NASA DEVELOP National Program
Colorado – Fort Collins

Summer 2024

Jemez Pueblo Agriculture
Monitoring Rangeland Conditions to Inform Drought and Land Management in New Mexico

DEVELOP Technical Report
August 9th, 2024

Dayna R. Dominguez (Project Lead)
Matthew B. Eland
Alivia Gustrowsky
Aditya Iyer

Advisors:
Nicholas Young, Colorado State University, Natural Resource Ecology Laboratory (Science Advisor)
Dr. Tony Vorster, Colorado State University, Natural Resource Ecology Laboratory (Science Advisor)
Dr. Paul Evangelista, Colorado State University, Natural Resource Ecology Laboratory (Science Advisor)
Dr. Catherine Jarnevich, Colorado State University, Natural Resource Ecology Laboratory (Science Advisor)
Chris Choi, Colorado State University, Natural Resource Ecology Laboratory (Science Advisor)

Lead:
Truman Anarella (Colorado – Fort Collins)

1. Abstract

The Jemez Pueblo, a community located in the semi-arid high desert region of northcentral New Mexico, faces challenges with drought mitigation and livestock management. NASA DEVELOP partnered with the Pueblo of Jemez Natural Resources Department and The Nature Conservancy to provide recent and historical rangeland conditions to aid present decision-making, which relies on cultural practices, site familiarity, available resources, and physical data. This partnership offers the opportunity to support management practices by leveraging remote sensing and virtual fencing technologies. Our project explored Rangeland Analysis Platform (RAP) products incorporating NASA Earth observation Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI, and Landsat 9 OLI-2 remote-sensed imagery as an agricultural land management tool. We performed linear regression analysis to evaluate RAP data to field data and explored RAP annual herbaceous biomass, ground cover trends, and climatic factors at the pasture level. We then computed study area summary statistics, performed pixel-by-pixel trend analysis across the study period, and evaluated ground cover trends near water sources. Based on available data, RAP was poorly correlated to bare ground and herbaceous biomass, generally underestimating the former and overestimating the latter. To improve the evaluation of RAP products, we suggest increasing the spatiotemporal distribution of the field dataset. According to RAP, from 1986 to 2023, the site became hotter and drier, bare ground increased, and annual forbs and grasses increased while perennials decreased. RAP products did not agree with field-collected data; however, the trends over time may be useful for informing rangeland management actions.

Key Terms

remote sensing, Landsat, agriculture, New Mexico, Jemez Pueblo, Rangeland Analysis Platform, drought, cattle grazing management

2. Introduction

2.1 Background Information

The southwest region of the United States is a dry expanse that faces limited precipitation and frequent droughts (Fesenmyer et al., 2018). Despite the harsh climate, the region includes vast rangelands that have historically supported large herds of grazing megafauna and specialized flora that thrive under the conditions of periodic grazing and variable precipitation. After westward expansion by North Americans in the early 1800s, the free-roaming fauna were replaced with domesticated livestock. Land managers now occupying this environment are becoming more aware of the effects of climate change and the heightened risks of drought-related natural disasters. They have subsequently recognized a need for implementing sustainable and regionally appropriate agricultural practices to include livestock operations. Apfelbaum et al. (2022) details the importance of sustainable agriculture, highlighting how grazing management practices can simultaneously impact local and smaller-scale ecosystem functions and the overall region's ecological robustness by improving soil health. One example of a unique grazing management strategy is virtual fencing, where livestock wear GPS collars and ranchers can designate areas the livestock can and cannot go. This practice can reduce overall rangeland degradation and act as a way to control and mitigate landscape disturbances. Gadizia & Sayre's (2009) technical guide further expands upon this sentiment, highlighting how grazing management directly impacts water availability, biodiversity, and other natural resources in the short- and long-term, which have direct impacts on forage quality and quantity for successful livestock operations. Modified grazing practices that mimic the disturbance impacts of the once present free-roaming large megafauna (bison in this example) can also promote gains in foundational ecosystem functions, improving ecological resilience (Boyce, 2021). Remote sensing has been a promising way to track rangeland conditions over time, especially in the unique landscapes in the American west. The Rangeland Analysis Platform (RAP) aggregates and processes satellites data from the Landsat missions to provide useful products for analyzing rangeland conditions such as net primary productivity and ground cover type (Jones et al., 2021).

2.2 Project Partners & Objectives

This project partnered with the Pueblo of Jemez Natural Resources Department (NRD) and The Nature Conservancy. The Nature Conservancy was a collaborator on the project with an interest in biodiversity conservation and the role of regenerative grazing using virtual fencing to support this effort. The Pueblo of Jemez was the project's end user, with the grazing pastures under their ownership and management. They are a tribal nation in north-central New Mexico that aims to improve their land use management for agricultural purposes. The partners currently use rotational cattle grazing on their rangelands to ensure areas susceptible to drought aren't being overused. The Pueblo of Jemez NRD also intends to implement virtual fencing technology to sustainably manage cattle grazing on their lands. They strive to gain insight into recent and historical ground cover trends that can aid in these processes and inform plans for water improvements and grazing rotation locations and timing.

We sought to address three objectives to support the partners' rangeland management goals throughout the term. The first objective was to evaluate biomass and bare ground using RAP products compared to field-collected data. This would allow the partners to understand the feasibility of using RAP for their future decision making. The second objective was to summarize ground cover trends and forage production over time. We used RAP to examine these trends and investigate and identify key inflection points such as wet versus dry years. Our final objective was to explore the trends between ground cover and herbaceous biomass from distance to water sources which informed water source placement and animal stocking rates.

The study area for this project is approximately 26,763 acres (10,831 hectares) of non-irrigated rangeland that supports year-round cattle grazing operations across four permanent, fenced pastures (Figure 1). This area has sandy loam, well-draining soils and supports key herbaceous species such as western wheatgrass and blue grama (Bishop et al., 2023). The study period is from 1986 through 2023 primarily due to the availability of data products and the intent to identify long-term trends in ground cover within the study area (Figure 1).

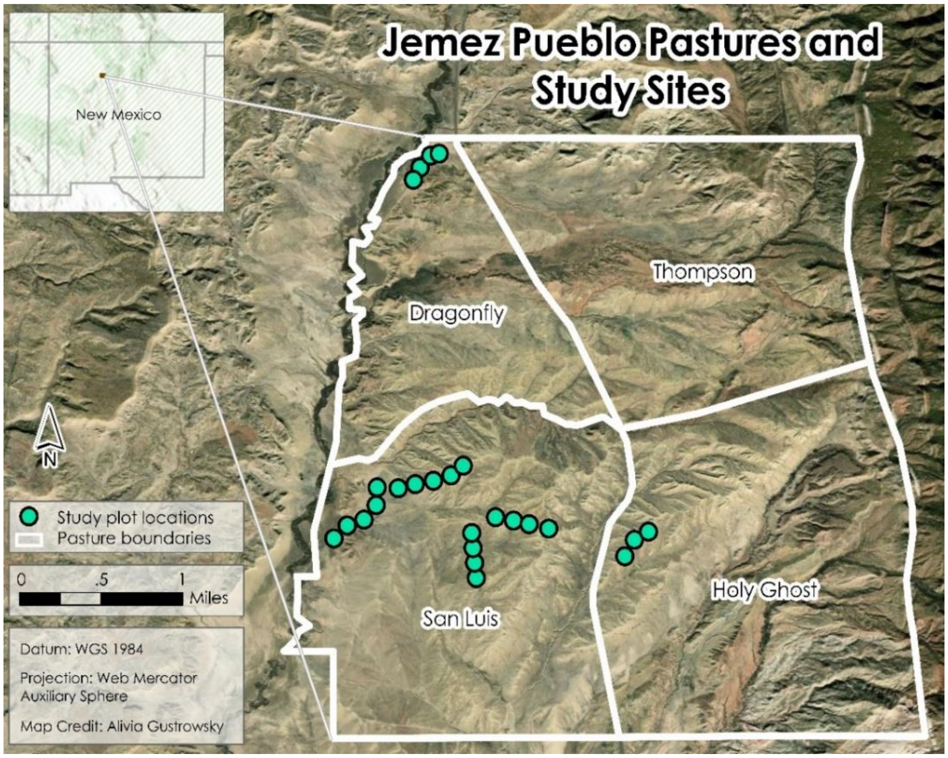


Figure 1. Map of the Jemez Pueblo study area with the four permanent pastures outlined in white. The green dots show the locations of individual study plot sites where field data was collected. [Basemap Credits: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Maxar Earthstar Geographics, TomTom, Garmin, FAO, NOAA, OpenStreetMap contributor, Intermap and the GIS user community]

3. Methodology

3.1 Data Acquisition

3.1.1 Field Data

The Pueblo of Jemez NRD collected plant clippings from 25 plots within the study area to measure above-ground biomass and percent ground cover type between August 10 – 24, 2023. Research scientists at Colorado State University's Natural Resource Ecology Laboratory (NREL) aggregated the clipping data for each plot, providing mean grass and forbs biomass values in kilograms per hectare (kg/ha; NREL, 2023a) and percent ground cover type for six functional classes (bare ground, forbs, grass, litter, shrub, and tree; NREL, 2024). Additional files containing each plot's recent collection date, location data, and relevant observations supplemented this data (NREL, 2023b).

3.1.2 Spatial Data

In addition to the designated study area shapefile (Pueblo of Jemez, 2021a), Colorado State University provided us with three vital shapefiles for use in mapping, data acquisition, and analysis. The first of these is a polygon shapefile that divided the study area into the primary grazing pastures at present: Dragonfly, San Luis, Thompson, and Holy Ghost (Pueblo of Jemez, 2023). The remaining two datasets are point shapefiles that provide the locations of permanent and seasonal water sources for livestock respectfully (Pueblo of Jemez, 2021a; Pueblo of Jemez, 2021b).

3.1.3 Remote Sensing Data

One of the primary data resources for our investigation was RAP which utilized Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 Operational Land Imager (OLI), and Landsat 9 OLI-2 (Table1) to estimate vegetation and ground cover (McCord & Williamson, 2022; Rangeland

Analysis Platform, 2023a). Products are made available on a continuously updating interval spanning back to 1986. Allred et al. (2021) provides details on the development of RAP version 3.0 annual fractional cover product, produced at a 30m resolution, that calculates the ground cover of herbaceous plants (annual and perennial), shrubs, trees, litter, and bare ground on a percentage scale. Fractional cover estimates help preserve the heterogeneity of the landscape represented in each pixel by representing it as a proportion covered versus traditional estimates that assign the predominant vegetation cover type to each pixel. To supplement surface reflectance data, RAP utilizes the normalized difference vegetation index (NDVI) and normalized burn ratio two (NBR2) to model the rangeland fractional products across the United States. Jones et al. (2018, 2021) discuss the benefits of using NDVI, NBR2, and plant functional types (PFTs) in conjunction and explain in greater detail how PFT-adjusted by indices can account for in-pixel variations. RAP also calculates the 16-day gross primary production and annual biomass of PFTs as net primary productivity given in rate of gross primary production in grams of carbon per square meter (g C m-2 16-day-1) for each 16-day period and net primary productivity (g C m-2 year-1) annually, for each PFT of each pixel (Robinson et al. 2019); these products are then converted to pounds per acre (lb./ac) by RAP for ease of use (Rangland Analysis Platform, 2023a).

