Questioning the Cause of Calamity:
Using Remotely Sensed Data to Assess Successive Fire Events

by

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To my friends, Jeff Lauder and Mackenzie Kilpatrick

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List of Abbreviations

AVHRR	Advanced Very High-Resolution Radiometer
BLM	Bureau of Land Management
EVI	Enhanced Vegetation Index
FWS	Fish and Wildlife Service
GIS	Geographic information system
MODIS	Moderate Resolution Imaging Spectroradiometer
NBR	Normalized Burn Ratio
NDA	Nevada Department of Agriculture
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
PRISM	Parameter elevation Regression on Independent Slopes Model
USDA	United States Department of Agriculture
USGS	United States Geological Service
WFMI	Wildland Fire Management Information

Abstract

Bureau of Land Management policy regarding wildfire events on public rangelands dictates that burned areas are closed to livestock grazing until the vegetation in the burned area has reestablished itself. Ranchers and their supporters contend that extended duration of such grazing closures increases the likelihood of subsequent fire events during the grazing rest period. The ranchers attribute this effect to an over-accumulation of vegetation during the grazing rest period. With the goal of testing the claim made by ranchers, this project utilized fire history records, grazing allotment data, and remote sensing vegetation indices to identify and analyze potential rest period fires between 2000 and 2016 in and around the Nevada counties of Humboldt and Elko. GIS proximity tools were used to identify initial and subsequent fires on BLM grazing allotments which met the spatial and temporal requirements of a rest period fire. The four most likely candidates for rest period fires were selected for further examination as case studies. Scaled NDVI was used as an estimator of vegetation cover and change between selected initial and subsequent fires. Precipitation and land cover data were incorporated to provide further context. Three of the four fire perimeters showed increased vegetation cover when compared to similar nearby unburned sites during the second spring after the initial fires. This pattern suggests that increased fuel loads before the secondary fire may have been present. Evidence of cheatgrass and anthropogenic fire activity in the case study area suggest more complex explanations. Ways to improve monitoring and post-fire recovery through better record keeping, more complex sensors for satellite imagery, and targeted grazing research are discussed.

Chapter 1 Introduction

Land management agencies such as the Department of the Interior's Bureau of Land Management (BLM) often create and enforce livestock grazing closures on public grazing allotments after wildfire events. The purpose of these closures is to allow the vegetation in a burned area to recover or recolonize (BLM 2007). Ranchers argue that the durations of post-fire grazing bans are longer than they need to be. Their concern is that grazing bans remain in place long enough that plant litter accumulates more than it might otherwise, leading to a subsequent fire reburning the area soon after the original fire. Although not specifically dealing with post-fire bans, news articles by Halladay (2015) and Valla (2015) both feature ranchers citing grazing bans as major factors in recent fire events. Despite ongoing disputes between policy makers, ranching advocates, and environmentalists, there have been no major studies specifically examining the arguments opposing such closures. The studies which do exist focus on how post-fire grazing affects vegetation recovery, not rest period fire rates (e.g., Bruce et al. 2007).

1.1. Research Questions Investigated by this Study

The purpose of this project was to test the claim that closures and rest periods on grazing allotments managed by the BLM lead to an increase of fuel load in the form of vegetation and consequently to subsequent fire events during the rest period. There were two questions this project intended to answer:

1. Which, if any, fires within BLM-managed grazing allotments burned areas previously burned during an earlier fire season within three years?
2. If there are fires which fulfill the spatial and temporal requirements of question one, is there evidence that these fires were preceded by greater vegetation growth/recovery than

similar nearby unburned areas as measured by fuel load, biomass accumulation, or a similar indicator of vegetation health or abundance?

To answer these questions, this project utilized available spatial data to identify any potential fires that possessed the attributes described in the first question. Upon finding any such fires, this project acquired and processed historical satellite imagery data to construct vegetation index time series. The time series were used to estimate vegetation recovery and/or biomass accumulation. Because this project took the form of historical case studies, data that could directly answer the research questions were not always available or trustworthy. In such a case:

1. Alternative methodologies were considered to answer the questions and when appropriate data were available, some were implemented.
2. When necessary, modifications to the original questions that were answerable with available data were made.

1.2. Project Background and Impact

The background knowledge used in this project pulls from topics such as fire science, botany, agriculture, and the political interaction between local and federal stakeholders. Likewise, the policy issues considered by this project are typically approached by assessing the effect of grazing on burned rangeland. This project instead examined the fire risk of grazing closures.

Underlining all the issues discussed in this chapter is the fact that the Bureau of Land Management has jurisdiction over almost 47 million acres in Nevada, approximately two-thirds of Nevada's land (BLM 2017). Any action or policy change taken by the BLM has a considerable impact on the state.

1.2.1. Historical Background

Two key milestones in the history of public lands in the American West were the passage of the Taylor Grazing Act of 1934 and the establishment of the BLM in 1946 (Knapp 1996). The Taylor Grazing Act regulated grazing on public lands to prevent rangeland deterioration from overgrazing. This regulation created a system of grazing allotments that could be leased by private operators. The private operators would have the sole rights to graze livestock on their allotments, but also sole responsibility for degradation of the rangeland. The BLM was created over a decade later to act as a manager for these grazing allotments and other public lands. This aspect of federal land management has been a persistent source of contention between federal policymakers and land users, leading to noteworthy events such as the Sagebrush Rebellion of the late 1970s and the 2016 occupation of the Malheur Wildlife Refuge in Oregon. Given the economic, environmental, and political impact of land use policies, it is important that such policies are rigorously evaluated and based on both physical evidence and community needs.

1.2.2. Economic Impact

Livestock production is an important component of the Nevadan economy. In Elko County, livestock production generated 85% of all agricultural receipts in 2012 (NDA 2015). Cattle ranching specifically was the 12th largest industry in Elko County, generating about $83 million for the county. In Nevada, the ranching industry depends on access to public lands for leased grazing allotments. Preventing, managing, and recovering from wildfires in the rangelands is thus vital to the economies of rural Nevada counties such as Elko. Improved understanding of wildfires and more effective land management could benefit these economies.

1.2.3. Ecological Impact

There are multiple ecological concerns in the region involving wildfire management. The greater sage-grouse (*Centrocercus urophasianus*), a native bird species in the region, is sagebrush obligate, and thus highly sensitive to habitat damage in the sagebrush steppes (FWS 2015). Wide-spread or uncontained wildfires can adversely affect the sage-grouse population. This can be exacerbated by post-fire invasion by non-native grasses, most notably cheatgrass (*Bromus tectorum*). Cheatgrass is less palatable than native plants to both wild and domestic grazers while being more flammable than native plants (NRCS 2015). The post-fire spread of cheatgrass thus induces a positive feedback loop increasing the likelihood of future fires. Nevada experienced prolonged periods of drought during the 2000s and 2010s, with severe droughts in 2006 and 2011. The drier and warmer climate further increases the likelihood of wildfires and the need to properly understand and manage them.

1.2.4. Policy Background

At the center of the ranchers' claim and the research questions posed by this project is the BLM's "Burned Area Emergency Stabilization and Rehabilitation Handbook" (the "Handbook") (BLM 2007). This document is the official enunciation of BLM fire recovery policies, including section III.B.10, which describes how fencing and other barriers should be used to protect a burned area during recovery, and section III.B.18, which is concerned with post-fire livestock grazing. Section III.B.18 states "Livestock are to be excluded from burned areas until monitoring results… show emergency stabilization and rehabilitation objectives have been met… In the case of treatment failure, other factors may need to be considered" (BLM 2007, 35).

Section III.B.10 of the handbook notes that "It often takes two years or longer to successfully establish a new seeding" (BLM 2007, 31) which is the policy justification for two-year grazing closures. The policy recommends reseeding burned areas to enable native vegetation regrowth and to prevent post-fire colonization by invasive plants. The policy states that shorter or longer rest periods might be used depending on climatic, meteorological, and other environmental factors. Drought conditions may justify longer periods, while wetter climate might require shorter periods. The handbook also states that closures lasting more than three years are turned over to the jurisdiction of the local BLM office in charge of the allotment or pasture. Because the federal jurisdiction over the recovery effort ends after three years, any subsequent fire events occurring more than three years after the initial fire are excluded from the list of candidate rest period fires examined in this study.

Section III.B.10 also guides BLM managers to limit closure areas to the minimum needed to protect reseeding efforts from grazers (both domesticated and wild). Section III.B.18 however suggests that it can be more cost effective in some cases to close entire allotments if the damage is wide-spread and the cost of new fencing is not feasible. The policy gives an example of "75 percent or more of an allotment or pasture" as a situation where the entire allotment might be placed in a grazing closure. The competing constraints of "minimum closed area" and "least costly enclosure" lead to situations where larger burn perimeters might be enclosed using existing fencing as a cost-saving measure. This can result in grazing closure areas that are larger than the fire perimeter and include adjacent unburned land.

1.3. Study Area and Key Terms

This section describes the study area for the project and some of the key terms used in this document.

1.3.1. Study Area: BLM Grazing Allotments

BLM grazing allotments are parcels of federally managed public rangeland which are leased to private operators for economic use. The study area for this project consists of 339 BLM Grazing Allotments located wholly or partly within the Nevada counties of Humboldt and Elko, which are part of the interstate Great Basin region (Figure 1). Allotments range in size from 62.5 acres to over 1.3 million acres, with the majority being between 1,000 and 100,000 acres.

In this project, grazing allotments are the actionable spatial unit. All other events (closures, wildfires, and vegetation growth) occur within the allotments. Events which occur outside of allotments are not bound by BLM fire response policy and are therefore outside the scope of this project. Understanding wildfire events at the allotment level of perception is the primary purpose of the first component of this study.

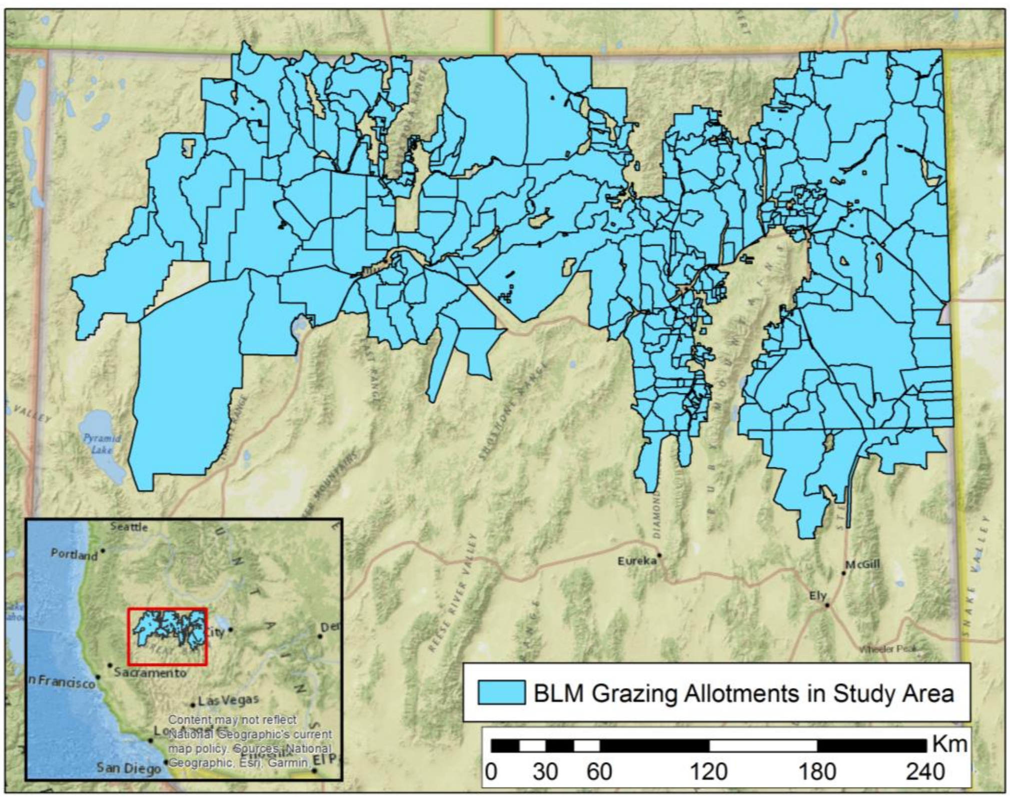

Figure 1. BLM Grazing Allotments in Study Area

1.3.2. Rest Periods

The rest period of a grazing closure is the time from when the fire is contained to when grazing resumes on the closed area. BLM post-fire recovery policy establishes a set of goals or conditions to be met by the closure before the rest period can end (BLM 2007). These goals are determined per-fire and can be different across fires or between two allotments affected by the same fire. As described in the policy background section above, rest periods which extend beyond the 3 years are outside the scope of this project.

While the true lower bound of a rest period is immediately after the fire is contained, such a constraint makes little sense in the objectives of this project. It is not reasonable to argue that excessive vegetation accumulation can happen within a day or two after a fire has ended. In fact, most wildfires in the study area occur between the months of June and September (Figure 2), suggesting that rest period fires need at least one or two Spring seasons for fuel accumulation.

It is however necessary to identify all fires within the study which occurred within three years of a previous fires. Two fires with an interval of two or three years could potentially have a third fire occurring between them. An intervening fire would complicate the vegetation index time series and the interpretation of the results. The fires for the case study were selected to have two or three Spring seasons between fires and to have no recorded fire events in between.

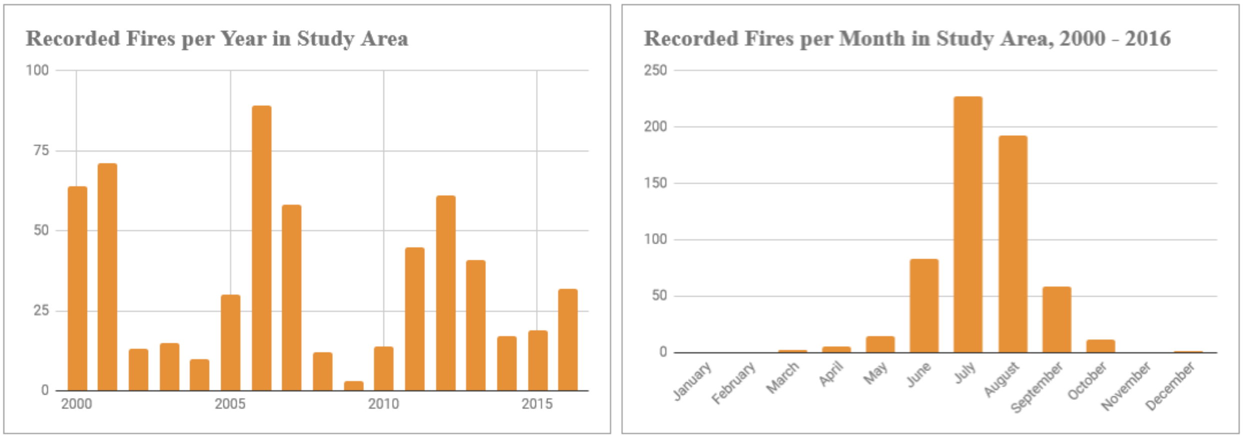

Figure 2. Recorded Fire Frequency by Year and by Month

1.3.3. Grazing Closure Areas

The grazing closure area is the area which is closed to livestock grazing after a wildfire has been contained. The purpose of closures is to allow the vegetation in a burned area to recover before allowing livestock to graze. BLM policy mandates the use of temporary fencing to secure the closure area (BLM 2007). In some cases, the burned area is large enough that temporary fencing is too costly or time consuming to put up. BLM policy can instead mandate the use of pre-existing permanent fencing used to separate individual pastures within an allotment. When permanent fencing is authorized, the unburned areas within the pasture fencing are also closed to grazing. In the worst scenario, a large burned area may result in the BLM closing entire allotments.

1.3.4. High Vegetation Accumulation

High vegetation accumulation during the rest period is, according to the claims made by ranchers, the cause of rest period fire events. Testing these claims thus requires observing vegetation changes between the previous and subsequent fires. Chapter 2 discusses the scientific literature about the LANDSAT sensors and their use in vegetation monitoring. This project used data from the LANDSAT 5 Thematic Mapper sensor to record a time series for fractional vegetation cover before, during and after the rest periods. The second part of Chapter 3 discusses the methods used in this project in greater detail.

1.4. Structure of this Document

The remainder of this document details the research, methodology, and outcomes of this project. Chapter 2 is a discussion of relevant background research, primarily on the topics of vegetation indices, fire regimes, and Great Basin vegetation and ecology. Chapter 3 discusses the case study selection process and the construction of vegetation index time series for each site. Chapter 4 describes the direct outcomes of the processes described in Chapter 3, specifically comparing the observed time series graphs to the expected time series if the ranchers' claim is valid. The final chapter provides qualitative context to the outcomes from Chapter 4 while also discussing alternative explanations, additional research questions raised during this project, and opportunities to improve rangeland policy and data collection.

Chapter 2 Related Works

To answer the research questions, this project requires a method to assess the historical condition of rangeland vegetation during rest period events. To place the answers into context, a background understanding of the Great Basin fire regime is needed. The first part of this chapter discusses literature related to the remotely sensed vegetation indices, particularly as they related to semi-arid shrub and grasslands. The remaining parts of this chapter review literature on rangeland fire regimes, invasive plant species, and the human factor in wildfires.

2.1. Measuring Vegetation Remotely

The case study selection method used in this project is described in detail in the next chapter. Suffice to say, the method in its simplest form involved finding intersecting fire perimeters and then using attribute and areal data to find the fires which met the spatial and temporal definitions of a rest period fire. The second part of this project dealt with accessing vegetation growth between the initial and secondary fires. Developing the procedure for this assessment required the following literature review.

2.1.1. Vegetation Indices as Estimators of Biomass and Regrowth

Box et al. (1989) took note of several contemporary studies which had used the NDVI product based NOAA's AVHRR sensor as a proxy for accessing a variety of biological properties of vegetation. The authors devised a study which would compare AVHRR NDVI values to field measurements of properties such as biomass and net productivity. They found that while NDVI could be useful as proxy to measure net productivity and evapotranspiration, it was an inconsistent tool for assessing plant biomass.

Santin-Janin et al. (2009) also took a critical view of their contemporaries. The authors were concerned that other studies were using NDVI as a proxy for biomass without accounting for the tendency for NDVI to become saturated when observing areas with high biomass. The oversaturation is a consequence of using two-dimensional data to measure a three-dimensional property such as biomass. The authors devised a non-linear model to fit field measurements of vegetation on the Kerguelen Islands in the Indian Ocean to NDVI observations from AVHRR. Of note was this paper's use of a vegetation index time series as a visualization and analysis tool.

