings and trampling erosion can change streamside vegetation, reduction of cover and food for fish, wildlife, and soil compaction, erosion, and sedimentation (**Carter 2014**). Water is already a known limiting factor in many ranchlands; therefore, ranchers must carefully consider the consequences cattle grazing and movement can have on soil compaction. Soil compaction can lead to a decrease in water infiltration, increase in water runoff, and potentially lead to further desertification.

People

Some argue that both cattle and people must be removed from any conservation efforts to restore arid landscapes; that the effects on vegetation and water cycles are dependent on the ways in which humans intervene in the environment. This perspective argues that changes in ranchland systems are a direct result of the presence of humans, agriculture, and management systems. Conservationists and Ecologists argue that "if the overgrazing by livestock and human presence are one of the main factors contributing to the destruction of the habitat, then the solution would be to remove the cause of the problem" (**Carter 2014).** Western notions of conservation have idealized the isolation of wilderness and the pushout of people. It is important to recognize that this act is inequitable and a case of environmental justice. The people pushing others out are wealthy, urban residents, and privileged by their selective access to the outdoors. And the people being pushed off land are the most vulnerable, marginalized, and politically powerless communities of people. Let us be reminded that part of the land we stand on is the result of pushing indigenous people out and justified by conservation initiatives. With that said, I acknowledge that both Chico Basin Ranch and Colorado College is located on the territory of the Ute Peoples including the Apache, Arapaho, Comanche, and Cheyenne. American ranching and cattle herding is located in indigenous land use management that has been implemented on most arid lands for the past 5,000-10,000 years. The solution to cattle ranching should not focus on excluding people but on adapting management strategies to be more resilient to recent ecological changes.

iii. Conclusion

By untangling the various opinions on Holistic Ranch Management, we are able to zoom out and understand why it is so important to consider the ecological interactions, fragilities, and vulnerabilities of a landscape before adapting Holistic Ranch Management. These considerations include whether cattle grazing includes watershed scale gazing? What the ecological and livestock criteria? And the ways to replicate holistic management to different arid landscape scales (**Carter 2014**). This literature review of Holistic Ranch Management provides us a framework for the foundation of holistic collaboration between scientific knowledge and management strategy. We will now shift into the complexities of human impacts by inviting the ranch perspective into this conversation.

b. TRADITIONAL RANCHER KNOWLEDGE

Scientific knowledge has dominated the debate on cattle ranching and ranch conservation in academic literature and policy-making decisions. Minimal academic research includes or is written by the perspectives of ranchers themselves; the people that are most intimate with the environment, and most in control of the outcomes of cattle ranching. We categorize the rancher perspective and ecological contributions as traditional rancher knowledge. While scientific knowledge and traditional rancher knowledge have contrasting methods and sources of evidence, they both share the same concern for protecting ranchlands, and should be used collaboratively

Traditional rancher knowledge is based on indigenous knowledge systems (IKS) and other forms of traditional knowledge of local resources. Though this manuscript does not largely focus on IKS, we acknowledge that the origins of American ranching come for a variety of indigenous influences. For instance, Chico Basin Ranch is located on the unceded territory of the Ute Peoples including the Apache, Arapaho, Comanche, and Cheyenne indigenous groups that lived and moved on these arid landscapes. For more information on the history of cattle ranching in Colorado and the presence of Indigenous groups refer to the following source (**BLM Cultural Resource**).

In this study, we will be situated on the traditional rancher knowledge of modern ranchers and scientific knowledge. The defining characteristics of traditional rancher knowledge is that it is observation based, general/holistic, situated locally, adaptive, and sustainable with low population densities. In contrast, scientific knowledge is characterized by experimentation, specialized/partial, profit goals, and not sustainable (**Dewalt 1994**). Summed up, any form of traditional knowledge can produce mutable immobiles, which means "relatively malleable knowledge that is finely tuned to the continually changing circumstances that define a particular locality" (**Kloppenburg 1991**). While scientific knowledge is an immutable mobiles- "information that can be transferred without transformation to any spatial or social location" (**Dewalt 1994**). There are limitations and benefits to both of these knowledge systems, suggesting that a combination of these knowledge systems would give the most complementary management style for cattle ranching.

c. RACHER INTERVIEWS

It would be a disservice to address the issues of knowledge exchange without having conversations with ranchers and inviting them to write their own narrative into my manuscript. Therefore, I conducted two informal 45 minutes interviews with two ranchers. The goal of the interview was to act as a listener and allow Chico Basin Rancher Samantha Bradford and Gila Goowdin the opportunity to speak their truths. The best way to truly understand the reality of cattle ranching and the complexities of the ecology and livelihoods is by sharing knowledge, stories, and individuals.

i. Samantha Bradford

Samantha (Sam) Bradford is a rancher at Chico Basin Ranch in Pueblo, Colorado. Her position at Chico includes rancher, education director, outreach coordinator, and conservation and land monitoring director. During the interview, Samantha was transparent about the questions ranchers have to ask themselves, such as “what makes sense for a business strategy with cows? Do we want a herd that only survives on this landscape or do we want to cultivate a herd that can succeed on a landscape without additional add-ins?”. She shared that at Chico Ranch they understand the shifting changes of their environment, specifically inconsistent rainfall and strive to cultivate animals adaptive to these changes. To do this, they have invested and engaged in sustainably feasible and financially responsible management strategies. Chico engages in a holistic ranch management style that focuses on day-to-day observations and adaptations. “We will watch how our cattle graze a pasture, to know when the land needs time to rest and when our cattle need to move for a higher degree of protein”. Sam finished off the conversation by pointing out the frustrations between ranching communities and scientific communities. “Ranchers are constantly being criticized and judged by scientists that don’t fully understand the seasonal changes at Chico... We all need to come together to discuss how proper cattle ranching can be beneficial local and regionally” **(Bradford 2020).**

Because this research focuses on the ecological interactions of Chico Basin Ranch, it is critical to highlight the experience and perspective of Samantha, a rancher who has spent days, months, and years facilitating the changes of Chico Basin to highlight Samantha’s perspective as a part of the Chico Basin Ranch. We will be diving deeper into the specific practices of Chico and their values, process, and politics later on.

ii. Gila Goodwin

The second interview conducted was with a fellow Colorado College student, Gila Goodwin. The Goodwin family obtained The Guadalupe Cattle Ranch in the 1960s with an emphasis on a type of Holistic Ranch management. The Guadalupe ranch is located along the border of Arizona and Mexico. The ranch "focuses on large landscape management by using cattle as a conservation tool to sustain and help create healthy ecosystems for human and non-human life". Large landscape management means that single ranches and ranchers come together to a shared goal of preserving the ecological integrity of the land while being financially supportive for each rancher. Goodwin points out that this management system is heavily reliant on conservation easements. "A conservation easement is when an organization buys the development rights from ranchers, therefore protecting the land from the rise of subdivision and development". These easements "protect the environment while still respecting and incorporating the needs of the ranchers". By giving up their rights to develop, in return, ranchers receive organization funding as compensation. In Goodwin's ranch community, conservation easements are agreed and funded by an organization called MALPAI Borderlands group which we will discuss in more detail later. Overall, Goodwin emphasizes that the collaboration of both scientists, ranchers, and nonprofits, results in best protection for the environment (**Goodwin 2020)**

iii. Rancher Perspective Continued

The consequence of excluding the rancher perspective from scientific research is that people are excluded from ranching and desertification solutions. Both of these interviews have revealed that when the land is extremely susceptible and vulnerable to changing climates, so are people. Bill Mcdonald, a long time rancher in Douglas AZ, shares his perspective saying, “Ranching is not easy and not a profitable business, so why do we do it? Because we love the land.”(**Mcdonald 1999)** Mcdonald’s words bring something unique to this conversation. Love. That ranchers are on the land because they love it, cementing the idea that ranchers are as equipped and invested in protecting the land as scientists. He goes on to say that “there are so many things out of control. If ranchers seem standoff-ish or rigid, it's because we've had a lot of people take advantage of us, so we are reluctant to jump into new ideas” (**Mcdonald 1999)**. And at the end of the day “everyone is here to talk about how to manage the land. And if we all start pointing fingers, everyone loses. The first thing to suffer will be the habitats and the landscape” and that needs to be the priority (**Mcdonald 1999**). To address ranch management, we must first address the facts that the vulnerability of people and land are intrinsically connected.

d. CHANGING LANDSCAPES

Ranchers are aware that the climate is changing and so are their lands. Combating the effects of climate change includes the effects on grasslands, vegetation, agriculture business, and the future of ranching (**Gosnell 2020)**. With no support, the threats of climate change and urban development force ranchers to reconsider their priorities and either change land ownership, sell their land, or change their management style.

i. Exclusionary Conservation

A wave of conservation and environmental activism has overflowed into the land use of arid landscapes in America. Ranch ownership change has become more popularized these recent years as a consequence. Ranches have shifted away from livestock income and more towards maintaining and enhancing the protection of environmental amenities, giving a new value to the land (**Gosnell 2016)**. For instance, a study in Yellowstone National Park highlights the current turnover pattern in ranchlands during the 21st century, finding that most land buyers and management shifts are towards conservation and natural amenities investment. While this shift in management may seem beneficiary to conservation initiatives, dramatic changes in land management from cattle grazing to complete isolation from any human contact have had ecological impacts on vegetation that is adapted to grazing pressures and competition (**Gosnell 2016**). Through holistic ranch management and other community based methods, ranchers should look towards adapting conservation and recreational programs within their current land uses instead of complete exclusion and ranch turnover.

ii. Threat of Development

The threat of fragmentation can be seen through both conservation initiatives and urban expansion/development. With the continued threats of climate change and lack of support, ranchers are more likely to sell ranches over to larger industries which fragment and shift ecosystem functional. Ranch turnover becomes irresistible, pushing ranchers to their own cataphoric bifurcation, their own tipping point, where they tip into the temptation of selling their land to complete urbanization or conservation (**Brunson 2007**). Therefore, a new interest in "creating an agricultural industry that can withstand development pressures and maintain open, semi natural landscapes has increased" (**Brunson 2007**). One strategy is to support ranchers through private land conservation mechanisms such as land trusts or government open space programs (**Brunson 2007**). As mentioned in her interview, Gila Goodwin stated that some ranchers in the Borderlands area do not have the financial support to protect their land against the pressures of climate change or development. This vulnerability is addressed through the use of conservation easements by increasing the collaborative involvement of NGOs, scientists, governments, education and more. This support extends to increasing communal access to public grazing lands, treating ranch lands in state and federal tax codes, pushing land use planning and regulation, providing landowner incentives, and supplying ranchers with direct payments. This collaboration both addresses the concerns of climate change and development, while maintaining the livelihoods of ranchers and integrity of the land.

e. BEYOND HOLISITIC RANCH MANAGEMENT

The collaboration of knowledge and perspectives can manifest in many forms and scales. While holistic ranch management has been coined the most popular method, there are other forms of collaboration ranch management within local contexts. Here, we will elaborate on methods that scale up or scale down the idea of knowledge collaboration. First, we will discuss the foundational pillars of *community conservation* then we will scale down to the localized approach of *regenerative ranching*.