Table 1
Remote Sensing Data

Product	Platform/Sensor	Data Product	Spatial Resolution	Temporal Resolution	Dates	Acquisition Method
RAP	Landsat 5 TM Landsat 7 ETM+ Landsat 8 OLI Landsat 9 OLI-2	Forage Production, Herbaceous Biomass, Fractional Ground Cover	30m	8 to 16 days presented at 16-day or annual intervals	1986 – 2023	RAP online tool and through Google Earth Engine

In addition to the obtained summary data directly from the RAP website (Rangeland Analysis Platform, 2023b), we accessed RAP for desired raster data products (Table 1) using Google Earth Engine. We maintained the use of these products from within Google Earth Engine or downloaded them for further processing in original raster format. We utilized RAP via gridMET-MAT and the most current RAP image collections v3.0 (Rangeland Analysis Platform 20204a, 2024b). We included all ground cover types: annual and perennial grass and forb growth, shrubs, trees, bare ground, and the calculated annual biomass net primary productivity.

3.2 Data Processing

3.2.1 Field Data

We started by compiling the plot data into one spatially indexed shapefile, to use in maps and to extract data for validation. We developed the plot points shapefile by using the raw data from all three data files proved by NREL (2023a, 2023b, 2024), converting the Excel files to CSV format, and following the customary protocol for converting data to an XY Table to Point and joining tables for ArcGIS Pro 3.3.1. After this, we calculated pounds per acre (lb./ac) from the kg/ha plot biomass data using a conversion rate of 1kg/ha = 0.892 lb./ac to facilitate direct comparisons with RAP raster data within the attribute table calculate tool in ArcGIS Pro. Additionally, we split the study area shapefile into four separate shapefiles, one for each pasture, using the ArcGIS Pro Select By Attribute feature. After exporting each pasture, we mapped and viewed the field data points within the study area to ensure proper placement of the (x, y) coordinates (Figure 1). Errors noticed during the visualization process were cross-referenced to the plot description data file (NREL, 2023b), corrected, re-projected, and visualized as done previously.

3.3 Data Analysis

3.3.1 Data Validation

Once we had RAP 2023 annual biomass and ground cover products exported from Google Earth Engine, we began investigating the validity of the data compared to the field data collections using R version 4.4.1. We extracted the data from the respective RAP raster files using a bilinear interpolation method at each plot point. This method interpolates using distance-weighted averages of the four pixels closest to the point data. This was the most accurate choice for our data since the collection plots were averages across line transects and not one singular point/pixel. We then obtained linear regression statistics with RAP data compared to the plot data.

3.3.2 Summary of RAP Data by Pasture

We uploaded individual shapefiles of each pasture into the RAP online analysis tool to begin time series (1986 – 2023) calculations. We downloaded and processed CSV data files of all ground cover types and annual biomass in Microsoft Excel Version 2407 to create individual (annual forb & grass, perennial forb & grass, bare ground cover, tree, shrub, and litter) variable comparison graphs between the four pastures. Mean annual temperature and annual precipitation, obtained through RAP, became additional variables we considered in our investigation, which underwent the same Microsoft Excel processing as the ground cover types. Generating trend lines (pasture-specific and overall) allowed us to interpret long-term ground cover type changes over the entire study period.

3.3.3 Summary Statistics

We created data summaries for annual biomass and bare ground cover in two separate ways from 1986 – 2023. We first created two image stacks using Google Earth Engine, one for biomass and one for bare ground cover, each with 38 image layers (one image layer representing a single study year) utilizing the annual values rasters per year as the layers. We then generated a raster layer of the mean, minimum, maximum, median, and range at the pixel level to visually and spatially identify trends across all years. For example, we created the mean stacked image for bare ground cover by using the .mean() function on the Image collection containing all bare ground images from 1986 – 2023. The .mean() function then found the mean value within the time frame for each individual pixel, subsequently stacking them together to create an image displaying all the means of all the analyzed years. We performed this same procedure for the other parameters by using the .min(), .max(), .median(), and .range() functions accordingly.

We then used Google Earth Engine to generate visual time series GIFs to represent the changes in biomass and bare ground cover types for the given period. We used the getVideoThumbURL() function in conjunction with our specified visual parameters to generate GIFS that filtered through the different images for each year of the datasets. These GIFs change at a pace of 3 frames per second, with each frame representing a different year. We aimed to evaluate notable trends within the datasets by visualizing the time-series in this manner.

3.3.4 Pixel-by-Pixel Trend Analysis

We downloaded the image stacks of annual biomass and bare ground cover from Google Earth Engine for further analysis in R. We then calculated the pixel-by-pixel linear regression across various time series (wetter period, drier period, and halving the study period to develop a sense of past vs. present) and exported the resulting .TIF file. The .TIF file contained the value of the slope of this linear regression for each pixel of the study area, representing the trend in annual biomass and bare ground throughout the pastures.

To calculate these zonal statistics within ArcGIS Pro, we first isolated the water sources to be used for each set of analyses (for example, permanent water locations in the San Luis pasture) using the Select Layer by Location geoprocessing tool. We then chose a .TIF file (either for annual biomass mean slope or for bare ground cover mean slope) and trimmed it to the size of the pasture (or study site) boundary using the Extract by Mask tool. Then we calculated a series of buffers around each of the chosen water locations at distances of 300m, 600m, 900m, and 1200m from the water source, using the Buffer tool.

After this, we used the Clip tool to trim the calculated buffers to stay within the pasture (or study site) boundaries since distances of 300m – 1200m often extended outside the area we were measuring. Once the buffers were trimmed to stay within the desired area, we used the Erase tool to create “donuts” out of the buffers so that each zone excluded the next-smallest zone's radius. That way, the calculated mean slopes would generate only within the ranges 1m – 300m, 300m – 600m, 600m – 900m, and 900m – 1200m.

With the "donut" buffers created, we used them to calculate zonal statistics of the given area of the pasture (or study site) that they represented, either for annual biomass mean slope or for bare ground cover mean slope, depending on the chosen .TIF file. We used the Zonal Statistics as Table tool to do this for each combination of water type (permanent vs seasonal), distance from water (300m, 600m, 900m, or 1200m), trend type (annual biomass change vs bare ground cover change), and study boundary (San Luis, Holy Ghost, Dragonfly, Thompson, and study site as a whole). These tables were then exported to Excel files using the Table to Excel tool.

4. Results & Discussion

4.1 Analysis of Results

4.1.1 Data Validation Results

The correlation of herbaceous biomass between RAP and plot field data was very low, with an adjusted R^2 value of 0.17 (Figure 2, panel A). RAP generally had higher biomass values than the plot data when plot biomass was less than 300 lb./ac and lower values when plot biomass was greater than 300 lb./ac. Bare ground remote sensing data is also not correlated, with an adjusted R^2 value of -0.03 (Figure 2, panel B). RAP data generally underestimates the amount of bare ground present based on the available field data.

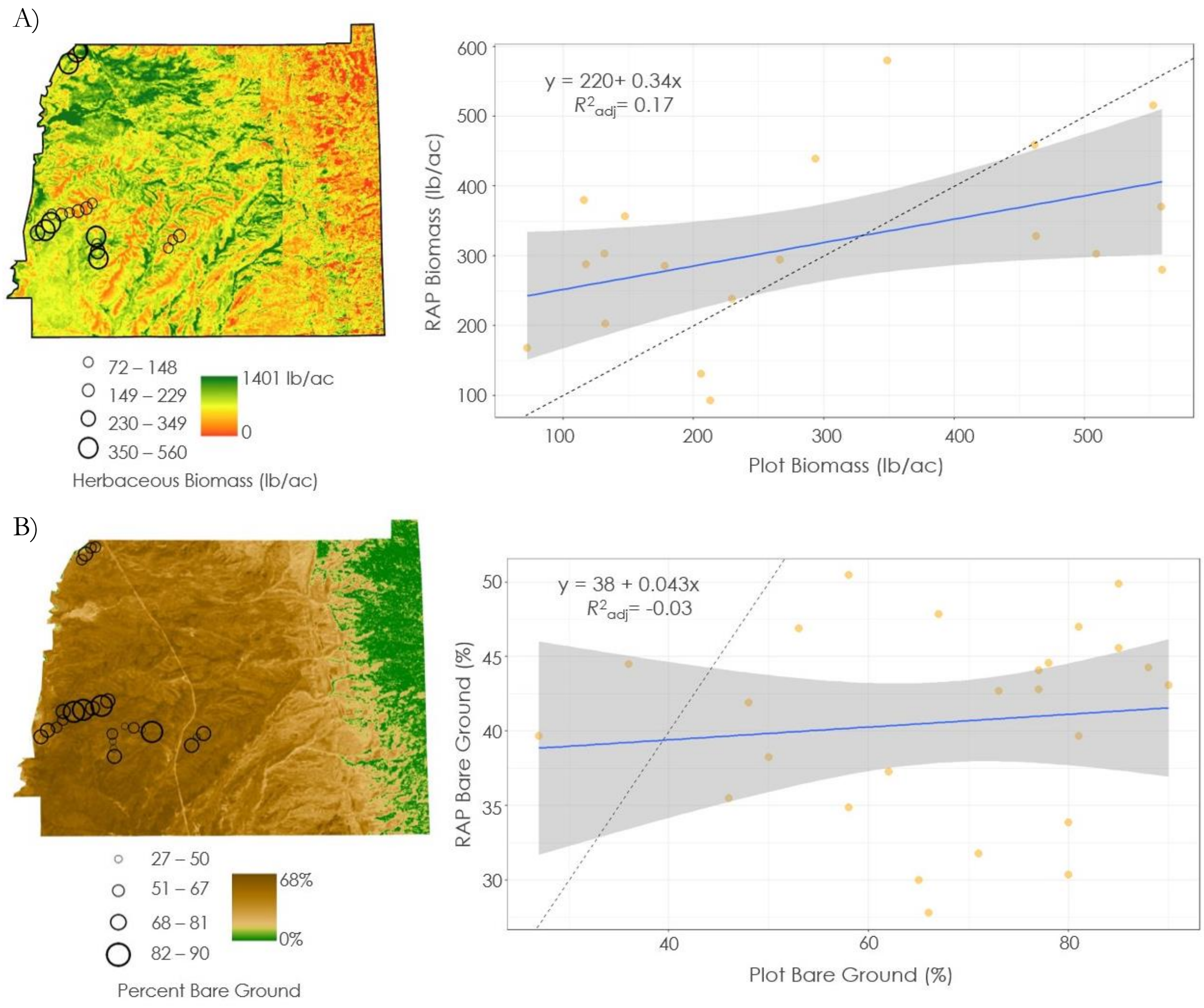


Figure 2. The maps in panel A) and B) are visual representations of the plot data values at each location relative to the raster values across the study site. The above graphs are the linear regression analysis of the A) RAP annual herbaceous biomass and B) bare ground cover for 2023 compared to the grass and forbs biomass and bare ground field data of August 2023.

4.1.2 Summary of RAP Data by Pasture

Between 1986 and 2023, annual forb and grass cover percentage increased with an overall trendline slope of 0.016 (Figure 3a). Perennial forb and grass cover percentage decreased with an overall trendline slope of -0.0466 (Figure 3b). Bare ground cover percentage increased with an overall positive trendline slope of 0.0743 (Figure 3c). Comparing the graphs' slope values reveals that the bare ground centage has the greatest incline with perennial ground cover having the "middle" value and annual ground cover having the "lowest". Meaning, over the study period bare ground cover percentage has increased the fastest as perennial ground cover declines at a more progressed rate than the gains in annual ground cover occur.