The analysis and visualization of changing vegetation can also be a problem for vegetation indices. One typical method to measure vegetation change is to find the difference between a pre-event image and a post-event image. The resulting dataset is called the "delta" or "differenced" version of the vegetation index. One potential pitfall of this method is that the original data (the pre-event and post-event data) are not retained with the results of the subtraction operation (the differenced data). This can be important when trying to evaluate burn severity, as noted in Miller and Thode (2007). In this paper, the authors were specifically concerned with the Normalized Burn Ratio (NBR) rather than NDVI. However, the observations they had regarding the delta NBR (dNBR) can also apply to delta NDVI and other differenced calculations. They noted that a smaller fire can be more devastating to a lightly-vegetated area than it would be to a densely-vegetated area. The dNBR can describe the intensity of the fire, but the pre- and post-fire are not retained. With only the delta indices, it is not possible to accurately describe the conditions at the site. One can only describe the absolute magnitude of the change. Taking inspiration from Santin-Janin et al. (2009) and heeding the warnings of Miller and Thode (2007), this project created a vegetation times series as an analysis and visualization tool.

Another consideration when using vegetation indices like NDVI is that they are sensitive to photosynthetically-active green vegetation but not to photosynthetically-inactive dry vegetation. This is important as dry vegetation is a significant factor in fire frequency and intensity (Nagler et al. 2000, Guerschman et al. 2009). Nagler et al. (2000) developed one potential solution to this problem through the Cellulose Absorption Index (CAI). The authors based their work off earlier studies which noted that cellulose and lignin absorb radiation at wavelengths of 2.1 μm. The authors took direct reflectance measurements of plant litter and soil, both when wet and dry, and found that soils did not absorb radiation at 2.1 μm. The CAI has high values when 2.1 μm reflectance is lower when compared to reflectance at 2.0 μm and 2.2 μm, indicating that cellulose may be present. In material without significant cellulose, the reflectance of the three wavelength is roughly the same, yielding a low CAI value.

Guerschman et al. (2009) developed a framework for estimating the relative surface cover of green vegetation, dry vegetation, and bare soil by comparing NDVI and CAI values. Study sites in the Australian savannah were measured for the relative surface cover and plants and soils were measured for reflectance values. Data for calculating CAI for the study site were requested from the Hyperion sensor aboard the USGS's EO-1 satellite. NDVI values were derived from MODIS data. The framework used NDVI to distinguish green vegetation from the other two surface classes. CAI was then used to distinguish dry vegetation from bare soils. Areas covered in bare soil would have low values in both indices, while dry vegetation would have high CAI but low NDVI. The relationship between CAI and NDVI thus depends on the relative surface cover of the three categories.

While the NDVI-CAI framework could be useful in this project, the components for calculating CAI were not available. The EO-1 sensors were not continuously collecting data like the LANDSAT and MODIS sensors. Instead, EO-1 data had to be requested by the users and EO-1 sensor data are thus only available for locations and times that were requested. Additionally, the sensors aboard LANDSAT and MODIS are unable to distinguish between the three wavebands used to calculate CAI, due to the sensors grouping the three wavebands within the larger shortwave infrared (SWIR) band.

2.1.2. Scaled NDVI

Realizing the potential weaknesses of common vegetation indices like NDVI and NBR, Baugh and Groeneveld (2006) sought to quantitatively analyze the relative performances of 14 vegetation indices for performance in low vegetation environments. The study site they chose was the San Luis Valley in New Mexico and they were specifically looking at how well these indices estimated the known vegetation response to over-winter precipitation in the region. The San Luis Valley, much like the Great Basin, is an arid and semi-arid habitat dominated by various grass and shrub species.

The authors then acquired 14 mid-summer LANDSAT TM scenes spanning from 1986 to 2002. The scenes were processed into imagery for the vegetation indices being tested and compared to the historical precipitation records. The authors chose sampling sites from areas that were known to have stable groundwater levels and were unaffected by fire events, thus precipitation would be the primary influence on the vegetation response.

The index with the best fit to the precipitation data was Scaled NDVI (NDVI*), which is the result of taking the raw NDVI values less the NDVI value of bare soil and then dividing the difference by the range between a saturated vegetation NDVI value and the bare soil value. Thus NDVI* is proportional to the saturated value with respect to the bare soil value. In their testing, NDVI* yielded an r^2 value of 0.7749 when a linear model was created to relate antecedent precipitation to the value of the index. By comparison, NDVI only yielded an r^2 of 0.3686. NDVI* differs from NDVI in that the NDVI pixels values are rescaled so that a bare soil NDVI value ($NDVI_0$) is set equal to 0 and an NDVI value for a cell saturated with green vegetation ($NDVI_S$) is set equal to 1. Baugh and Groeneveld (2006) also used center-pivot farming sites to calculate $NDVI_S$, as they were easily identifiable in LANDSAT imagery and were likely to have the highest green vegetation densities in the region. Because center-pivot agriculture is also present in northern Nevada, this method was also used for this project.

Scaled NDVI was selected as the vegetation index for this project not only because of the favorable results it had in the Baugh and Groeneveld (2006) paper, but because it also linked the index values to tangible environmental conditions (bare soil and saturated vegetation). Other studies (Carlson et al. 1994, Carlson and Ripley 1997, Scanlon et al. 2002) have shown a relation between Scaled NDVI and fractional green vegetation cover. This supports the use of Scaled NDVI as an estimator of vegetation regrowth when values are compared over time.

One concern noted by Montandon and Small (2008) is that Scaled NDVI is sensitive to changes in the bare soil NDVI value. Within the rescaling process, $NDVI_0$ is used both remove the bare soil component from cell NDVI values and to determine the rescaling factor by removing the bare soil component from the saturated NDVI value. In dry grasslands and shrublands, such as the Great Basin, a lower bare soil value can give the impression of significantly higher green vegetation coverage. A higher bare soil value results in the opposite impression that the area has much less green vegetation. Consequently, if the bare soil NDVI cannot be directly measured, the method for determining $NDVI_0$ must be logical and consistent.

2.2. The Great Basin Fire Regime

At the core of the ranchers' claim is the concept of areas affected by multiple fire events. The pattern and frequency of fire events in a region are that region's fire regime. Information about the current, historical, and prehistorical fire regimes in the Great Basin can be used to determine if the patterns described by the ranchers are typical or divergent with the greater regional fire regime.

The ranchers' claim is partially supported by Westerling et al. (2003), a report on fire patterns in the western United States. The authors compared the spatial and temporal fire history of the region to the Palmer Drought Severity Index (PDSI), which is based on temperature and precipitation data. Fire history data were derived from over 410,000 reports from multiple government land agencies, included the BLM. The data covered approximately 21 years, though the authors noted that earlier but less reliable data were available. They found that in the Great Basin and Mojave Desert greater fire occurrence and larger fires were correlated with anomalously wet conditions during the previous year's Spring and Summer. Their explanation for this pattern is that wetter years can lead to greater vegetation growth and increased fuel load. The vegetation dries out during the following year when normal conditions return and provides fuel for more and larger fires.

This is further supported by Mensing et al. (2006). In this study, pollen and charcoal sediments were recovered from dry lake bed cores from central Nevada. Lakebed core reconstructions work on the sample principles are ice core reconstructions. Aerosolized particulates, such as dirt, pollen, and charcoal, land on the water's surface and settle down to the bed. Over time, newer sediments become layered on top of older sediments. The age of the core samples gets older as depth increases. Fire events can be inferred from peaks in the relative accumulation of charcoal particulates. One of the observed charcoal peaks was correlated with a 1986 fire. The pollen can be divided into plant species favoring wetter climates and plant species favoring drier climates. Changes to the relative abundance of the two pollen groups can indicate changes to the climate in the area. For this paper, the authors calibrated the upper core data against recent fire and climate records from other sources and then reconstructed the fire and climate histories for the area. They found that fire events in sagebrush-dominated environments were more frequent in wetter climates, which supports the ranchers' view that increased fuel load lead to more fires. The authors also noted that their findings could not directly establish reburn rates, but the findings did support other models which point to multi-decadal fire intervals before European American settlement in the region.

The multi-decadal reburn rates of the past and the sub-decadal rates of more recent times suggest that European American settlement changed the fire regime significantly. A 1990 report by Stephen G. Whisenant summarized previous investigations into this topic and discussed the results of his own study. Whisenant identified several sites in the Snake River Plain of southern Idaho and compared the fire frequency and vegetation compositions at those sites. Much like the Great Basin, the Snake River Plain has a mix of shrublands and grasslands as the main habitat features. Whisenant found that sites with greater species diversity were dominated by sagebrush varieties and had reburn rates comparable to the pre-settlement rates. Sites with more frequent fires were dominated by invasive annual grass species, most notably *Bromus tectorum*, known locally as "cheatgrass". Whisenant found a positive correlation between cheatgrass abundance at a site and the frequency of fires at that site. He concluded that the introduction of cheatgrass when European Americans began settling the region has been the most significant factor in the changing fire regime. Whisenant's report was later supported by Balch et al. (2013) which conducted a similar analysis over an area including the Great Basin, the Snake River Plain, and Eastern Oregon. The authors of this study concluded that cheatgrass dominated regions had more frequent fires and larger fires than regions dominated by other vegetation types.

The presence of cheatgrass throughout the semi-arid shrublands and grasslands of the American West is one of the major concerns for wildfire management. The effect cheatgrass has on regional ecosystems and fire regimes is one of the reasons why the details of fire recovery policy matter.

2.3. *Bromus tectorum* (Cheatgrass)

D'Antonio and Vitousek (1992) provides a general overview of the effects of invasive grass species on the environments they are introduced to. The authors are especially concerned with the ease with which grass species can alter soil nutrient cycles, regional climates, and fire regimes. Invasive species are noteworthy because they can out-compete native plant species, leading to the noted environmental changes. The invasive grasses may have different moisture and nutrient requirements, which eventually results in a change in soil chemistry as the invasive species takes over the area. Different root structures can affect the physical structure of the soil through increased or decreased erosion. The chemical and biological structure of the invasive species may result in a different response to fire events, when compared to native species.

In the case that an invasive species is better able to survive fire events, the invader may expand further while the native vegetation is recovering. If that same invader has a chemical or physical structure which increases the fuel load in the area, it can also cause or contribute to fires which reduce the native vegetation.

A historical and environmental overview of cheatgrass can be found in an article by Knapp (1996). According to the author, cheatgrass was introduced to the Great Basin near the end of the 19th Century. The lack of other dominant annuals allowed cheatgrass to establish itself in the region. Selective grazing of native vegetation acted as a selective pressure favoring the spread of cheatgrass. Perhaps the most important factor is how cheatgrass altered the fire regime in the region.

As an annual plant, cheatgrass dies off after producing seeds. The dead cheatgrass vegetation dries out and contributes to the area's dry fuel load. Ignition events in cheatgrass areas use that fuel load to spread further and do more damage to native perennials. The cheatgrass seeds are more likely to survive these fires and germinate during the winter, well before any native perennials can recolonize the burned areas. The result of this is a positive feedback loop where the presence of cheatgrass increases the likelihood of fire events and the fires do more damage to biota that competes with cheatgrass for space and resources. Thus, the colonization by cheatgrass of a burned area could be a significant contributing factor to the frequency and/or severity of subsequent fires.

2.4. The Role of Humans and Livestock

The introduction of cheatgrass into the Great Basin was a direct but unintended result of the introduction of European Americans and their farm animals. The influence of humans and livestock on the fire regime of the region requires some discussion.

2.4.1. Human-caused Fires

The semi-arid climate of the Great Basin is a consequence of orographic and continental rain shadows limiting the amount of precipitation that enters the region. Additionally, the bulk of the precipitation occurs during the winter, with the summer months being relatively dry. One consequence of this climate pattern is that there are far fewer lightning strikes in the Great Basin when compared to more humid regions in the United States. Given that lightning strikes are the source of most naturally occurring fire ignitions, this suggests that human activity is a significant factor in fire ignitions in the region. The various fire monitoring agencies that operate within the Great Basin will often identify fires as “human-caused” when the ignitions cannot be linked to lightning events.

One study, Martínez et al. (2009) compared a 13-year fire history in Spain to multiple factors thought to be linked to human-caused ignitions. The comparison used GIS to determine the magnitude of the factors throughout the study area. A binary model based on the ignitions in the fire history was used to determine whether or not a location had an ignition. A linear-regression model was then applied to evaluate the relative influence of each factor on causing or not causing an ignition. The authors found the most influential factors were related to mechanized agriculture and increase incursion of urban space into wilderness areas.

This is significant because the Great Basin has some similar features. Center-pivot agriculture and other forms of farming are prevalent in the region. Mining, which involves extensive machinery, landscape disturbance, changes to the water table, and motorized transportation, is common activity in northern Nevada. Many of the wilderness area, including the grazing allotments, are accessible by automobiles and can be used for recreational activities such as off-roading, camping, and hunting. While fuel load and fuel types are major components to wildfires, they often require human activity, whether deliberate or accidental, to get started.

2.4.2. Grazing and Fire Recovery

The main rationale for excluding livestock from burned areas is the assumption that grazing will further stress and damage surviving plants and seeds. Two studies, Davies et al. (2009) and Diamond et al. (2009), however support the idea that limited and target grazing can reduce fire danger and impede cheatgrass invasion. Both studies created plots of land to which different grazing treatments could be applied. The Davies et al. study compared grazed and historically ungrazed lands for their response to fire events. They concluded that the grazed areas had greater volumes of plant litter removed, leading to less severe fires and more resistance to cheatgrass invasion. The Diamond et al. study was similar in construction but focused more on targeted grazing of cheatgrass during the Spring as method to reduce cheatgrass biomass. After cheatgrass dies off during the early summer, the dried litter becomes less palatable to livestock and thus reducing their willingness to eat it. Targeted Spring grazing resulted in livestock removing 80 to 90% of the cheatgrass biomass. The reduced cheatgrass and litter volumes led to less severe fires in subsequent years. While neither study directly tested post-fire grazing, they do present an opportunity for targeted grazing to be a potential fire recovery tool.

2.5. Review Summary

Previous research suggests that directly assessing biomass and fuel load using only satellite-based vegetation indices would be problematic. Scaled NDVI was identified as a way to estimate vegetation cover as a proxy for vegetation change and recovery. The literature also showed that the sub-decadal fire frequencies that are attested to in the ranchers' claim are a recent phenomenon, caused primarily by the introduction of cheatgrass by European-American settlers during the 19th Century. Humans also increase fire frequency through ignitions caused by agricultural activities, machine operation, and increased access to wilderness areas. Finally, there is literature citing the possibility that targeted or seasonal cattle grazing could help reduce fuel loads and fire frequency.

Chapter 3 Data and Methodology

This chapter describes the data and the methods used in this project. The first section covers the data sources and gives a brief description of how the data were used. The second section describes the methods used and any alternative methods that were considered.

3.1. Data description

Spatial data for this project are all available for free from United States government agency websites. Once downloaded, spatial data were reprojected to UTM 11N (using the NAD83 datum) if necessary.

3.1.1. US County Boundaries

The US County Boundaries are polygon features taken from the 2017 US Census TIGER/Line "Counties (and equivalent)" shapefile product. This dataset is available from the US Census website. The metadata for this dataset did not specify a spatial accuracy as the data are created and updated from a variety of sources, including local updates from Census Bureau staff, older datasets, and other maps. The metadata for the TIGER/Line products state that the product is not appropriate for high-precision projects, such as property transfers and engineering projects. However, it should be noted that the TIGER/Line products are actively maintained and go back at least a decade. As this project only needed polygons for study area selection, the lack of "high-precision" accuracy was not a significant concern. The polygons for Humboldt and Elko Counties in Nevada were used to select the grazing allotments that make up the study area.

3.1.2. BLM Grazing Allotments

The grazing allotments are polygon features created by the BLM which describe the boundaries and attributes of BLM managed grazing allotments in Nevada. This dataset was recorded through GPS records of the boundaries or vertices and should have a positional accuracy of 12 m according to Michael Schade of the Nevada BLM's Geographic Sciences Branch (email message to author, May 23, 2018). The general significance of the allotments to this project was discussed in the Study Area section of Chapter 1. Allotment data were used to construct fire histories and to select or extract data from other features.

3.1.3. BLM Nevada Wildfire Fire Perimeters

The wildfire fire perimeters are polygon features created by the BLM to depict the boundaries and attributes of wildfire events. Between 2000 and 2016, the BLM recorded 594 Fire perimeters in the project's study area (Figure 3). The recorded burned areas are between 10 and 10,000 acres in size. A contact at Nevada BLM stated that more recent fires perimeters are recorded with GPS at 12 m accuracy (Stephen Levitt, email message to author, May 16, 2018). The older fire perimeters were derived from previous maps and orthophotography of the fires and may be less accurate. The dataset is actively maintained by the BLM and corrections can be made, though many updates may be for recent unrecorded fires. Other fire records (which are described later) indicated that there may be many fires smaller than 10 acres. The BLM fire perimeter data however do not record these fires. Fire perimeter data were used to construct fire histories, to identify rest period candidates, and to create zones for zonal statistics.

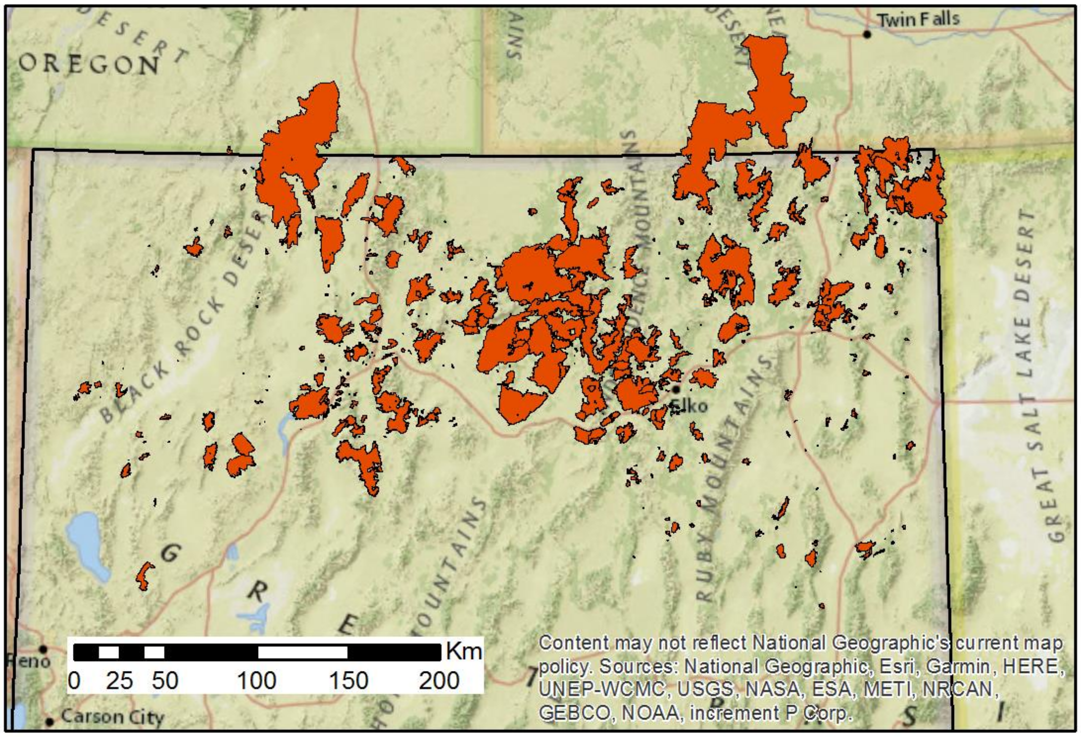

Figure 3. Recorded Fire Perimeters in Study Area, 2000-2016.