i. Community Conservation

Community conservation, similar to holistic ranch management, urges conservationists to invite community-based knowledge into their methods (**Curtin 2002**). The goal is "to sustain local agrarian livelihoods with the aim of protecting the structure and function of the landscapes within which their community and culture are embedded" (**Curtin** 2002). It prompts the question of how can science be a tool for community initiatives? And how can communities be a tool for scientific initiatives? For instance, scientist Charles Curtin conducted research testing the impact of fire and cattle stressors on Gila Goodwin's ranch. His research incorporated the traditional knowledge of the ranch owners by studying their methods of cattle rotations and fire burning. He concluded that the plot of land that was exposed to both fire and grazing was the healthiest. His work suggested that natural stressors are critical for building up resilience and biodiversity of the landscape. Community conservation is the foundation of holistic ranch management strategies at a larger scale. It is key for us to step back here and be reminded that aspects of traditional knowledge can be useful towards climate monitoring and should be molded to the local context of communities.

ii. Regenerative Ranching

"It's not the cow, it's the how". This phrase embodies another mode of holistic management coined "Regenerative Ranching" by **Gosnell** (2020). Here **Gosnell** comments on the misinformation of cattle ranching. Conservationists, scientist, and the general public hyperfocus on the presence of cow and cattle when in reality, we must focus on the how. How are cows being managed, how can we make landscapes more resilient, and how can we embed multiple knowledge systems into a holistic management style? Regenerative ranching embraces the intricacies of ranching, both ecological and humanitarian. Unlike holistic ranch management, this method is focused on understanding ecosystem processes which define ranching and manipulating these systems to support the effects of climate change. Efforts prioritize providing ranchers with the skills of a scientific observer, so that they can identify and address warning signs for climate impact independently. Its focus is primarily on the mineral cycle (soil), water cycle (riparian systems), and energy flows between herbivory and vegetation. Ranchers say that "once you shift toward acknowledging and recognizing that you are part of the whole land you become more in flow with it rather than being at the pinnacle of the top of the food chain looking down". By providing the tools to recognize the biological interactions between the landscape and the people, ranchers are credible observers. Ranchers can then regenerate the system adequately, understanding which areas are more vulnerable or more resilient to changing conditions. This management strategy goes beyond knowledge exchange and works on knowledge distribution and practice. Proving that everything must be adaptive, both the climate, landscape, ranchers, scientists, and observers.

f. THEORY TO PRACTICE

Thus far we have exposed the benefits and consequences of holistic ranch management, brought attention to the divide between scientists and ranchers, introduced the rancher perspective, and discussed conservation easements. Holistic ranch management, community conservation, and regenerative ranching, all share the goal of prioritizing the resilience of both the environment and people through the collaboration of scientific and traditional knowledge. While we can all preach and push for these objectives, understanding the feasibility, and how these theories can be translated into practice is the next step. In this section we will be honing in on the work of the MALPAI borderlands group in the Southwest USA to give an example of how regenerative management can be successful. We will be primarily focusing on their use of conservation easements and scientific research.

i. Conservation Easements

Land rights and development rights are highly vulnerable and susceptible to the pressures of development and buyers. In the mid 1980s, "the U.S.D.A Natural resources conservation service has been working with landowners and partners with conservation organizations to protect private land through their easement program" (**NRCS**). Conservation easements are a type of voluntary, legal contract between a land conservation agency and a rancher which restricts the use of the land to promote conservation values (**Reeves 2018**). The development rights are transferred to the conservation agency either through donations or by direct purchase of the rights. By giving development rights away to conservation organizations, both the environment and the ranchers are socially, ecologically, and financially supported. Environmental services such as carbon sequestration, agricultural production, timber production, water infiltration, and soil stability are just a few of the priorities conservation agencies seek to protect with these easements. As rancher, Gila Goodwin, pointed out, conservation easements are also a great management tool for ranchers who are struggling to adapt with changes in climate change. As mentioned previously, arid ecosystems are highly susceptible to long drought periods and effects of desertification, therefore, maintaining proper mitigation management takes political, financial, and social support. Conservation easements alleviate some of the stress ranchers face and inevitably allow for successful holistic cattle management.

ii. MALPAI Borderlands Group

We bring attention to a conservation based organization in the Southwest region called the MALPAI Borderlands group to give a concrete example of how community conservation can positively affect both the environment and ranchers. The MALPAI borderlands region remains around the borders of Mexico, New Mexico and Arizona; and it is home to viable ranching communities that are most vulnerable to fragmentation and development (**Bemis**). The MALPAI borderlands group is organized and led by ranchers in a collaborative effort to protect their collective land, innovate cooperative land management strategies, invest in habitat restoration, and dedicate to community outreach. The MALPAI group works in an 8000,000-acre region that extends from the Chiricahua Mountains in Arizona to the Eastern Playas valley of Southwest New Mexico. Their goals also include promoting profitable ranching and other traditional, yet scientific, management methods which sustain people and their land. The MALPAI group has acquired conservation easements on 78,000 acres of private land on fifteen ranches. By investing and integrating conservation easements into their program, MALPAI borderlands group is deconstructing the separateness and divide between shared landscapes. The conservation easements are not defined by one rancher's plot of land, but instead encompass the whole landscape. Therefore, when drought or stress hits a ranch land, the community can financially and socially support cattle and ranchers by giving the land time to rest and revive.

The MALPAI borderlands group also implements a long-term systemic program that incorporates active research and monitoring to each of their lands (**Edminister** 1999). This means developing a multidisciplinary collection of knowledge which identifies and prioritizes land needs. Some of these categories include: the status of knowledge and importance of humans' natural disturbances on plant communities, status of wildlife, prehistoric background of the ecosystem, threats of development, delineation of interpretation of geomorphic surfaces, mapping current vegetation changes, and filling the knowledge gaps between scientific and local knowledge (**Edminister** 1999). This organization has become the mecca of incorporating scientific research to better equip ranchers with management tools and confidence to recognize early warning signals of desertification and changes to arid landscapes. It has brought together the basis of inclusive biological science with the recognition of social and economic conditions. By recognizing the success and continuous work of the MALPAI borderlands group we can be hopeful for the many ways this knowledge blend can facilitate positive management change in other arid landscapes to build the resilience of both the land and the people.

iii. Chico Basin Ranch Management

While "The Scientist" section uses a one acre study site at Chico Basin Ranch as a case study to understand vegetative spatial patterns, The Rancher section uses Chico Basin Ranch as a case study example of successfully incorporating scientific and traditional rancher knowledge.

As mentioned previously, Chico Basin Ranch is part of the larger Ranchlands organization which is founded on the principles of holistic conservation management, specifically turn-key ranch management model. This model "increases the value of the land resource through vigilant business management and a vigorous conservation program that builds biodiversity while eliminating the out-of-pocket costs of owning a ranch" permitting Chico Basin to be self-sufficient. Gaining financial stability enables ranchers to invest more energy and time for conservation efforts and mitigation strategies. Chico Basin ranch embodies the idea of knowledge collaboration by working with conservation organizations such as the Bird Conservancy of Rockies, the Nature Conservancy, Quivira coalition, Colorado parks and wildlife, and the Colorado state land board. They additionally engage in local conservation entities to help with site specific expertise and resources such as conservation easements, wetland mitigation banks, and carbon offsets. The staff at Chico Basin ranch acknowledge their active role in restoring and facilitating ecological balances of arid landscapes. They are invested in the scientific knowledge of animal behaviors, stocking rates, densities and grazing patterns, vegetation growth and dormancy season, moisture requirements, and larger ecosystem dynamics.

CONCLUSION

This manuscript emphasizes the collaboration of scientific knowledge and rancher knowledge to better develop holistic mitigation strategies against climate change. This effort is two-fold. The collaboration begins by focusing on the scientific theories and ecological i

access and literacy of scientific theories on ecological interactions to the ranching community. Then we must inform scientists on the validity of rancher knowledge and the importance of management strategies in the context of cattle ranching and desertification. The question of cattle ranching should be approached collaboratively, involving the perspective, knowledge, and investments of scientists, conservationists, ranchers, politicians, students and more. Research published should be written comprehensively, therefore, the results can be understood and translated to local scales of interests.

This Scientist section scaled concepts of desertification, spatial patterns, periodicity to the context of Chico Basin Cattle Ranch in Colorado. Our objective was to test whether cattle grazing, climate, or a combination of both were the driving mechanisms pushing this arid ecosystem towards catastrophic bifurcation and desertification. Our results concluded that.

Zones with higher cattle presence have...

(1) High cow hooves impact
(2) Higher annual vegetation (NDVI)
(3) Large distance between bare and grassy patches (wavelength)

This data suggests that while cattle grazing does have an impact on vegetation spatial distributions between grassy and bare soil patches, cattle movement and hoof disruption of the soil crusts has a greater impact on the ecological dynamics of soil, infiltration, evapotranspiration, and vegetation. These effects are also exacerbated by the impacts of increased temperature and climate change. Concluding that *both* cattle presence and climate change are potentially pushing the ecosystem towards desertification.

The Rancher section suggests that ranchers and scientists should engage in a form of holistic ranch management that is localized and collaborative. This means a form of citizen science where ranchers are equipped with scientific knowledge and monitoring techniques to best adapt management strategies to the changing vulnerabilities and demands of the land. Furthermore, we emphasize examples of conservation easements, specifically the work of MALPAI Borderlands group, as inspiration for other ranchers and scientists. As mentioned previously, the essence of these efforts is to support ranchers politically, socially, and financially through the pressures of climate change on their ranchlands.

Above all, my manuscript attempts to break the hierarchy of scientific knowledge production and validation. Research and studies, such as mine, need to acknowledge the variables of trust, community values, and people in our scientific inquiries. We are connected to the environment and the best way to develop solutions and mitigation tools is to incorporate economic, social, and financial factors into our conversations. Scientific results need to extend beyond scholarly papers, and into community meetings, flyers, events, and a multitude of other mediums. We have to ask ourselves, who is going to read these results? What is the purpose of this study? What are we going to do with them? By honing in on who audiences are and the methods of our communication, we are able to successfully engage and invite community conservation into building communal resilience. I urge my readers to ask themselves, where are you situated in the complexities of desertification, cattle ranching, and climate change? What are your stakes in this conversation, where are your privileges, where do your interests lie? What are you going to do after reading this? For me, I am highly aware that I cannot continue research in this area without investing time and energy into working on ranches, talking to ranchers, and actively engaging in the collaborative knowledge production I emphasize.