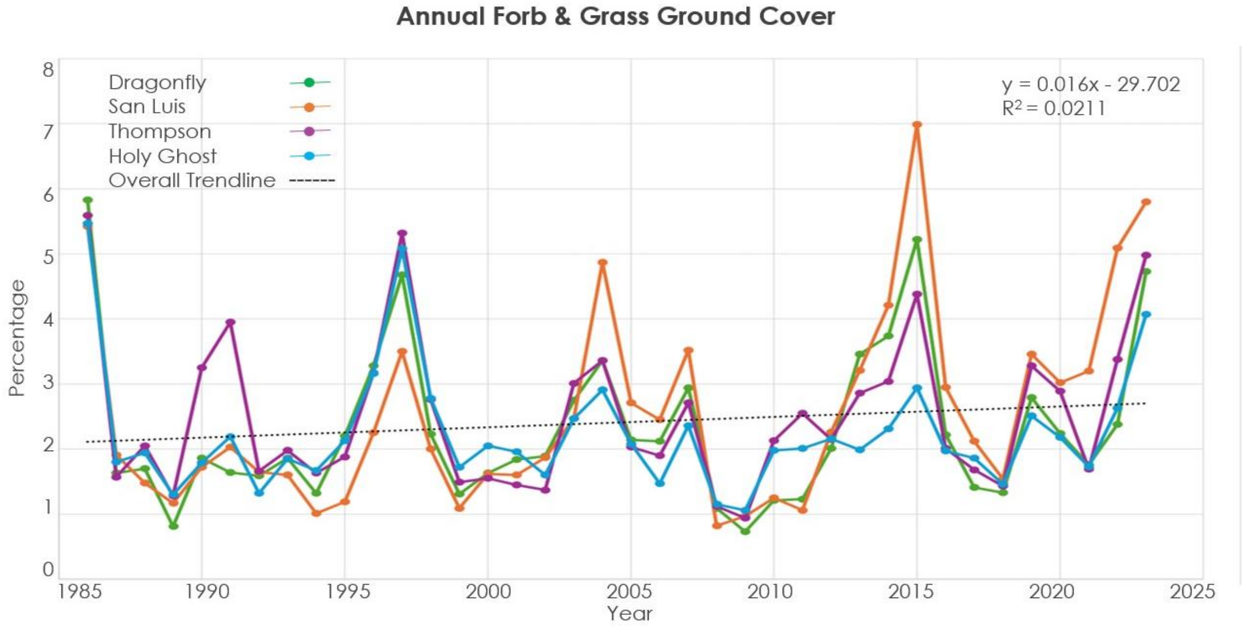


Figure 3a. Annual forb and grass ground cover percentages within each pasture over the study period. An overall trendline is applied to reveal a general trend within the study area.

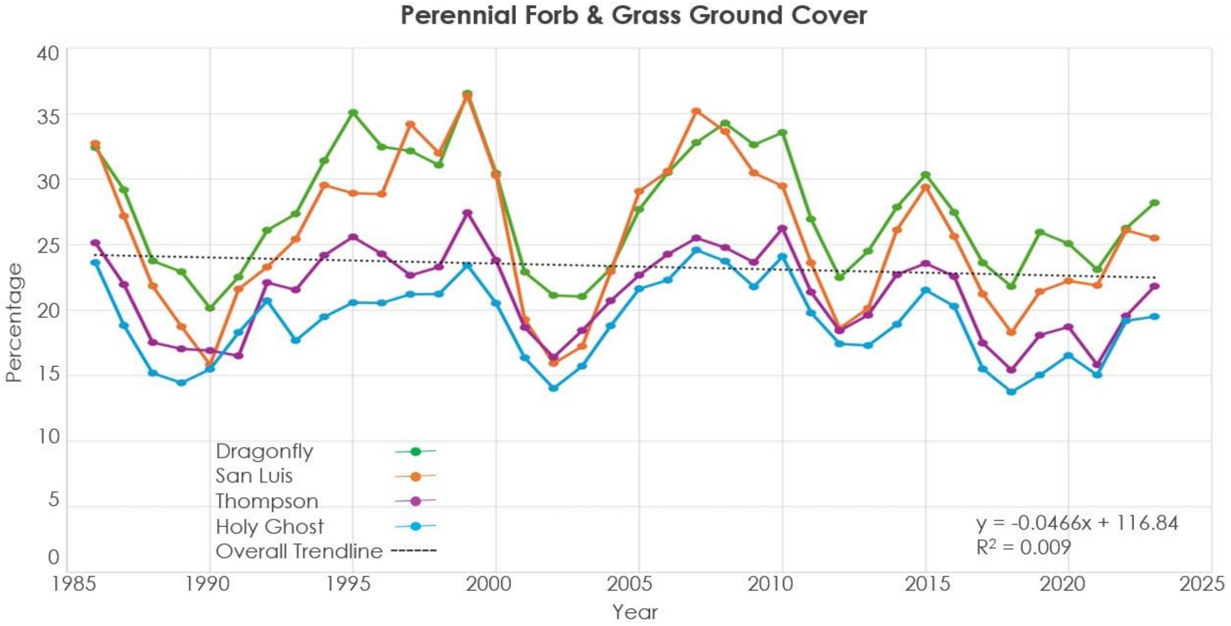


Figure 3b. Perennial forb and grass ground cover percentages within each pasture over the study period. An overall trendline is applied to reveal a general trend within the study area.

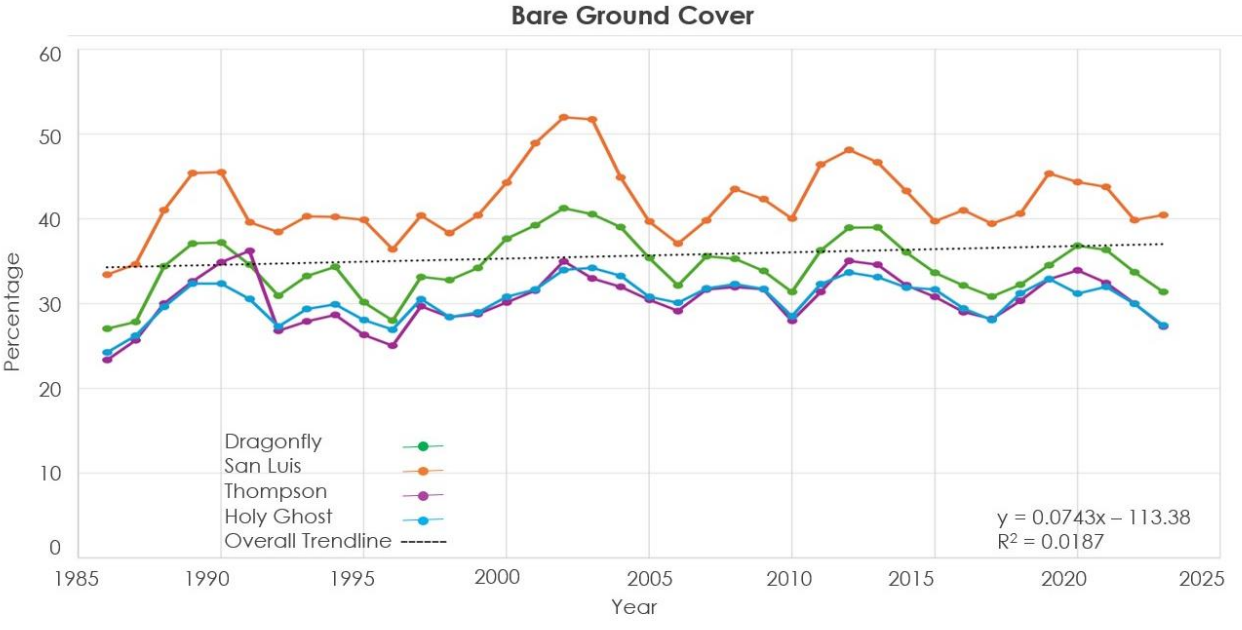


Figure 3c. Bare ground cover percentages within each pasture over the study period. An overall trendline is applied to reveal a general trend within the study area.

Precipitation and temperature are commonly known factors that influence plant growth. Figure 3d combines each pasture's RAP-obtained mean annual temperature (in lines) and annual precipitation values (in bars) with corresponding pasture-specific trendlines. From this data, a positive trendline in mean annual temperature was observed within each pasture, while negative trendlines in annual precipitation amount are concurrently happening. These results suggest the study area is becoming hotter and drier as time progresses. Figure B1 provides additional ground cover trend analysis of tree, shrub, and litter cover.

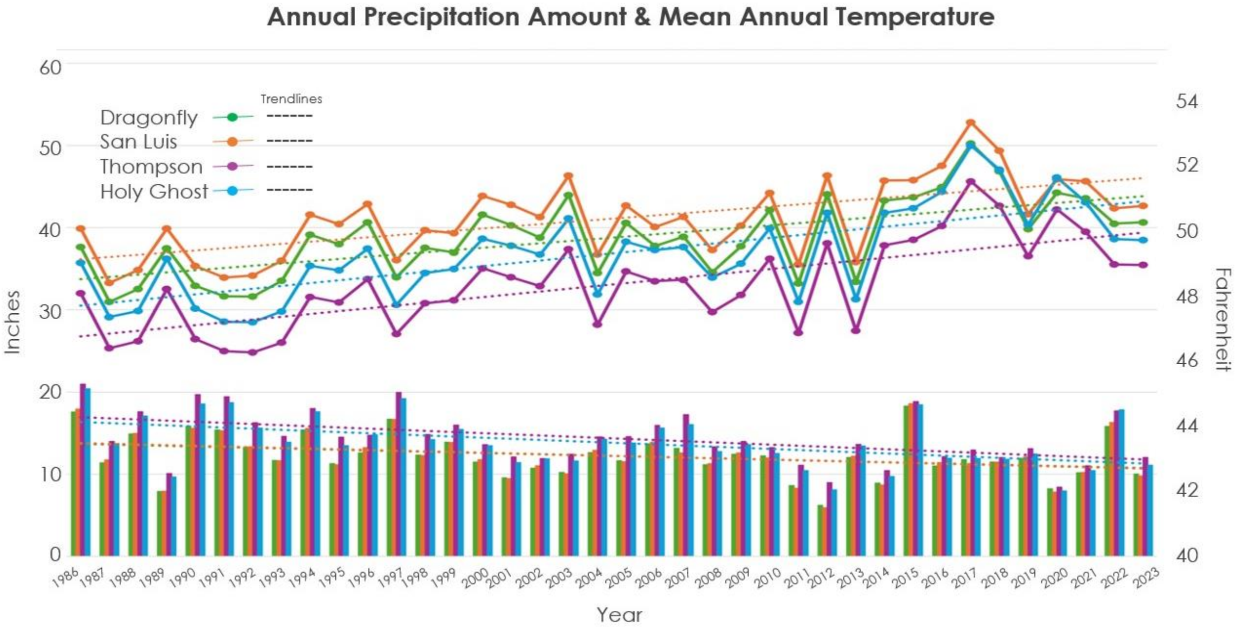


Figure 3d. RAP-generated mean annual temperature (in lines) and annual precipitation values (in bars). Individual trendlines are applied to reveal pasture-specific trends.

4.1.3 Summary Statistics

The minimum and maximum stacked images (Figure 5; Figure 6) represent the extreme conditions possible within the analyzed timeframe for bare ground cover and herbaceous biomass. The bare ground cover across the study area for 1986 – 2023 resulted in a range of 0 – 68% with a mean value of 34.2%, and the herbaceous biomass cover resulted in a range of 0 – 1401 lb./ac with a mean value of 302 lb./ac. The western portions of the pastures saw the greatest variation in forage production and bare ground cover (Figure 5; Figure 6). These figures display results visually to highlight the areas where there is the greatest possible variation in forage production and bare ground cover (greatest difference between the min and max). Figures C1 and D1 provide additional insight into herbaceous biomass and bare ground cover trends across the study site.

