IMPACTS OF VEGETATION MANAGEMENT ON WILDFIRE SEVERITY:

A STUDY OF THE 2021 CALDOR FIRE

by

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To my family, with heartfelt gratitude for your love and support.

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Table of Contents

List of Tables

List of Figures

Abbreviations

ANOVA	Analysis of variance
B	Brightness
G	Greenness
GIST	Geographic information science and technology
dB	Change in brightness
dG	Change in greenness
dNBR	Differenced normalized burn ratio
dW	Change in wetness
FACTS	Forest Service Activity Tracking System
NBR	Normalized Burn Ratio
RAVG	Rapid Assessment of Vegetation
RxFire	Prescribed Fire
US	United States
USFS	USDA Forest Service
W	Wetness

Abstract

Wildfire intensity has increased in the 21st century, posing a serious threat to forests in the Sierra Nevada mountain range of the western United States. This increase is the result of dense forest fuel loads that accumulated during the total fire suppression policies of the 20th century. Longer, drier summers exacerbate these hazardous fuel conditions and provide further potential for extreme wildfires. Land management agencies such as the USDA Forest Service are tasked with mitigating wildfire risk. The goals of wildfire risk mitigation are to increase forests' resilience to wildfire by reducing burn severity and preserving forests' ability to recover post-fire. These goals are achieved through fuel reduction treatments composed of thinning and prescribed fire, thus reducing the amount of vegetation that can fuel extreme wildfire. There is a consensus that fuel treatments are effective at reducing wildfire intensity, but the efficacy of specific treatment types is less understood. Understanding how fuel treatment type affects wildfire intensity can help land managers optimize wildfire risk management. This research studies the 2021 Caldor Fire, exploring how different types of treatments influenced two aspects of wildfire intensity: burn severity and post-fire forest change. Fuel reduction treatments are assessed using a temporal analysis of Landsat imagery, comparing pre-fire and post-fire conditions to measure burn severity and post-fire forest changes to vegetation and moisture. The treatment types of comparison are thinning, prescribed fire, and a combination of thinning and prescribed fire. The results show that the treatment types experienced statistically significant differences in burn severity and variations in post-fire forest recovery, with treatments incorporating thinning only experiencing the lowest burn severity and the smallest degree of forest change. This research can help land managers understand how different treatment methods impact wildfire intensity and implement wildfire risk management more effectively.

Chapter 1 Introduction

Wildfire risk management in the Sierra Nevada forests of the western United States (US) has become a complex and dangerous undertaking. Wildfires have grown in size and intensity since the 1980s, posing a serious threat to these forests (Sierra Nevada Conservancy 2023). The major causes of this trend are forest vegetative conditions, historical land management practices and climate change (Taylor et al. 2022). Land management agencies such as the USDA Forest Service (USFS) are tasked with mitigating wildfire risk by reducing burn severity and increasing the forests' resilience to wildfire (USFS 2022a). To achieve this goal, land managers implement fuel reduction treatments. The objective of these treatments is to reduce the amount of hazardous vegetation, or fuels, that can serve as fuel for extreme wildfire (USFS 2022a). Although land managers and researchers agree that fuel treatments are effective for minimizing wildfire risk, the influence of specific treatment types is less understood. This research examines the 2021 Caldor Fire to explore the impact that different fuel treatment types had on burn severity and post-fire forest change.

1.1 Causes of Increased Wildfire Risk

The growing intensity of wildfires is driven by two primary factors: forest fuel conditions and climate. Forest fuel conditions conducive to extreme wildfire increased in the 20th century due to the historical land management practice of total fire suppression. The removal of fire from the ecosystem led to the accumulation of flammable small trees and ground fuels, increasing wildfire risk in western US forests (Parsons and DeBenedetti 1979). Wildfire risk is further exacerbated by the longer and drier summers emerging from climate change, as the combination of excess forest fuels and intensified summer conditions provides the optimal setting for extreme wildfire when ignitions occur (USFS 2022a).

1.1.1 Historical Fire Suppression

In the late 19th and early 20th centuries, landowners perceived wildfire solely as a threat to human safety and property (Parsons and DeBenedetti 1979). The American migrants establishing new settlements in the western US had little to no knowledge of the role of natural fire in the forest ecosystem. Therefore, the nascent land management agencies implemented a policy of total fire suppression, working to extinguish any wildfire that threatened human development, regardless of size or intensity (Agee and Skinner 2005). Forests in the western US are adapted to fire, with historical fire intervals on average of 15 years (USFS 2014). The omission of fire from the natural cycle led to the accumulation of overgrown vegetation, referred to as fuels. The high density of forest fuels resulting from a history of total fire suppression is a major driver of the current wildfire crisis.

1.1.2 Environmental Conditions

In addition to excessive fuel conditions, changing climate is exacerbating the wildfire crisis. Average summer temperatures in California have risen by 3°F in the 20th century, with the majority of warming occurring after 1970 (Scripps Institution of Oceanography n.d.). The consequence of this warming is increased aridity in forests, as hotter temperatures increase the atmospheric vapor pressure deficit (Williams et al. 2019). The warming trend extends the summer season and therefore, the wildfire season. Dry forests with dense fuels, combined with a lengthier wildfire season, provide the conditions for extreme wildfire.

1.2 Managing Wildfire Risk

The USFS manages wildfire risk by reducing hazardous fuels, i.e. the excess vegetation on the ground or in the forest canopy that can increase wildfire severity (USFS 2022b). These "fuel reduction treatments" are implemented using two primary methods: thinning and prescribed fire (Agee and Skinner 2005). Thinning can reduce hazardous fuels using mechanical masticators that are capable of uprooting, lopping, and transporting smaller and medium size trees. Thinning can also be achieved by hand with a chainsaw crew. Prescribed fire is the method by which land managers intentionally set low-intensity fire to burn the underlying hazardous fuels in the forest understory.

Researchers and forestry experts agree that fuel reduction treatments are effective at mitigating wildfire behavior, and numerous studies have confirmed this consensus (e.g. Petrakis et al. 2018; Prichard et al. 2010). Land managers consider a staged treatment of thinning, followed by prescribed fire, to be the most effective treatment method. However, a lack of agency capacity and funding can serve as a barrier to the implementation of prescribed fire (USFS 2022b). Thinning is commonly the only treatment that land managers can implement due to these obstacles. The logistical constraints to implementing both thinning and prescribed fire raise the following question: how much more effective at reducing wildfire severity is a combination of prescribed fire and thinning compared to prescribed fire or thinning alone? A more complete understanding of the impacts of different treatment types can help land managers implement forest resilience programs with greater effectiveness. To address this need, this thesis explores a case study on how the two major treatment types, thinning and prescribed fire, affected burn severity and post-fire forest change in 2021 Caldor Fire in northern California.

1.3 Motivation

There is an urgent need to protect Sierra Nevada forests from the threat of extreme wildfire. Geographic information science and technology (GIST) can contribute to this need by enabling the assessment of wildfire severity over larger extents than is feasible through traditional field research. Land management agencies are implementing intensive fuel reduction treatments across the landscape in areas where the forest vegetation is overgrown and contains an increased fuel load. The goal of these treatments is to increase forests' resilience to wildfire, by reducing burn severity and by improving forests' self-renewal capabilities post-fire (USFS 2022a). However, when wildfires do inevitably burn through treated forest, there is an opportunity to study the impact that treatments had on wildfire behavior. GIST methods and satellite remote sensing data can be used to measure the efficacy of fuel treatments and to draw comparisons between treatment types. More research is needed to understand the efficacy of specific treatment types, to inform land managers of the optimal way to manage wildfire risk. The research topic in this thesis assesses fuel treatment influences on wildfire behavior by comparing burn severity and post-fire forest change within different fuel treatment types. The analysis is a case study, focusing on the 2021 Caldor Fire. This research contributes to the field by adding a new case study to the wildfire ecology literature and demonstrating how the analysis can be done using geospatial analysis techniques with open-source, authoritative data.

1.4 Research Goals and Objectives

The research objective is to compare the influence of various types of fuel reduction treatments on wildfire intensity of the 2021 Caldor Fire. The aspects of wildfire intensity analyzed in this thesis are burn severity and post-fire changes to forest conditions, such as vegetation cover and soil moisture. This thesis aims to explore the following questions about the

Caldor Fire: did areas receiving a particular treatment experience higher severity burns than other treatments? Did the forest change more drastically in areas receiving particular treatments, and how do forest conditions related to vegetation and moisture recover through time?

The hypothesis is that different treatment types experienced variations in burn severity and post-fire forest change, and that certain treatments experienced lower burn severities and smaller changes to forest conditions. The null hypothesis is that all of the treatments experienced similar patterns of burn severity, and that no particular treatment experienced statistically significant differences in burn severity or post-fire forest change. The general methodology entails the comparison of pre-fire and post-fire conditions to derive raster datasets measuring burn severity and post-fire forest change, extracting the raster values to each of the treatment types, and comparing the distribution of burn severity and post-fire forest change values within each treatment type.

1.5 Study Area

The Sierra Nevada is a mountain range located in the western US, predominantly within the state of California, as shown in Figure 1. This region features a mix of rugged mountains, deep valleys, and alpine meadows, supporting a variety of vegetation types including coniferous forests, chaparral, and grasslands (Fites-Kaufman et al. 2007). Within this range, the Eldorado National Forest spans approximately 596,724 acres and is known for its dense forests primarily composed of Ponderosa pine, Douglas fir, and oak woodlands (USFS 2019).