3.1.4. LANDSAT 5 TM Raster Images

As will be shown later in this document, the fires selected for the case study all occurred between 2001 and 2008 and were confined to the area north-northwest of Battle Mountain, NV. Specifically, the fires were all within two World Reference System 2 (WRS2) path/row scenes: path 41 and rows 31 and 32 (Figure 4). The LANDSAT 5 remote sensing platform was in operation from March of 1984 to June of 2013. The primary sensor used on LANDSAT 5 was the Thematic Mapper (TM), which took 185 km wide swathes in 7 spectral bands. Except for Band 6, the TM bands had 30 m by 30 m pixel resolution. The satellite could image the entire world in 16 days.

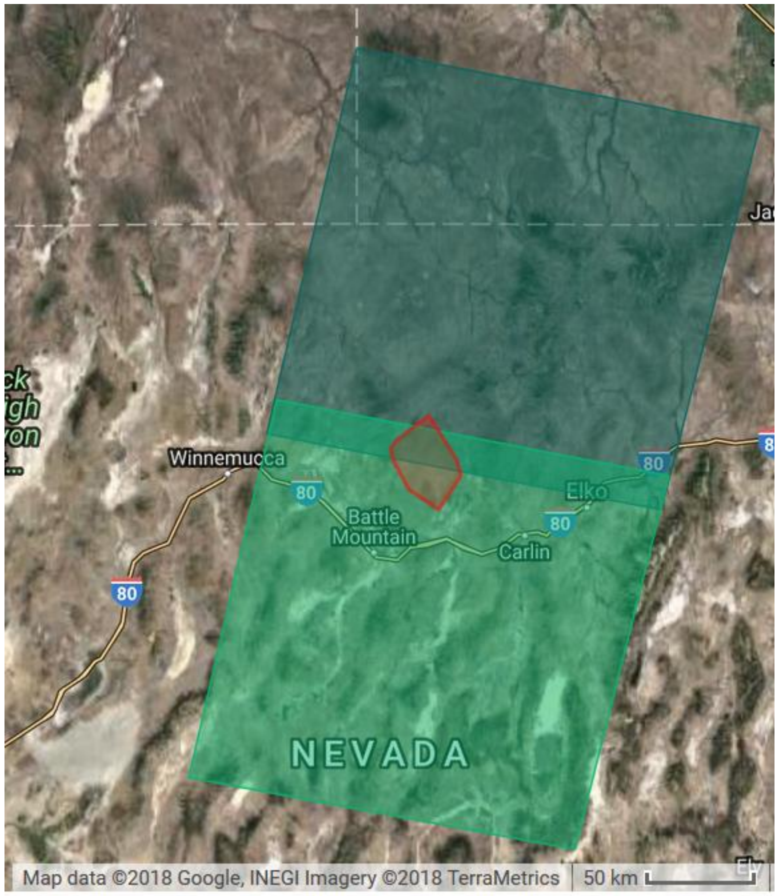

Figure 4. Footprint of LANDSAT scenes (green) from Earth Explorer. The red polygon is based on the Sheep Fire perimeter and is used to spatially select scenes.

The LANDSAT imagery is available from the United States Geological Survey's Earth Explorer website. The website makes this data available as path/row scenes, which are compressed folders containing band imagery as well as any processing quality assurance layers. The imagery is available as "Level 2" surface reflectance data, where the top of the atmosphere images are processed to surface reflectance values. This is a necessary step as the intervening atmosphere can distort the reflected surface radiation. The LANDSAT 5 data for path 41, rows 31 and 32 are projected as UTM Zone 11N, however it uses the WGS84 datum instead of the NAD83 datum used in the vector data. Using this imagery thus requires either reprojecting the raster images to use NAD83 or reprojecting the polygons to use WGS84. The exact processing method is described in the methods section of this chapter.

3.1.5. National Land Cover Database

The National Land Cover Database (NLCD) is a dataset created by the Multi-Resolution Land Characteristics (MRLC) consortium, a collection of federal agencies and offices which collaborate to provide land cover data for the United States. The NLCD dataset was generated by applying a decision tree regression model to paired LANDSAT observations. Paired scenes are used to adjust for season variations in reflectance. The NLCD has a cellular resolution of 30 meters because it is based on LANDSAT 30 m imagery. The NLCD using the 2011 methodology is currently available for the years of 2001, 2006, and 2011. Homer et al. (2015) describes the process of creating the NLCD in detail.

Of interest to this project are the land cover classes for Shrublands and Grasslands. The NLCD assigned a value of 52 to shrubland pixels, which are defined as areas where shrub canopies cover at least 20% of the surface. Species typical of shrublands in the Great Basin region include woody shrubs like big sagebrush (*Artemisia tridentata*) and shadscale (*Atriplex confertifolia*). The other 80% of the surface cover could be various grasses or bare soil.

Grasslands are assigned a value of 71 and defined as areas where grasses and other herbaceous vegetation cover at least 80% of surface. Species in Great Basin grasslands could be native perennial grasses or invasive *Bromus* annual grasses like cheatgrass. The NLCD classification system does not distinguish between invasive and native grasses. Nor does it distinguish between annual or perennial grasses.

Shrublands and grasslands are the dominant land cover classes and vegetation groups within the grazing allotments. The two land cover classes also have different responses to precipitation and fire, especially in grasslands dominated by cheatgrass. Literature described in Chapter 2 also notes that grasslands and shrublands have different NDVI signatures throughout the year. In this study area, the NDVI observations showed peaks during early spring and lower values during the summer and early autumn.

The NLCD data were used to gain a general understanding of the vegetation types present in the study area and to select secondary fire control zones that would have approximately the same ratio of shrubland to grassland.

3.1.6. PRISM Precipitation Data

Historical precipitation data for this project were acquired from the PRISM Climate Group at Oregon State University. The PRISM (Parameter-elevation Regressions on Independent Slopes Model) monthly precipitation products are raster images which record the total precipitation for each month in millimeters at a cellular resolution of 4x4 km. This data used observations from weather stations and elevation data to generate estimates for total precipitation. Positional accuracy of the data is based on the DEM images used and is stated to have a circular error of 130 m with 90% probability. The PRISM model is further described in Daly et al. (2008).

Monthly precipitation data were used to generate charts showing four-month precipitation totals for each zone. The months were grouped based on the seasonality of fire events, such as June through September being the peak fire season. Westerling et al. (2003) and other sources found that reduced drought conditions often led to accelerated vegetation growth and increased fire activity. This analysis was used to measure the influence of precipitation on the fire events.

3.2. Methods

This section is divided into parts describing how the methodology of this project developed. The first section deals with the first research question.

3.2.1. Secondary Fire Identification

The desired outcome of the first research question is to create a list of fires within the study area which are linked spatially and temporally with a previous fire event. The specific relationship being investigated is fires which ignited within a grazing closure during the closure's rest period.

3.2.1.1. Original methodology based on closure and ignition data

The original methodology devised to generate the list of secondary fires would have used the Select by Location tool (or a similar tool) to identify the ignition points within the closure perimeters. Attribute data would then be used to keep only the ignition points where the ignition occurred during the rest period. The resulting table of ignition points would be the list of secondary fires answering the first question.

Thus, an ideal situation would be to have the closure perimeters and rest period dates for post-fire grazing bans on BLM allotments. Such data would provide a complete spatial and temporal record of the BLM policies in action. However, Paul Peterson, the BLM Nevada State Fire Management Officer, clarified that closure area and rest period data are not available (Paul Peterson, Oct. 11, 2017, e-mail message to author). Without this data, an alternative methodology would need to be developed and the answer provided for the first question would be less exact.

3.2.1.2. Alternative methodology using fire perimeters and ignition points

Without the closure data, there were two components that needed to be approximated: the area closed to grazing and the duration of the rest period. Fire perimeters provided by the BLM would be the best approximate of the grazing closure perimeters. Because closures and fire perimeters are not perfectly aligned, there is some uncertainty of what later ignitions are closure ignitions.

The methodology chosen to handle this approximation was to create a Near Table comparing ignition data to fire perimeters. The Near Table would pair each fire perimeter and ignition point within a search radius and then list the distance in map units between them. The assumption with this methodology is that the closer the points, the greater the likelihood that the ignition occurred within a grazing closure.

The duration, which would have been specific to each closure, was replaced by a search window. The lower boundary of the search window was set to the spring of the year after the initial fire. This was based on logically extending the ranchers' argument. Fires which occurred during the same year are not likely to have any vegetation regrowth between them, thus the secondary fire in such pairs were not affected by BLM policy implemented on the initial fire. Same year fires could thus be removed from the list.

The upper bound for the search window was set to three years (1095 days). This value was derived from the BLM policy handbook (BLM 2007). If post-fire recovery goals have not been met after three years, BLM policy relinquishes authority over fire recovery efforts to local or regional BLM offices. The local offices can then choose to continue, cease, or modify the grazing closure as they deem fit. Once recovery authority has been turned over to local offices, there is greater uncertainty regarding the rest period duration.

The lack of closure data has introduced spatial and temporal uncertainty into the answers for the research questions. While reasonable approximations have been selected, the answer derived from this is not a perfect answer. Far worse for the alternative methodology was the poor quality of the ignition points.

The National Interagency Fire Center provides a Wildland Fire Management Information Fire Reporting Annual Dataset. This dataset is a comma delineated file containing date and point of origin/ignition data for wildland fires. Many of the data fields in this dataset match attributes in the BLM fire perimeter data, which would have allowed pairing between fire perimeters and ignition points. Initial testing of the dataset, showed that 475 fires had records in both sets. The ignition point data would have allowed this project to identify the origins of fires and related fire events.

The fields storing the coordinates from these records were converted into point features following the instructions provided by the source website. Ignition point data were stored as NAD 83 Latitude and Longitude coordinates. It was necessary to convert the CSV file into Excel format, as converting directly to an XY Event Layer in ArcGIS caused attribute data types to not process correctly and attribute values to be lost.

Further testing revealed that there were ignition points recorded for fires that were outside the recorded fire perimeters. The dataset was redownloaded and reprocessed, then a more thorough comparison of the two datasets was conducted. The comparison utilized the Near Table tool to measure distances between the ignition points and fire perimeters. The resulting table was filtered so only rows for matched fire identifiers were kept. Of the 475 pairs, only 200 had an ignition point within the paired fire perimeter. Of the 275 fires showing external ignition points, 239 were within 2 km of the fire perimeter. Four of the perimeters were paired with ignition points that were 10 km or more outside of the perimeter. This suggested that the accuracies of the 200 ignition points within the fire perimeters were also in question.

Visual comparison of the fire perimeter polygons with differenced Normalized Burn Ratio (dNBR) images taken from LANDSAT sensors confirmed that the datasets identified similar regions as burned. For this reason, this project discarded the Fire Reporting Annual Dataset. A second alternative methodology was needed to account for the unknown ignition points of fires.

3.2.1.3. Final methodology using self-intersecting fire perimeters

The ideal method for identifying rest period fire candidates would be to compare ignition point locations to the closure areas of previous fires and the time of the ignition to the rest period of the previous fires. The results of such a search would yield every ignition event which occurred within the closure area and during the rest period of a previous fire. As previously discussed, these datasets were unavailable or unreliable which caused this project to go down a different direction. A general workflow diagram of this final methodology is shown in Figure 5.

The BLM fire perimeter data include the areas directly affected by a fire and the discovery and control dates for the fire events that are recorded. It should be noted that the smallest recorded fire in the study area between 2000 and 2016 was about 9.5 acres. Any smaller fires were not recorded by this dataset. The fire perimeters recorded are polygon vector data and can be intersected with other polygon data.

Self-intersecting the fire perimeter data yields an unusual dataset. Given a dataset where there is no overlapping topology within the spatial data, self-intersect does not produce any useful results. In data with internally overlapping topology, such as the fire perimeter data, multiple intersections are identified.

Pre-Processing:
1. Removed Grazing Allotments not intersecting Humboldt and Elko Counties to create a new feature: Study Area Allotments
2. Removed Fire Perimeters **not** intersecting Study Area Allotments
3. Removed Fires discovered before 2000 to create a new feature: Study Area Fires
4. Dissolved a copy of the Study Area Allotments to create a new feature: BLM Managed Area

Self-Intersect:
1. Used the Intersect tool listing the Study Area Fires feature twice to perform self-intersect
2. Extracted intersections where the secondary fire was discovered 3 years or fewer after the initial fire control date
3. Dissolved remaining intersections using non-spatial attributes as dissolve fields
4. Intersected the dissolved intersections with BLM Managed Area feature to create a new feature: Three Year Overlaps

Select Fires for Case Studies:
1. Divided the area of the Three Year Overlaps by the area of their respective secondary fires
2. Selected fires for the case studies based on which had greater overlaps to secondary fire area ratios
3. Exported the selected initial and secondary fires from Study Area Fires to create a new feature: Case Study Fires

Figure 5. Workflow for Secondary Fire Identification and Case Study Selection

A quick way to understand this is to imagine two overlapping circles “A” and “B” in a single dataset. When the dataset is self-intersected, it will create polygons for four overlapping regions: “A to A”, “A to B”, “B to A”, and “B to B”. This is because the Intersect tool will create new polygons where borders from any input layers intersect. The polygons for “A to B” and “B to A” are bound by the same line segments (the intersecting borders of “A” and “B”) and are thus congruent polygons. The main difference between the two is which set of attribute data are listed first. In the case of the fire perimeters, this enabled the project to identify the first set of attributes as the initial fire and the second set as the secondary fire.

A Date Difference field was added to the intersected perimeter dataset. The value of this field (D_{diff}) was difference between the control or ending date of the first fire (F_{cont}) and the discovery or starting date of the second fire (S_{disc}).

$$D_{diff} = S_{disc} - F_{cont} \tag{1}$$

The Date Difference field had values between 1 and 1095 days for pairs of fires that occurred within 3 years of each other. Date Difference values higher than 1095 would show fires more than three years apart. Date Difference values of 0 or lower would signify fires which occurred before the previous fire, a logical impossibility. The unwanted intersections generated by the self-intersecting process had Date Difference values of 0 or less, and were filtered out by keeping only the intersections where the Date Difference value was between 1 and 1095.

The Intersect tool can split a single intersection into multiple polygons if the intersection is crossed by the perimeter of a temporally unrelated fire. The Dissolve tool was used to recombine split intersections. When the Dissolve tool was used for this purpose it was necessary to select all non-spatial and non-object ID attribute fields as dissolve fields to retain the data in those fields after the dissolve. The perimeter length, area, and object ID fields were automatically recalculated by the Dissolve operation.

The resulting polygons identify areas which were burned by more than one fire event within three years. This dataset was then intersected with the grazing allotment polygons to create a dataset of three-year repeat fires that were on BLM grazing allotments. The intersection areas from this dataset were compared to the total area of the secondary fires. A higher ratio indicated that a greater area of the secondary fire was within the perimeter of the initial fire and was more likely to have its ignition point within the initial fire’s perimeter. Without exact ignition point data, this ratio became a proxy for estimating if the secondary fire ignited within the fire perimeter of the previous fire. A ratio of 1:1 would indicate that the entire secondary fire, including the ignition point, was within the perimeter of the previous fire.

One consequence of this search procedure is that secondary fires that are smaller than the initial fires are more likely to be identified as rest period fire candidates. While larger secondary fires could have ignited within the initial perimeters, it is a far less certain assertion to make. If only 5% of the secondary fire overlaps with the previous fire, that leaves another 95% of the secondary fire's area where it could have ignited.

This also does not imply that the ratio of intersection to total area is equal to the probability that the ignition occurred in the intersecting area. The probability of ignition events is not homogenous throughout the fire perimeter but is greater at locations with more lightning strikes or more human access. The relationship between ignition probability and intersection ratio is generally fuzzy except at the ends (the 1:1 ratio case). For the purposes of this project, the secondary fires with the greatest intersection ratios will be selected as case studies to test the ranchers' claim using vegetation index time series.

Implementing this methodology resulted in a list of 54 secondary fires that reburned areas within three years of the initial fire with at least one winter in between. Due to differences between the closure perimeters and fire perimeters, there is some uncertainty about this list regarding answering the first research question. Likewise, the overlapping area ratio from self-intersecting the fire perimeters is only a perfect approximation for ignition points when the ratio is 100%, which indicates the ignition had to be within the initial fire, or 0%, which indicates the ignition could not have possibly been within the initial fire. Four of the 54 secondary fires had ratios at or near 100%. The 54 secondary fires and the four fires selected for the vegetation index case study are described in greater detail in Chapter 4.

3.2.2. Evolution of Project Methodology Using LANDSAT5 TM Data

The second research question is a more difficult question to answer. If the ranchers' claim is correct, the fuel load, a combination of dead plant litter and living vegetation biomass, within the grazing closures should be higher than the fuel load in nearby areas open to grazing during the same period. The ideal way to measure this would be to monitor the amount of biomass, especially dry biomass, in areas closed to grazing and open to grazing. However, the historical nature of this project limited what data were available and adjustments to the methods and qualifications to the research question were necessary.

3.2.2.1. Original methodology using NDVI or NBR

The original design of this project involved the use of dNDVI and/or dNBR as estimators of biomass change. The basic steps would have been to compare annual vegetation index data starting with dates from just before the secondary fire and going back year-by-year to the time before the initial fire. As discussed in Chapter 2, Miller and Thode (2007) demonstrated that dNBR and other delta indices are only capable of showing how much change has occurred and these kinds of data obscure the initial and final index values. Box et al. (1989) showed that while NDVI was a good estimator of primary productivity, it was a poor estimator of biomass.