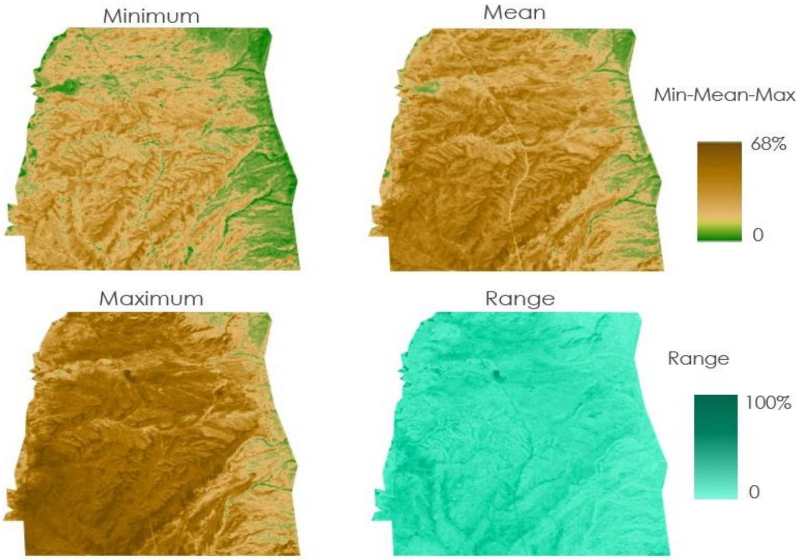


Figure 5. Study site summary statistics for bare ground cover. The top-left image depicts the minimum value from 1986 through 2023, while the bottom-left image depicts the maximum value. Study site mean values are shown in the top-right image, and the range between min and max values is displayed in the bottom-right.

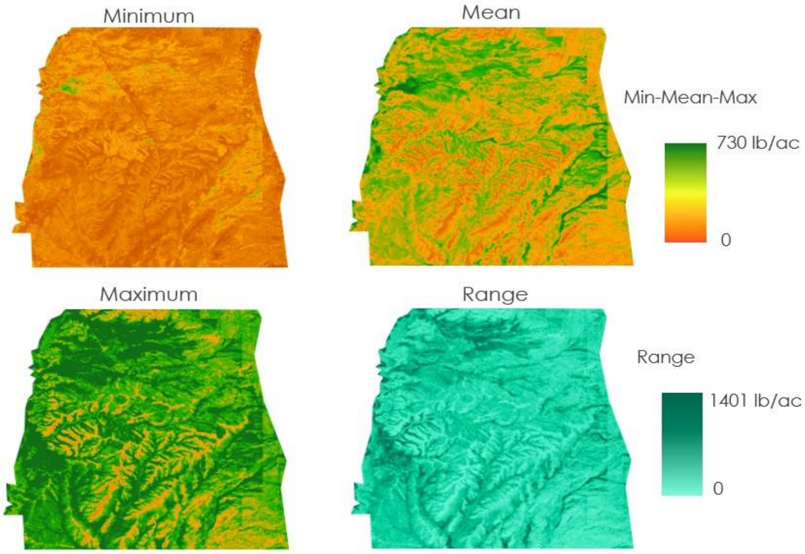


Figure 6. Study site summary statistics for herbaceous biomass. The top-left image depicts the minimum value from 1986 through 2023, while the bottom-left image depicts the maximum value. Study site mean values are shown in the top-right image, and the range between min and max values is displayed in the bottom-right.

4.1.4 Pixel-by-Pixel Trend Results

Biomass trends at different distances from water sources (Figure 7, panel A) reveal there is more variability in mean change in biomass closer to the water locations and less variability getting farther away. In the zones closest to the water sources, some locations are losing biomass at a high rate, while others appear to be quickly gaining biomass. While mean slope averages within each pasture are very similar, with a range of 0.89 (Figure 7, panel A), visual analysis of the map shows that these trends are not representative of every water location in every pasture.

A similar phenomenon is noticed with mean change in bare ground for the study area. Looking at the box plot for bare ground (Figure 7, panel B), we can see that, like the biomass trend analysis, there is more variability in mean change in bare ground cover closer to the permanent water sources and less variability farther away. Additionally, some areas close to water sources are experiencing a quick increase in bare ground, while for others, the amount of bare ground is declining. In general, from this trend analysis of both annual biomass and bare ground, we noted that it is important to analyze each water source and the surrounding area independently, as the results do not show similar trends in slope over time at every water location. Figure E1 shows the permanent and seasonal water zonal analysis of the entire study area, for annual biomass and bare ground trends. Figures E2, E3, E4, and E5 have these same zonal analysis results for the individual pastures of San Luis, Holy Ghost, Dragonfly, and Thompson, respectively, and their water sources.

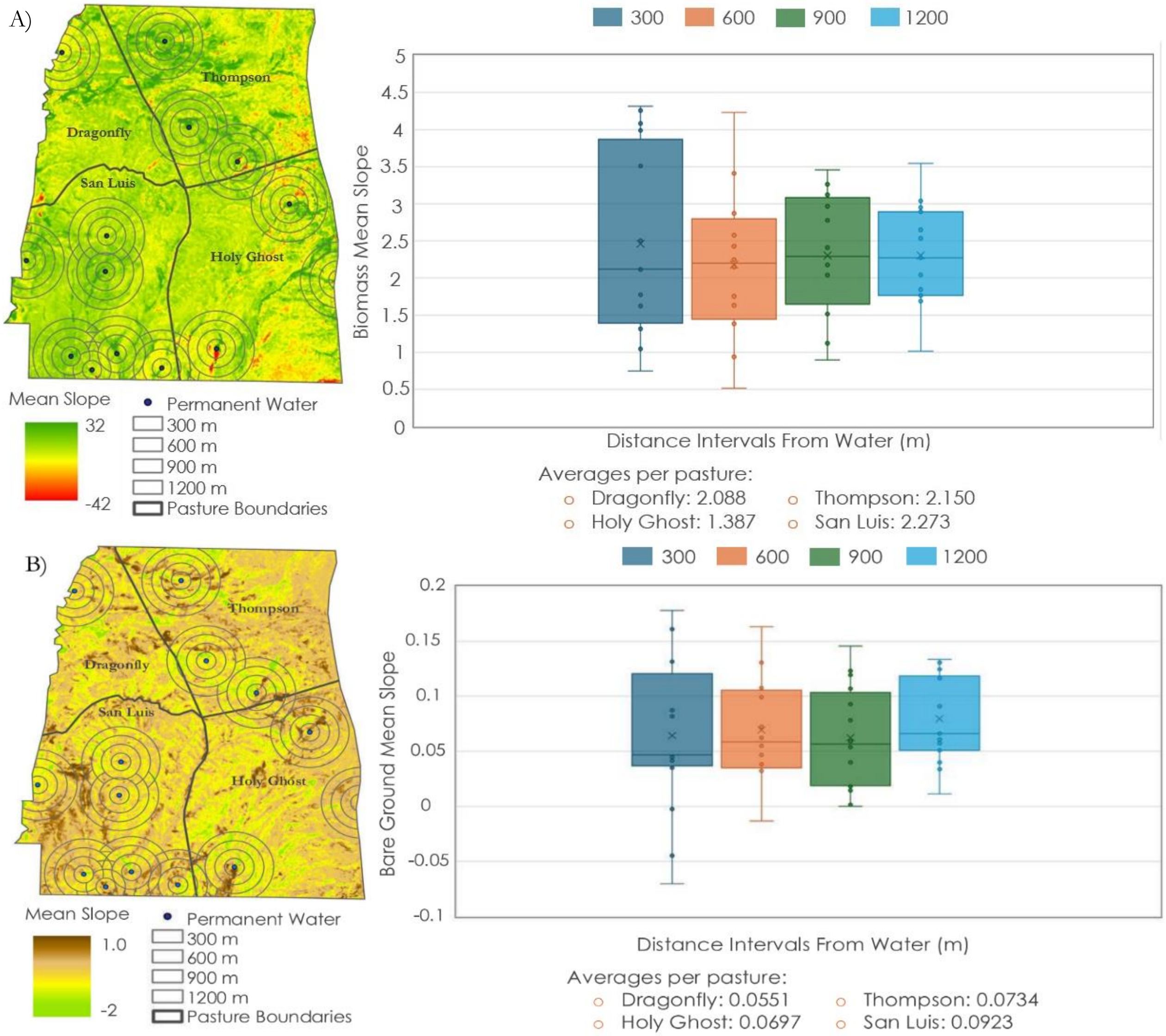


Figure 7. Mean slope trends by pixel from 1986 – 2023. The maps show the zonal statistics areas and respective box plots in the chart to the right of herbaceous biomass panel A) and bare ground cover panel B).

4.2 Errors & Uncertainties

It is important to appreciate the potential for error in the remotely sensed RAP products, particularly since there is a noticeable discrepancy between RAP's bare ground and biomass products and the 2023 field-collected data (Figure A1). It is important to consider all the factors that could have played into this uncertainty, such as the low sample size of field data observations (25 maximum), the single season of field data, and the lack of representation of some pastures in the field data samples. San Luis contained most of the sample locations (18/25 locations), while Holy Ghost had only three and Thompson had none.

Other factors to examine would be those that affect plant vigor/growth. These include stocking density in the pastures, grazing timing (such as the time the satellite image is taken with respect to recent livestock grazing activity), and the impacts of wildlife or human presence at certain times of the year. Fluctuations in annual precipitation (including periods of prolonged drought or wetter conditions and differences between western and eastern pastures) will also directly affect plant growth and can contribute to errors and uncertainties. As with any satellite imagery, ground-truthing or comparing collected field data to the remotely sensed items will continue to be needed, and scrutiny must be applied to all models, coding, and calculations to ensure minimal bias influences.

4.3 Feasibility & Partner Implementation

Despite the noted limitations of this project, remotely sensed imagery holds promise for continued use by our project partners and for similar rangeland monitoring applications. RAP is freely available to the public but does require an internet connection and, from our investigation, a desktop or laptop. Additionally, having physical knowledge of the landscape in question will greatly impact the implementation of the RAP tool, as this can help determine a level of "trust" in the application's output products. Appreciating the level of uncertainty within RAP, land managers can reasonably use this information to develop a grazing management plan that includes virtual fencing technology.

5. Conclusions

This study explored the feasibility of using RAP products as an agricultural land management tool to characterize the historical and recent rangeland conditions to assist with drought mitigation and livestock management decisions in a semi-arid desert landscape. Based on RAP, overall pasture trends from 1986 – 2023 show a slight increase in annual herbaceous presence with a slight decrease in perennial presence and a limited increase in bare ground cover across the study area. Climate data obtained through RAP also suggests the study area became hotter and drier as the years progressed. We noted different maximum and minimum precipitation years between the western and eastern pastures, which could help explain the differences in ground cover types between these areas. We also evaluated herbaceous biomass and bare ground cover changes using a pixel-by-pixel mean slope trend analysis over a wetter period (1990 – 1997) and a drier period (2016 – 2023). The comparison of these two datasets did not match expectations, and in the most recent eight years, we identified trends of increased herbaceous biomass and decreased bare ground cover (Figure C1; Figure D1). According to RAP, herbaceous biomass experienced wide fluctuations in annual amounts across the entire study site and study period. This indicates that herbaceous biomass production can be high in certain years, while in other years, it may be much lower. Additional investigation revealed that bare ground cover changes tend to be more spatially specific and generally have less range variability across the entire study area. We did not detect any noticeable differences in trends between herbaceous biomass or bare ground cover as the distance from water sources increased. Overall, remotely sensed imagery can help inform grazing management practices that incorporate virtual fencing technology. However, it is essential to evaluate these products and understand the limitations of their application. We stress the need to use caution when interpreting RAP products for this landscape, especially specific values, due to the poor performance of RAP products compared to field data. It would be prudent to evaluate RAP further using additional field data, both spatially and temporally. However, there is still value in RAP products as a consistent measure over time to provide insights into ground cover type trends.

6. Acknowledgements

Our wholehearted thanks and gratitude to:

- Partners: Jonathan Romero (Pueblo of Jemez NDR) and Tegan May (The Nature Conservancy)
- Advisors: Nicholas Young (Colorado State University [CSU]), Dr. Tony Vorster (CSU), Dr. Paul Evangelista (CSU), Dr. Catherine Jarnevich (CSU), Chris Choi (CSU)

- DEVELOP Colorado Lead: Truman Anarella
- DEVELOP Project Coordination Team: Amanda Clayton, Marisa Smedsrud, and Jane Zugarek

This material is based upon work supported by NASA through contract 80LARC23FA024.