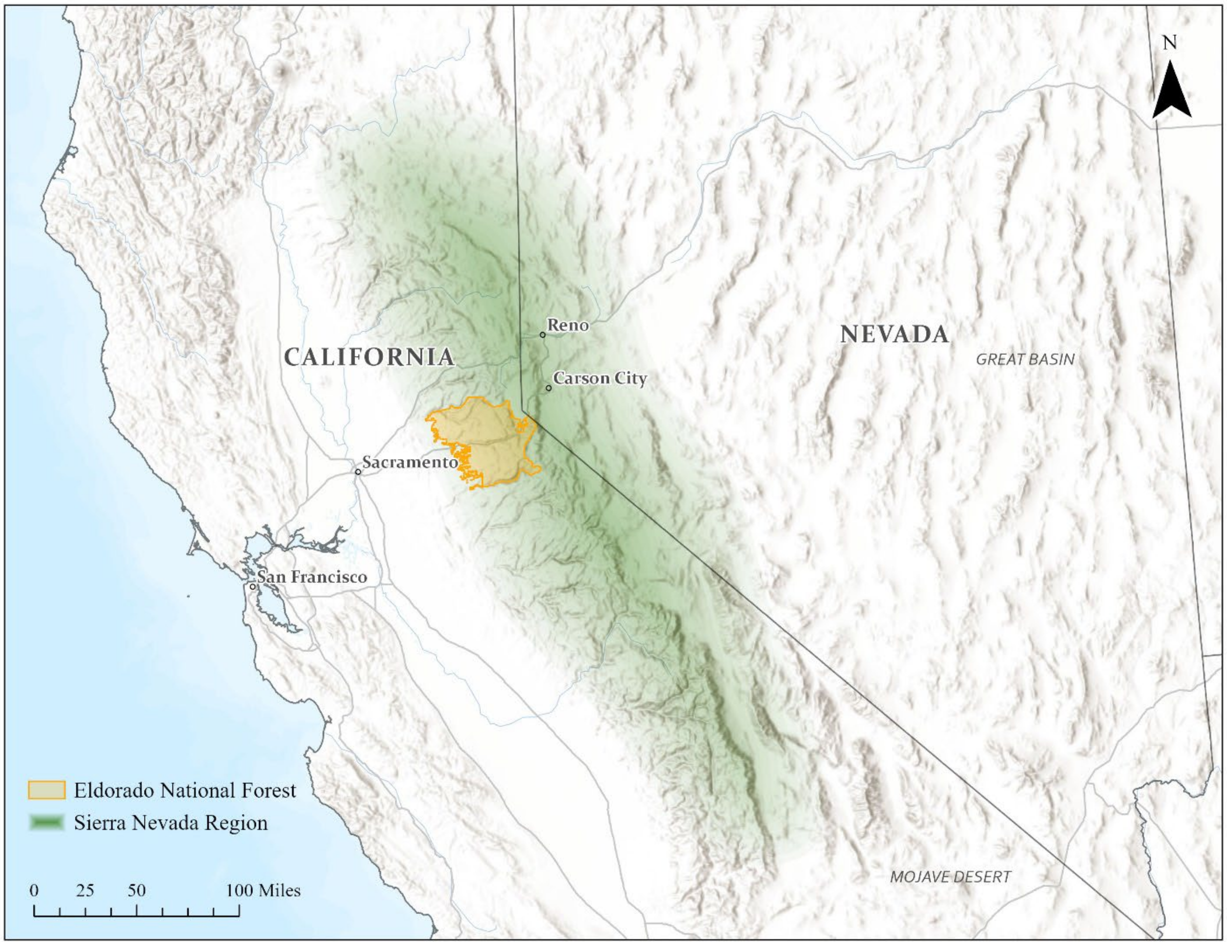

Figure 1. Sierra Nevada region of the western US

The Caldor Fire, which ignited on August 14th, 2021, was a large wildfire that burned 221,835 acres in the Eldorado National Forest and other areas in the Alpine, Amador, and El Dorado counties of Northern California (Figure 2). The fire’s footprint spanned approximately 46 miles across the Sierra Nevada mountain range, primarily between Highways 50 and 88. The fire's impact included significant tree mortality, soil exposure, and changes in vegetation cover, which have implications for the forest's recovery and management strategies (CalFire 2021). The fire was fully contained on October 21, 2021 (CalFire 2021).

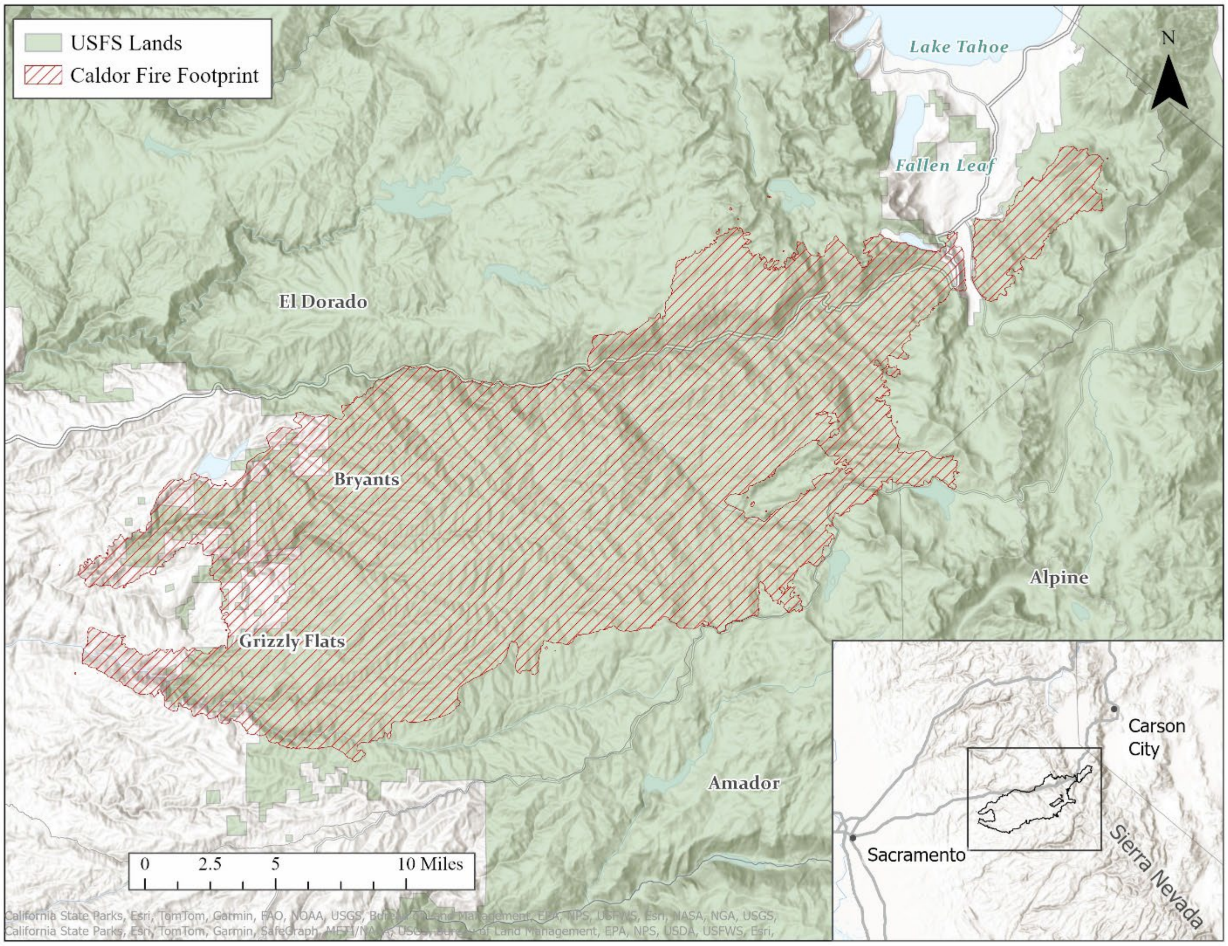

Figure 2. Location and extent of the 2021 Caldor Fire

The Caldor Fire presents an opportunity to evaluate fuel treatments because it burned through forest that had undergone prior treatments. Assessing the landscape post-fire enables a comparison of the wildfire intensity experienced by different treatment types. This thesis employs a case study of the Caldor Fire to explore how different treatment types may have impacted wildfire intensity, specifically burn severity and post-fire forest change.

1.6 Methods Overview

The methodology employs a temporal analysis of Landsat imagery to assess burn severity in the aftermath of the Caldor Fire. The temporal analysis consists of comparing pre-fire and post-fire images to measure the degree of burn severity. Burn severity is mapped across the Caldor Fire using raster datasets, and the raster values within various treatment types are compared. The Landsat imagery is further transformed to assess post-fire changes to forest conditions such as vegetation cover and soil moisture. The primary sources of data include Landsat imagery and the location of fuel reduction treatments from the USFS.

1.7 Document Overview

Moving forward, this thesis contains four chapters. Chapter 2 covers the related research on fuel treatment implementation and efficacy. Chapter 3 describes the analysis used to achieve the research objective of comparing fuel treatments. Chapter 4 presents the results of the analysis described in Chapter 3. Chapter 5 discusses the implications of the findings, limitations of the analysis, and opportunities for future research.

Chapter 2 Related Work

This chapter covers what others have researched on the topic of wildfire risk management and fuel reduction treatments. The research principles on fuel treatments are discussed, followed by studies on fuel treatment efficacy and comparisons of treatment types.

2.1 Basic Principles of Fuel-Reduction Treatments

Due to the rigorous fire suppression policies implemented in the forests of the western US during the 20th century, forests in the Sierra Nevada have become overgrown with vegetation that can serve as fuels for extreme wildfire (Parsons and DeBenedetti 1979). These hazardous fuel conditions prompted the federal government to pass the Healthy Forests Initiative, empowering land managers to maintain forests that are more resilient to wildfire (USFS 2004). Despite management efforts, wildfires have been growing in size, duration, and severity over the past 20 years (USFS 2022a). The hazardous fuel conditions, combined with the longer and drier summers characteristic of climate change, have rendered modern forests more vulnerable to extreme wildfire (USFS 2022a). To address the growing wildfire risk, land managers implement fuel reduction treatments to reduce the hazardous fuels on the landscape. These treatments are implemented through two primary methods: thinning and prescribed fire.

2.1.1 Principles of fuel reduction treatments

As noted, the intensive 20th century fire suppression policies, combined with the selective extraction of large, fire-resistant trees, caused an accumulation of small trees and high fuel loads in western forests (Agee and Skinner 2005). This accumulation enables wildfires that normally remain on the forest floor, referred to as surface fires, to move up into the forest canopy, a process referred to as "torching" (Agee et al. 2000). The small trees that elevate surface fire are referred to as ladder fuels, because they serve as a “ladder” for surface fire to climb into the live foliage of the forest canopy, referred to as “crowns” (Agee and Skinner 2005). Agee and Skinner (2005, 85) define a crown fire as occurring when “surface fires create enough energy to preheat and combust live fuels well above the ground”. Once a crown fire is initiated, fire can move from tree crown to tree crown, in a process referred to as “active crown fire spread” (Agee et al. 2000; Van Wagner 1977). Active crown fire is characteristic of high severity wildfire, as it induces mass tree mortality because the trees cannot survive without their leaves. To summarize this process, the density of small trees and undergrowth in modern forests serve as ladder fuels for surface fire to elevate into the forest canopy. The resultant crown fires burn the leaves of many trees, causing the mass tree death characteristic of high severity wildfire. Fuel reduction treatments can be used to reduce the surface, ladder, and canopy fuels in overgrown forests, which can help reduce the risk of crown fire and high severity wildfire (Agee and Skinner 2005; USFS 2022b).