Based on Miller and Thode (2007) and Santin-Janin et al. (2009), futher methods were designed around creating time series showing mean values of a vegetation index for grazed and ungrazed regions. Due to Box et al. (2009), alternative vegetation indices were investigated.

3.2.2.2. Alternative methodology using CAI and NDVI

Guerschman et al. (2009) found that using the Cellulose Absorption Index (CAI) in conjunction with NDVI, one could estimate the relative surface cover between green vegetation, dry vegetation, and bare soil. The process for this would have been to calculate the two indices and determine the fractional cover in a cell based on the index values. A high NDVI value would indicate more green vegetation. Likewise, a high CAI value would indicate more dry vegetation. Low CAI and NDVI values would indicate more bare soil. This would have been a useful tool as NDVI is poor at distinguishing between bare soil and dry vegetation. A better estimate of dry vegetation in the grazed and ungrazed areas would have provided a better estimate of fuel load.

This method was set aside due to the lack of necessary historical data. As discussed in Chapter 2, the wavebands used to calculate CAI are unified into a single band within the MODIS and LANDSAT sensors. The combined waveband prevents the calculation of CAI and any further use of this method.

3.2.3. Selected Methodology for Scaled NDVI Time Series

Scaled NDVI was settled on as the time series vegetation index due to its relationship with fractional green vegetation cover. The assumption here is that changes to green vegetation cover over time can show regrowth or recolonization, senescence, and disturbance events. Without a direct way to measure historical biomass and fuel load, vegetation regrowth in an area may serve as a proxy for later biomass accumulation. Senescence likewise could provide an estimate of green vegetation turning into dry vegetation during the late spring, prior to later fires.

There are three main steps to generate the time series for each of the cases: image acquisition and preprocessing, vegetation index calculations, and the creation of zonal statistics tables and charts. The workflow for this process is diagrammed in Figure 6.

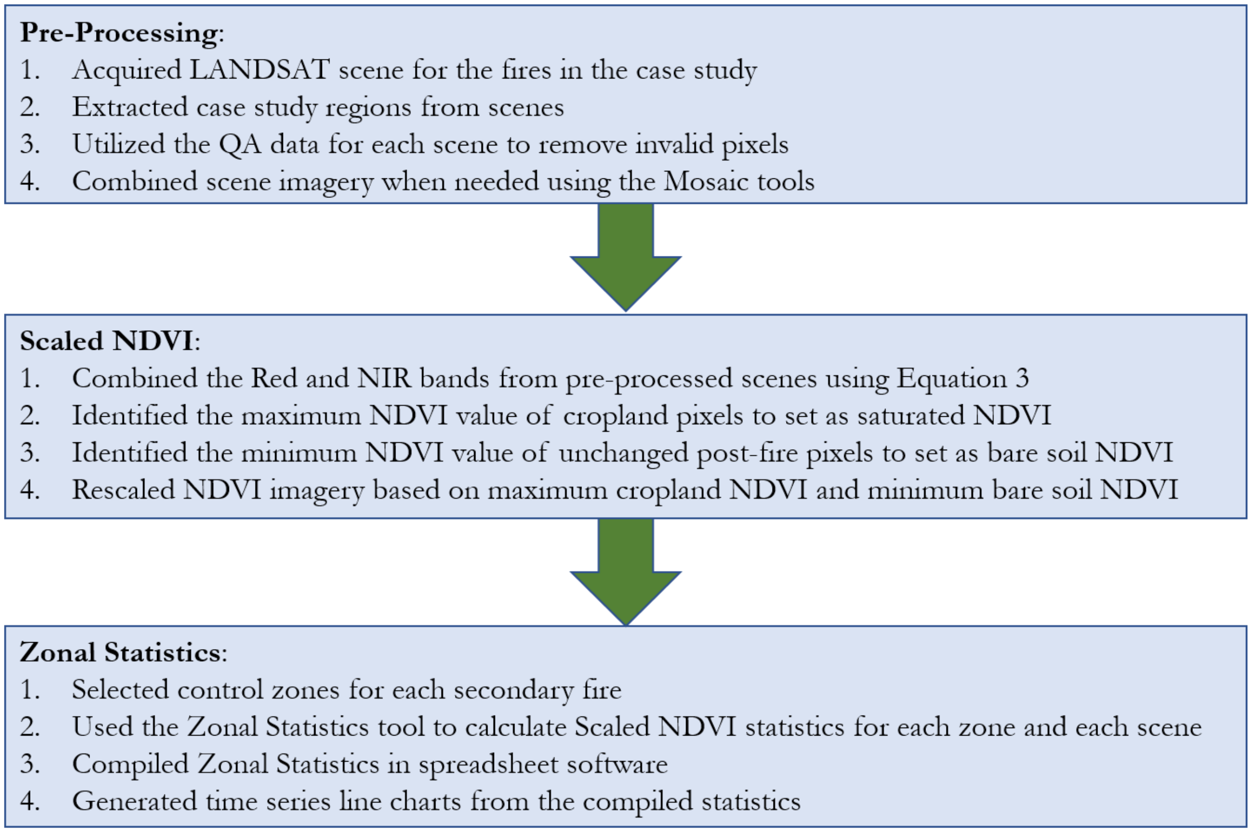

Figure 6. Workflow for Vegetation Index Processing

3.2.3.1. Remote Sensing Preprocessing

Once the candidate fires for the case studies were identified, LANDSAT surface reflectance data covering the spatial extent and timeframe of the initial and secondary fire pairs were acquired. This data are available as a Level 2 product from the USGS Earth Explorer website. The website allows users to upload simple (maximum 30 vertices) polygons as shapefiles. The uploaded polygons are used to select the spatial extent of the LANDSAT data and the time range was selected as the year of the initial fire to the year of the subsequent fire, inclusive. Images for November through February were not included due to snow cover, cloud cover, and almost complete absence of fire events during those months.

The file names of LANDSAT imagery provide specific information to the end user, but the names are long and can be tedious to work with. A bulk renaming utility was used to quickly rename the images to keep only path/row location, date of acquisition, and spectral band labels. The naming system was used with Model Builder in later steps to automate most of the procedures described. List Iterators in Model Builder were used to select scenes for processing and to label the output files.

Working with multiple, full-sized LANDSAT 5 images can be taxing on file storage and processing time, making it necessary to extract the relevant parts of the image before any further processing. The enveloping rectangles, once reprojected to UTM 11N WGS84, were used with the Extract by Mask tool to clip out the areas needed for processing and to discard the unnecessary regions.

LANDSAT surface reflectance products include Quality Assurance (QA) images with each scene. PIXEL_QA raster images assigns a value to each pixel based on the surface and atmospheric quality of the pixel. Pixels showing clouds, snow, water, and other undesirable features needed to be excluded. PIXEL_QA values of 66 and 130 identify pixels showing unobscured surface. The PIXEL_QA values are derived from a direct classification and from a cloud confidence calculation. In this case, the value of 66 represents “clear skies with low chance of clouds” and the value of 130 represents “clear skies with medium chance of clouds”. Any pixels with a high chance of clouds would not be classified as “clear skies”. Pixel values of 66 and 130 were remapped to a value of “1” and all other values were remapped to “No Data”. The resulting raster images had only valid pixels.

RADSAT_QA is a quality assurance image which tracks over-saturated pixels in the various spectral bands. Each pixel value in RADSAT_QA stores one bit of data for each spectral band. These bits of data function as true or false values to determine if the pixel is oversaturated. The bits are combined into a single byte value for the pixel. It was necessary to remove oversaturated pixels as they do not represent true values of surface reflectance. This process involved using raster arithmetic to extract the bit flags for Bands 3 and 4 from the rest of the QA image. Finding the modulus of the QA image over 32 would yield pixels values where Bands 5 through 7 (which have bit values of 32, 64, and 128) are ignored. The pixel values in this image will be greater than 8 if and only if Band 3 (bit value of 8) and/or Band 4 (bit value of 16) are oversaturated.

Equation 2 can be used to identify pixels with valid saturation. The "%" in this case represents the modulo operation which returns the remainder after division. The pixels with valid saturation (SAT_v) resulting from this were assigned values of "1" and invalid pixels were assigned to "No Data". As with PIXEL_QA, the resulting images had only valid pixels.

$$\text{If (RADSAT\_QA \% 32)} < 8 = \text{true, then } SAT_v = 1\text{. Else } SAT_v = \text{NoData} \quad (2)$$

The surface reflectance calculations can sometimes result in negative values in the spectral bands. Negative reflectance is not possible, so such values are invalid and must also be removed. This only required remapping negative surface reflectance values to "No Data". Raster multiplication with the two processed QA images worked like a Boolean AND operation. The resulting images had negative, oversaturated, and obscured data removed.

In cases where the fire perimeter spanned multiple LANDSAT scenes, it was necessary to create a mosaic image from the scenes after any invalid pixels were filtered out by the quality assurance process. The mosaic process was performed at this place in the process because any earlier mosaic may have incorporated invalid values. Performing the mosaic later (after the vegetation index was calculated) could have affected the index values on the borders of the scenes.

One potential consideration for mosaicking LANDSAT imagery is that a burn perimeter might cross multiple swaths. One consequence of using orbit-based imaging platforms is that adjacent swaths will not be imaged at the same time. LANDSAT 5 was no exception to this, having used a near-polar, sun-synchronous orbit to ensure as much daylight as possible for its images. In northern Nevada adjacent LANDSAT 5 swaths were taken either 7 or 9 days apart because of the offset of the orbit. A fire spanning multiple swaths would need images from at least a week apart to create the mosaic image. Fortunately, the cases investigated in this project were all from the same swath (WRS2 Path 41), which alleviated this concern.

3.2.3.2. Vegetation index calculations

In the LANDSAT 5 Thematic Mapper, spectral band 3 records reflected energy with wavelengths associated with red light (0.63-0.69 µm). Spectral band 4 records the reflected energy at wavelengths labeled as Near Infrared or NIR (0.76-0.90 µm). The Normalized Difference Vegetation Index (NDVI) provides an estimate of green vegetation productivity by comparing the difference in NIR and visible red reflectance to the sum of the two values. Chlorophyll activity in green plant matter absorbs red light and emits NIR radiation during the evapotranspiration processes. High NIR reflectance coupled with low red-light reflectance can thus be a signature of chlorophyll activity. Equation 3 is the basic algorithm for calculating NDVI from LANDSAT 5 TM NIR (B_4) and visible red (B_3) surface reflectance values. Figure 7 shows how Equation 3 can be implemented in ArcGIS Model Builder.

$$NDVI = (B_4 - B_3) / Float(B_4 + B_3) \tag{3}$$

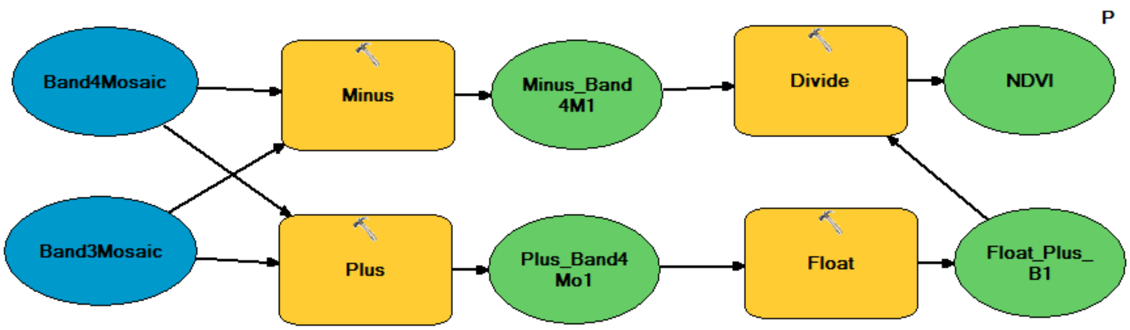

Figure 7. Model Builder Layout for NDVI Calculations.

The Float operation converted the integer format of the input values into floating point values. The integer data type was carried over from the LANDSAT surface reflectance source data and not relevant until this point in the process. Without the Float operation, the raster division operation in ArcGIS would detect integer-formatted inputs and yield an integer-formatted output. On an NDVI image, this would result in NDVI values being rounded to -1, 0, and 1. When the denominator of the Divide operation has a floating-point data type, the resulting image will also have a floating-point data type.

The NDVI raster images were reprojected to the NAD83 datum from the WGS84 datum of the LANDSAT 5 source data. The reprojection facilitated subsequent operations involving NAD83 datum datasets.

Equation 4 is used to calculated Scaled NDVI (NDVI*) from NDVI values. The calculation requires determining a *saturated NDVI* ($NDVI_S$) and a *bare soil NDVI* ($NDVI_0$). The saturated NDVI represents the maximum achievable NDVI value due to vegetation. The bare soil NDVI is the NDVI value for unvegetated areas.

$$NDVI^* = (NDVI - NDVI_0) / (NDVI_S - NDVI_0) \quad (4)$$

Agricultural areas were identified by visually searching for tell-tale signs of center-pivot agriculture (Figure 8) and using the cells classified as “Cropland” in the NLCD 06 data. Croplands are well-suited for estimating $NDVI_S$ because farmers will optimize the growth of crops for use and sale. Crops, when compared to wild vegetation, will have better irrigation and better soil due to the actions and choices of the farmers. Thus it can be expected for croplands to out-produce wild vegetation.

Figure 8. Example of Center-Pivot Irrigation Systems in Nevada

Determining $NDVI_0$ was not as straight-forward as determining $NDVI_S$. The idea of using the values from nearby mining sites was considered. However, it was determined that the mining sites were potentially too disturbed by human and industrial activity to represent the true bare soil value. The methods described in the literature were not available for this project, as they required either direct measurements from training sites or the use of unusual statistical analyses. The method chosen for this project looked at the pre- and post-fire NDVI values to find the least changed cells in the fire perimeters. The assumption was made that these cells represent areas unaffected by pre-fire vegetation and post-fire charcoal. The lowest value of the least disturbed cells was then selected as $NDVI_0$.

A more complicated method for calculating Scaled NDVI would involve recalculating saturated and bare soil values scene by scene. Each scene in the time series would have a specific and relevant Scaled NDVI formula which could better account for variation over time and seasonal variation. This method was not implemented in this project due to time constraints and is described here as an area of future research.

Scaled NDVI raster images had values ranging from 0 (bare soil) to 1 (saturated vegetation) or No Data. The Scaled NDVI data were used in the following steps to generate zonal statistics and time series graphs.

3.2.3.3. Zonal statistics

To see the effects of the initial fires, control plots were created for each case study. The control plots would have same size and shape as the secondary fire. A general workflow of this process is shown in Figure 9. Zones were created by using the ArcGIS Edit tools to create copies of the secondary fires and to move the copies to the control locations. One copy of the secondary fire was used as a *burned control*. The burned control was placed at a location that was within the fire perimeter of the initial fire, but was unaffected by the secondary fire. Another copy of the secondary fire was used as an *unburned control*. The unburned control was placed at a location near the secondary fire, but otherwise unaffected by any recorded fires up until and including the secondary fire.

It should be noted that while this method of zonal selection attempted to control for various attributes, it is not statistically strong enough to make definitive statements. A method utilizing random sampling points throughout larger regions would provide a more through and significant estimate of the Scaled NDVI values in the regions. Additional controls could be put into place so that the random points could have the correct ratio of land cover types. Since statistical conclusions were not the objective of this study given the nature of the research questions, the random sample method was not used here. It is, however, definitely a direction for future research.

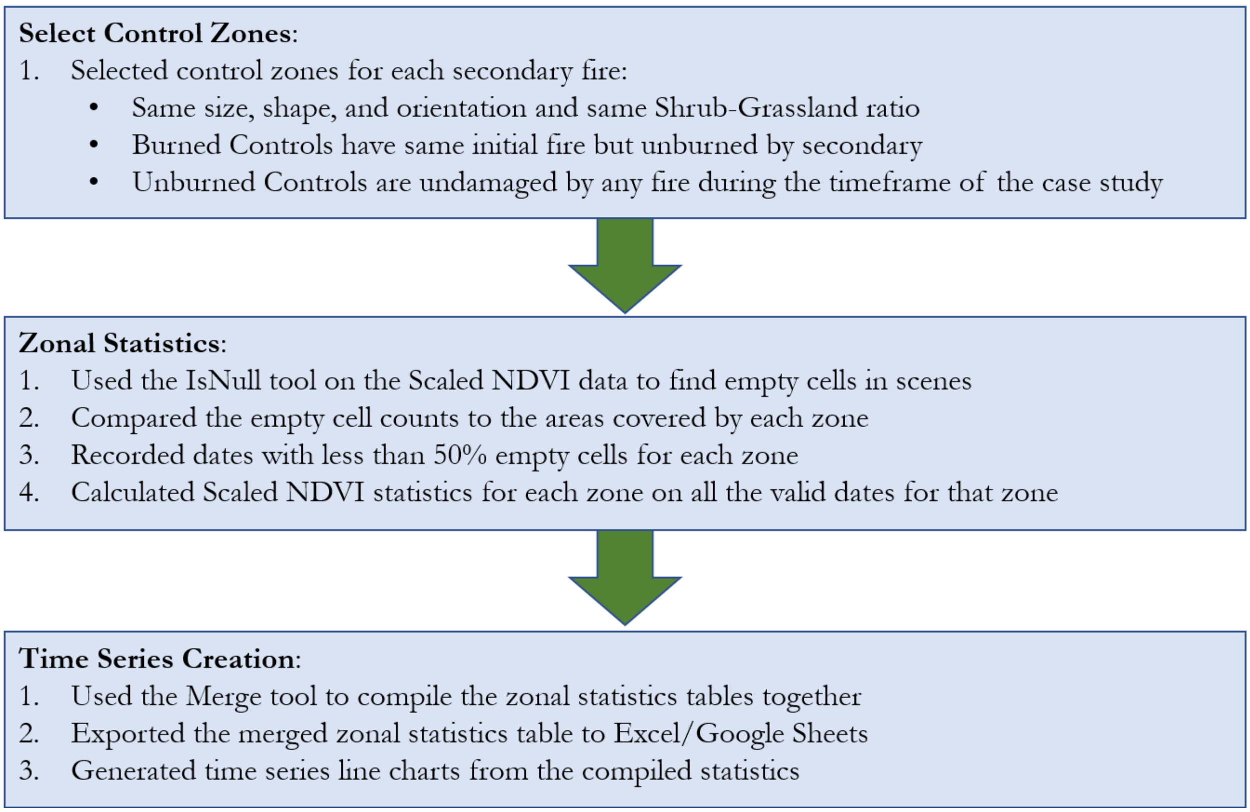

Figure 9. Workflow for Zonal Statistics and Time Series Creation

The control zones were also selected based on the ratio of shrubland to grassland. Vegetation based land cover data were used to attempt to control for the different responses and influences that different vegetation types can have with fire events. NLCD data from the closest year to the fire events were used to determine the ratio of shrub-dominated cover to grass-dominated cover. The burned and unburned control sites for each secondary fire were selected to have approximately the same ratio of cover types.