7. Glossary

Bilinear Interpolation – Interpolation of the functions of two variables using repeated linear interpolation
Biomass (herbaceous, annual) – The total mass of organic matter within a given area or volume
Buffer – Boundaries surrounding an object within which spatial statistics are calculated
Distance-Weighted Averages – A calculated average where data points are assigned varying degrees of importance, or "weight", depending on their distance to the reference point
Fractional Cover – Percentage of vegetation cover found on the ground
Geo-fencing (also: virtual fencing) – A fencing method for cattle done with the use of GPS collars to virtually implement fencing boundaries without physical fences
Geoprocessing (ArcGIS Pro) – A framework and set of tools for processing spatial data on ArcGIS Pro
GIS – Geographic Information Systems
Ground-Truthing – Method of verifying the validity of satellite imagery with direct observation and measurements
Image Stack – An image compiled of pixels from a group of separate images all within the same frame of reference
NBR2 – Normalized Burn Ratio 2
NDVI – Normalized Difference Vegetation Index
NRD – Natural Resources Department, Pueblo of Jemez
NREL – Natural Resource Ecology Laboratory, Colorado State University
PFT – Plant Functional Types
RAP – Rangeland Analysis Platform
Raster (data/layer) – A matrix of pixels organized into rows and columns, with each pixel containing an inherent value
Stocking Density – A value representing the number of animals placed within an area relative to the maximum capacity of that area
Zonal Stats – Statistics calculated upon the cell values of a raster that is within zones defined by another dataset

8. References

Allred, B. W., Bestelmeyer, B. T., Boyd, C. S., Brown, C., Davies, K. W., Duniway, M. C., Ellsworth, L. M., Erickson, T. A., Fuhlendorf, S. D., Griffiths, T. V., Jansen, V., Jones, M. O., Karl, J., Knight, A., Maestas, J. D., Maynard, J. J., McCord, S. E., Naugle, D. E., Starns, H. D., Twidwell, D., & Uden, D. R. (2021). Improving Landsat predictions of rangeland fractional cover with multitask learning and uncertainty. *Methods in Ecology and Evolution*, *12*(5), 841–849. https://doi.org/10.1111/2041-210X.13564

Apfelbaum, S. I., Thompson, R., Wang, F., Mosier, S., Teague, R., & Byck, P. (2022). Vegetation, water infiltration, and soil carbon response to Adaptive Multi-Paddock and Conventional grazing in Southeastern USA ranches. *Journal of Environmental Management*, *308*. https://doi.org/10.1016/j.jenvman.2022.114576

Bishop, C., Sylvester, D., Wright, E., Tunberg, J., & Carpinelli M. (2023). *Ecological site description: DX035X03A113 sandy*. United States Department of Agriculture, Natural Resources Conservation Service. https://edit.jornada.nmsu.edu/catalogs/esd/035X/DX035X03A113

Boyce, M. S. (2021). *Mimic the bison: Burying carbon tax revenues in soil.* Royal Society of Canada. https://rsc-src.ca/en/voices/mimic-bison-burying-carbon-tax-revenues-in-soil

Fesenmyer, K. A., Dauwalter, D. C., Evans, C., & Allai T. (2018). Livestock management, beaver, and climate influences on riparian vegetation in a semi-arid landscape. *PLOS ONE, 13*(12). https://doi.org/10.1371/journal.pone.0208928

Gadizia, K., & Sayre, N. (2009). Rangeland health and planned grazing field guide. *The Quivira Coalition, Earth Works Institute and The New Ranch Network, 4.* https://quiviracoalition.org/rangeland-health/

Jones, M. O., Robinson, N. P., Naugle, D. E., Maestas, J. D., Reeves, M. C., Lankston, R. W., & Allred, B. W (2021). Annual and 16-day rangeland production estimates for the Western United States. *Rangeland Ecology & Management, 77*, 112 – 117. https://doi.org/10.1016/j.rama.2021.04.003

Jones, M. O., Allred, B. W., Naugle, D. E., Maestas, J. D., Donnelly, P., Metz, L. J., Karl, J., Smith, R., Bestelmeyer, B., Boyd, C., Kerby, J. D., & McIver, J. D. (2018). Innovation in rangeland monitoring: Annual, 30 m, plant functional type percent cover maps for U.S. rangelands, 1984–2017. *Ecosphere*, *9*(9), e02430. https://doi.org/10.1002/ecs2.2430

McCord, S., & Williamson, J. (2022). Awesome-GEE-community-catalog: Rangeland Analysis Platform layers [Computer software]. Github. https://gee-community-catalog.org/projects/rap/

Natural Resource Ecology Laboratory. (2023a). [Jemez 2023 Mean Biomass by Plot] [Unpublished raw dataset]. Nicholas Young, Colorado State University.

Natural Resource Ecology Laboratory. (2023b). [Jemez Plot Info] [Unpublished raw dataset]. Nicholas Young, Colorado State University.

Natural Resource Ecology Laboratory. (2024). [JP Summ by Plot – DEVELOP 2] [Unpublished raw dataset]. Nicholas Young, Colorado State University.

Pueblo of Jemez. (2021a). [Jemez Boundary Shapefile] [Unpublished raw dataset]. Pueblo of Jemez Natural Resources Department.

Pueblo of Jemez. (2021b). [Permanent Water Locations Shapefile] [Unpublished raw dataset]. Nicholas Young, Colorado State University.

Pueblo of Jemez. (2021c). [Seasonal Water Locations Shapefile] [Unpublished raw dataset]. Nicholas Young, Colorado State University.

Pueblo of Jemez. (2023). [Pasture Boundaries Shapefile] [Unpublished raw dataset]. Nicholas Young, Colorado State University.

Rangeland Analysis Platform. (2023a, March 17). *Rangeland Analysis Platform Website*. https://rangelands.app/

Rangeland Analysis Platform. (2023b, March 17). *Rangeland Analysis Platform App*. https://rangelands.app/rap/?biomass_t=herbaceous&ll=50.9175,-101.1641&z=4

Rangeland Analysis Platform. (2024a, January 28). projects/rap-data-365417/assets/vegetation-cover-v3 [Data set]. http://rangeland.ntsg.umt.edu/data/rap/rap-vegetation-cover/

Rangeland Analysis Platform. (2024b, January 28). projects/rap-data-365417/assets/npp-partitioned-v3 and projects/rap-data-365417/assets/gridmet-MAT [Data set]. http://rangeland.ntsg.umt.edu/data/rap/rap-vegetation-biomass/

Robinson, N. P., Jones, M. O., Moreno, A., Erickson, T. A., Naugle, D. E., & Allred, B. W. (2019). Rangeland Productivity Partitioned to Sub-Pixel Plant Functional Types. *Remote Sensing*, *11*(12). https://doi.org/10.3390/rs11121427

US Geological Survey Earth Resources Observation and Science Center. (2020). *Landsat 5 TM* [Data set]. US Geological Survey. https://doi.org/10.5066/F7N015TQ

US Geological Survey Earth Observation and Science Center. (2020). *Landsat 7 ETM+* [Data set]. US Geological Survey. http://doi.org/10.5066/P9TU80IG

US Geological Survey Earth Observation and Science Center. (2020). *Landsat 8-9 OLI/TIRS* [Data set]. US Geological Survey. https://doi.org/10.5066/P9OGBGM6

9. Appendices

Appendix A: *2023 Data Validation Linear Models by Cover Type*

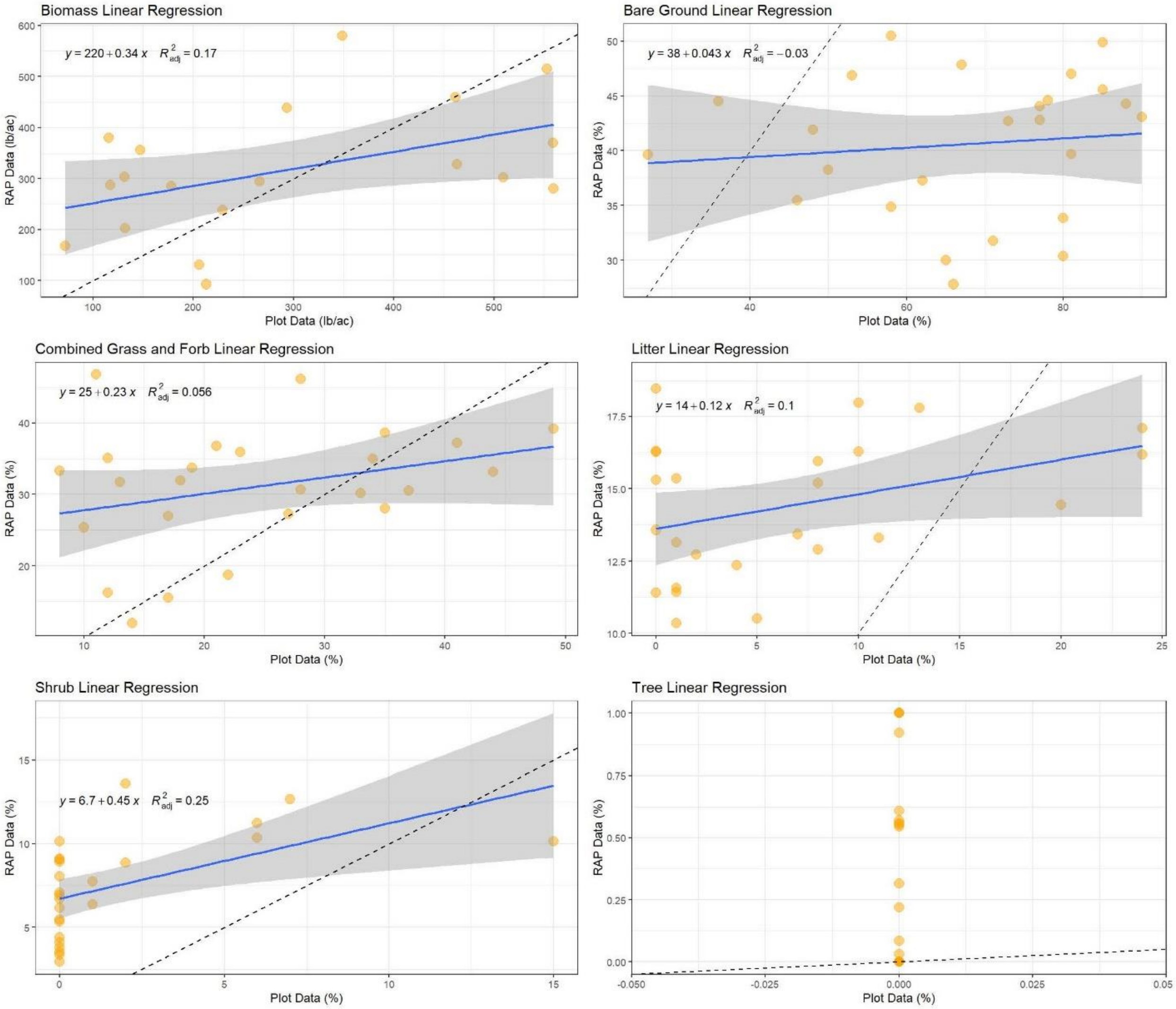


Figure A1. Linear regression model (blue line) for RAP data validation to plot data for all cover types and biomass for 2023. Bare ground was generally underestimated by RAP data relative to the plot data. RAP Biomass and Grass and Forb cover was generally overestimated at the lower end of the scale and underestimated at the higher end of the scale compared to the plot data. Higher estimates of cover from RAP than the plot data consisted within the Shrub, Litter, and Tree categories. P-values are as follows, Biomass = 0.471*, Bare Ground = 0.5952, Grass and Forbs = 0.1334, Litter = 0.0730, Shrub = 0.0064**. No trees were recorded within the plot data limiting the ability to perform a linear regression to RAP data.