FIGURES: SCIENTIFIC KNOWLEDGE

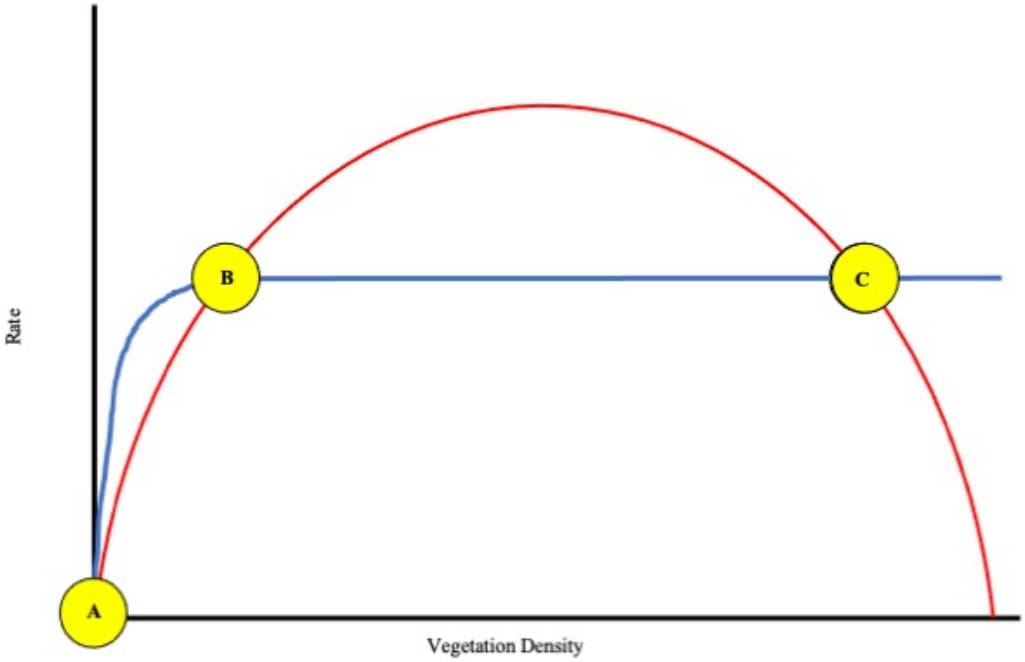


Figure 1: Depicts the consumer resource dynamic between vegetation growth and cattle grazing (vegetation death). The red line represents the parabolic shape of the rate of vegetation rate while the blue line represents the type-two response of cattle grazing rate. These rates are plotted against overall vegetation density. Points A, B, and C represent points where rate of both cattle grazing and vegetation growth equal each other, these points are known as system equilibria. Point A represents a desert, point C represents a grassland, and point B represents a critical threshold of vegetation density. The area between point A and B represents an attraction towards the desert equilibrium because cattle grazing is greater than vegetation growth. While the area between point B and C represent the growth and attraction towards the grassy arid land equilibrium since vegetation growth is greater than cattle grazing. This means that point B is the threshold conditions that when surpassed, either attract to a grassy equilibrium or a dry desertification state.

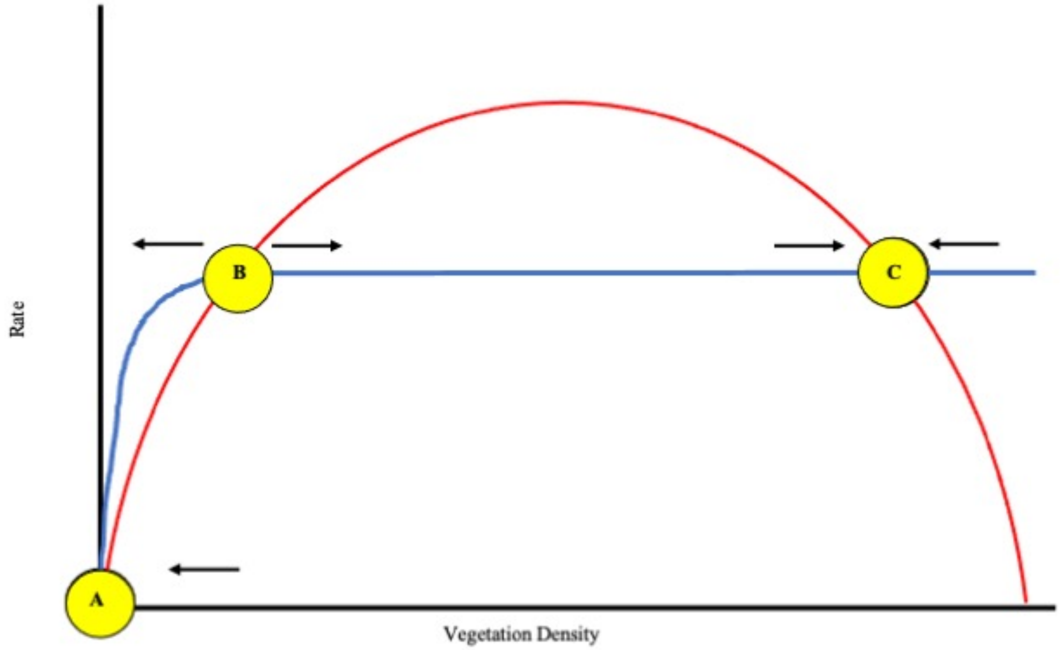


Figure 2 : Emphasizes the role of attractors and repelors on the same consumer resource graph outlined in Figure 1. The equilibrium threshold (B) acts as repellor that can push the system either towards desertification (A) or towards a healthy grass land (C). The distance between point B and C are highly dependent on sets of environmental conditions and resilience.

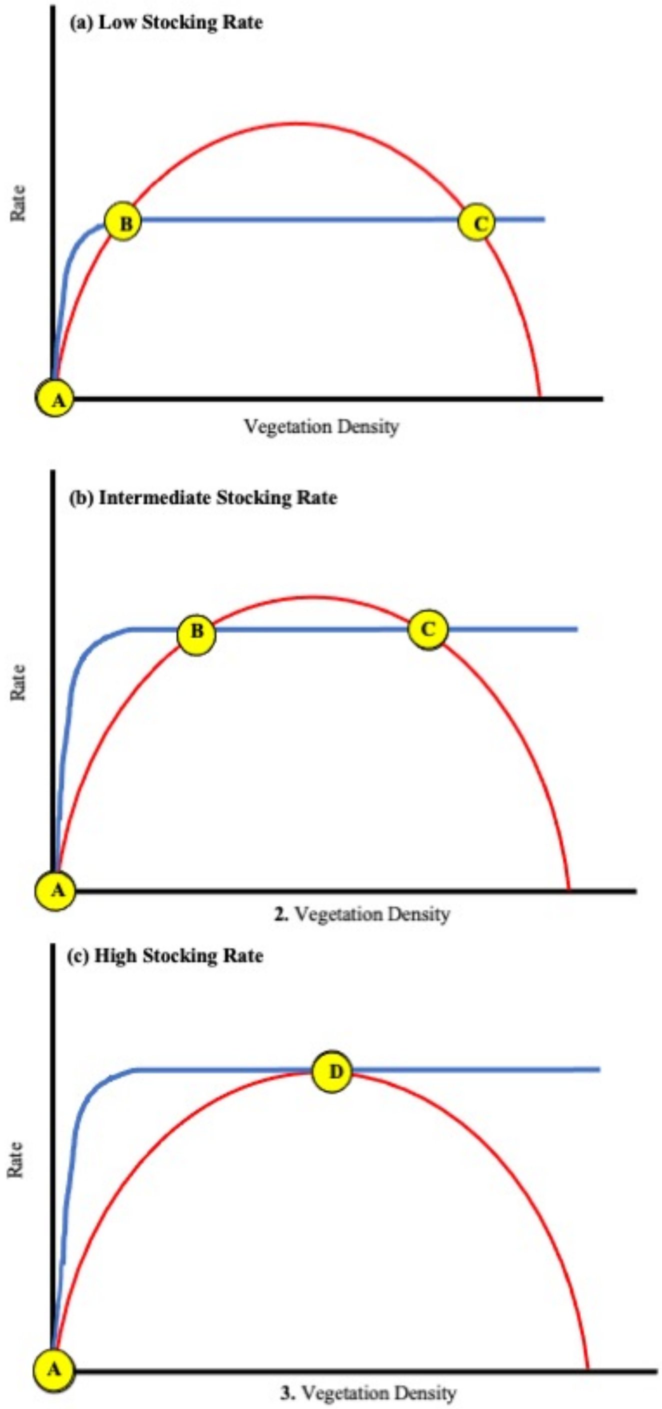


Figure 3 : Uses a consumer resource model to show the progression of a system to catastrophic bifurcation at low intermediate, and high stocking rates. Note the migration of point B and C stocking rate increases. At High stocking rate the two equilibria (B and C) intersect and mark catastrophic bifurcation (D).

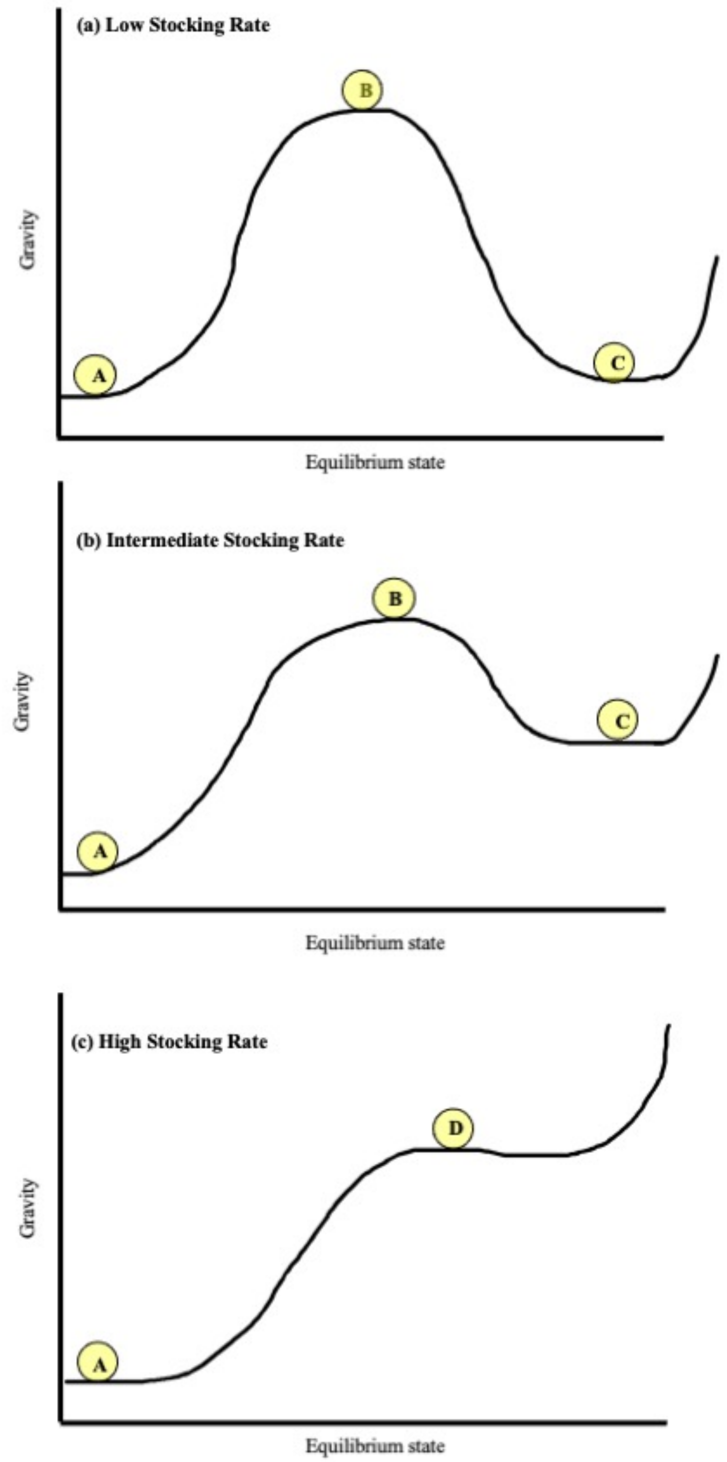


Figure 4: A stability landscape progression of a system to catastrophic bifurcation as stocking rate increases. The slope of the line represents the rate of movement of the system, as if gravity was moving a marble through a landscape. When the slope is positive the system is moving downslope towards desertification state (A), when the slope is negative the system is moving upslope towards grasslands (C). A low stocking rate provides a relative stable state with equal slopes between points A, C and the threshold B. As stocking rate increases, the vegetated attractive equilibrium (C) migrates upwards, therefore its slope between the threshold (B) decreased. At a high stocking rate, points C and B intersect at catastrophic bifurcation (D).