Based on the ranchers' claim, the secondary fire and the burned control zone would at first have less green vegetation and less biomass than the unburned control due to the initial fire. However, the areas burned by the initial fire would be protected from livestock grazing allowing for greater fuel accumulation over time than what would be seen in the unburned (and open for grazing) control zone.

Before calculating zonal statistics, it was necessary to filter out observations where too many of the pixels were invalidated either by the quality assurance process or by the rescaling of the NDVI values. For the purposes of this project, it was decided to filter out observations where less than half of the pixels for a zone were valid. To keep as many observations as possible, the fires and control zones were analyzed separately for valid cell counts. This avoided situations where valid data for two of the zones would have been thrown out due to missing data for the third zone.

Determining the valid cell percentage only required generating a new raster image for each observation where valid cells in the Scaled NDVI image were assigned a value of 1 and invalid cells were assigned a value of 0. In ArcGIS, the IsNull tool does the opposite of this, assigning null cells a value of 1 in the new image. Because the quality assurance and NDVI scaling processes assigned null values to invalid cells, the IsNull tool effectively assigned values of 1 to invalid cells. As shown in Equation 5, subtracting the IsNull result from a raster with a constant value of 1 resulted in a raster image where valid cells in the original image were assigned values of 1.

$$\text{IsValid} = 1 - \text{IsNull}(\text{NDVI}^*) \qquad (5)$$

Calculating zonal statistics using the valid cell images yielded the necessary calculations for valid cell percentage per zone. In the valid cell image, the only possible values are 1 for valid cells and 0 for invalid cells. The mean cell value for a given zone in the valid cell image is therefore equal to the valid cell count divided by the total cell count for the given zone. Any observation date where the zonal mean of the valid cell image was greater than 0.5 was listed as a valid observation for the given zone.

Once the list of valid observation dates for each zone was determined, zonal statistics for each zone on each of the valid observation dates was calculated. The Zonal Statistics as Table tool was used to generate a table output that could be exported and manipulated. The observation date and zone name were added as fields to the resulting tables. The new fields were used to uniquely identify rows once the zonal statistics tables were combined using the Merge tool. The merged table was exported as an Excel spreadsheet.

Charts showing the changes in mean Scaled NDVI for the secondary fires and their respective control zones over time were created in Excel from the exported tables. The time series charts were used to analyze the ranchers' claim that burned areas under grazing closures will have greater regrowth than unburned lands open to grazing. If the ranchers' claim is accurate, the fire perimeters and burned control zones should have higher Scaled NDVI values when compared to unburned control zones near the time of the secondary fire.

3.2.4. Precipitation Data

As described earlier, the PRISM precipitation data have a cell resolution of 4 km. It turned out that this cell size was larger than many of the secondary fires identified in the site selection process. The size difference prevented the Extract by Mask tool from working as intended. The cell resolution instead warranted the use of zonal centroids and the Sample tool.

The Feature to Point tool created the centroids for the secondary fire perimeters and the control zones. The Sample tool took the series of precipitation imagery and found the values of cells marked by the centroid features. The sampled values were then added to a table containing the list of zones and columns for each monthly precipitation estimate.

This table was exported to Excel and line charts were generated for each zone and fire perimeter. Precipitation estimates for winter months on a year-by-year basis were also calculated. The four-month precipitation totals were used to analyze the influence of precipitation on the Scaled NDVI in the zones.

3.2.5. Additional Procedures

The grazing allotment data were spatially joined with burn perimeter data within ArcGIS. As part of the spatial joining process, a new field was calculated containing the count of burn perimeters for each allotment. The data resulting from this operation have the same geometry and topology as the grazing allotment data and included the count of burn perimeters. This data were used to identify fire hot spots within the grazing allotments. Intersecting the allotment and burn perimeter data provided a list of fire events affecting each allotment. A similar analysis was performed using a grid with 10 x 10 km cells as the spatial base. The gridded fire count was created to control for the Modifiable Areal Unit Problem (MAUP). Grazing allotments, which have a variety shapes and sizes, are prone to MAUP concerns.

As discussed in Chapter 2, Martinez et al. (2009) studied various factors to determine which were more correlated with human-caused ignitions. They found that sites with highly partitioned and mechanized agriculture were more prone to human caused fires. Other factors were related to increased development near the sites, such as increased access to the wildlands by humans. Imagery of the study site was overlaid with the perimeters of grazing allotments that had the highest fire occurrence during the study's timeframe to provide a qualitative estimate of the influence of human factors.

Chapter 4 Results

This chapter reports the results of carrying out the selected project methodology. The first section goes over the results of the secondary fire search/case study selection process and provides a basic overview of the selected case study sites. The next section discusses the vegetation index time series for each of the cases. The preliminary methods considered in Chapter 3 were not carried out and are therefore not discussed.

4.1. Secondary Fire Search and Case Study Selection

Of the 594 fires investigated as part of this study, 58 fires had a fire perimeter which overlapped with another fire within the previous three years. Additionally, four of the 58 secondary fires occurred on the same year as the initial fires, with intervals ranging between seven and 38 days. The ranchers' claim is based on vegetation regrowth, thus same-year fires are not considered valid rest period fire candidates. These four were included in the initial results out of a concern that other fire pairs might have been affected by a same-year reburn. The four incidents fortunately did not affect the fires selected for the case studies. The 54 remaining secondary fires, which reburned areas within three years but not during the same year, are the best answers for the first research question given the available data.

Table 1 lists selected pairs of fires which had overlapping perimeters within three years. The top four unshaded rows are the fire pairs where 99% or more of the secondary fire was contained in the initial fire perimeter. These four secondary fires (Little One, Green Monster, Rock Creek, and Squawvalle) and the respective initial fires (Winters, Sheep, and Hot Lake) were selected for the case studies.

The blue-shaded rows are two fires pairs where more than half of the secondary fire was within the initial perimeter. While there is a chance that the secondary fires ignited within the respective initial perimeters, it is not a near certainty as in the case of the four pairs that were selected. The probability that an unknown ignition point was at a specific spot is not equally likely throughout the fire perimeter. Areas prone to lightning strikes or with more human activity (the primary sources of ignitions) are more likely to contain the point of ignition. As such, a 67% overlapping area does not mean a 67% chance that the ignition point was within the overlap. Nonetheless, these two pairs were noted as possible alternative cases if needed.

Table 1. Selected Three-Year Overlapping Fire Perimeters (16 out of 58 total). Column names starting with "I." indicate initial fire attributes and "S." indicate secondary fire attributes. Shaded regions are described in the text.

I. Fire Code	I. Fire Name	I. Contained	S. Fire Code	S. Fire Name	S. Discovered	Days Between	Overlapping Area
C1FR	Winters	8/3/2006	ED9N	Little One	7/30/2008	727	100.0000%
C1FR	Winters	8/3/2006	EK88	Green Monster	9/16/2008	775	100.0000%
C5W7	Sheep	9/10/2006	EF6Z	Rock Creek	8/10/2008	700	100.0000%
X305	Hot Lake	9/30/2001	A5LA	Squawvalle	6/23/2004	997	99.8051%
B5DR	Chance	9/1/2005	DXZ9	Second Chance	8/21/2007	719	68.2586%
GHQ5	Indian Creek	10/13/2011	JBQ0	Coyote Canyon	8/10/2014	1032	65.3291%
Z511	Ndfassis35	6/26/2000	J092	Ten Mile	6/16/2003	1085	42.1528%
B5GH	North Road	9/4/2005	DQ2K	Dump	7/15/2007	679	37.4123%
B0MG	Carlin	7/21/2005	DXC6	Party	8/18/2007	758	24.1151%
FM4L	Seven Troughs	7/26/2010	F9MF	Last Chance	8/6/2011	376	16.5174%
B8JV	S Trout	10/24/2005	DJ2N	Bailey	6/20/2007	604	15.4632%
A5LA	Squawvalle	6/24/2004	C5W7	Sheep	9/3/2006	801	0.2461%
B2HT	Mint	7/30/2005	C1FR	Winters	7/26/2006	361	0.1855%
B0H1	Wilson	7/21/2005	C1FR	Winters	7/26/2006	370	0.0085%
B0JT	Esmeralda	7/21/2005	C5W7	Sheep	9/3/2006	409	0.0019%
B0JT	Esmeralda	7/21/2005	C1FR	Winters	7/26/2006	370	0.0003%

The yellow-shaded rows after that are the five pairs where 10 to 50% of the secondary fire were within the initial perimeters. These pairs are included in the table to demonstrate how quickly the overlapping area percentage decreased in this dataset. Only 11 of the 58 Three-Year Overlaps had areas that were 10% or more of the secondary fire's area.

The red-shaded rows are five fire pairs that involve either the Winters Fire or the Sheep Fire, which are initial fires for three of the case study fires. If these five pairs represented fires which met the requirement of the ranchers' claims, they could have implied that there are cycles of wildfires and grazing closures in the region. As it stands, the five pairs have overlapping areas that are less than 0.5% of the burnt area of the secondary fires. The low overlapping percentages suggest that the five listed initial fires had little to no impact on the Winters and Sheep Fires.

In all four of the case study pairs the secondary fires are smaller than the initial fires. As described in Chapter 3, this is a consequence of using the overlapping percentage value as a filter. It does not indicate that all secondary fires are smaller than the initial fires. Rather, missing ignition point data makes it unlikely, if not impossible, to determine if a larger secondary fire ignited within the perimeter of a smaller initial fire.

4.2. Case Study Fire Events

The case study selection process described in Chapter 3 identified four fire events that, given the available data and selected methodology, best met the spatial and temporal criteria of a rest period fire. All four events were concentrated in the area north-northeast of the town of Battle Mountain (Figure 10). Two of the events (Little One and Green Monster) shared the same initial fire (the Winters Fire). Three of the events (Little One, Green Monster and Rock Creek) covered the same timeframe, having the initial fires in 2006 and the secondary fires in 2008. While the 2004 Squawvalle Fire and the three initial fires were listed as having natural causes, the other three secondary fires were listed as human-caused. Additionally, the Squawvalle Fire of 2004 has an overlap with the Sheep Fire of 2006. The overlap percentage for this pair is less than 0.25%, so it is not likely that the Squawvalle Fire had a significant effect on the Sheep Fire.

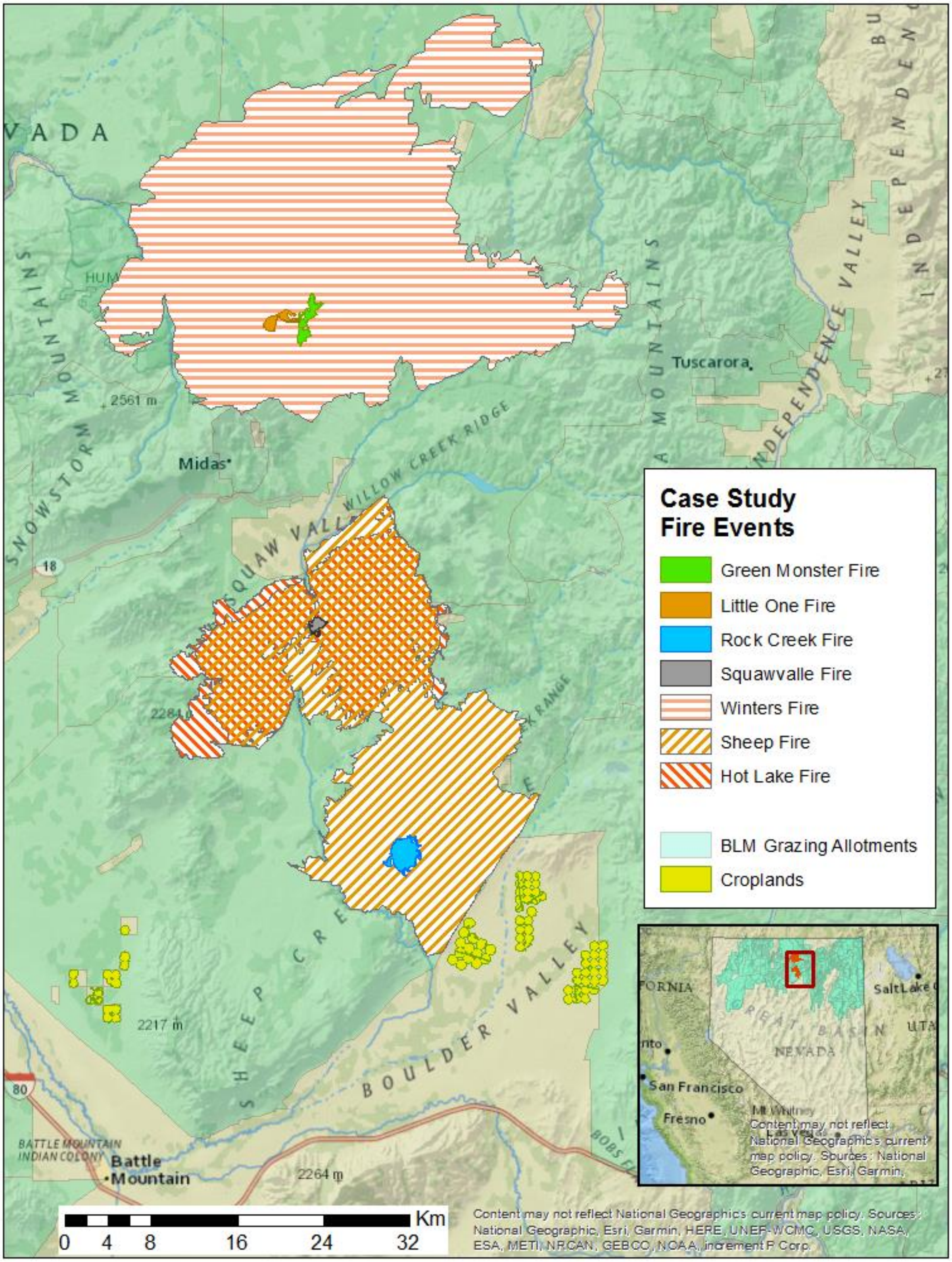

Figure 10. Map of Fire Events from Case Studies

4.2.1. Squawvalle Fire Zones

The Squawvalle Fire was discovered 18 km south-southeast of Midas, NV, on June 23, 2004. It was preceded by the Hot Lake Fire, which was contained on September 30, 2001, 997 days earlier. Approximately 0.2% of the area of the Squawvalle Fire extends past the perimeter of the Hot Lake Fire. The Squawvalle Fire is on the western edge of the Hot Lake Fire's eastern lobe (Figure 11). The Burned Control Zone for this case was placed to the immediate northeast of the fire perimeter. Because the Squawvalle Fire was centrally located within the Hot Lake Fire's fire perimeter, the Unburned Control Zone was placed about 15 km to the west-southwest of the fire perimeter.

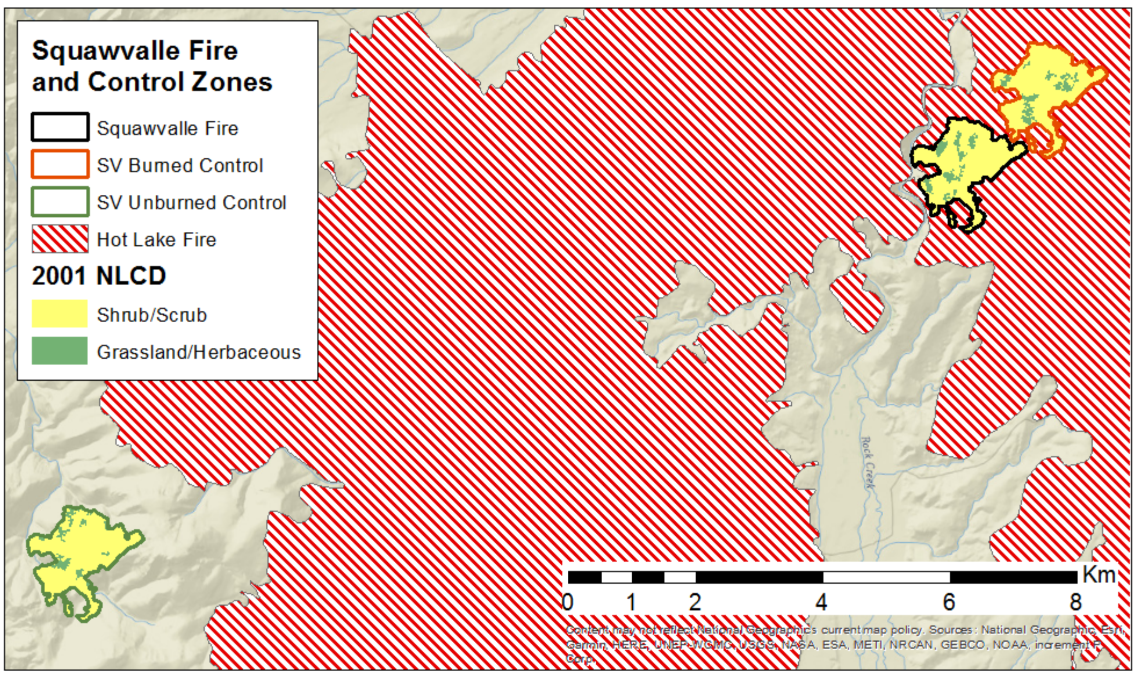

Figure 11. Squawvalle Zones

Control Zones were selected to have approximately the same ratio of shrub-dominated area to grass-dominated area based on the 2001 NLCD data. Table 2 shows the total counts for both categories in all three zones and compares the counts in the control zones to the areas burnt by the Squawvalle Fire. Error for this table is the difference in the counts of the two categories.

The Burned and Unburned Control Zones had classification errors of 1 cell and 8 cells, respectively. The difference in the total cell count between zones is due to boundary errors between vector masks and raster images when using the Extract by Mask or Zonal Statistics tools. Adjusting the position of the vector mask or zone can cause the tools to include or exclude cells at the vector boundary. According to the 2001 NLCD, approximately 90% of the cells in the Squawvalle Fire and the control zones represented shrub-dominated cover.