Appendix B: *Additional Ground Cover Graphs by Pasture*

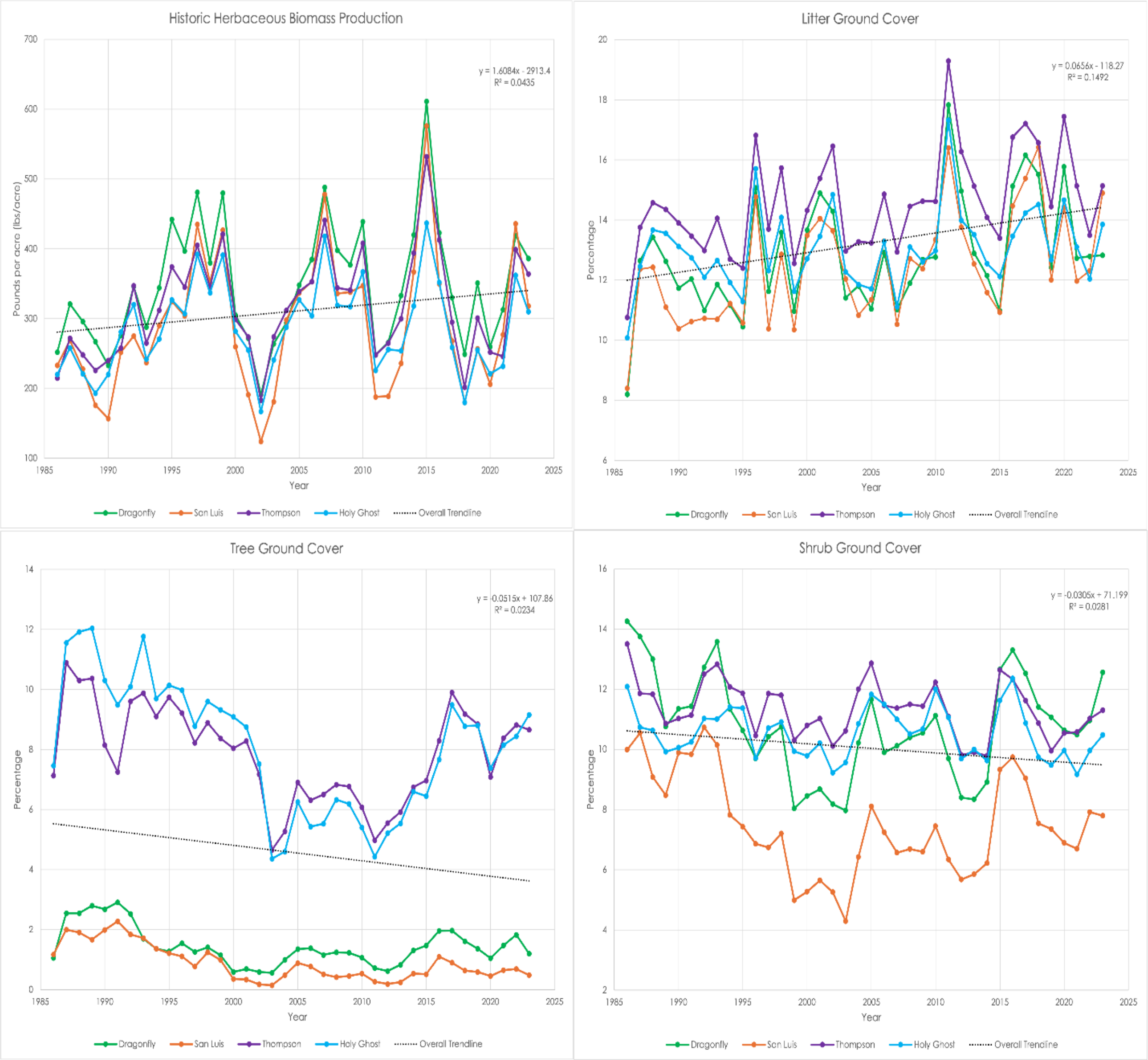


Figure B1. Additional ground cover trends by pasture with an overall trendline through the study period. Annual herbaceous biomass production (annual and perennial) shows an overall increasing trendline over the study period. Tree and shrub ground cover types are shown to have, generally, decreasing trendline while litter ground cover is increasing.

Appendix C: *Pixel Trend Analysis at Varying Time Slices for Herbaceous Biomass*

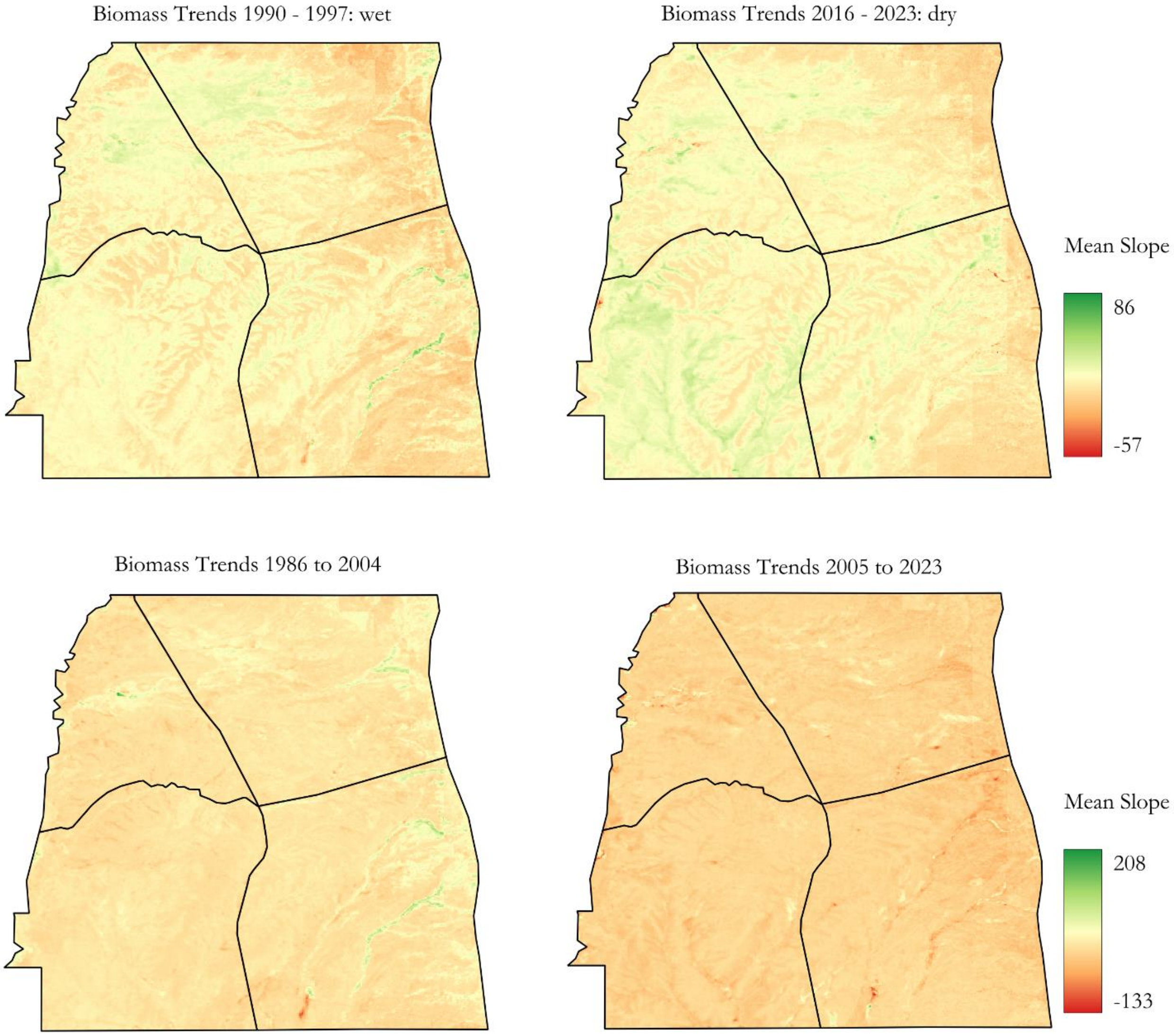


Figure C1. Pixel trend analysis was taken at varying time slices to compare changes at these temporal scales. The comparison of eight years of wet years relative to eight years of dry years is inconclusive. We see increasing biomass levels during the most recent dry years and a decrease in biomass in the wet years which is counterintuitive, and more details are needed to understand these trends. It could be that plant species that do best in dry bare ground areas are thriving, such as cacti and tumbleweeds in recent years. The second set of maps is just a time split down the middle of our full study period. The most recent 19 years show an overall decrease in biomass, contrasted with the recent 8 years in the upper left map.