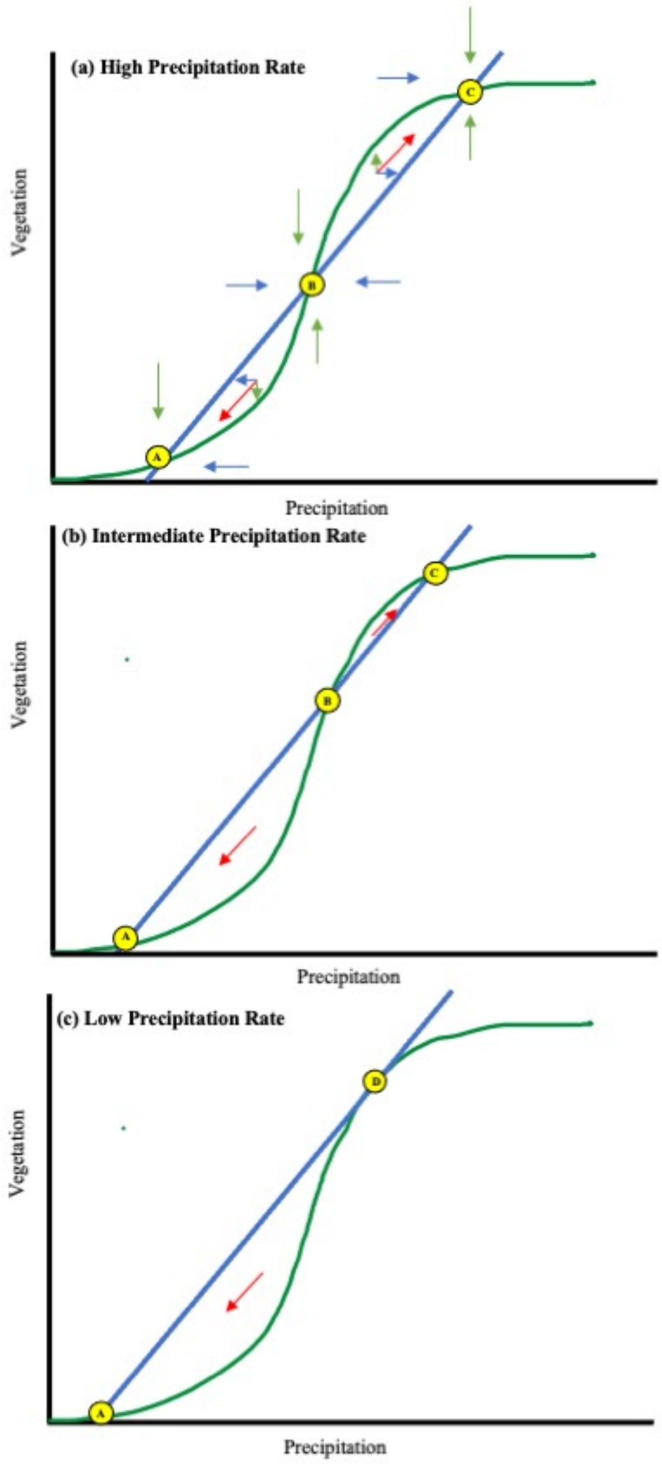


Figure 5: Progression of a system moving towards catastrophic bifurcation as precipitation increases through a vegetation and precipitation equilibrium model. The green line represents the vegetation equilibrium, while the green arrows represent the direction of system change if vegetation is above or below that equilibrium level. The blue line represents the precipitation equilibrium, while the blue arrows represent the system change if precipitation is above or below that level. The three equilibria (ABC) represent points where the supply and demand for precipitation are equal. As precipitation rates progress from high to low, the vegetated equilibrium migrates towards the repellor threshold (B) and eventually intersects at catastrophic bifurcation (D).

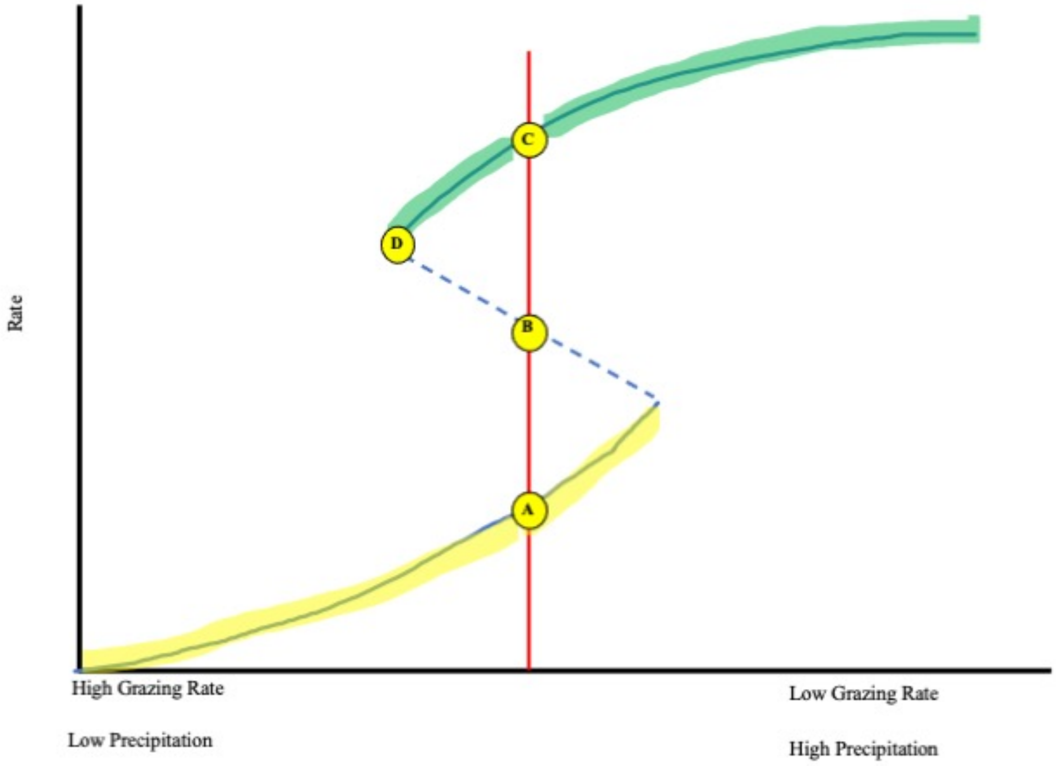


Figure 6: Combines the rates of both vegetation growth and cattle grazing to show where attractors, thresholds, and repellors lie on a vertical axis. As precipitation increases and grazing rates decrease the system rests in a grassy state with point C. The red line resembles a snapshot of system dynamics where equilibria C and A are an equal distance from the repellor threshold. However, as precipitation decreases and grazing rates increase, the red line moves left towards catastrophic bifurcation (D).

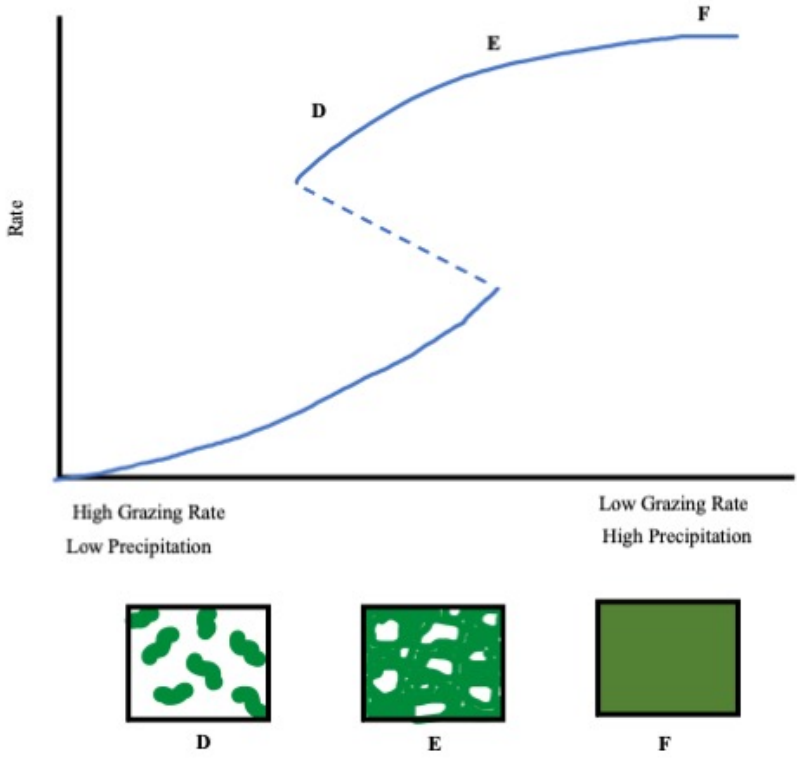


Figure 7: Displays the vegetation patterning of grasslands as it approaches catastrophic bifurcation. The vegetation changes and adapts to the conditions of cattle grazing and levels precipitation. A transition towards desertification is from homogenous grassy (F) to labyrinth (E) and to catastrophic bifurcation spottiness (D).