Table 2. Squawvalle Land Cover Cell Count

		Squawvalle				
		Fire Perimeter	Burned Control	*FP - BC*	Unburned Control	*FP - UC*
2001 NLCD	Shrubland	1496	1496	*0*	1503	*-7*
	Grassland	172	171	*1*	171	*1*
	Total	**1668**	**1667**	***1***	**1674**	***-6***

4.2.2. Little One Fire and Green Monster Fire Zones

Figure 12 shows the locations of the Little One and Green Monster Fires, which are notable for being physically adjacent events that occurred only a month and a half apart. Both fires followed the Winters Fire that was contained on August 3, 2006. The Little One Fire was discovered 727 days later, on July 30, 2008. The Green Monster Fire was discovered later in the season, on September 16, 2008. The boundary between the two fires is a small creek passing through the area. Both fires as well as the initial Winters Fire are all north of Midas, NV.

The control zones for the Green Monster Fire ended up being relatively close to the fire perimeter. The burned control is just east of the fire, while the unburned control is about 18 km to the west. The control zones for the Little One Fire were set further away due to land cover balancing. The burned control is about 10 km northwest of the fire perimeter, while the unburned control is west of Midas.

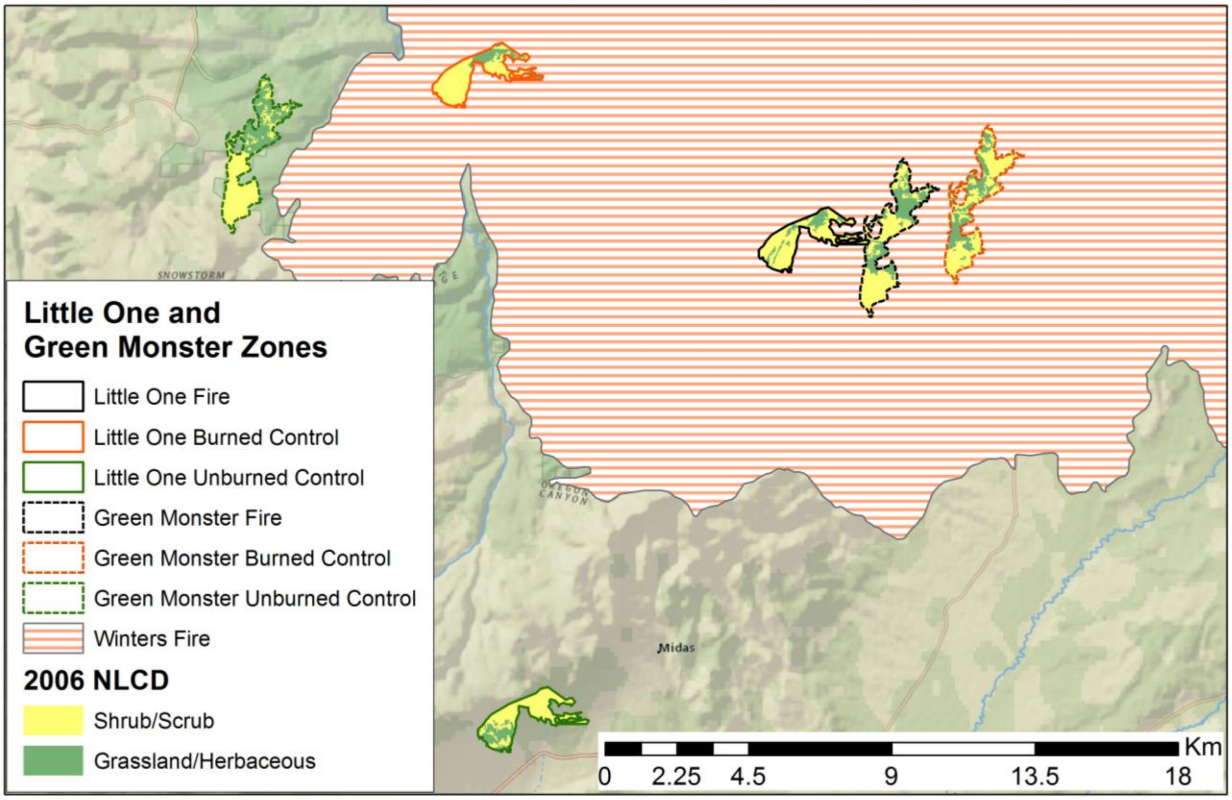

Figure 12. Little One and Green Monster Zones

Table 3 shows the relative count of shrub and grass land cover types based on the 2006 version of the NLCD. The burned controls for both fires were better matched to the fire perimeter land covers, but the category errors for all four control zones were less than 1% of the cell count. The Little One Fire had a ratio of about 10 to 3 in favor of shrubland cover. The ratio for the Green Monster Fire was closer at 8 to 5 in favor of the shrubland.

Table 3. Little One and Green Monster Land Cover Cell Count

		Little One					Green Monster				
		Fire Perimeter	Burned Control	*FP - BC*	Unburned Control	*FP - UC*	Fire Perimeter	Burned Control	*FP - BC*	Unburned Control	*FP - UC*
2006 NLCD	Shrubland	2036	2039	*-3*	2042	*-6*	2428	2428	*0*	2421	*7*
	Grassland	596	591	*5*	583	*13*	1563	1563	*0*	1556	*7*
	Error	--	--	***8***	--	***19***	--	--	***0***	--	***14***
	Cell Count	**2632**	**2630**	***2***	**2625**	***7***	**3991**	**3991**	***0***	**3977**	***14***

4.2.3. Rock Creek Fire Zones

The Rock Creek Fire (Figure 13) was discovered on August 10, 2008. This was 700 days after the Sheep Fire was contained, on September 10, 2006. The Rock Creek Fire is centrally located in the lower lobe of the Sheep Fire. The Rock Creek Fire is the largest secondary fire selected for the case studies. Control zones were set further away (approximately 18 km to the northwest) to find locations with comparable land cover ratios. The Unburned Control Zone is divided by the Rock Creek Road, which appears to divide the shrubland and grassland cover types.

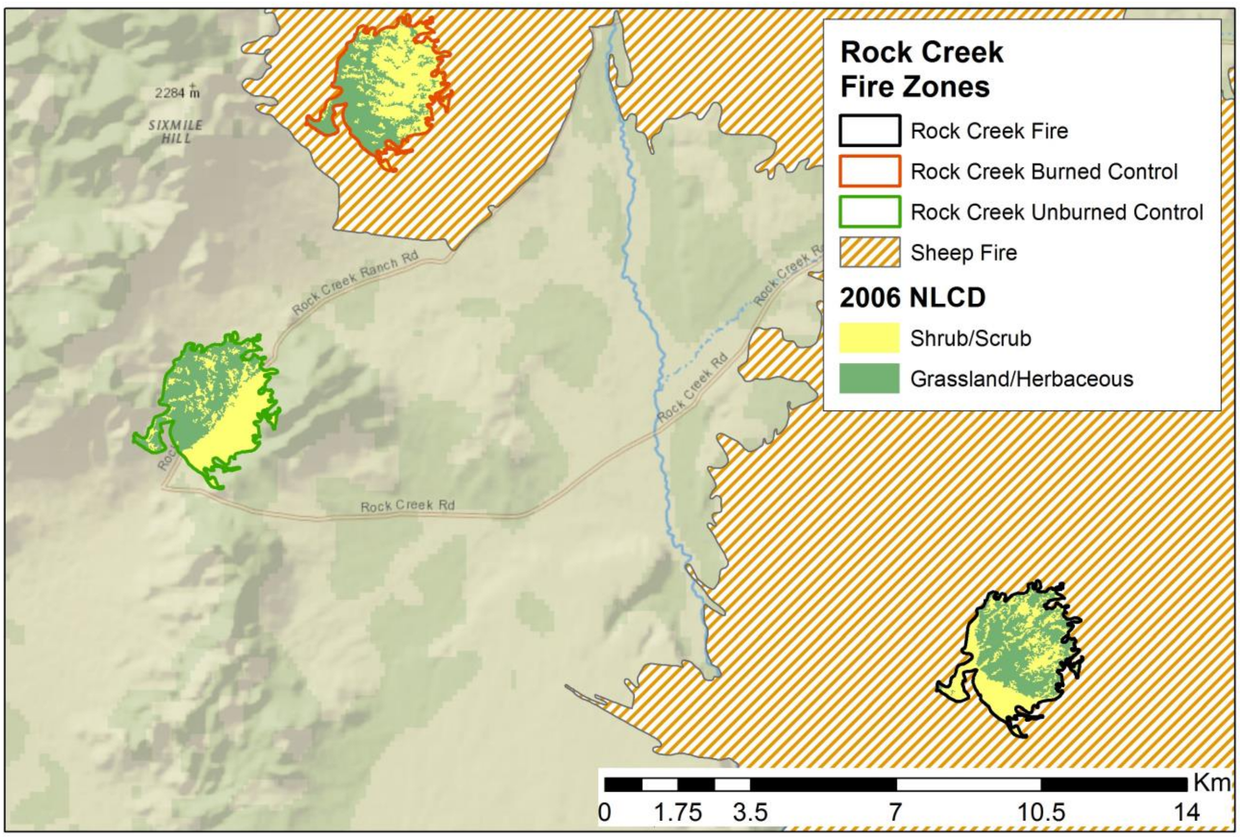

Figure 13. Rock Creek Zones

Finding ideal locations for the control zones was problematic due to the abundance of grassland dominant cells. Unlike the previous fires, The Rock Creek fire perimeter has a roughly even ratio of shrublands to grass lands (Table 4). While the absolute classification error for both zones was around 1% of the total number of cells.

Table 4. Rock Creek Land Cover Cell Count

		Rock Creek				
		Fire Perimeter	Burned Control	*FP - BC*	Unburned Control	*FP - UC*
2006 NLCD	Shrubland	3652	3706	*-54*	3679	*-27*
	Grassland	3739	3680	*59*	3696	*43*
	Error	--	--	***113***	--	***70***
	Cell Count	**7391**	**7386**	***5***	**7375**	***16***

4.3. Scaled NDVI Time Series and Four-Month Precipitation Totals

Due to the spatial and temporal proximity of the Little One, Green Monster, and Rock Creek Fires, common values for $NDVI_s$ and $NDVI_0$ were used for these three case studies. A different set of values for $NDVI_s$ and $NDVI_0$ were used for earlier Squawvalle Fire.

$NDVI_0$ values were calculated from the least disturbed post-fire pixels in the Squawvalle perimeter (for the 2001 to 2004 data) and the Rock Creek perimeter (for the 2006 to 2008 data). $NDVI_S$ values for the two time periods were calculated from the maximum observed NDVI in cropland pixels during the time periods. For the Squawvalle Fire case study, $NDVI_s$ was set to 0.9237 and $NDVI_0$ was set to 0.1154. For the 2008 case studies, $NDVI_s$ was set to 0.9021 and $NDVI_0$ was set to 0.0835.

4.3.1. Squawvalle Fire

The mean Scaled NDVI values for the Squawvalle Perimeter and Burned Control Zones during the spring after the Hot Lake Fire are lower than both the previous spring and the subsequent spring. By comparison, the mean Scaled NDVI values for the Unburned Control show less change during this time period. By the second spring after the fire, the mean values of

Scaled NDVI in burned areas are similar to mean values in the unburned area. This confirms there was some form of vegetation regrowth in the burned area within two years of the initial fire. This would lend support to the ranchers' claim that vegetation in areas under a grazing closure were recovering to levels comparable to the nearby unburned area.

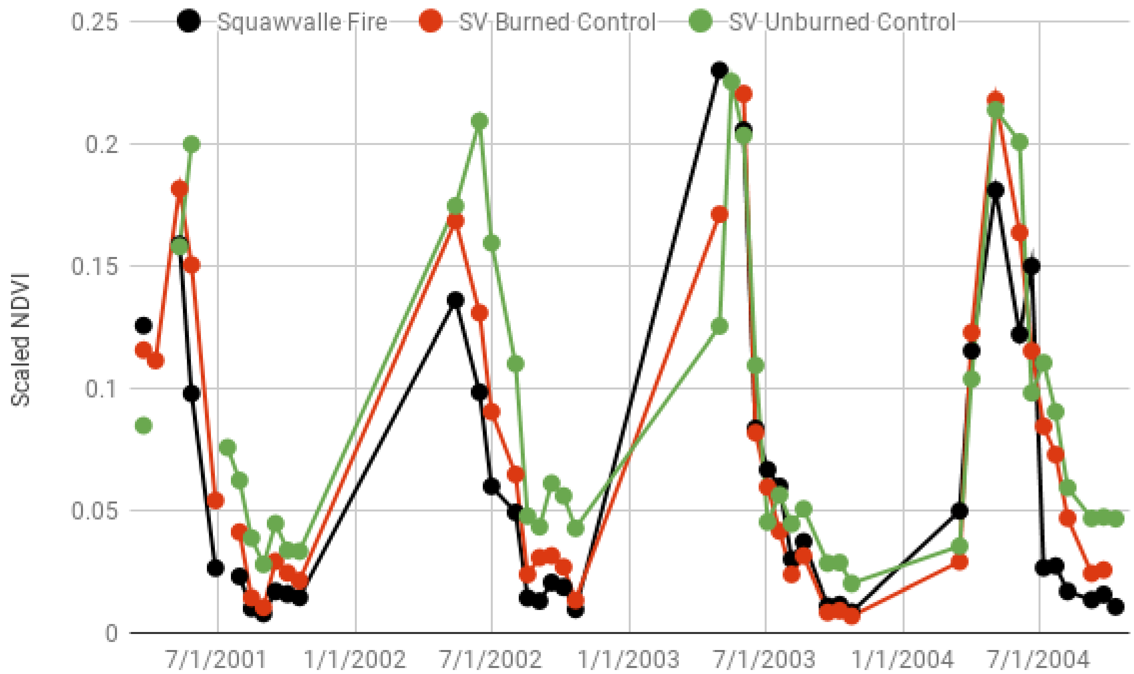

Figure 14. Scaled NDVI over time for the Squawvalle Zones

The four-month precipitation series for the Squawvalle Zones (Figure 15) has a few interesting features to discuss. The four-month periods ending May 2000, September 2003, and September 2004 all had greater precipitation than comparable periods in other years. Oppositely, the January 2003 precipitation totals are much lower than previous January observations. The spike in Spring Scaled NDVI values in 2003 and 2004 do not seem to correlate well with any of the precipitation observations.

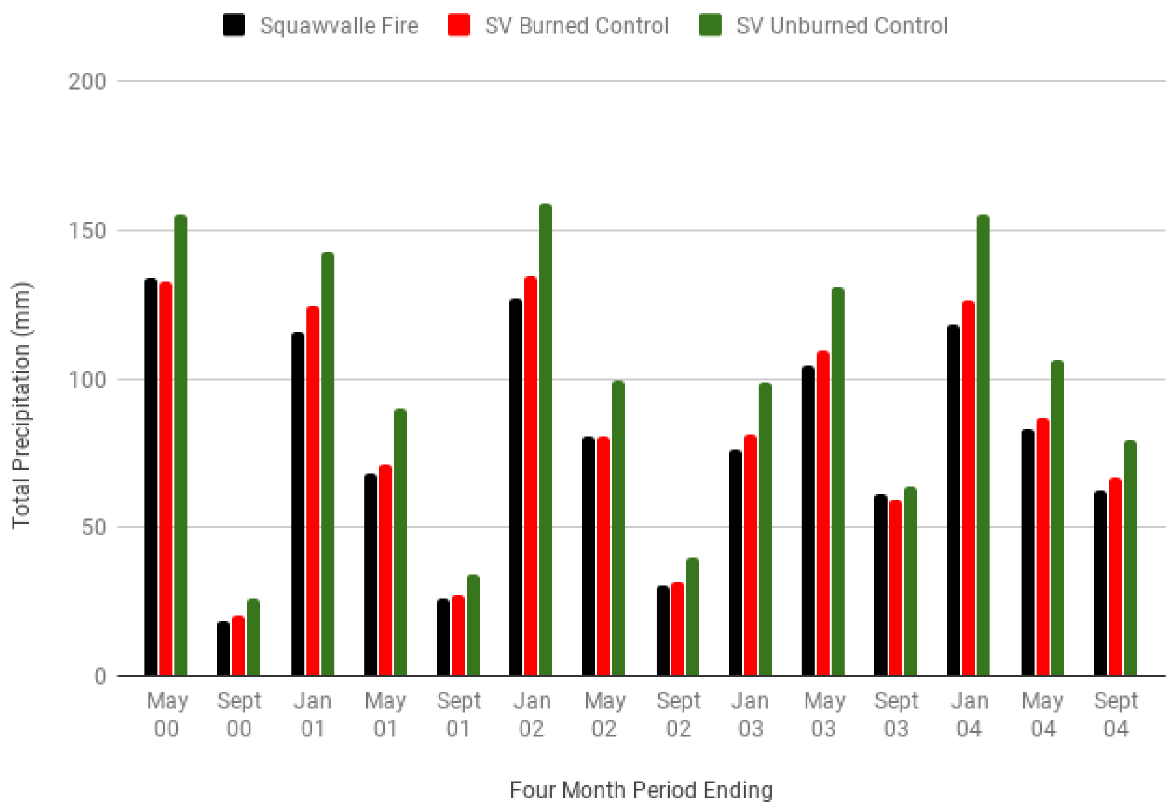

Figure 15. Squawvalle Four-Month Precipitation Totals

4.3.2. Green Monster and Little One Fires

Figures 16 and 17 show the Scaled NDVI graphs for the Green Monster Fire and the Little One Fire, respectively. Like with the Squawvalle data, the mean Scaled NDVI values show a post-fire drop of live vegetation cover in burned areas during the first spring after the initial fire. By the second spring, the live vegetation cover in burned areas is comparable to the cover in the unburned area. These results also suggest that the ranchers' claim regarding post-fire regrowth may be valid.