Agee and Skinner (2005) summarize four key principles for the implementation of effective fuel reduction treatments. The overarching objective of these principles is to reduce the surface, ladder, and canopy fuels that can lead to dangerous crown fires. The first principle is to reduce surface fuels such as small trees and undergrowth. Reducing surface fuels mimics the role of natural, low severity wildfire, and minimizes the threat of a potential crown fire. The second principle is to increase the height to live crown. Elevating the forest crowns reduces the potential for surface fire to elevate to a crown fire. The third principle is to decrease crown density, meaning reduce the foliage in the forest canopy. This can minimize the potential for wildfire to travel throughout the canopy, jumping from crown to crown. The final principle is to retain the large, mature trees that are resistant to burning. Retaining the healthy, older trees that have fire-resistant bark preserves forest structure. Administration of these principles can be achieved by implementation of the two primary fuel reduction treatment methods: thinning and prescribed fire.

2.1.2 Definitions of Thinning and Prescribed Fire

Thinning as a general practice entails the reduction of trees and other vegetation in a forest stand, where a stand refers to an area of forest (Graham et al. 1999). Thinning can be implemented to return a forest stand to a desired composition, to prepare a site for a commercial harvest, or as a means of managing hazardous fuels (Graham et al. 1999). Thinning as a fuel reduction treatment is used to reduce surface, ladder, and canopy fuels. The objective is to increase the vertical and horizontal space between fuels, reducing the potential for a crown fire. Thinning is commonly implemented using machines called masticators, which can chop down trees and remove the branches in an efficient manner. Thinning can also be implemented by crews equipped with chainsaws.

Prescribed fire entails the controlled burning of a forest stand under safe weather conditions to reintroduce the benefits of natural fire to the landscape (USFS 2022b). Prescribed fire is especially effective at reducing surface fuels occurring on the forest floor (Agee and Skinner 2005). Other benefits include the recycling of soil nutrients, improving habitat for wildlife, and triggering the reproductive cycles of fire-dependent tree species (USFS n.d.).

In terms of Agee and Skinner's firesafe principles (2005), prescribed fire is effective at addressing the first and second principles: reducing surface fuels and increasing the height to live crown. Prescribed fire is effective at reducing surface fuels and increasing the high to live crown because it is used to burn the vegetation occurring on the forest floor. Thinning is effective at addressing the second, third and fourth firesafe principles: increasing the height to live crown, decreasing crown density and retaining large, mature trees. Prescribed fire cannot be used to decrease crown density (i.e. canopy density), as the risk of causing an uncontrollable crown fire is too high. In contrast, thinning can be used to selectively thin the forest crowns and to select which trees to remove and which ones to retain. One drawback of thinning is the creation of additional dead, woody debris that can increase ground fuels, so land managers try to follow thinning with prescribed fire when possible (Agee and Skinner 2005).

Land management agencies implement these treatments separately or as a combination, depending on the fuel conditions and logistical constraints. Treatments are effective for approximately 10-15 years, so land managers must implement treatments with regularity (Agee and Skinner 2005). Limited and uncertain funding has impacted the feasibility of treatment projects, and the schedule of treatments has not met the scale of required work (USFS 2022a). Implementation of prescribed fire treatments can be particularly complicated, as environmental constraints such as air quality standards must be maintained (Agee and Skinner 2005). Furthermore, the risk of a prescribed fire growing out of control is always present (WFCA 2022). Adding to the complexity of fuel treatments are the social hurdles, as community members and stakeholders can be resistant to management strategies that remove trees and vegetation, altering the landscape (Toman et al. 2014). To justify their wildfire risk management strategies, land management agencies rely on the scientific literature establishing the efficacy of fuel reduction treatments.

2.2 Fuel Treatment Efficacy

The efficacy of both prescribed fire and thinning as treatments for reducing wildfire severity is well documented. Research has demonstrated the capacity of prescribed fire to mitigate wildfire behavior, as a reduction in surface fuels can minimize various wildfire parameters such as rate of spread, flame length, and heat per unit of area (Van Wagtedonk 1996). The USFS studied the influence of thinning though a comprehensive literature review, finding that thinning can minimize crown fire potential and wildfire severity by reducing the density of foliage in the canopy (Graham et al. 1999). In sum, prescribed fire and thinning methods that effectively reduce surface fuels, ladder fuels, and crown density can reduce crown fire potential and mitigate wildfire behavior (Omi and Martinson 2002). Subsequent research has emphasized the efficacy of the combining these treatments (e.g. Martinson and Omi 2013; Safford et al. 2012). These papers do not make direct comparisons between prescribed fire and thinning but look at fuel treatments generally and their influence on wildfire severity.

2.3 Comparisons of Fuel Treatments

Expanding on the literature regarding fuel treatment efficacy, researchers have also compared fuel treatments to one another, which is the focus of this thesis. The goal of such research is to compare the efficacy of different treatments for mitigating wildfire severity. Generally, the treatments of comparison are separated into three categories: thinning, prescribed fire, and a combination of both. Research in this specific field employs various methodologies. Earlier studies rely on simulation or field-based methods, and remote-sensing methods have become popular as satellite imagery has become more accessible. The conclusions from these studies support the consensus that a combination of both prescribed fire and thinning is the most effective treatment type when compared to thinning or prescribed fire alone. This is consistent with Agee and Skinner's Firesafe Principles describing the need to treat surface, ladder and canopy fuels to minimize wildfire risk and reduce wildfire severity.

A simulation-based study from the USFS compared the effects of prescribed fire, thinning, and combination treatments at six national forests across the western US. By modelling fire behavior with the wildfire simulation software Fuels Management Analyst Plus, the researchers were able to draw broad conclusions about the influence of treatment type on surface fuel loads, forest structure, and potential wildfire severity. The USFS researchers predicted that areas treated only with thinning have the highest surface fuel loads, increasing the probability of high severity wildfire. They also predicted that areas receiving the combination treatment have a significantly lower crown fire potential, due to the reduction of fuels at both the surface and in the crowns (Stephens et al. 2009).

In contrast to simulation-based methodologies, field studies have the advantage of using empirical, observed data collected from past wildfires. In their study of the 2006 Complex Fires in Washington state, Prichard et al. measured various metrics of wildfire severity in areas that had undergone thinning only or a combination of thinning and prescribed fire. They found that wildfire severity was significantly different between the two treatment types, observing three times more tree mortality in areas that had been treated with thinning only (Prichard et al. 2010).

As satellite data has become more accessible, researchers have turned to GIST methods to analyze fuel treatments and wildfire severity. GIST studies are similar to field-based studies, but measurements of burn severity are obtained from satellite data rather than field observations. These remote sensing studies analyze satellite data through time, observing the landscape before and after a wildfire to assess the burn severity. Researchers studying past wildfires throughout the western US in Arizona, California, Montana and Washington have employed this remote sensing based approach, with results emphasizing the combination of prescribed fire with thinning to optimize fuel treatments (e.g. Taylor et al 2022; Wimberly et al. 2009). Two studies deserve special attention because they comprise the exemplar methodologies used in this thesis.

2.3.1 Exemplar Study One: Arizona Creek Fire

Petrakis et al. (2018) examined how different types of fuel treatments influenced wildfire behavior in the 2013 Creek Fire that burned in Arizona's San Carlos Apache Reservation. Their methodology employed remote sensing and statistical analysis to assess the impact of various forest fuel treatments on burn severity and post-fire forest change. The primary source of remote sensing data came from Landsat 8 Operational Land Imager (OLI). The researchers calculated the Normalized Burn Ratio (NBR) to measure burn severity by comparing pre-fire and post-fire imagery. The difference in NBR (dNBR) was calculated to classify burn severity into different groups. Post-fire forest change was assessed using the Tasseled Cap transformation of Landsat data to measure changes in the land surface characteristics corresponding to vegetation presence and soil moisture.

Their results showed that areas that had undergone prescribed fire or low intensity wildfire showed significantly lower burn severity than areas where only thinning was applied (Petrakis et al. 2018). Regarding post-fire forest change, the authors observed that Thinning Only treatment areas experienced the greatest decrease in vegetation and moisture content after the wildfire. In contrast, areas that experienced either prescribed or resource benefit burns showed significantly smaller changes in vegetation and moisture content, with values approaching pre-wildfire levels two years after the fire.

2.3.2 Exemplar Study Two: Caldor Fire

The second research paper that provides an exemplar analysis is a study on the Caldor Fire by Baker and Hanson. They conducted a study on cumulative severity, measuring the total tree mortality arising from both the treatment itself and the Caldor Fire. Their results indicated that cumulative severity was higher in treated forest compared to untreated forest. The authors also include a comparison of burn severity within the treatment types thinning only, thinning with prescribed fire, and an unmanaged/untreated control. Their results show that thinning only and thinning with prescribed fire experienced similar burn severities, enduring 51% and 52% tree mortality, respectively. The unmanaged control treatment type experienced higher burn severity with 56% tree mortality (Baker and Hanson 2022). These results are somewhat unexpected, as prior research suggests that thinning with prescribed fire treatments are more effective at reducing burn severity than thinning only.

Although cumulative severity is not the research focus of this thesis, the Baker and Hanson study is relevant because of its focus on the Caldor Fire and its inclusion of a treatment type comparison. Elements from the Baker and Hanson studies regarding treatment types and land types are adopted for analysis in this thesis.

2.4 Measurements of Burn Severity and Forest Conditions from Remotely Sensed Data

Before beginning the methods chapter, it is important to cover the concepts regarding the methodology used to measure burn severity and forest conditions with remote sensing data.

2.4.1 Remotely Sensed Measurements of Burn Severity

Remote sensing research in the wildfire and forest management domain commonly measure wildfire burn severity using the Normalized Burn Ratio, NBR. The NBR is sensitive to changes in the near-infrared and shortwave infrared portions of the electromagnetic spectrum, which correspond to biomass and soil and plant moisture content, respectively (USGS n.d.). Key and Benson established the methodology for assessing burn severity as the change in NBR, dNBR, with larger values indicating a larger degree of change post-wildfire. Utilizing the dNBR quantifies the decrease in biomass and moisture content, with larger dNBR values indicating higher burn severity (Key and Benson 2006).