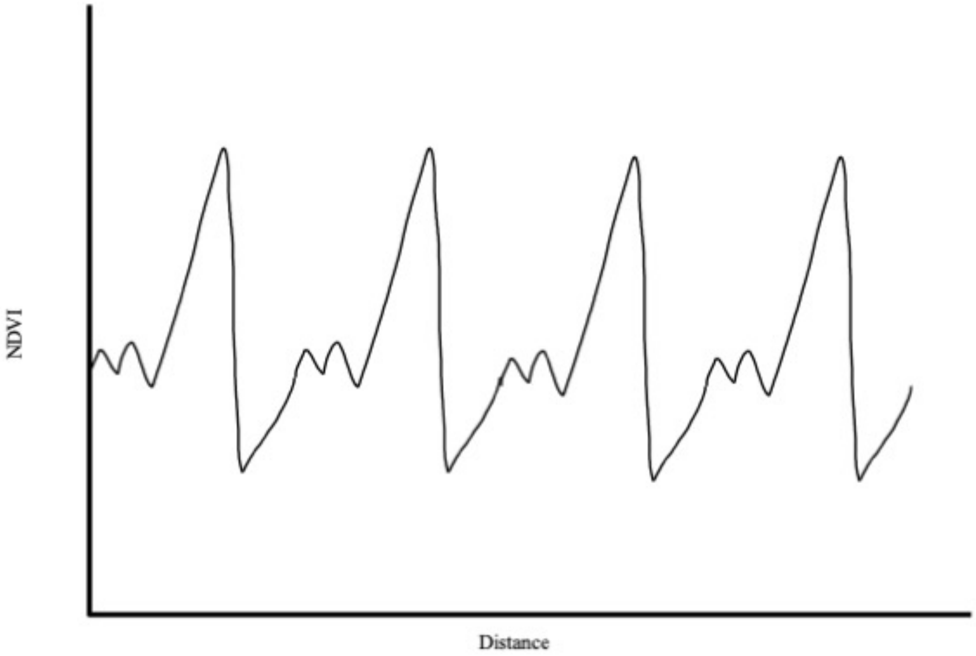
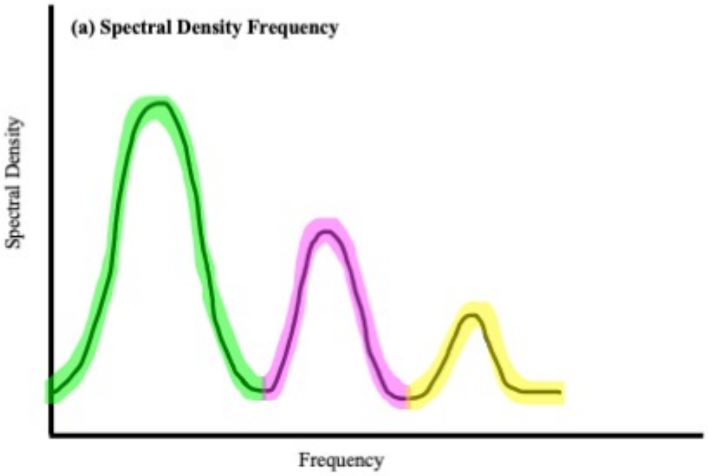


Figure 8: NDVI values (vegetation presence) plotted over a transect distance. Data is processed by Fourier analysis, resulting in a compilation wavelength of multiple smaller waves.



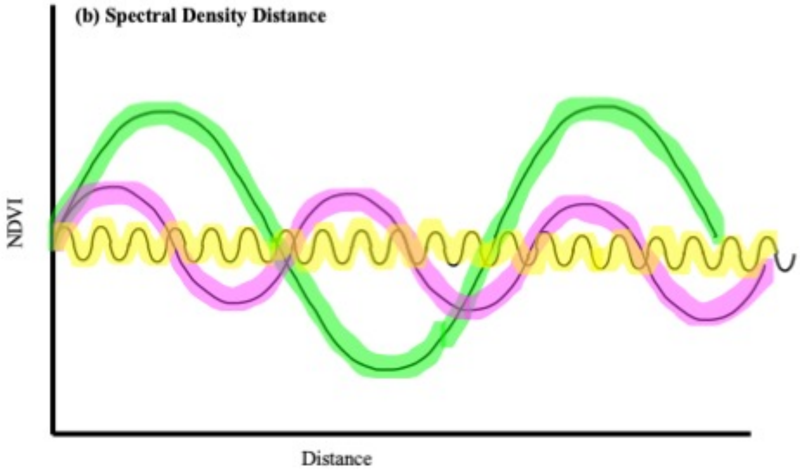


Figure 9: Extracts the major wavelengths from Figure 8. Graph (a) shows three different wavelengths with varying amplitudes and frequencies. The green wave has the lowest frequency but highest spectral density (amplitude) meaning that it is a long wavelength with a high NDVI. The pink and yellow waves resemble lower spectral densities, NDVIs, and shorter wavelengths. Graph (b) plots each of the waves on top of each other as a comparison with Figure 8

FIGURES: RESULTS

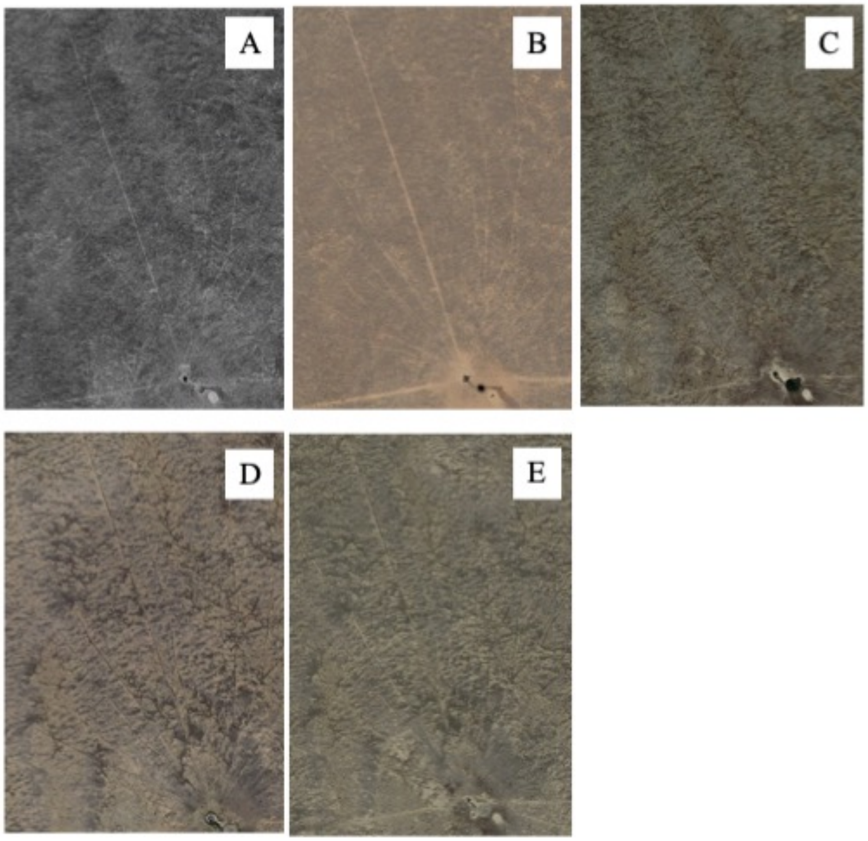
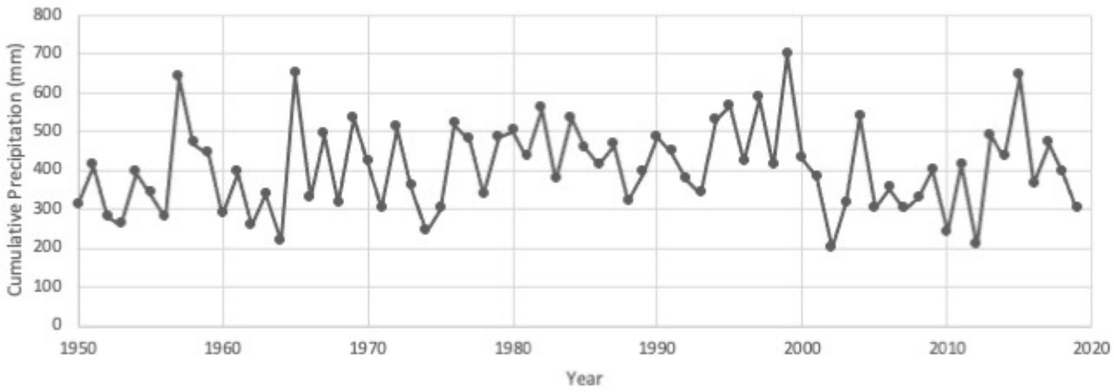


Figure 1: Aerial photographs from Google Earth showing the development of vegetation patterns over time. Time stamps are the following: 1999 (A), 2003 (B), 2015 (C), 2017 (D), 2019 (E). The vegetation patterning does not visibility strengthen until 2015-2019

(a) Cumulative Precipitation Over Time



(b) Average Temperature Over Time

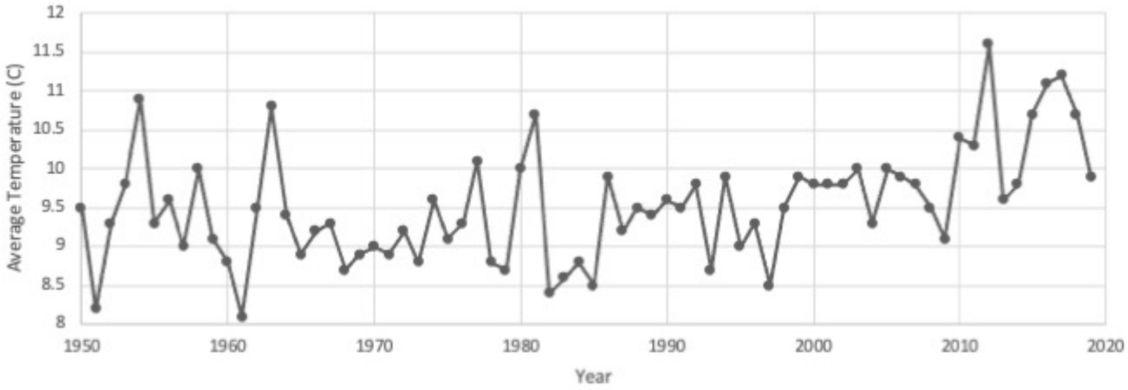


Figure 2: Change of cumulative precipitation and average temperature between 1950-2020. Data was taken at the Colorado Springs Weather Station from National Historical Climatology Network. Cumulative precipitation experiences occasional dips of drought, but no significant increase/decrease. However, over this timeline average annual temperature increased significantly with an R^2 value of 0.194, n value of 72, and p value of 0.0001.