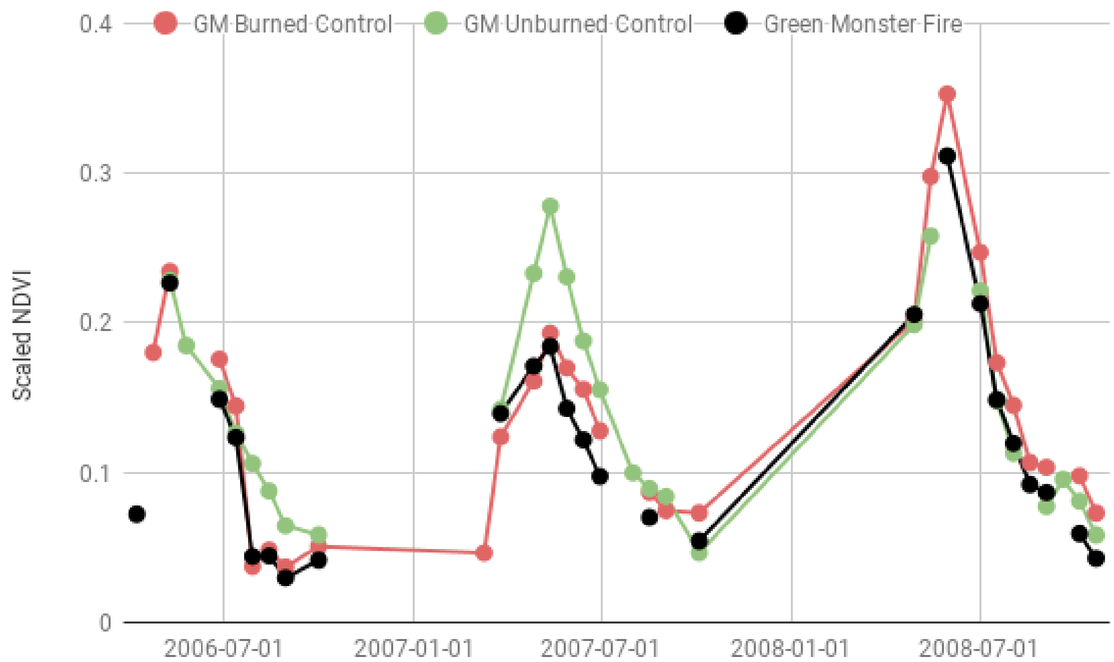

Figure 16. Scaled NDVI over time for the Green Monster Zones

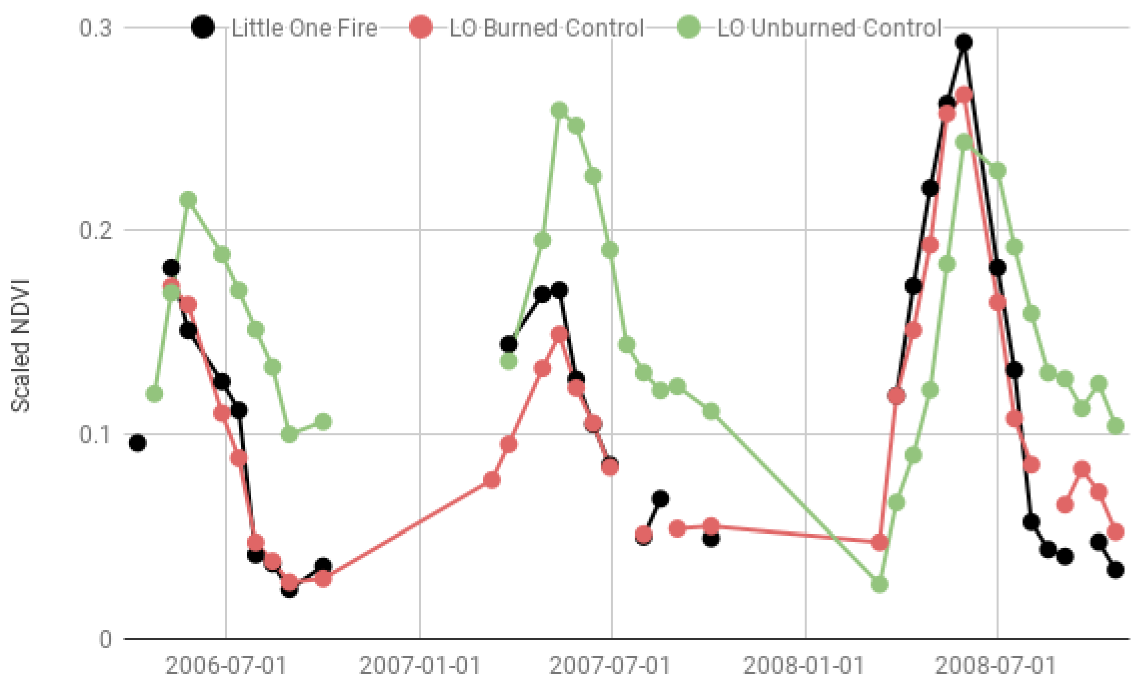

Figure 17. Scaled NDVI over time for the Little One Zones

The Four-Month Precipitation Totals for both fires (Figures 18 and 19) tell similar stories. The Winter and Spring months in 2005 and 2006 have higher precipitation totals on average than the same months in 2007 and 2008. This is consistent with Westerling et al. (2003), as 2006 was a peak fire year while 2008 had very few recorded fire events (Figure 2).

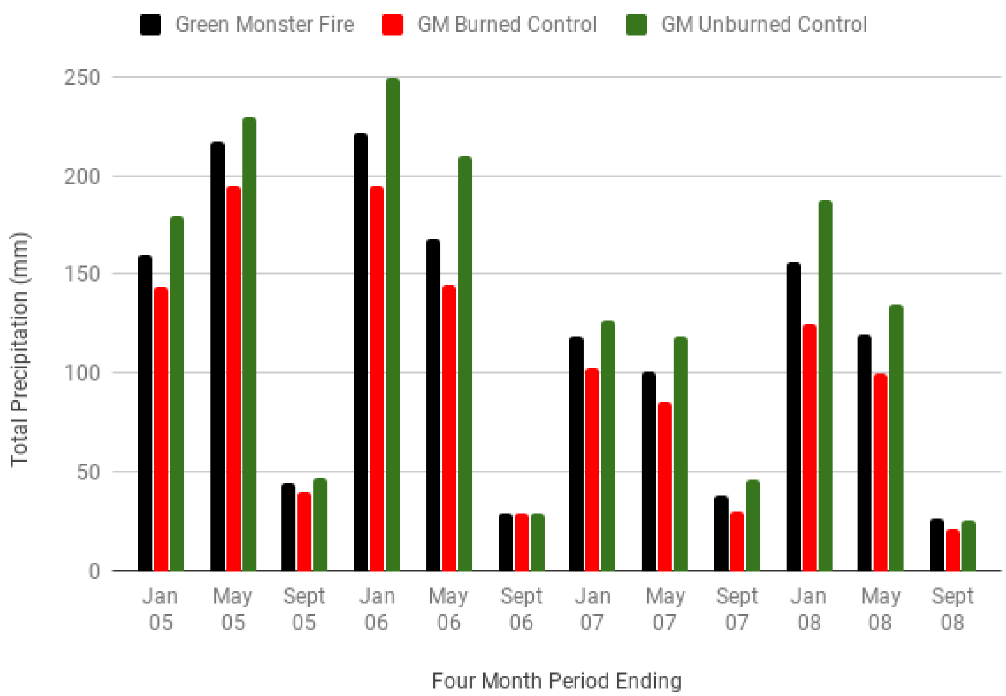

Figure 18. Green Monster Four-Month Precipitation Totals

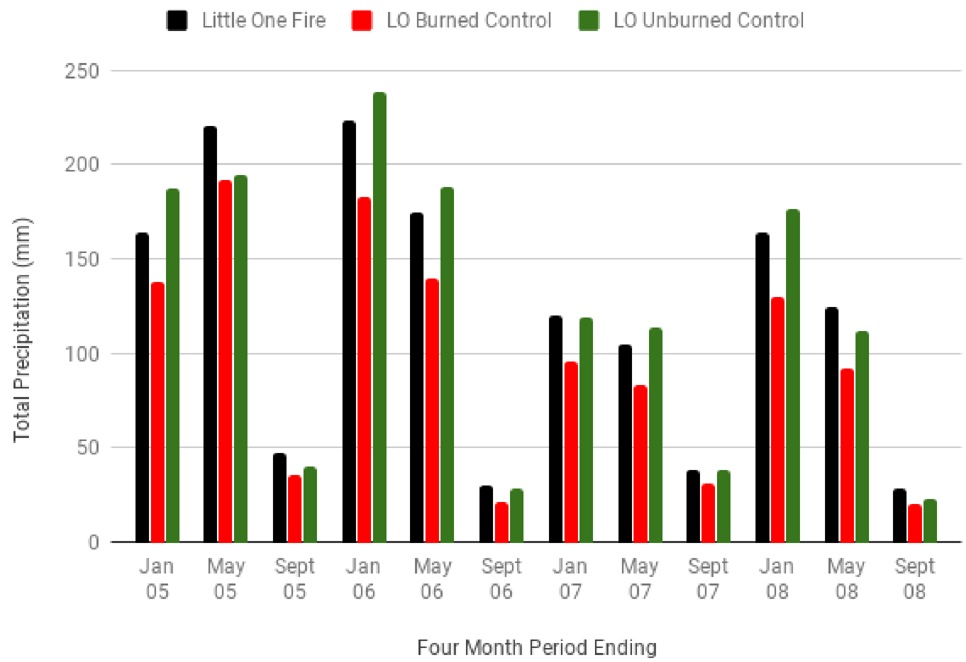

Figure 19. Little One Four-Month Precipitation Totals

4.3.3. Rock Creek Fire

The Scaled NDVI time series for the Rock Creek Zones is shown in Figure 20. Due to cloud cover, some of the observations of the initial Sheep Fire were excluded as invalid data. The signature of the Rock Creek Fire can be seen as the drop in the mean Scaled NDVI values of Fire Perimeter zone at the end of the series. Perhaps the most unusual aspect of this time series is the drop in the Unburned Control Zone values during 2008. The drop in the Unburned Control could be the result of a region-wide disturbance. A more thorough analysis method and further research would be needed to confirm that possibility. The Rock Creek data, with a seemingly constant mean Scaled NDVI in the burned areas during spring observations, seem to be the least consistent with the ranchers’ claim.

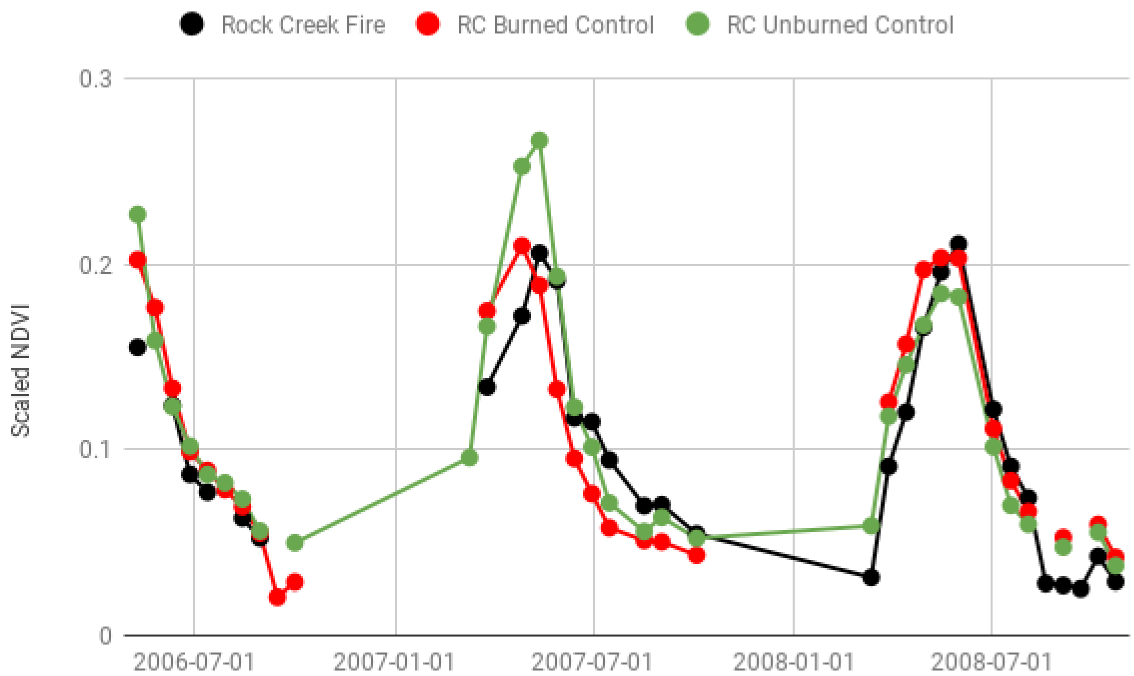

Figure 20. Scaled NDVI over time for the Rock Creek Zones

The Four-Month Precipitation Totals for the Rock Creek Zones (Figure 21) are consistent with the precipitation data from the Little One and Green Monster Fires (Figures 18 and 19). 2005 and 2006 appear to be wetter years than 2007 and 2008, which is consistent with the fire occurrence per year data (Figure 2). Since all three cases were concerned with spatially proximate and contemporary fires, it is not surprising that the precipitation data are consistent for all three.

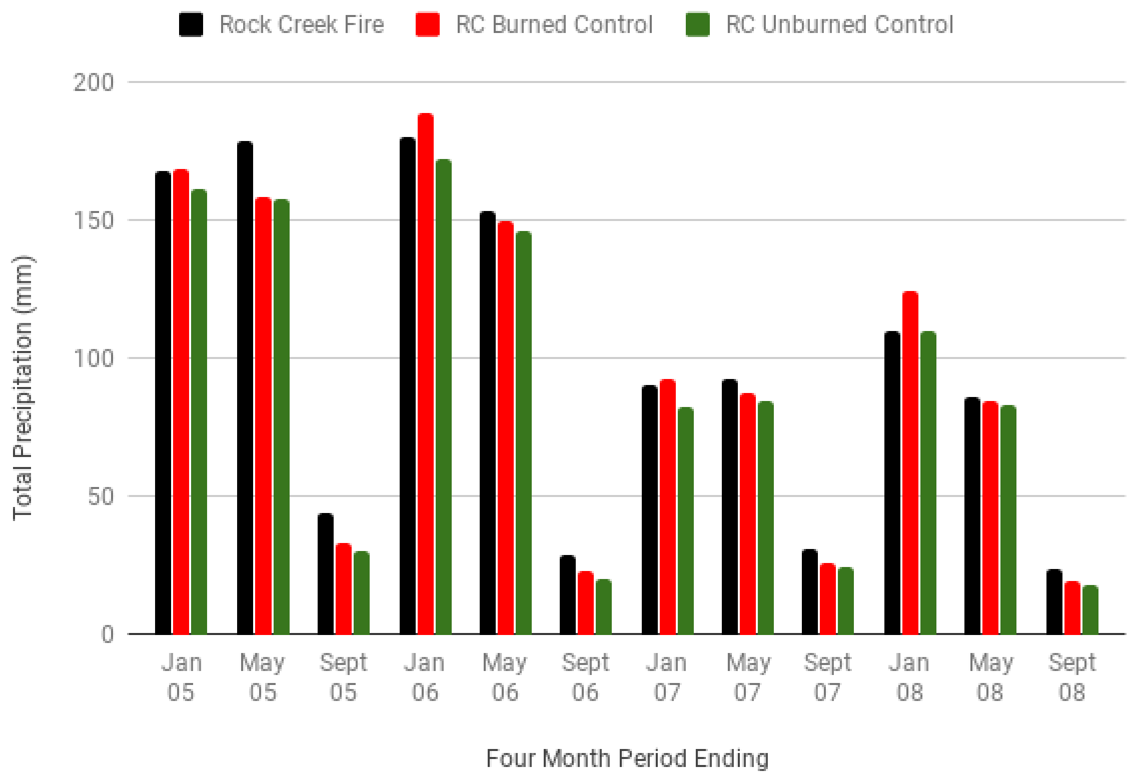

Figure 21. Rock Creek Four-Month Precipitation Totals

4.4. Other Observations

In Chapter 1, Figure 2 included a bar chart for fire frequency per year. It is interesting to note that all the case studies had initial fires during years with more fires (2001 and 2006) and secondary fires during years with fewer fires (2004 and 2008). This appears to be another artifact of the case study selection process (with the larger initial fires occurring in the more active years). The selection filter favored larger initial fires and smaller secondary fires. As noted Westerling et al. (2003), larger and more frequent fires are associated with wetter climates in the previous year.

Chapter 5 Discussion and Conclusion

This chapter summarizes the main findings of the case studies, suggests methods that could be used to further explore the study objectives, discusses other factors that might affect the frequency of fire events or the perception of fire frequency, and describes potential developments that could improve post-fire vegetation monitoring in the future.

5.1. Discussion

This study originally intended to use a method based on comparing ignition data to the exact closure areas and rest periods. As described in Chapter 3, the fire identification methodology was revised to use self-intersections of recorded fire perimeters due to the unavailability of the closure dataset and unreliability of the ignition dataset. The self-intersected perimeter data showed 54 fire events which reburned areas affected by fires one, two, or three years before. The reburned areas for these fires covered almost 13,000 acres in total. While these fires represent reburned areas, they do not represent the true closure areas or ignition points. Other fires could have been added to this list if the ignition points and grazing closures were known. Some of the 54 could also be removed from this list if the actual rest periods were known. The search window of "less than three years but not the same year" was chosen as a proxy for rest period durations based on the nature of the ranchers' claim and the details of BLM policy.

Of the 54 secondary fires, four were entirely or almost entirely within the perimeter of the previous fire, indicating that the ignitions for the four fires were within the previous fire perimeter. Because of this, these four fire pairs were selected for further analysis in the vegetation case studies designed to answer the second research question.

To answer the second research question, a method to assess the changes to fuel load and biomass during grazing rest periods was needed. Multiple methods to measure fuel load and/or vegetation biomass in the case study zones were considered. After reviewing background literature on vegetation indices and what historical data were available, options such as using unmodified NDVI, differenced imagery, and CAI were ruled out. Finally, Scaled NDVI was selected for use as an estimator of green vegetation cover and thus live vegetation recovery in the case studies.

The advantages of Scaled NDVI were that it was easily calculated from base NDVI values and that it related the observed values to bare soil and irrigated cropland. Time series graphs were created as analysis and visualization tools for Scaled NDVI observations as an alternative to creating differenced vegetation index imagery from pre- and post-event data. LANDSAT 5 Thematic Mapper data were used to calculate NDVI because it was available as high-resolution imagery of the case study locations during the periods of time covered by the case studies.

Three of the four Scaled NDVI time series showed vegetation recovery in burned areas within two years of the initial fire as estimated by the changes in vegetation cover. The recovery in the Little One Fire, the Squawvalle Fire, and the Green Monster Fire suggests the possibility that biomass and fuel load may also have recovered as would be expected under the ranchers' claim, though further research would be needed to verify those conditions. The Rock Creek Unburned Control zone had an unexplained drop of mean Scaled NDVI values in spring of 2008, while the Burned Control and Fire Perimeter zones had stable values across all spring observations.