In this thesis, wildfire burn severity in the Caldor Fire will be measured using dNBR. The dNBR is an established method for measuring burn severity. In an interagency partnership, the USFS utilized the dNBR to measure burn severity in a national wildfire mapping effort (Eidenshenk et al. 2007). The exemplar study by Petrakis et al. (2018) uses the dNBR to compare burn severity within different treatment types. As the dNBR is an established method for measuring burn severity, it will be used in this thesis to measure burn severity within the Caldor Fire.

2.4.2 Remotely Sensed Measurements of Forest Conditions

In addition to measuring burn severity, a method for assessing forest conditions related to vegetation cover and soil moisture has been established. This method employs a transformation of Landsat data to derive measurements of brightness, greenness, and wetness (Kauth and Thomas 1976). Known as the Tasseled Cap transformation, Kauth and Thomas demonstrated how to measure the brightness, greenness, and wetness occurring with a single Landsat pixel. This work was carried forward by Crist and Cicone (1984), who updated the transformation coefficients for the Thematic Mapper on Landsat 4 and 5. Furthermore, Zhai et al. (2022) developed new coefficients for Landsat 8.

The Tasseled Cap transformation provides measures of brightness, greenness, and wetness from Landsat images. Brightness corresponds to bare soil and rock, and values for brightness increase post-fire as soil and rock are exposed. Greenness corresponds to vegetation presence, and values for greenness decrease post-fire as vegetation burns and is destroyed. Wetness corresponds to the moisture content contained in an area’s vegetation and soil. Similar to greenness, values for wetness decrease post-fire as moisture from vegetation and soil is removed (Crist and Cicone 1984). By comparing pre-fire and post-fire values for brightness, greenness, and wetness, researchers can assess the degree of forest change due to wildfire. In this thesis, the forest condition variables of brightness, greenness, and wetness will be measured using the Landsat transformation method conceptualized by Kauth and Thomas (1976) and the updated transformation coefficients developed by Zhai et al. (2022).

Chapter 3 Methods

This chapter describes the methodology implemented to achieve the research objective. The goal of this chapter is to explain the conceptual framework for the production of the thesis. The research design, data requirements and sources, and procedures and analysis are described.

3.1 Research Design

The research objective is to compare the influence of various fuel reduction treatments on wildfire intensity of the 2021 Caldor Fire. The aspects of wildfire intensity analyzed in this thesis are burn severity and post-fire changes to the forest condition variables of brightness, greenness, and wetness. The overarching methodology is to compare pre-fire and post-fire images to measure burn severity and forest change, and then to analyze the distribution of these values within each treatment type. This design allows us to understand the influence that different treatment types have on burn severity and post-fire forest change in the context of the Caldor Fire.

The methodology is composed of three major stages. First, the treatment types are delineated to establish the location of and classify the different types of treatments. Second, burn severity is measured and the values within each treatment type are analyzed and compared. The final stage entails the assessment of the post-fire changes to the forest condition variables and the comparison of the values within each treatment type.

3.1.1 Treatment Type Delineation

This research focuses on the three major treatment types: thinning, prescribed fire, and a combination of thinning and prescribed fire. Delineation of these treatment types is necessary because the source data from the USFS is provided as specific subclasses of thinning and prescribed fire. For example, activities recorded in the source data such as a timber harvest or a forest stand improvement are both forms of thinning. Therefore, the source data was aggregated into classes representing thinning and prescribed fire. Additionally, the source data was inspected for any missing records and investigated using historical imagery.

3.1.2 Burn Severity Analysis

After delineating the treatment types, burn severity is mapped across the Caldor Fire footprint. The resultant burn severity raster dataset is extracted to each of the treatment types. The values of the raster within each treatment type are analyzed and compared using an Analysis of Variance (ANOVA) and Tukey HSD tests. The results reveal whether the various treatment types experienced statistically significant differences in burn severity.

3.1.3 Post-fire Forest Change Analysis

The post-fire changes in the forest conditions of brightness (B), greenness (G), and wetness (W) are mapped across the Caldor Fire footprint. One year and two year changes in these variables were calculated to display long term changes in forest conditions. The resultant raster datasets were extracted to each of the treatment types and compared. The median values within each treatment type were plotted to depict the relationship between treatment type and forest conditions. The relationship between burn severity and the change in forest conditions was also plotted.

3.2 Data

The data sources used for the analysis are composed of open-source and authoritative vector and raster datasets from government organizations. The Caldor Fire footprint is obtained from the Fire and Resource Assessment Program (FRAP) and used to delineate the study area.

The fuel treatment polygons are obtained from the USFS Forest Service Activity Tracking System (FACTS) and used to delineate the treatment type polygon layers. The Existing Vegetation Type raster dataset from Landfire is used to control for vegetation, ensuring that only treatments occurring on mixed conifer woodland are considered in the analysis. A digital elevation model (DEM) from the USGS is used to control for slope, ensuring that only areas occurring on a gradual slope are considered for analysis. Table 1 displays the data sources and their purpose.

Table 1. Data sources and their purpose

Name	Data type	Resolution	Source	Utility
Caldor Fire Perimeter	Vector	Vector	Fire and Resource Assessment Program (FRAP)	General study area
Elevation	Raster	30m	USGS	Control for slope
Landsat	Raster	30m	Landsat – open source	Measure fire severity and vegetation dynamics
Existing vegetation type	Raster	30m	Landfire –open source	Control for vegetation type
Hazardous fuels treatments	Vector	n/a	Forest Service Activity Tracking System (FACTS) – open source	Identify treatment polygons
Silviculture Timber Stand Improvement	Vector	n/a	Forest Service Activity Tracking System (FACTS) – open source	Identify treatment polygons
Timber Harvest	Vector	n/a	Forest Service Activity Tracking System (FACTS) – open source	Identify treatment polygons

3.3 Analysis stage 1: Treatment Polygon Delineation

The first major stage of the analysis is preparation of the spatial data layers for the three treatment types and the untreated control: Thinning and Prescribed Fire, Thinning Only, Prescribed Fire Only, and the untreated control, Unmanaged/untreated. Because the research objective involves comparisons across different treatments, it is important to control for vegetation type, considering only treatments that occur within forest, as opposed to other land types such as chaparral. It is also important to control for terrain, so that treatments are only being compared if they occur on a similar slope.

3.3.1 Description of the Treatment Types

Thinning and Prescribed Fire signifies areas that have been treated with both thinning and prescribed fire activities. Thinning Only signifies areas that have been treated with thinning activities only, and no prescribed fire has occurred. Prescribed Fire Only signifies areas that have been treated with prescribed fire activities, and no thinning has occurred. Unmanaged/untreated signifies forest that has not undergone any treatment. Descriptions of the treatment types are provided in Table 2. Thinning and Prescribed Fire and Prescribed Fire Only are notated as “Thinning and RxFire” and “RxFire Only”, respectively.

Table 2. Description of the three treatment types and the untreated control

Treatment type	Description
Thinning and Prescribed Fire (Thinning and RxFire)	Areas that have been treated with both prescribed fire and thinning
Thinning Only	Areas that have been treated only thinning only
Prescribed fire Only (RxFire Only)	Areas that have been treated with prescribed fire only
Unmanaged/Untreated	Areas that have not been treated with any fuel-reduction treatments

These treatment types are selected because they capture the three major types of treatments: thinning, prescribed fire, and a combination of the two. Additionally, this follows the precedent set by Hanson and Baker, who compare the same treatment types in their exemplar study of cumulative fire severity in the Caldor Fire.

The locations of treatments were obtained from the publicly available Forest Service Activity Tracking System (FACTS). The cutoff date for treatments is 15 years, so any treatment occurring before 2005 is not considered. 15 years is selected in accordance with Agee and Skinner's (2005) assessment of fuel treatment longevity. To explore the influence of treatment longevity, a separate dataset with a cutoff date of 10 years was also created and is described in Section 3.3.7.

3.3.2 Controlling for Vegetation Type

Vegetation type is controlled for by restricting the analysis to the mixed conifer woodland land type. This ensures that treatment types occurring on different vegetation types are not compared. The following vegetation types were selected from Landfire's Existing Vegetation Type raster dataset: Mediterranean California Dry-Mesic Mixed Conifer Forest and Woodland, Mediterranean California Mesic Mixed Conifer Forest and Woodland, Mediterranean California Lower Montane Black Oak-Conifer Forest and Woodland, and California Montane Jeffrey Pine (-Ponderosa Pine) Woodland. Selection of these land types follows the precedent set by Hanson and Baker, who consider the same land types in their exemplar study. Figure 3 shows where mixed conifer woodland occurs within the Caldor Fire footprint.