Appendix D: *Pixel Trend Analysis at Varying Time Slices for Bare Ground*

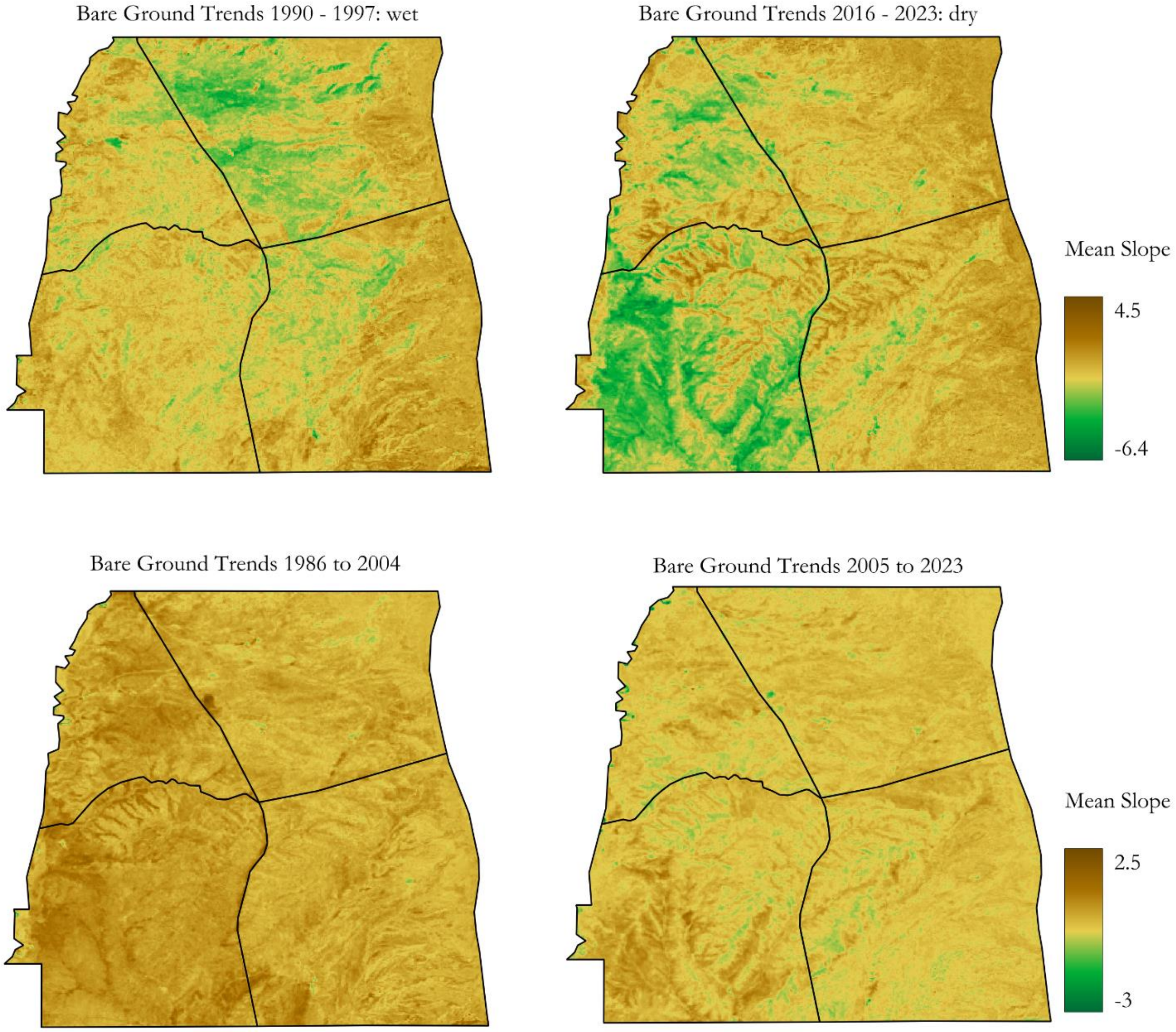
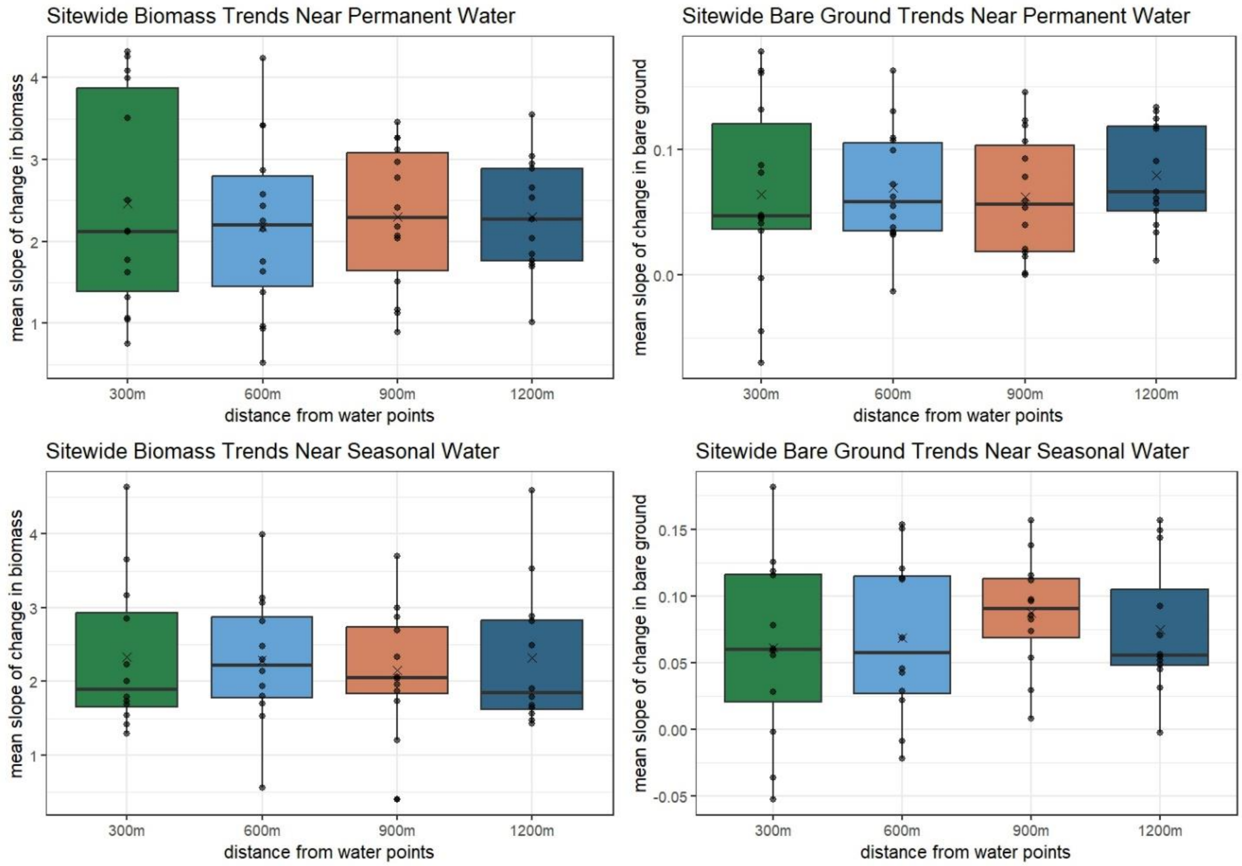


Figure D1. Pixel trend analysis was taken at varying time slices to compare changes at these temporal scales. The comparison of eight years of wet years relative to eight years of dry years is inconclusive. We see decreasing bare ground cover during the most recent dry years, especially on the east pastures, whereas the west pastures saw a decrease in bare ground during the wet years. More details are needed to understand these trends however they do coincide with the Figure C biomass trends. Such as what species could be accounting for increasing biomass in recent years. The second set of maps is just a time split down the middle of our full study period. The most recent 19 years show an overall decrease in biomass, contrasted with the recent 8 years in the upper left map.

Appendix E: *Zonal Trend Analysis at Permanent and Seasonal Water Sources for the Study Area*


Sitewide Biomass Trends Near Permanent Water

Sitewide Bare Ground Trends Near Permanent Water

Sitewide Biomass Trends Near Seasonal Water

Sitewide Bare Ground Trends Near Seasonal Water

Figure E1. Pixel trend analysis box plots of all permanent and seasonal water sources across the entire study area. Throughout the site as a whole we see that there is slightly more variation in mean change in both biomass/bare ground cover closer to permanent water sources, often at distances of 300m and 600m. Further away, there is less variation. With seasonal water locations, there is less conclusive evidence that mean change in biomass/bare ground correlates to distance from the water source-there is similar variation in mean slope at each distance

** To conduct a truly comprehensive analysis of mean change in annual biomass/bare ground cover at different distances from permanent and seasonal water sources in these pastures, more water sources (as data points) and intentional sampling of field data about their surrounding area would be necessary. These plots represent a zonal analysis of 14 permanent and 12 seasonal water sources across all four pastures, but not a conclusive trend about the study area or any individual pasture. It is recommended to analyze each water point independently when considering biomass/bare ground trends at that location over time.*

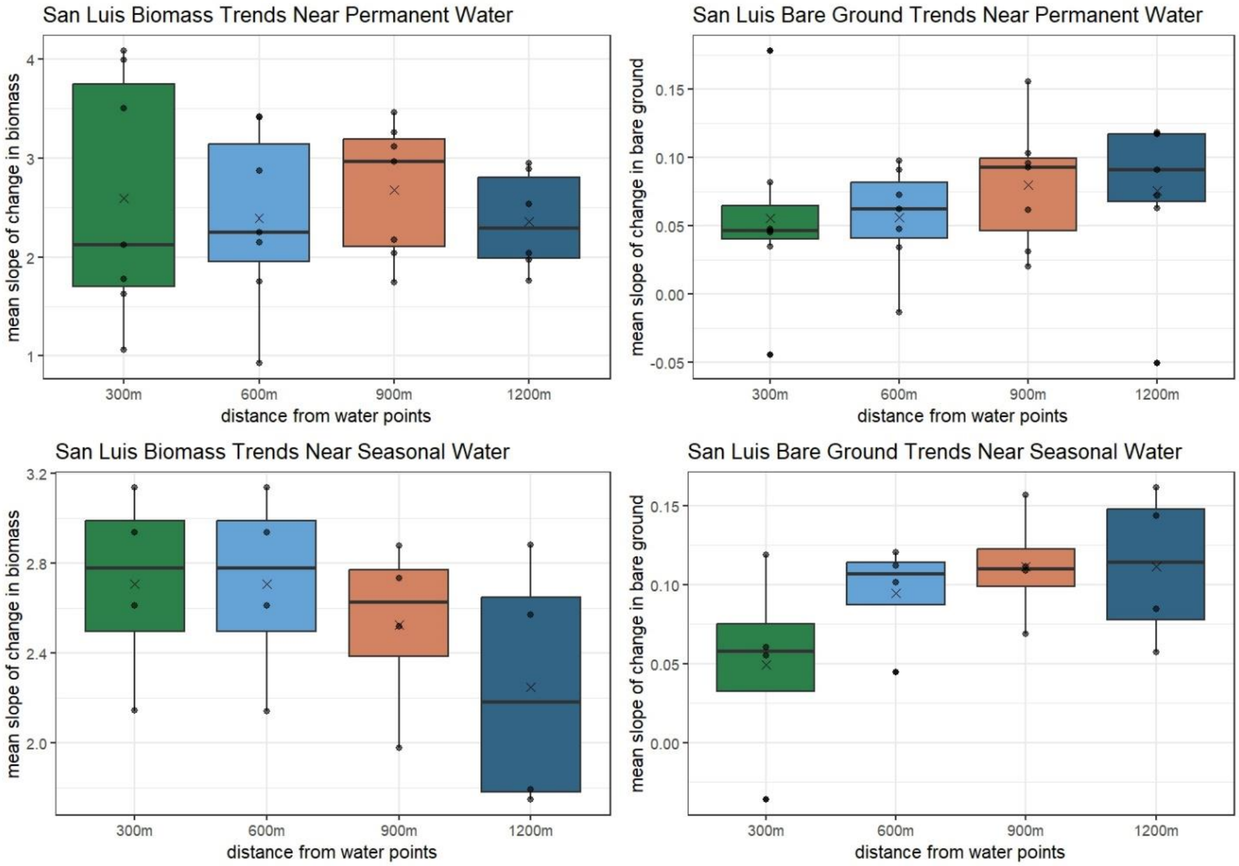


Figure E2. Pixel trend analysis box plots of all permanent and seasonal water sources across the San Luis pasture. Near permanent water sources we continue to see the trend of increased variability in change in annual biomass and bare ground cover closer to the water. Near seasonal water there is less conclusive evidence of any trend in slope of bare ground or biomass, but one interesting point of note is that there seems to be more variability overall in biomass mean slope, whereas the box plots for bare ground slope show less variability

** To conduct a truly comprehensive analysis of mean change in annual biomass/bare ground cover at different distances from permanent and seasonal water sources in these pastures, more water sources (as data points) and intentional sampling of field data about their surrounding area would be necessary. These plots represent a zonal analysis of 14 permanent and 12 seasonal water sources across all four pastures, but not a conclusive trend about the study area or any individual pasture. It is recommended to analyze each water point independently when considering biomass/bare ground trends at that location over time.*