Precipitation data seem to be consistent with the observations made by Westerling et al. (2003) and other literature sources. Wetter years seem to result in more and larger fires in the following year. The case study selection method, which preferred smaller secondary fires and larger initial fires, also found secondary fires which occurred during low fire years, which may be inconsistent with ranchers' claim that the secondary fire resulted from accumulated vegetation litter. However, if these are just artifacts of the search algorithm, it is possible there are other examples of rest period fires that are more consistent with the ranchers' claim.

Further investigation into these claims using a method such as sampling a sufficient number of randomly selected cells from the secondary perimeters and from burned and unburned regions for statistical analysis would be necessary to demonstrate statistically whether the vegetation cover regrowth was significant enough to support the ranchers' claim. Given the ratio of shrubland to grassland in the burned areas, a random points method would have to be stratified to balance that ratio for each case study fire. This could potentially be achieved by splitting sampling regions by land cover classification. Additionally, the unburned sampling region could be taken from the grazing allotments west of the Squawvalle and Rock Creek Fires or similar allotments northeast of the Little One and Green Monster Fires. These allotments had seven or fewer fires during the study period. This would require further consideration by researchers utilizing the random points method.

5.2. Other Considerations

There is a high level of consensus in the literature that cheatgrass invasion is a primary component of the current fire regime in the Great Basin. This project was concerned with fires that occurred within three years of each other. This three-year frequency is itself a product of the cheatgrass-modified fire regime. While the ranchers' claim is only but justifiably concerned with fuel accumulation during rest periods, the source of that fuel is also important. As such, ranchers in areas with more frequent fires might consider targeted grazing in the Spring to reduce cheatgrass biomass at their ranches.

Although fire suppression is no longer a popular land management practice, it may be necessary when fires start near cheatgrass patches. Cheatgrass benefits too much from large and uncontrolled fires to justify a hands-off approach in this region. Likewise, simply removing livestock and ceasing ranching operation will not result in the restoration of the native vegetation. Some level of direct management is necessary to remove cheatgrass and reestablish the original fire regime.

It may be helpful to consider the spatial distribution of fire events relative to the grazing allotments. In Figure 22, a grid with 10 km by 10 km cells was generated to cover the spatial extent of the study area grazing allotments. The grid was spatially joined to the fires investigated by the project so that a count of fires in each cell could be calculated. At this scale, there appears to be a crescent of high fire frequency in the central part of the study area, with lesser hotspots at the northwestern, northeastern, and southeastern corners. Also at this scale, the maximum fires recorded in a cell was 11, which would be a frequency greater than one fire per year.

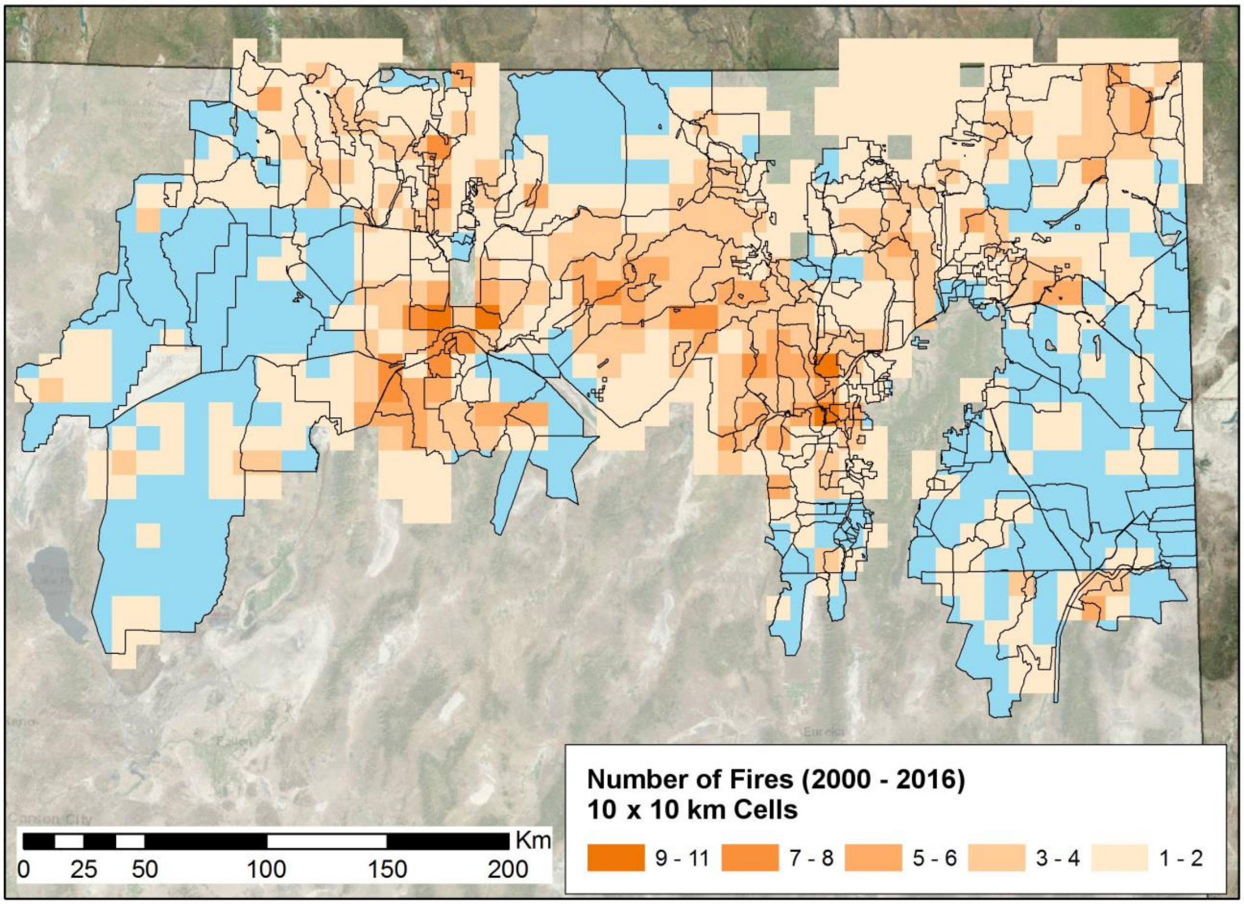

Figure 22. Fire Frequency per 10x10 km Grid

Another way to look at the spatial distribution of fire events is by allotment. A spatial join was used to count the number of study area fires that occurred within each study area grazing allotment. From the spatial join, a choropleth map using five classes grouped by natural breaks and a sixth class for allotments with no fires was created (Figure 23). It should be noted that the allotments have a wide range of sizes and a variety of shapes. As such, the Modifiable Areal Unit Problem (MAUP) applies to this information. Although there are exceptions, the larger allotments tend to have more fires, which is expected because the larger allotment have much more space for fires to start or to spread.

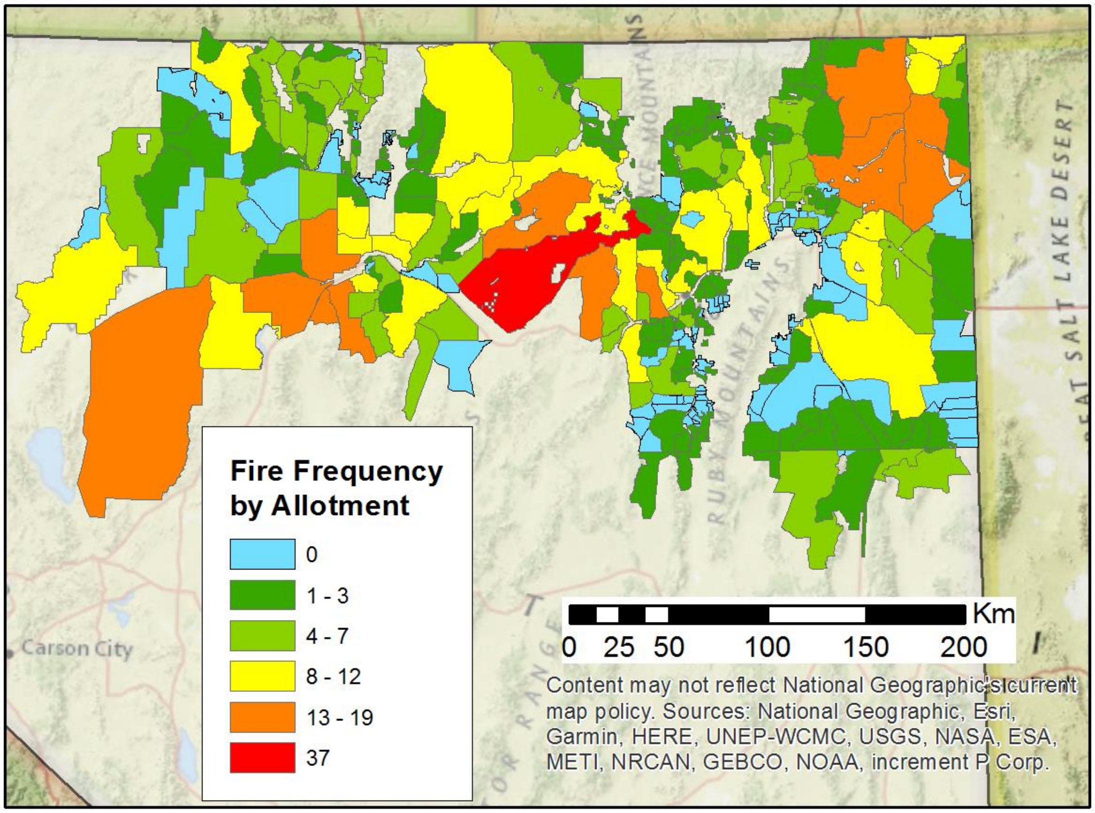

Figure 23. Fire Frequency by Allotment, 2000-2016

The real message from this map is somewhat anecdotal. The people and businesses who lease and manage these allotments are probably not going to care about the MAUP (though it would be helpful to spatial scientists if they did). They are going to care that their allotment had 19 fires or 37 fires in 17 years. The case studies in this project were attempts to find evidence for claims made by the lease holders and managers. The claims themselves were a consequence of the events aggregated in this map.

A frequency of at least one fire every three years, which was the maximum interval for this project, would result in 5 or more fires over the 17 years from 2000 to 2016. That frequency includes many of the light green colored allotments and all yellow, orange, and red allotments. While this study has shown that only 58 of the three-year fire pairs have overlapping perimeters, the situation could appear as a continuous series of closures and fires to the ranchers or managers present at these allotments.

Figure 24 shows all grazing allotments in the study area that had 17 or more intersecting fire perimeters between 2000 and 2016, yielding an average of one or more recorded fire events per year during the study period. The Twenty Five allotment, with 37 recorded fires between 2000 and 2016 (including the Rock Creek and Sheep fires) was the most frequently burned allotment. While all four allotments are among the larger allotments, size alone does not explain the frequency of fires in these allotments. One possible factor contributing to fire occurrence in these allotments is human activity. All four are near towns or unincorporated inhabited places (Winnemucca, Battle Mountain, Carlin, and Midas). There are two active mines in the area, including the Goldstrike Mine which occupies the northwestern corner of the T Lazy S allotment. All except the Squaw Valley allotment border Interstate 80. Farming sites with center-pivot irrigation can easily be identified near, adjacent to, and within these allotments. The ease of access and closeness to agricultural equipment and machinery could be signs that human activity in the area has contributed to the increased fire count.

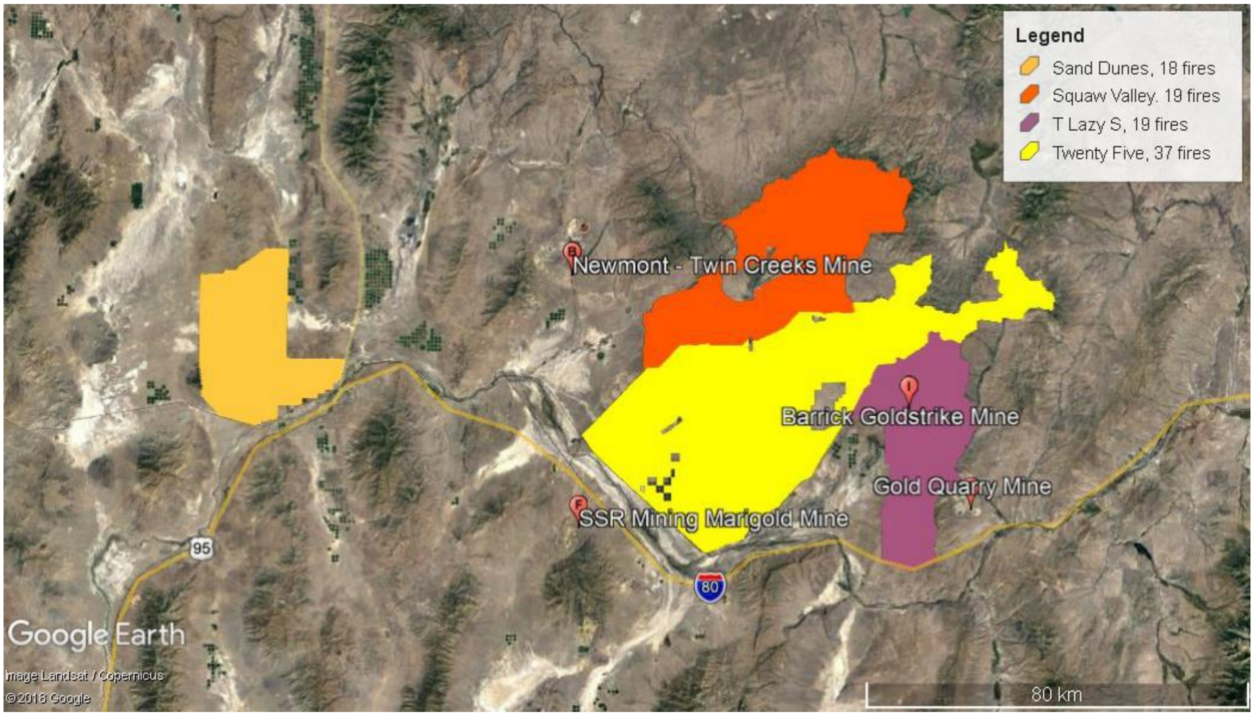

Figure 24. Mining Sites and Highways near Frequently Burned Allotments. The four allotments pictured were affected by 18 or more fire events during the 17-year study period. The image was created by importing the allotment shapefile into Google Earth.

5.3. A Better Tomorrow

As discussed in earlier chapters, the original concept for this project would have involved spatial data for closure areas and ignition points, as well as the true duration of any rest periods. Without access to accurate and complete copies of these data, this project instead identified repeat fires by looking at intersecting fire perimeters and assuming a rest period duration of three years, based on limits and descriptions from BLM wildland fire policies.

While the historical data are limited to what was collected at the time, attempts to track rest period fires in the future could benefit from improved spatial data collection and better record keeping. Accurate positional data could pinpoint spatially related events while rest period histories could be used to create a timeline of events and observations.

In addition to the assumptions about the duration of rest periods, another assumption made in this project was that the closure areas would include the entire fire perimeter. It is possible that a low-intensity fire might only cause severe damage sporadically within the fire perimeter. In such a scenario, the closure area might be smaller than the fire perimeter. This is case where the missing data might hurt the ranchers' claim. If two fires overlap and the intersecting area was not part of the first fire's closure area, then the second fire could not be the result of the grazing rest period. It is not possible to be certain about any rest period fire if the spatial and temporal information about the closure is not accurate and available.

The Cellulose Absorption Index (CAI) was also considered as a possible tool for measuring rest period vegetation growth. CAI would have been useful in distinguishing between dry vegetation and bare soil. However, the necessary bands to calculate CAI are all in the shortwave infrared (SWIR) range and grouped together as a single band in all available LANDSAT sensors. Information from the LANDSAT website suggests that the sensors on the upcoming LANDSAT 9 will continue to group SWIR as a single band. CAI is not likely going to be available through LANDSAT anytime soon. The remote sensing of rangeland health could benefit if more complex sensors and new vegetation indices were developed to address the shortcomings of current technology.

The final consideration is the lack of a means to assess the validity of the results statistically. While a method such as the use of random sampling points could provide a statistical result, the method used in this project was sufficient to demonstrate that there may be some validity in the ranchers' claim, suggesting that further research is called for. The method described here provides a foundation for further development of appropriate statistical methods. It also highlighted some of the main data concerns that can occur with a study such as this, such as the missing closure data, the inaccurate ignition point data, and the merged waveband data on LANDSAT sensors which prevented the use of CAI.

5.4. Conclusions

The two objectives of this project were to find fires that had the spatial and temporal qualities described by the ranchers' claim and then to analyze the accumulation of fuel in areas under a grazing closure compared to areas open to grazing. Due to the data concerns discussed throughout this document, the first objective was modified to find reburns of three-years or less and then identify candidates for rest period fires by estimating the likelihood of ignition within the reburned area by looking at the overlapping area. The second objective was modified to consider live vegetation cover as proxy for vegetation recovery as direct methods to measure historical biomass were not available.

The modified first question was successfully answered by identifying 54 recorded fire events which affected areas previously burned up to three years earlier and by further identifying four of those fires where the ignition point was within the previous fire perimeter.

The modified second objective was addressed by constructing Scaled NDVI time series for the case study areas. The Scaled NDVI time series created for three of the four fires showed vegetation cover similar to nearby unburned areas within two years of the initial fires, which suggests live vegetation recovery contrasting with the BLM statement that two to three years might be needed to see full recovery. Confirming this indication would require a stronger statistical analysis, such as the random points sampling method discussed in Chapters 3 and 4. Also, it is possible that the observed recovery is actually cheatgrass invasion, in which case methods to remove cheatgrass should be considered for revisions to BLM policy.

This project has shown that it is possible that rest period fire events are a valid concern for ranchers and land management agencies. Better data, both in the public records of grazing closures and in more complex sensors for observation satellites, and more statistically thorough methods will be needed to more confidently identify rest period fire events and to measure fire danger. The candidate fire selection method was the direct result of the ideal datasets being unavailable or unreliable. The selection method also had some unforeseen consequences, such as only selecting fires which were smaller than the initial fires.

In the future, whether a stakeholder is a rancher seeking to profit from a ranching operation or an environmentalist trying to protect Sage Grouse habitats, this study has demonstrated that all parties in the grazing lands of Nevada and elsewhere in the American West would benefit from better informed management practices developed from better data and statistically strong analysis of that data.

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