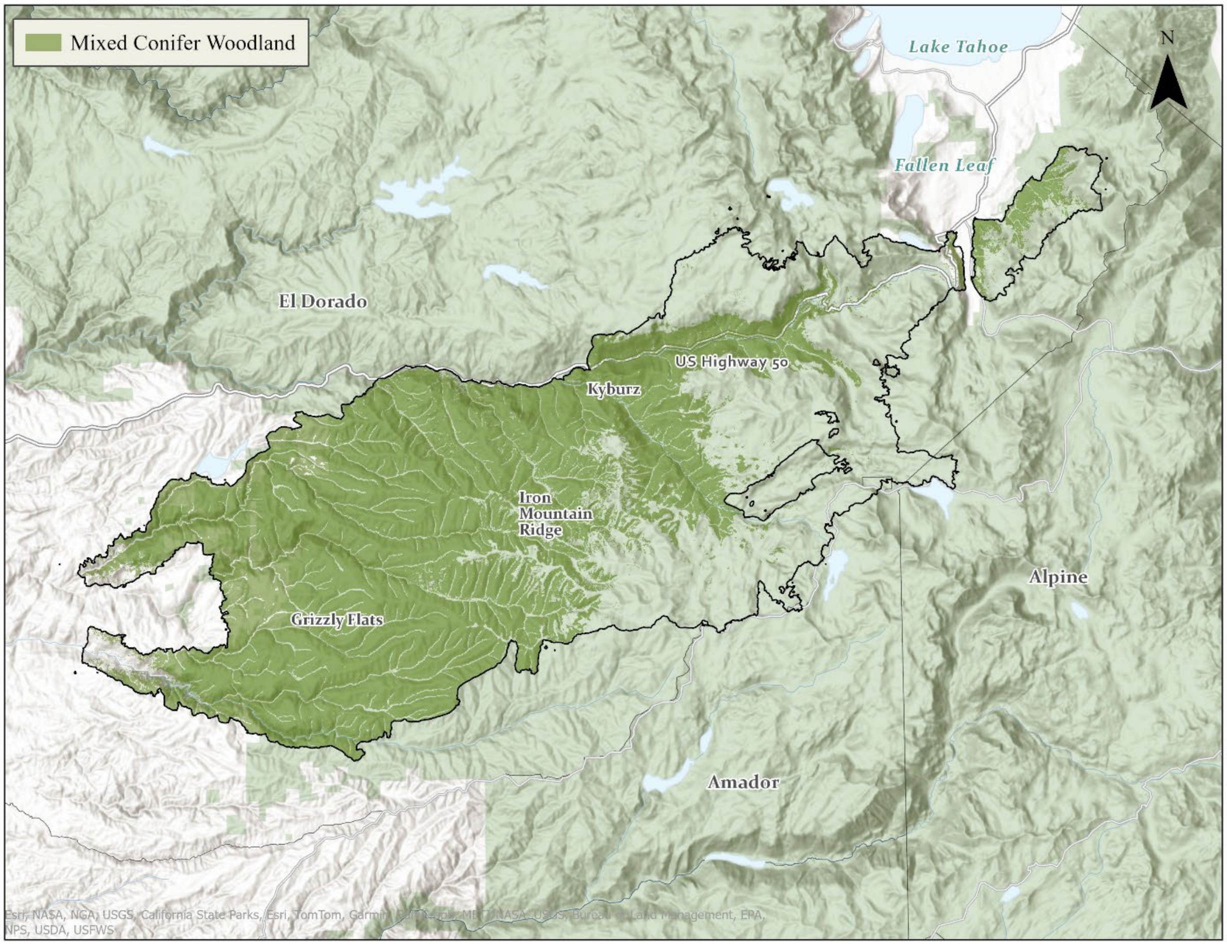

Figure 3. Extent of mixed conifer woodland within the Caldor Fire

3.3.3 Inspection and Cleaning of USFS FACTS Treatment Data

After establishing the mixed conifer woodland land within the Caldor Fire footprint, the treatment polygon data from the USFS was inspected. Three polygon datasets from USFS were used to delineate the final treatment polygons: Hazardous Fuels Treatments, Silviculture Timber

Stand Improvement, and Timber Harvest. These three datasets were visualized, cleaned, combined, and isolated in order to create the four treatment types that are used in the analysis. Using the Completed_Date field as a guide, any activities occurring before 2005 and after 2021 were removed from the analysis, as treatments older than 15 years are considered ineffective (Agee and Skinner 2005).

There were two cases of incomplete data that were resolved using an investigation of historical imagery. Two projects, the Scottiago and Trestle Forest Health Projects, had a null Completed_Date, and it was unclear whether or not the activities had been implemented. The projects were scheduled to be completed in 2019. Inspection of historical Google Earth indicated that the Scottiago project had not occurred and that the Trestle project had been implemented.

3.3.4 Creation of the Treatment Layers of Analysis

Creation of the three treatment layers Thinning and Prescribed Fire, Thinning Only, and Prescribed Fire Only was implemented by a process of combination and isolation of different activities from the initial USFS polygon data. All thinning activities and all prescribed fire activities were merged together into two large intermediate datasets. Areas where thinning and prescribed fire activities overlap were identified using the Clip tool and were exported to create the final Thinning and Prescribed Fire treatment layer. Using the Erase tool, the final Thinning and Prescribed Fire treatment layer was erased from the intermediate thinning dataset to create the final Thinning Only treatment layer. Creation of the final Prescribed Fire Only layer followed the same process, using the Erase tool to remove the final Prescribed Fire and Thinning layer from the intermediate burning layer. The end result of this process is three polygon layers for the following three treatments: Prescribed Fire and Thinning, Thinning Only, and Prescribed Fire Only. The next step was to control the final Treatment classes for slope.

3.3.5 Controlling the Treatment Types for Slope

After finalizing the spatial data layers for each of the treatment types, the next step was to model the terrain to explore the distribution of slope across the treatment types. The reason is that comparisons of treatment types should only occur on areas where the slopes are similar, as it would not be valid to compare areas with steep or gradual slopes to one another. Slope was calculated from a 30m DEM and the distribution of slope within the three treatment types was inspected. The slope for the three treatments was found to be gradual, normally distributed around 4° and tapering off around 8°. The common terrain features simplified the comparison process, as all the treatments occurred on similar terrain. For the Thinning Only treatment, slope is normally distributed around 4° and tapers off around 8° (Figure 4).

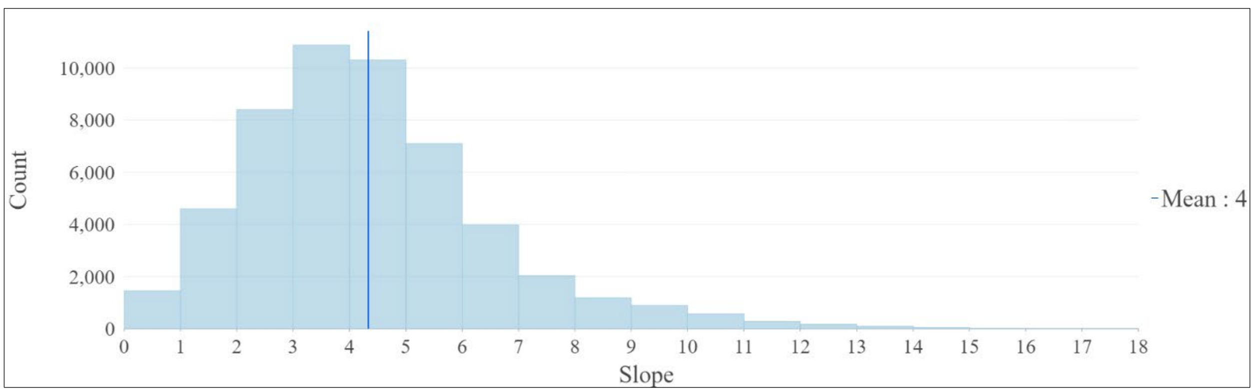

Figure 4. Distribution of slope within Thinning Only treatment

For the Prescribed Fire Only treatment, slope is normally distributed around 4° and tapers off around 7° (Figure 5).

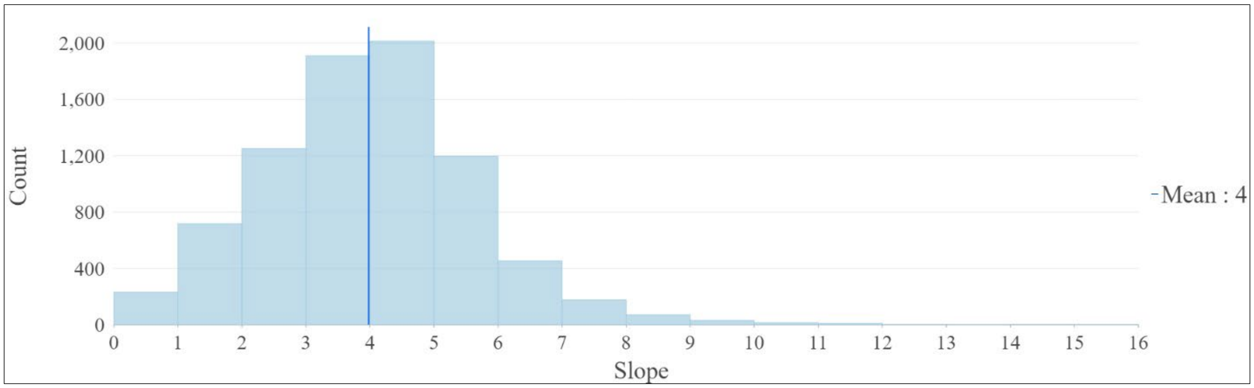

Figure 5. Distribution of slope within RxFire Only treatment

For the Thinning and Prescribed Fire treatment, slope is normally distributed around 4° and tapers off around 7° (Figure 6).

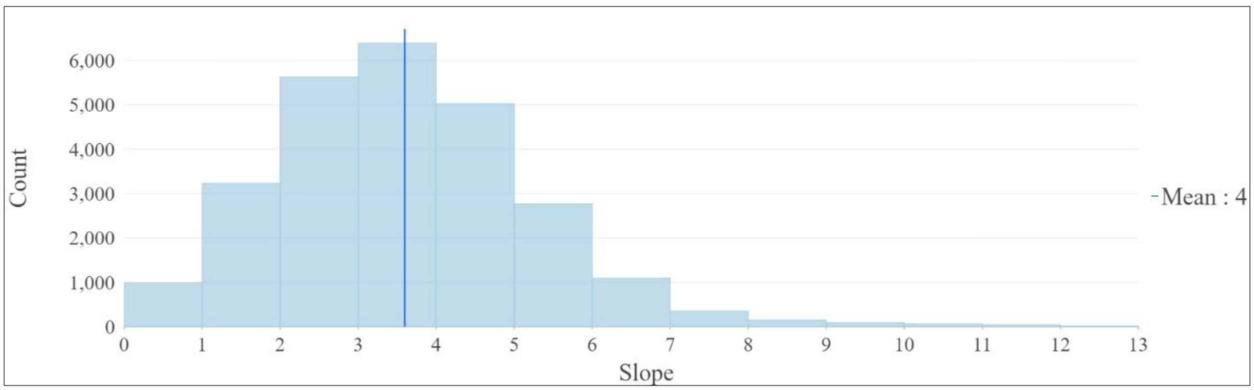

Figure 6. Distribution of slope within Thinning and RxFire Treatment

After controlling for slope, the next step was to create the untreated control, the Unmanaged/Untreated spatial data class.