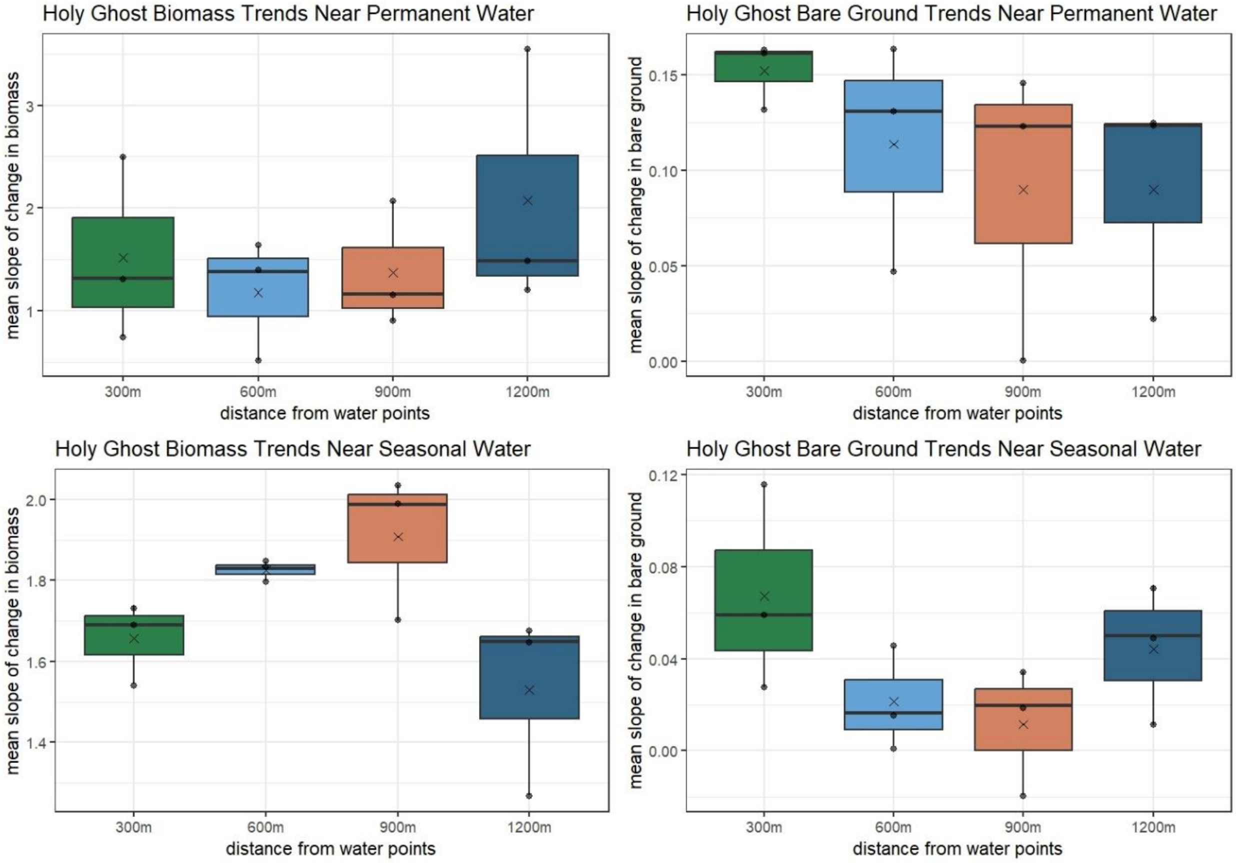
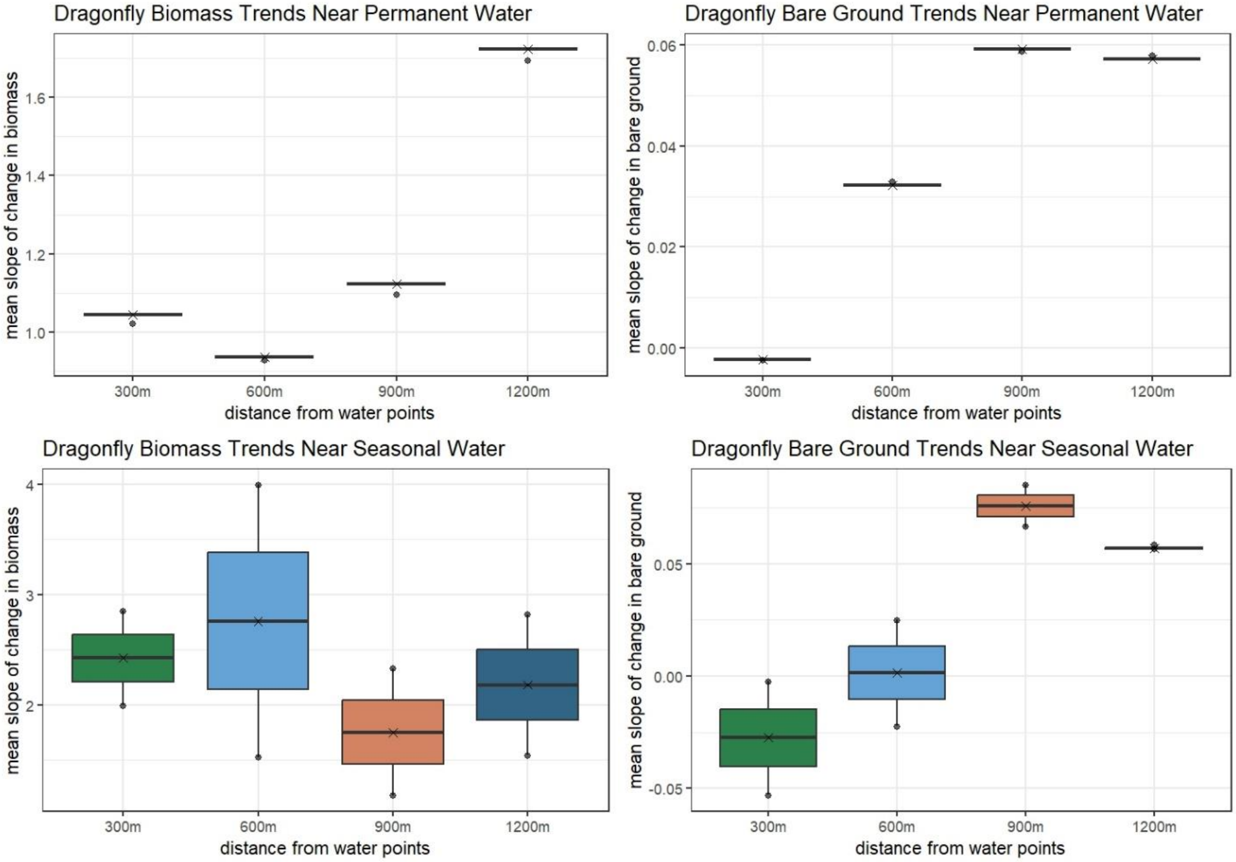


Figure E3. Pixel trend analysis box plots of all permanent and seasonal water sources across the Holy Ghost pasture. One interesting trend in seasonal water results is the 600m and 900m results, which show a higher rate of change in annual biomass than the other distances, but a lower rate of change in bare ground cover than the other distances. Most of these box plots demonstrate the effects of some more extreme values pulling the mean in their direction

** To conduct a truly comprehensive analysis of mean change in annual biomass/bare ground cover at different distances from permanent and seasonal water sources in these pastures, more water sources (as data points) and intentional sampling of field data about their surrounding area would be necessary. These plots represent a zonal analysis of 14 permanent and 12 seasonal water sources across all four pastures, but not a conclusive trend about the study area or any individual pasture. It is recommended to analyze each water point independently when considering biomass/bare ground trends at that location over time.*


Dragonfly Biomass Trends Near Permanent Water

Dragonfly Bare Ground Trends Near Permanent Water

Dragonfly Biomass Trends Near Seasonal Water

Dragonfly Bare Ground Trends Near Seasonal Water

Figure E4. Pixel trend analysis box plots of all permanent and seasonal water sources across the Dragonfly pasture. Dragonfly had fewer water sources to analyze, but from this data we can see that for these places in the pasture, mean change in biomass/bare ground cover increased at the farthest distances from the water source, with the exception of the bottom left plot, which does not demonstrate this trend

** To conduct a truly comprehensive analysis of mean change in annual biomass/bare ground cover at different distances from permanent and seasonal water sources in these pastures, more water sources (as data points) and intentional sampling of field data about their surrounding area would be necessary. These plots represent a zonal analysis of 14 permanent and 12 seasonal water sources across all four pastures, but not a conclusive trend about the study area or any individual pasture. It is recommended to analyze each water point independently when considering biomass/bare ground trends at that location over time.*

*** Dragonfly contains only 1 permanent water source*

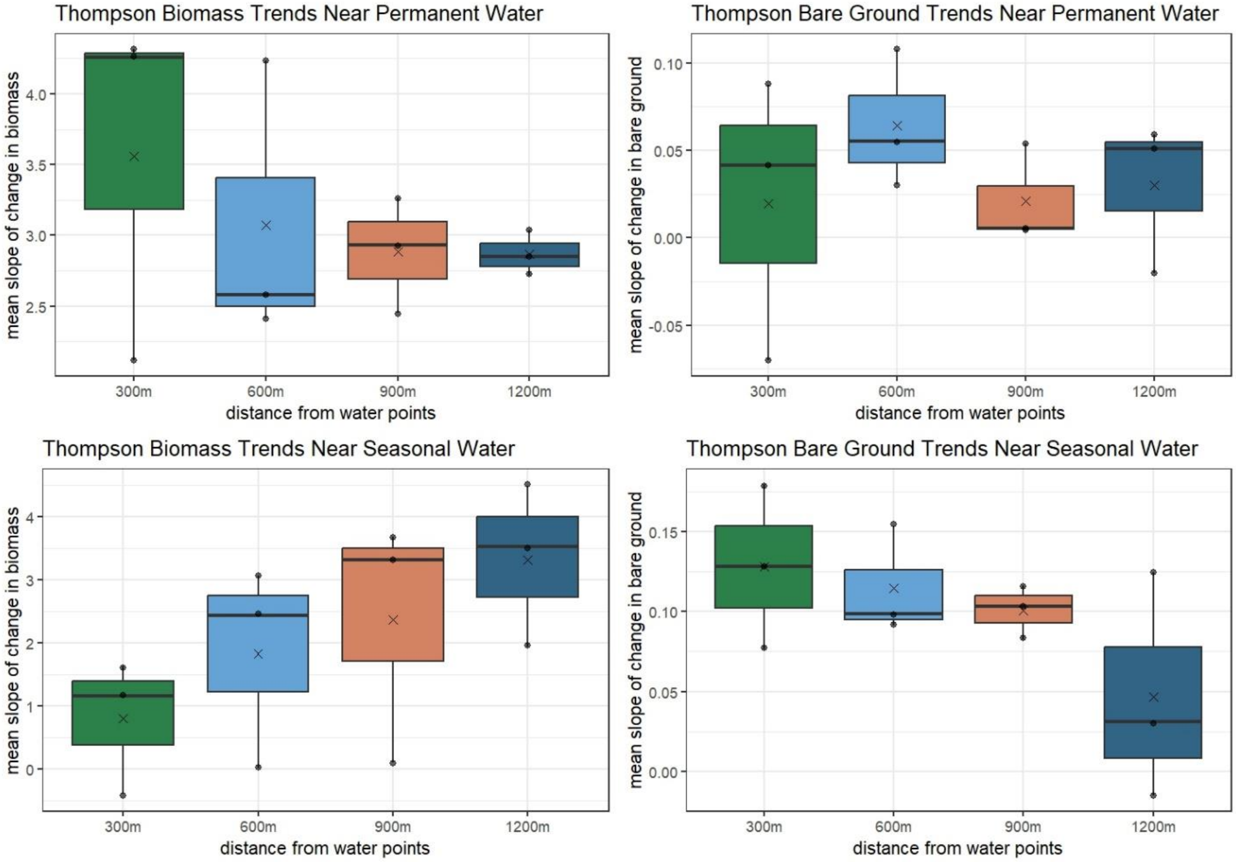


Figure E5. Pixel trend analysis box plots of all permanent and seasonal water sources across the Thompson pasture. These plots also demonstrate the effects of a few of the more extreme values pulling the mean in their direction (the 300m and 600m distances in the top left plot-Biomass Trends Near Permanent Water-are a good example of this), but one interesting relationship represented in these plots is the mean change in biomass, which, for these places in the pasture, increases with distance from seasonal water sources.

** To conduct a truly comprehensive analysis of mean change in annual biomass/bare ground cover at different distances from permanent and seasonal water sources in these pastures, more water sources (as data points) and intentional sampling of field data about their surrounding area would be necessary. These plots represent a zonal analysis of 14 permanent and 12 seasonal water sources across all four pastures, but not a conclusive trend about the study area or any individual pasture. It is recommended to analyze each water point independently when considering biomass/bare ground trends at that location over time.*