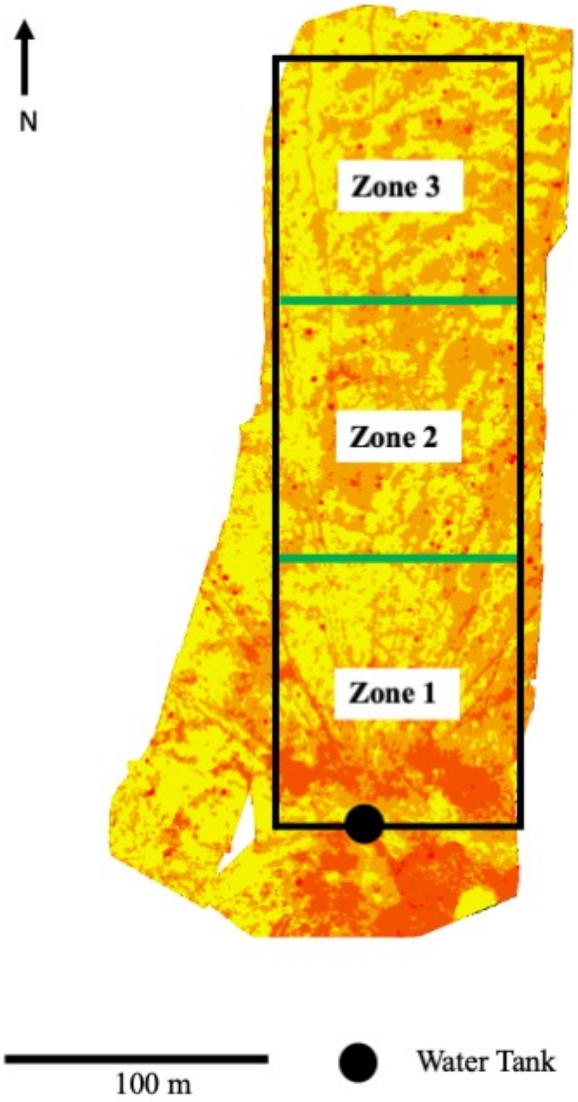


Figure 3: NDVI image of the Area of Interest. Three zones are outlined to represent areas of varying cattle grazing levels. Zone 1 is closest to the water tank representing highest grazing pressure, zone 2 represents intermediate grazing pressure, and zone 3 represents low grazing pressure. Each zone is approximately 1 hectare. Red represents a high NDVI of annual vegetation, orange represents an intermediate NDVI of grassy patches, and yellow represents a low NDVI of bare soil.

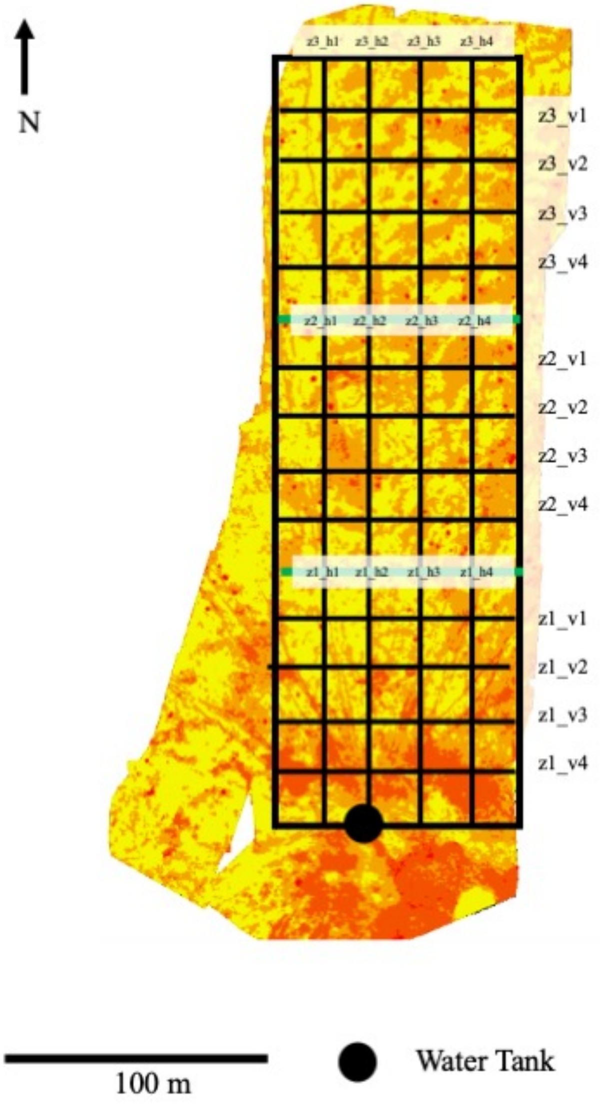


Figure 4: Twenty-four transects plotted in the AOI. Eight transects for each zone, four horizontal and four vertical. For instance, zone 1 includes H1, H2, H3, H4 (horizontal) and V1, V2, V3, V4 (vertical). Each transect was labeled by its zone and vertical or horizontal orientation ie. (z1_v2). NDVI values were generated at every 10 cm along each transect to analyze the periodicity of bare soil and grassy patches.

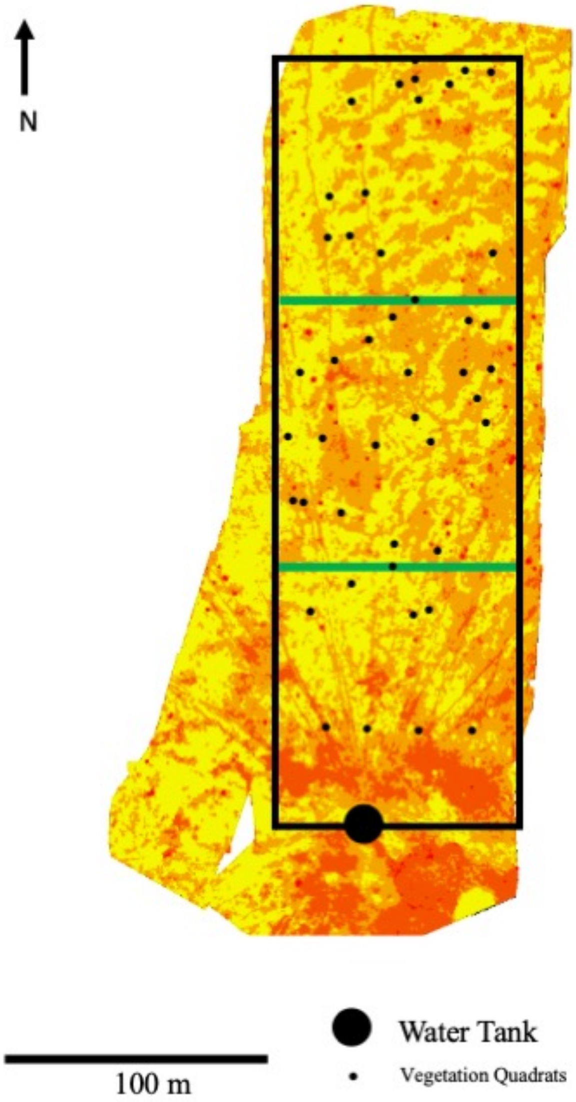


Figure 5: Approximately 30 random vegetation quadrat points distributed in zones 1, 2, and 3. Quadrat measurements include calculating vegetation percent and documenting hoof presence

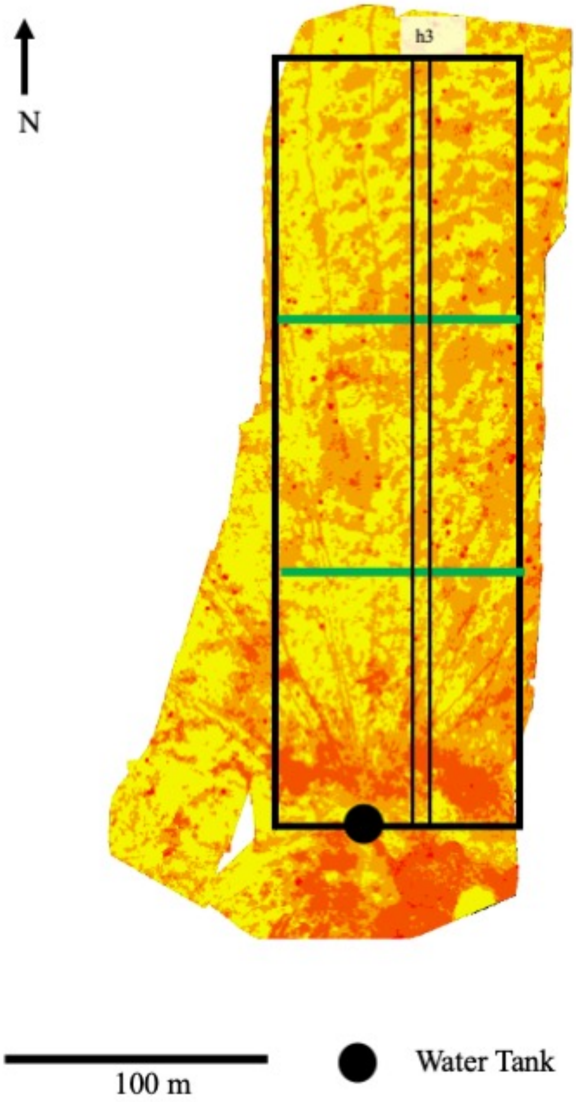


Figure 6: Spatial pattern distribution across horizontal transect 3 in all three zones. Transect 3 shows the strongest pattern in all three zones, therefore, we focused on this transect data for the remaining spatial pattern analysis.

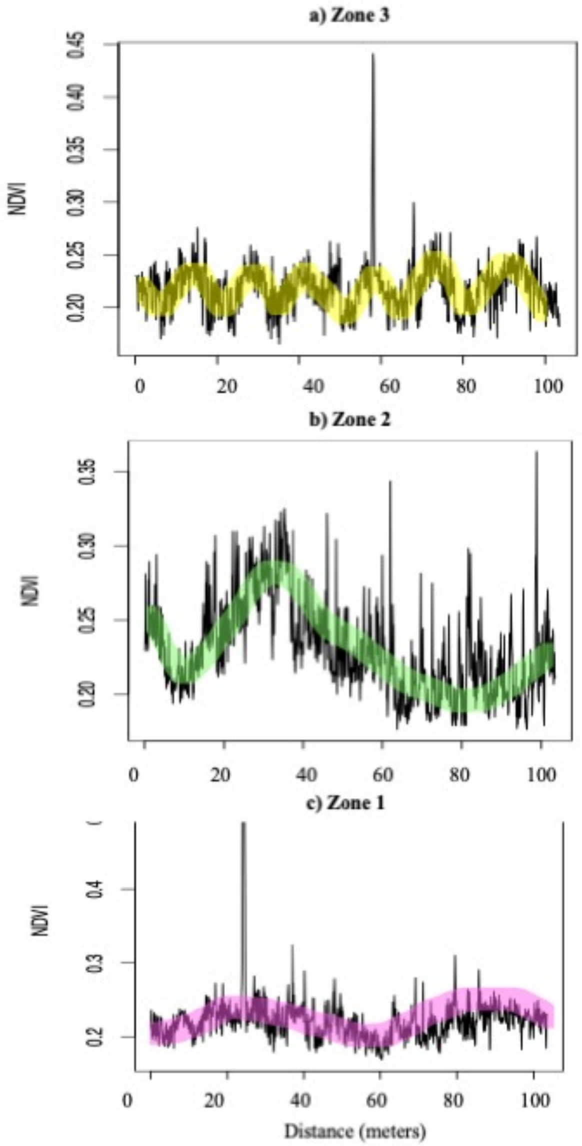
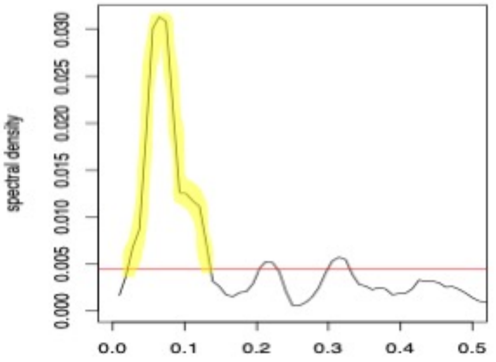
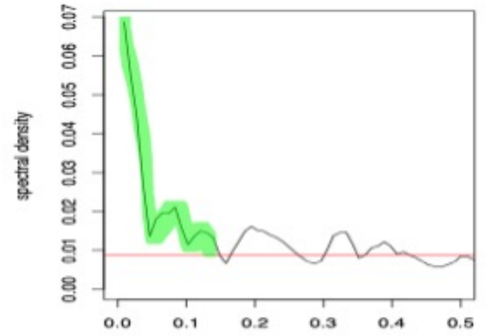