3.3.6 Creation of the Unmanaged/Untreated Polygon Layer

The Unmanaged/Untreated polygon layer is not literally a treatment type, as it is the lack of a treatment. However, it is necessary to include in the analysis as a control, to compare the impact of fuel-reduction treatments to a non-treatment scenario. It is analyzed as a treatment type for convenience but is not technically a treatment. The first step in the creation of the

Unmanaged/Untreated layer was to remove the other three treatment layers from the mixed conifer woodland vegetation type using the Erase tool. To ensure that a similar slope was used for the Unmanaged/Untreated polygon layer, any areas with a slope higher than 8° were removed. The end result was a final layer for the Unmanaged/Untreated treatment type, controlled for by vegetation and slope.

3.3.7 10-year Subset of Treatment Types

The treatment type dataset only considers treatments that were completed during the fifteen year timespan between 2006 and 2021, and any areas that underwent treatments outside of that timeframe were considered untreated. Because Agee and Skinner (2005) estimate that treatments are effective for ten to fifteen years, a separate subset of the treatments was created using a ten year timeframe between the years 2011 and 2021. This 10-year treatment dataset was created by simply removing the treatments with a Completed Date prior to 2011. Creation of both a 10- and 15-year treatment dataset enables a comparison of treatment longevity. Differences in the distribution of burn severity between the 10- and 15-year treatment datasets would have implications for the longevity of treatment efficacy.

3.4 Analysis Stage 2: Burn Severity Analysis

The burn severity analysis was implemented by measuring burn severity within the entire Caldor Fire footprint, and then by extracting the values to each of the four treatment polygon layers. The burn severity pixels were converted into points, and a sample of the 8,000 points for each treatment type was input to a table. The resulting table was imported into R and analyzed to determine if variance of the burn severity values within each treatment type were statistically different from each other. This process was completed with both the 10- and 15-year treatment datasets.

3.4.1 Burn Severity Variable

Measuring burn severity begins with the Normalized Burn Ratio, NBR. The NBR is obtained from satellite images such as Landsat and is calculated as a ratio of the near infrared (NIR) and shortwave infrared (SWIR) surface reflectance captured by the satellite. The comparison of NIR and SWIR reflectance makes the NBR sensitive to changes in vegetation and moisture, therefore it is a useful index for identifying areas burned in wildfire (USGS Landsat Missions 2024). The first step is to obtain pre-fire and post-fire Landsat images and to calculate the NBR according to the following equation:

$$NBR=(OLI5\text{-}0LI7)/(OLI5+OLI7) \tag{1}$$

where OLI5 and OLI7 equal the bands 5 and 7 of Landsat 8, respectively. Burn severity is further derived from the differenced NBR, dNBR, between the NBR taken at two dates. Higher values of dNBR indicate a larger change in moisture and vegetative, and therefore, higher severity burns. The equation for burn severity is:

$$dNBR = NBR_{pre\text{-}fire} - NBR_{post\text{-}fire} \tag{2}$$

In this analysis, the dNBR is measured across a one-year time span to identify burned areas while also minimizing seasonal variation in vegetation conditions.

3.4.2 Calculation of Burn Severity

Using a Landsat pre-fire image from June 2021 and a post-fire image from June 2022, a dNBR raster was derived for the entire Caldor Fire footprint. The Raster Calculator tool was used to calculate the individual pre and post-fire NBR rasters and the same tool was used to calculate the difference between the two NBR rasters. June 2021 was chosen as the pre-fire date as the summer months in CA provide reliable, cloud free images. Consequently, June 2022 was selected as the post-fire date to compare images one year apart, controlling for seasonal variability in vegetation and climate conditions. After calculating burn severity, dNBR, within the entire Caldor Footprint, the values were spatially extracted to the appropriate treatment type using the Extract by Mask tool. The final result is four unique dNBR raster layers for each of the four treatment types. This process was repeated for both the 10- and 15-year treatment datasets. After extracting the dNBR values to the treatment classes, the next step was to statistically analyze and compare the dNBR values contained within each treatment type.

3.4.3 Validation of Burn Severity Results

To validate the dNBR results, a regression was run between the calculated dNBR raster and burn severity dataset from the USFS Rapid Assessment of Vegetation Condition after Wildfire (RAVG) program. The purpose of the RAVG dataset is to evaluate burn severity shortly after a wildfire occurs (USFS 2007). The RAVG burn severity raster was created after the fire ended in October of 2021, whereas the calculated burn severity raster outlined in the previous section was based on a one-year difference.

3.4.4 Statistical Analysis of Burn Severity

The goal of the statistical analysis is to make a meaningful comparison of dNBR across the four treatment types. The first step was to convert the dNBR raster to a point feature class, and to take a sample of those points. A sample of 8,000 points was selected for each treatment type, because the smallest treatment type, Burning Only, was composed of only 8,600 points. The samples were compared to the full datasets to confirm similar distributions, ensuring that the samples are representative of the full datasets. The samples were merged into one large excel spreadsheet composed of 32,000 entries (8,000 samples x four treatment types) and imported into the statistical program R. The ANOVA function in R was used to test if dNBR was significantly different between treatment types. Finally, the Tukey-HSD post hoc test was used to determine which of the treatment types were statistically different from each other. This process was repeated for both the 10- and 15-year treatment datasets.

3.5 Analysis Stage 3: Post-Fire Forest Change Analysis

The variables for measuring forest conditions are brightness, greenness, and wetness. Brightness corresponds to soil and bare rock exposure, greenness corresponds to vegetation presence, and wetness corresponds to soil and plant moisture (Petrakis et al. 2018). The changes in these variables were measured to quantify the degree of change occurring post-wildfire. In the aftermath of a wildfire, it is expected that values for brightness will increase, as there will be an increase in the exposure of bare soil and rock. Values for greenness and wetness are expected to decrease, as wildfire would result in loss of vegetation, vegetation moisture, and soil moisture (Petrakis et al. 2018).

The Post-fire Forest Change analysis was implemented by obtaining the values for B, G, and W during pre-fire and post-fire conditions. To assess the change in B, G, and W through time, one-year and two-year post-fire changes in the variables were calculated, represented as dB, dW, and dG. The values of dB, dG, and dW within each treatment type are analyzed, compared, and visualized. A large, negative dB, dG, or dW indicate a significant decrease in brightness, greenness or wetness. A large, positive dB, dG, or dW indicates a significant increase in brightness, greenness or wetness. The relationship between dNBR and dB, dG, and dW was plotted to visualize and establish the relationship between burn severity and changes to the post-fire forest condition variables. To monitor post-fire forest change within treatments, the median values for one-year and two-year dB, dG, and dW within each treatment type was plotted. The Post-fire Forest Change analysis was implemented using only the 15-year treatment dataset.

3.5.1 Calculating B, G, and W

The calculation of B, G, and W requires the transformation of bands 2-7 of Landsat images. A pre-fire image from 2021, a one-year post-fire image from 2022, and a two-year post-fire image from 2023 were obtained from USGS Earth Explorer. Updated transformation coefficients for Landsat 8 were published for surface reflectance images, as shown in Table 3 (Zhai et al. 2022).

Table 3. Brightness, Greenness, and Wetness Coefficients

Component	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7
Brightness	0.3690	0.4271	0.4689	0.5073	0.3824	0.2406
Greenness	-0.2870	-0.2685	-0.4087	0.8145	0.0637	-0.1052
Wetness	0.0382	0.2137	0.3536	0.2270	-0.6108	-0.6351

The Raster Calculator tool was used to apply the transformation coefficients to the pre and post-fire Landsat images, as demonstrated by Yale University's Center for Earth Observation (n.d.). The equations for calculating B, G, and W are:

$$B = (0.3690)b2 + (0.4271)b3 + 0.4689(b4) + (0.5073)b5 + (0.3824)b6 + (0.2406)b7 \quad (3)$$

$$G= (-0.2870)b2 + (-0.2685)b3 + (-0.4087)b4 + (0.8145)b5 + (0.0637)b6 + (-0.1052)b7 \quad (4)$$

$$W= (0.0382)b2 + (0.2137)b3 + (0.3536)b4 + (0.2270)b5 + (-0.6108)b6 + (-0.6351)b7 \quad (5)$$

Where b is the Landsat bands 2 through 7.

Nine total rasters were generated for the three variables and for the three years: Brightness 2021, 2022, and 2023, Greenness 2021, 2022 and 2023, and Wetness 2021, 2022, and 2023. Finally, one- and two-year changes in B, G, and W were calculated. dB, dG, and dW are studied because B, G and W alone do not have meaningful units, as they are a transformation of Landsat surface reflectance values. The dB, dG, and dW values relative to one another, combined with their values through time, indicate the degree of post-fire change occurring after the Caldor Fire.

3.5.2 Plotting B, G, and W

A plot of dNBR and one-year dB, dG, and dW was created to establish the relationship between burn severity and the change in the forest condition variables across the entire Caldor footprint. To illustrate the long-term temporal change of B, G, and W and burn severity, the dNBR raster was reclassified into four burn severity groups: Low/unburned, Low, Moderate, and High using natural breaks. The one and two-year median values of each forest change variable within each burn severity group was plotted to highlight the distinct temporal trends.

To compare dB, dG, and dW across treatment types, the one-year and two-year dB, dG, and dW rasters were converted to points and sampled. As for the burn severity analysis, a sample of 8,000 points was used due to the limited amount of points in the Prescribed Fire Only treatment type. The median value for the one-year and two-year dB, dG, and dW within each treatment type was plotted to produce a visual comparison across treatment types through time. An unburned sample was also included.

Chapter 4 Results

The results of the three analysis stages are presented in this chapter. The results of the Treatment Type Delineation analysis show how the various treatments are distributed throughout the Caldor Fire. The results of the Burn Severity Analysis display the distribution of burn severity throughout the Caldor Fire footprint, illustrating the variations in burn severity throughout the region. The hypothesis that treatment types experienced unique distributions in burn severity is confirmed. The results of the Post-fire Forest Change analysis highlight the relationship between burn severity and the forest condition variables of brightness, greenness, and wetness. The results also confirm the hypothesis that treatment types exhibit unique post-fire responses for the forest condition variables.

4.1 Treatment Type Delineation

Figure 7 displays the location of the four treatment classes used in the Burn Severity and Post-fire Forest Change analysis. These classes are based on the 15-year treatment dataset. The area is dominated by the control treatment, Unmanaged/untreated. Of the three treatment types, Thinning Only covers the largest extent. Prescribed Fire and Thinning is the next largest treatment type, followed by Prescribed Fire Only.

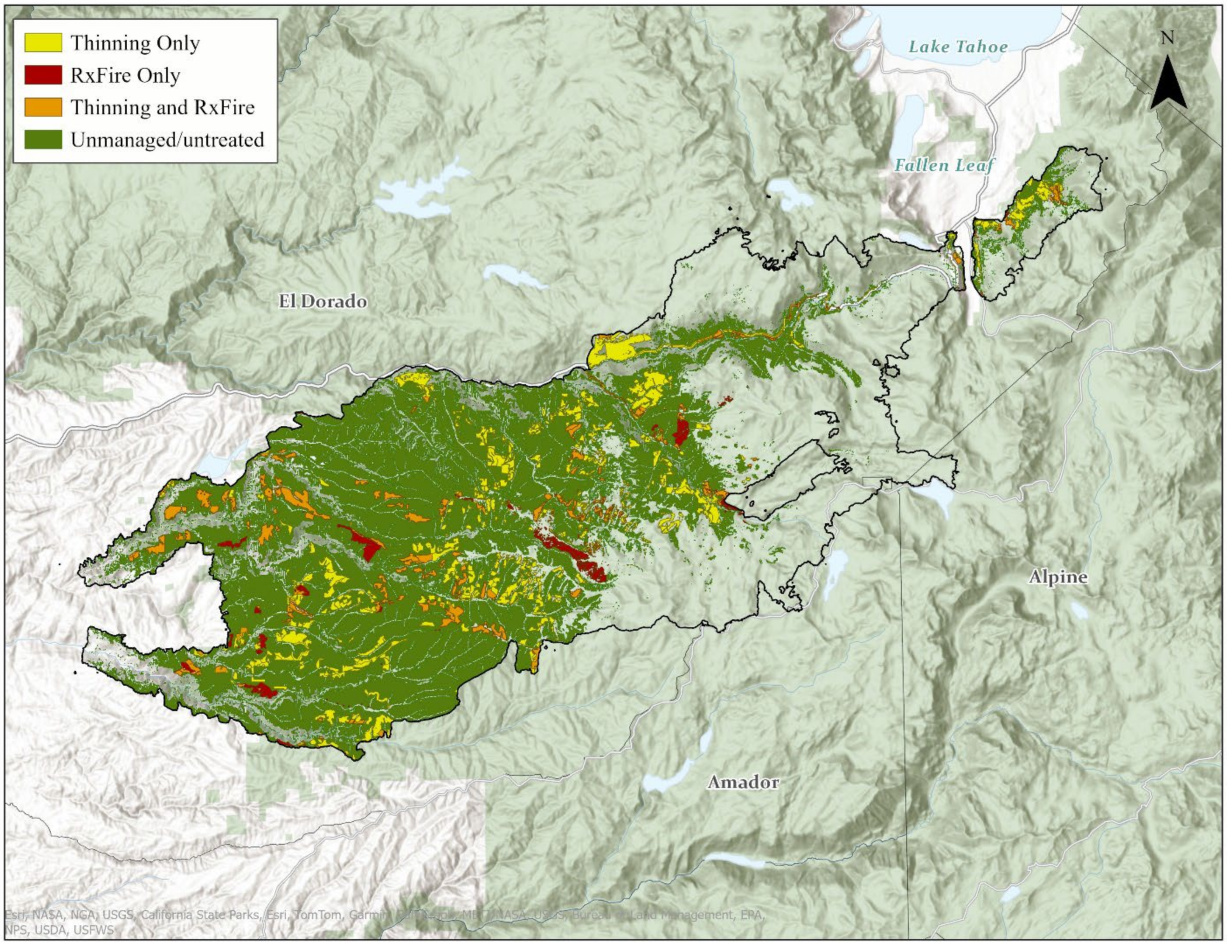

Figure 7. Distribution of treatment classes used in the analysis

4.2 Burn Severity Analysis

The results of the Burn Severity Analysis illustrate the distribution of burn severity throughout the Caldor Fire, and the unique patterns of burn severity experienced by the various treatment types.

4.2.1 Distribution of dNBR within each treatment type

Figure 8 depicts the distribution of burn severity throughout the Caldor Fire between June 2021 and June 2022. Red indicates higher severity burns, yellow indicates lower severity burns, and green indicates areas where vegetation has increased in the yearlong timespan. In general, low and medium severity burns occurred along the edges and within the center of the fire's footprint. High severity burns occurred in patches throughout the Caldor Fire and in one large region in the western half of the fire's footprint.

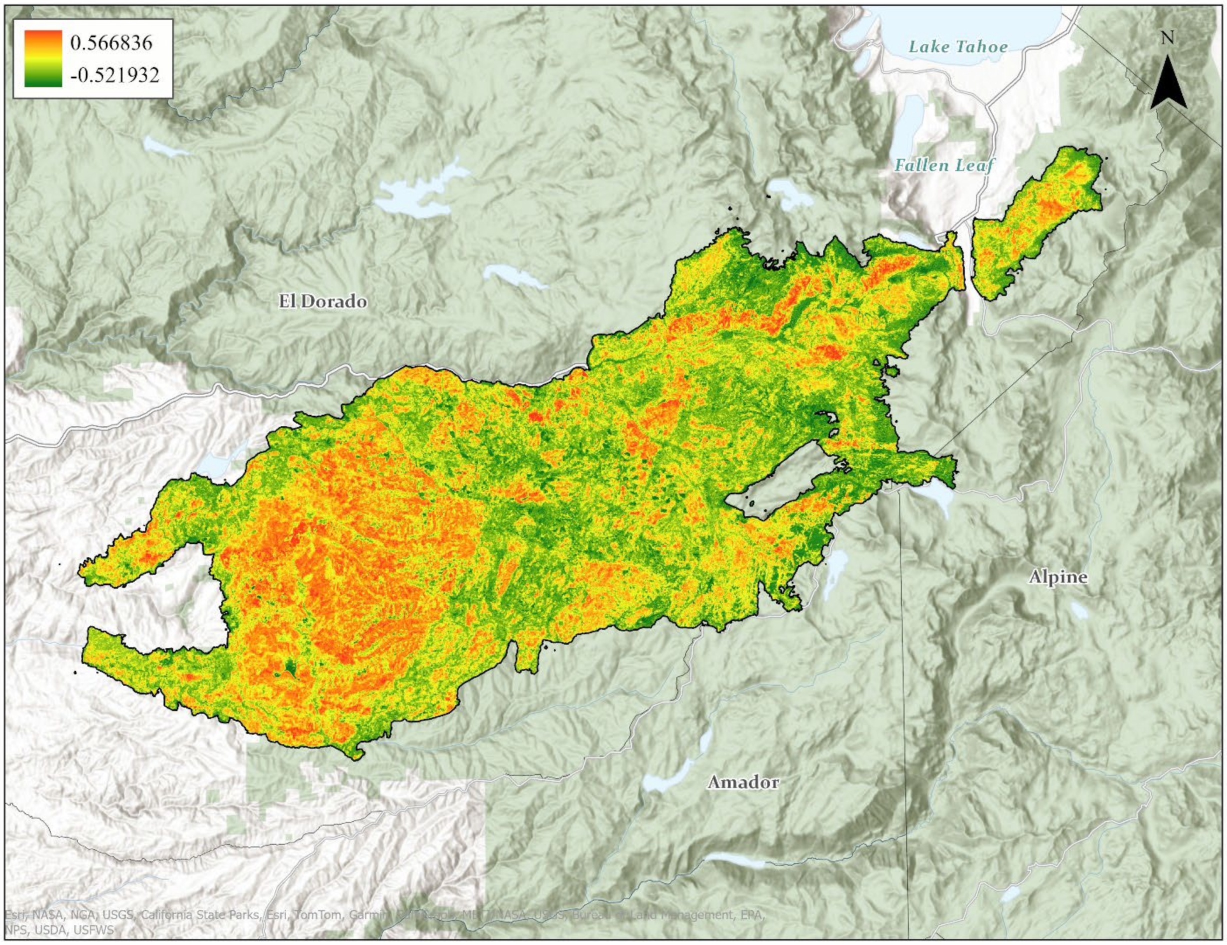

Figure 8. Calculated dNBR between June 2021 and June 2022

Validation of the calculated burn severity results was implemented using a regression with the authoritative burn severity dataset from RAVG, depicted in Figure 9. The values for the dNBR from RAVG are multiplied by 1000, per their standards. The results of the regression produced an R2 of 0.763, indicating a high degree of correlation between the calculated and authoritative dNBR datasets. Visual observation of the two datasets shows many similarities in the distribution of burn severity, with high burn severity occurring western half of the fire's footprint. The differences in the datasets can be attributed to the different timespans. The RAVG dNBR dataset was calculated based on a 3 month timespan, whereas the calculated dNBR dataset utilized a yearlong timespan, during which vegetation was able to recover.