Figure 7: Plots the distribution of NDVI values for transect 3 against distance for all zones. The peak NDVI represents the amplitude of waves and the distance from grassy patches to bare soil represents wavelength. Zone 1 has the lowest NDVI and the greatest distance between grassy patches and bare soil. Zone 2 has the highest NDVI and the second greatest distance between grassy patches and bare soil. Zone 3 has the second greatest NDVI and the shortest distance between grassy patches and bare soil.

a) Zone 3



b) Zone 2



c) Zone 1

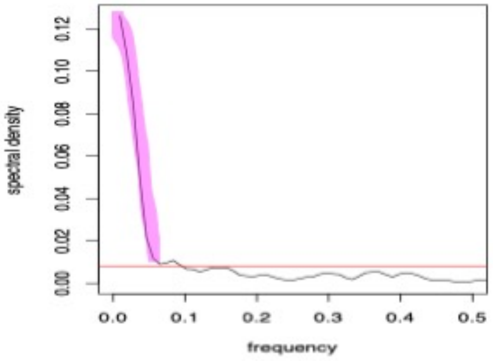


Figure 8: Spectral densities of NDVI values redistributed across frequency for each zone. The spectral density takes apart dominant waves within each zone. Spectral density peaks resemble the difference between grassy and bare soil and the frequency represents the inverse of the dominant wavelength. The red line signifies the upper limit of the 95% confidence integral for peaks in randomly resampled data per zone. Peaks that are higher than the red line show statistically significant periodicities.

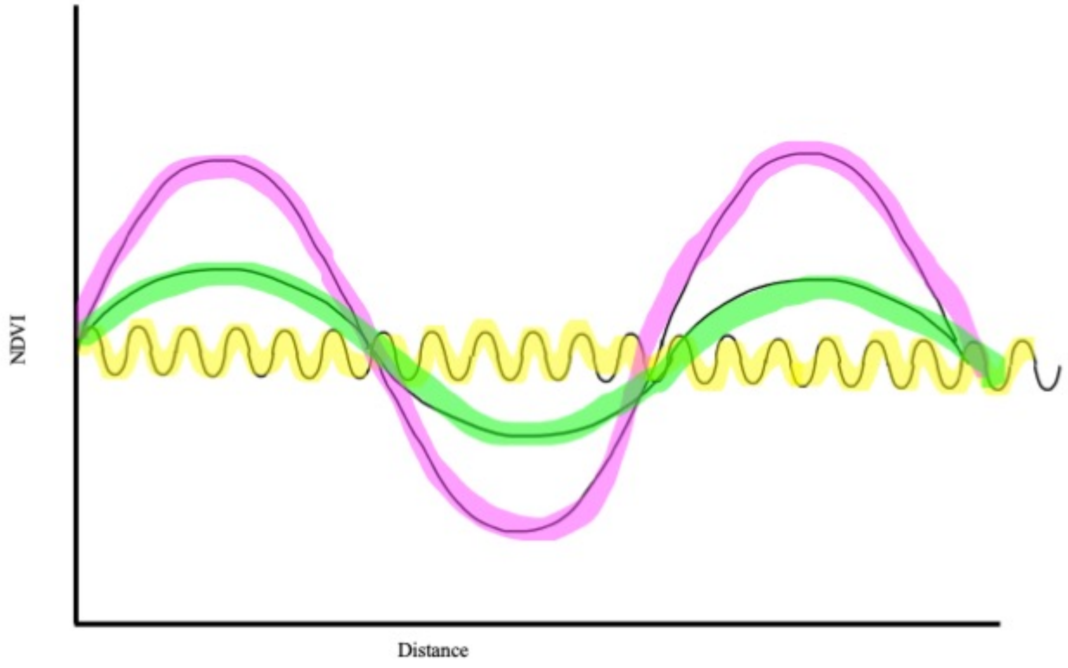


Figure 9: The overlap of dominant wavelengths for Transect 3 in Zone 1 (pink), Zone 2 (green), and Zone 3 (yellow) determined by Figure 8. Zone 1 and 2 have the longest wavelengths. Zone 3 has the smallest NDVI and shortest wavelength.

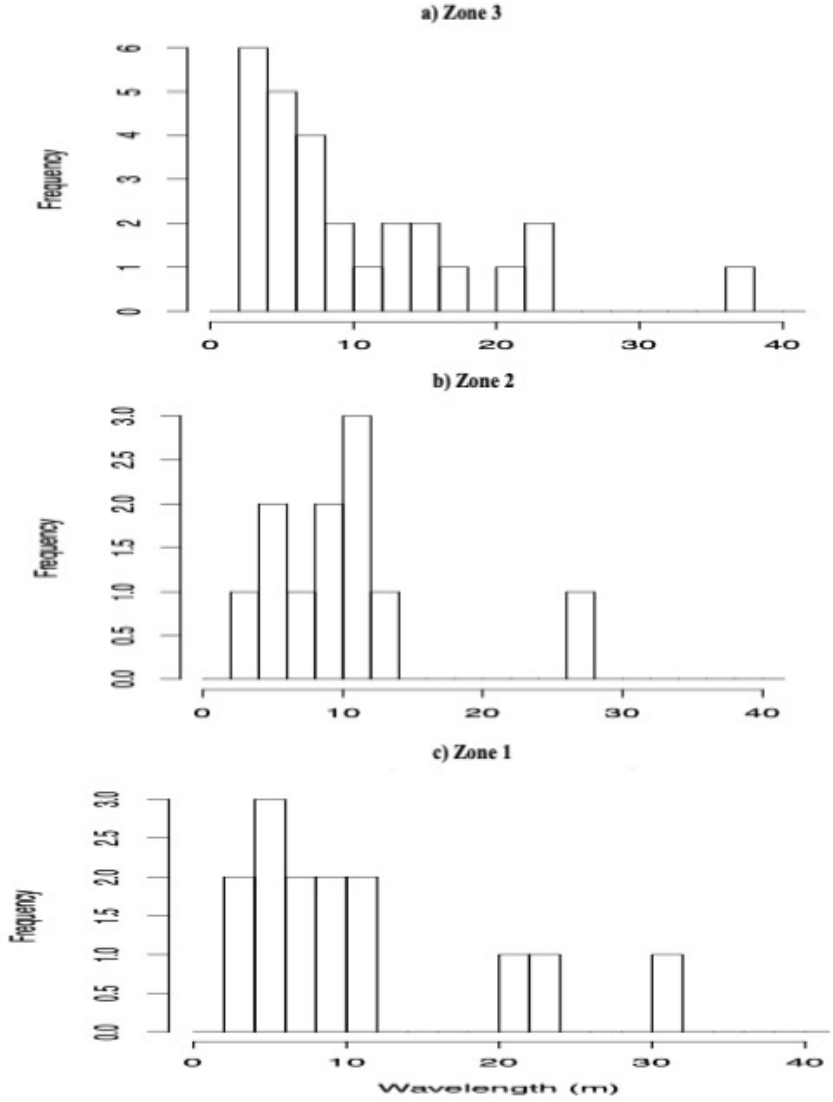


Figure 10: Histogram distribution of wavelength frequencies with 2m bins. Wavelength values are grouped together every 2m of distance. Note that zone 3 has 27 bin values while zones 2 and 1 only have 17 usable bin values, due to data limitations. The distribution of wavelengths show that zones 1 and 2 have most wavelengths fall below 10 m while zone 3 has a wider distribution spanning to 20. The peak wavelengths suggest that zones closest to the water tank (zone 1) have the largest wavelengths compared to zones furthest away (zone 3).

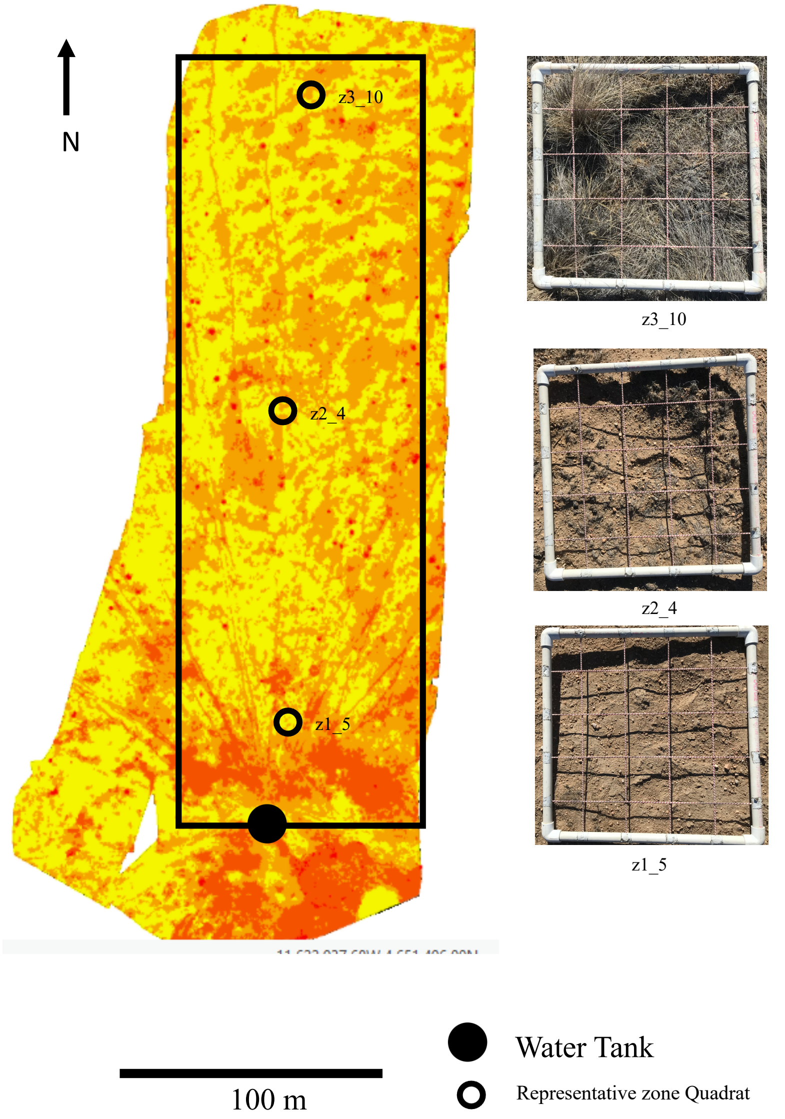
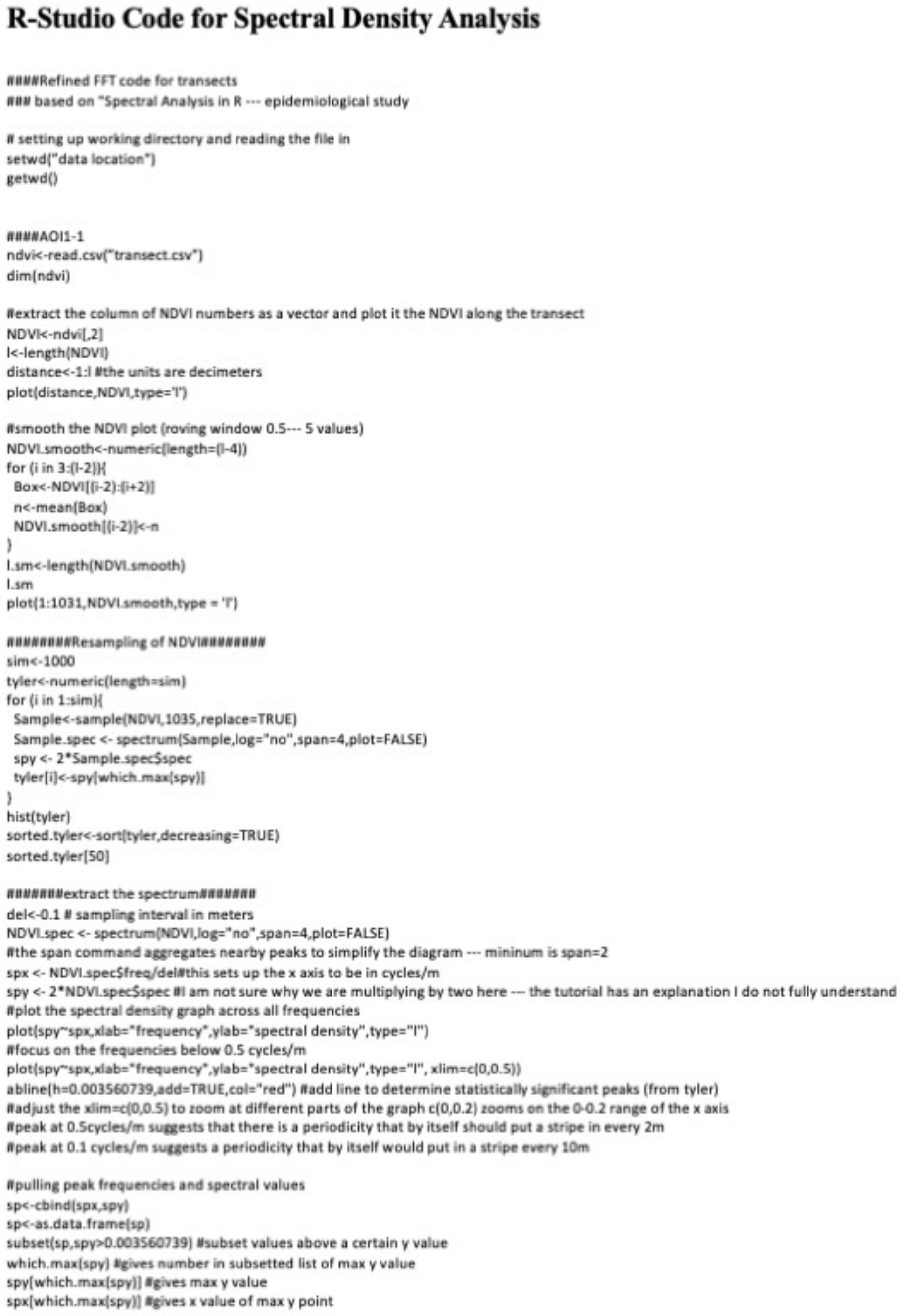


Figure 11: Representative quadrat points and images for each zone. Visible transition for bare soil (z1_5) to patchiness (z2_4) to full vegetation (z3_10).

APPENDIX 1:



R-Studio Code for Spectral Density Analysis

```
####Refined FFT code for transects
### based on "Spectral Analysis in R --- epidemiological study

# setting up working directory and reading the file in
setwd("data location")
getwd()


####AOI1-1
ndvi<-read.csv("transect.csv")
dim(ndvi)

#extract the column of NDVI numbers as a vector and plot it the NDVI along the transect
NDVI<-ndvi[,2]
l<-length(NDVI)
distance<-1:l #the units are decimeters
plot(distance,NDVI,type='l')

#smooth the NDVI plot (roving window 0.5--- 5 values)
NDVI.smooth<-numeric(length=(l-4))
for (i in 3:(l-2)){
 Box<-NDVI[(i-2):(i+2)]
 n<-mean(Box)
 NDVI.smooth[(i-2)]<-n
}
l.sm<-length(NDVI.smooth)
l.sm
plot(1:1031,NDVI.smooth,type = 'l')

########Resampling of NDVI#########
sim<-1000
tyler<-numeric(length=sim)
for (i in 1:sim){
 Sample<-sample(NDVI,1035,replace=TRUE)
 Sample.spec <- spectrum(Sample,log="no",span=4,plot=FALSE)
 spy <- 2*Sample.spec$spec
 tyler[i]<-spy[which.max(spy)]
}
hist(tyler)
sorted.tyler<-sort(tyler,decreasing=TRUE)
sorted.tyler[50]

#######extract the spectrum#######
del<-0.1 # sampling interval in meters
NDVI.spec <- spectrum(NDVI,log="no",span=4,plot=FALSE)
#the span command aggregates nearby peaks to simplify the diagram --- mininum is span=2
spx <- NDVI.spec$freq/del#this sets up the x axis to be in cycles/m
spy <- 2*NDVI.spec$spec #I am not sure why we are multiplying by two here --- the tutorial has an explanation I do not fully understand
#plot the spectral density graph across all frequencies
plot(spy~spx,xlab="frequency",ylab="spectral density",type="l")
#focus on the frequencies below 0.5 cycles/m
plot(spy~spx,xlab="frequency",ylab="spectral density",type="l", xlim=c(0,0.5))
abline(h=0.003560739,add=TRUE,col="red") #add line to determine statistically significant peaks (from tyler)
#adjust the xlim=c(0,0.5) to zoom at different parts of the graph c(0,0.2) zooms on the 0-0.2 range of the x axis
#peak at 0.5cycles/m suggests that there is a periodicity that by itself should put a stripe in every 2m
#peak at 0.1 cycles/m suggests a periodicity that by itself would put in a stripe every 10m

#pulling peak frequencies and spectral values
sp<-cbind(spx,spy)
sp<-as.data.frame(sp)
subset(sp,spy>0.003560739) #subset values above a certain y value
which.max(spy) #gives number in subsetted list of max y value
spy[which.max(spy)] #gives max y value
spx[which.max(spy)] #gives x value of max y point
```

APPENDIX 2:

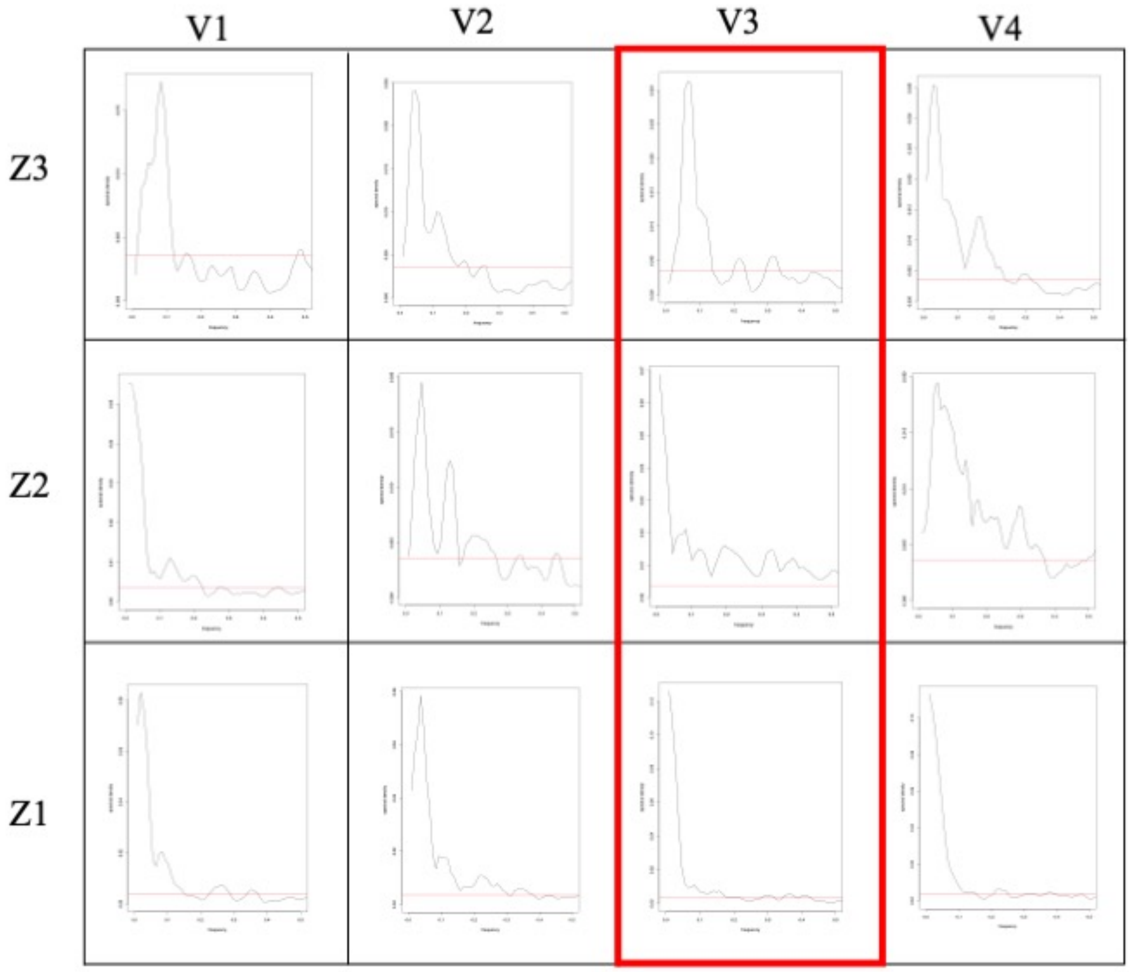


Figure 2: Spectral densities for vertical transects in Zone 1 (v1, v2, v3, v4), Zone 2 (v1, v2. v3, v4), and Zone 3 (v1, v2, v3, v4). Note that Transect 3 in all three Zones were selected for the proceeding spatial pattern analysis.

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