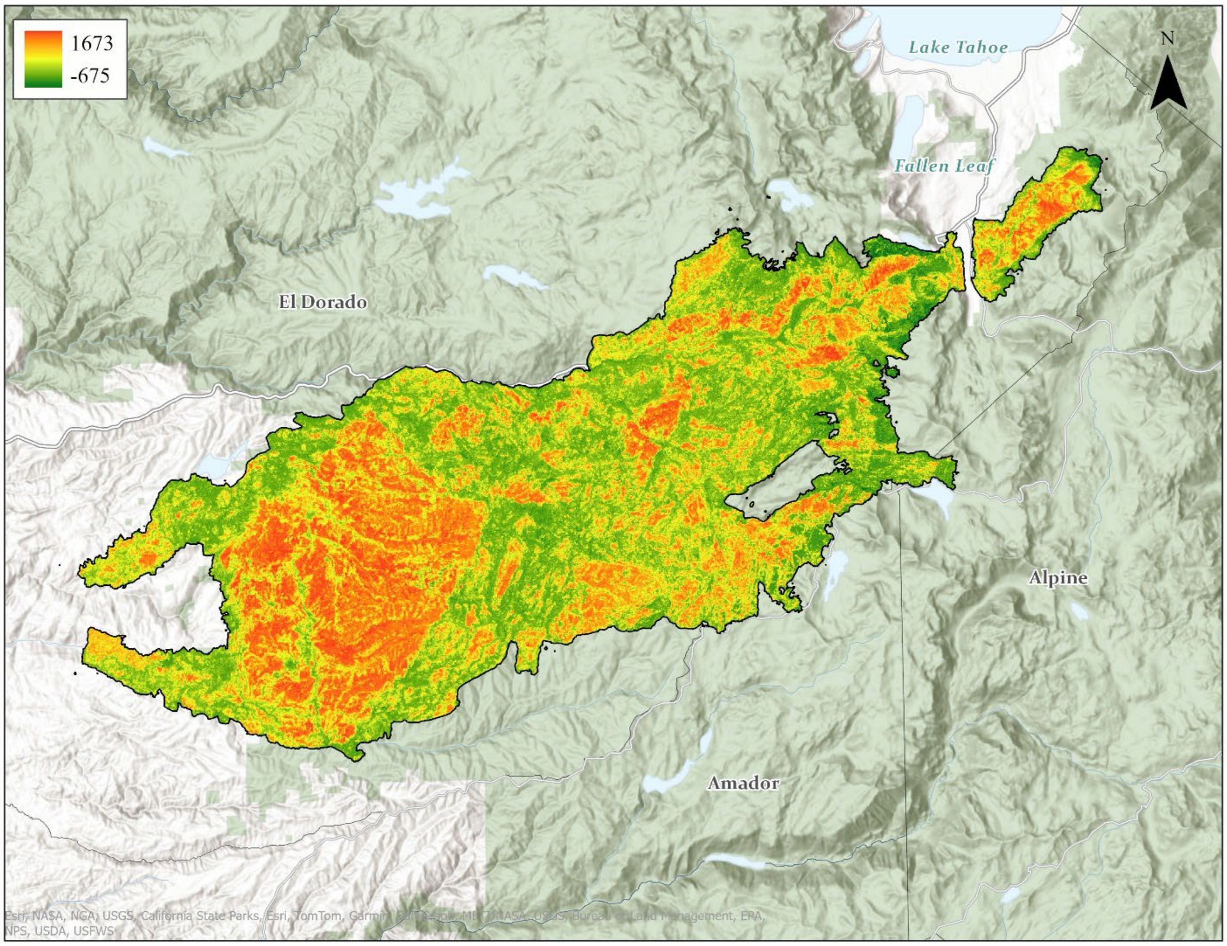

Figure 9. Authoritative dNBR from RAVG between June 2021 and October 2021

After mapping dNBR across the entire Caldor Fire, the dNBR raster was extracted to the four treatment types. The figures displaying dNBR extracted to the treatment types do not show the entirety of the treatment type within the study area but are zoomed in to provide a sense of the distribution of dNBR within the treatment type. The Thinning Only treatment occurred frequently throughout the study area, and displays a large proportion of low dNBR values, as shown in Figure 10.

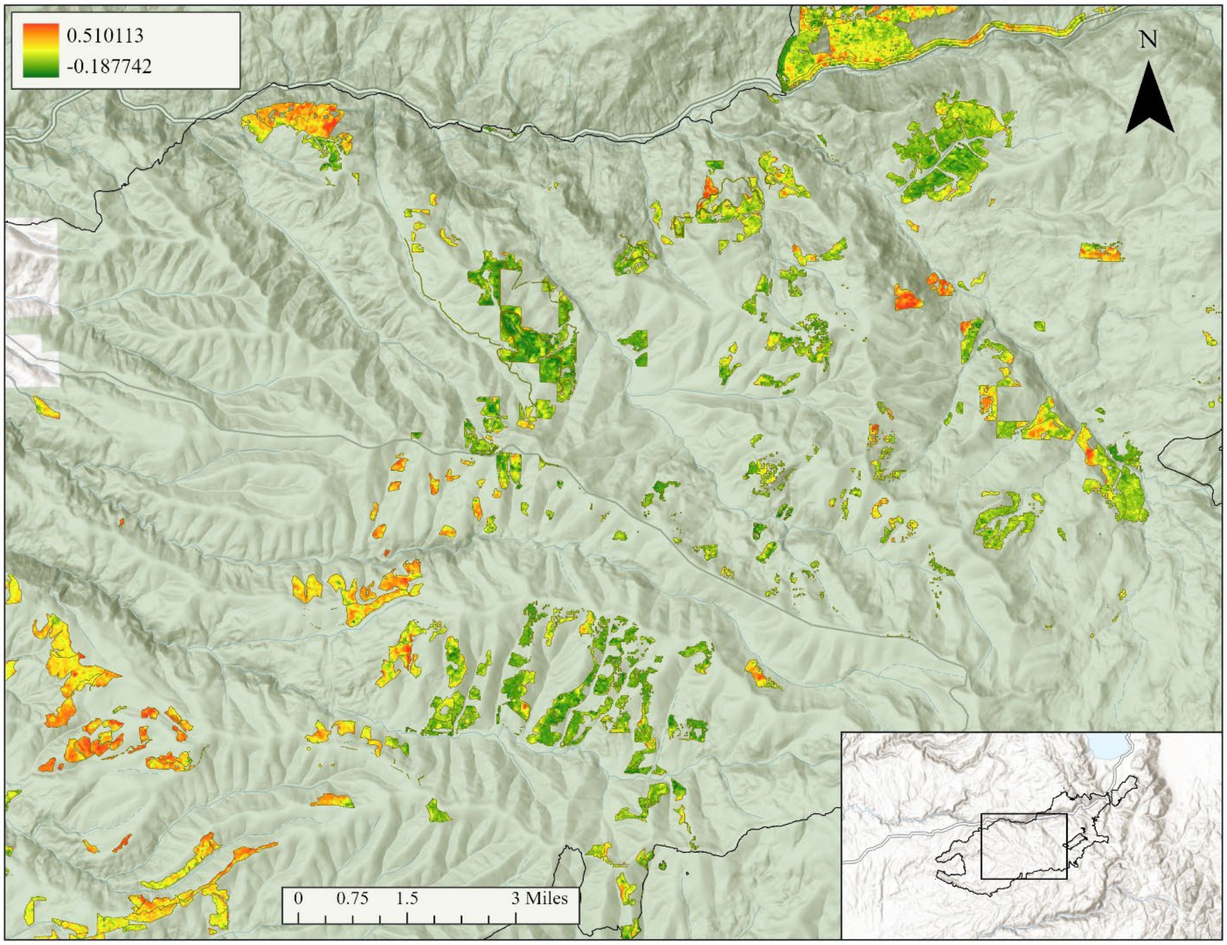

Figure 10. dNBR extracted to the Thinning Only treatment type

The Prescribed Fire Only treatment was implemented sparsely throughout the study area, primarily in the portion of the Caldor Fire that experienced high burn severity. dNBR values show a large proportion of moderate and high dNBR values, as shown in Figure 11.

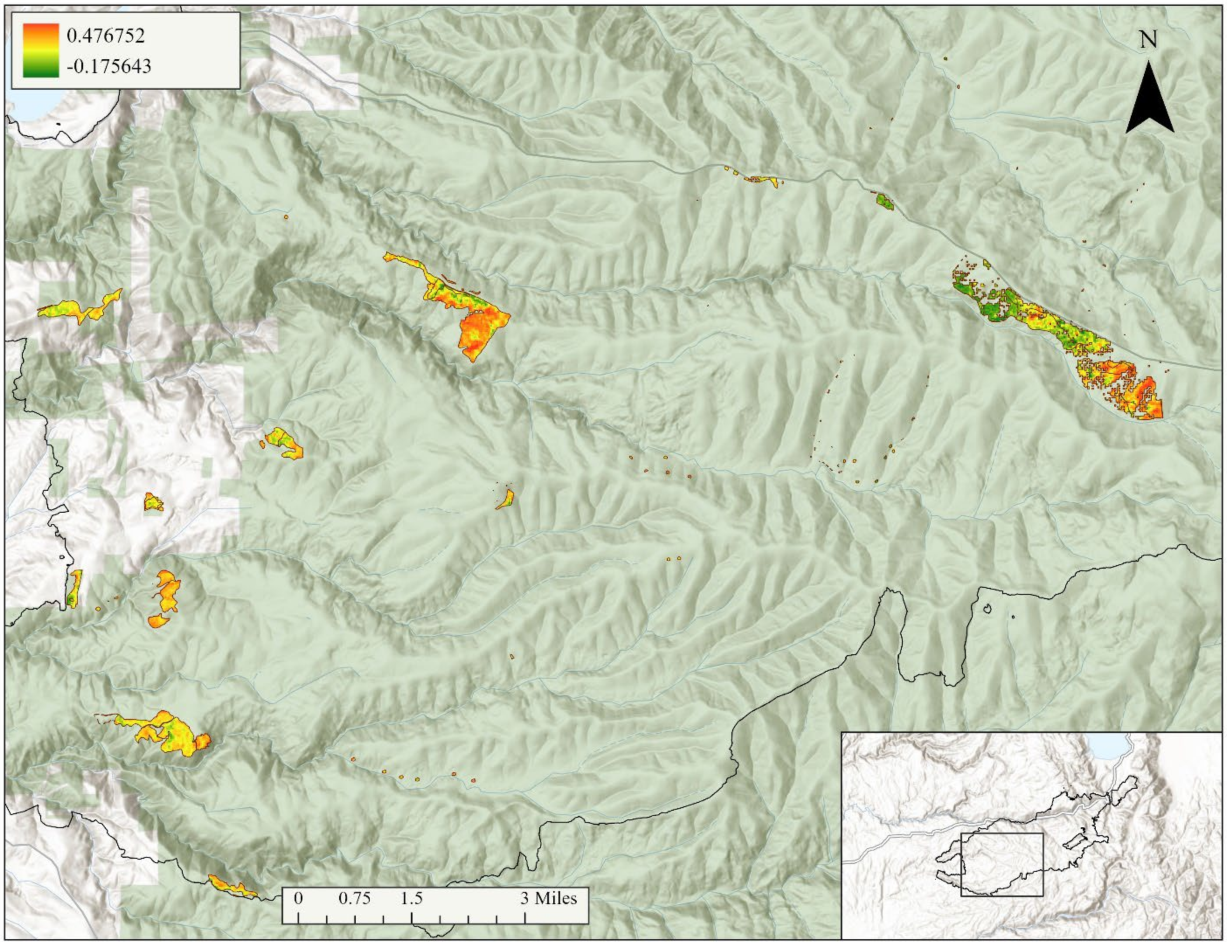

Figure 11. dNBR extracted to the Prescribed Fire Only treatment type

The Thinning and Prescribed Fire treatment occurred frequently throughout the entire study area, but less so than the Thinning Only treatment. The dNBR values appear evenly split between low and high severity, as shown in Figure 12.

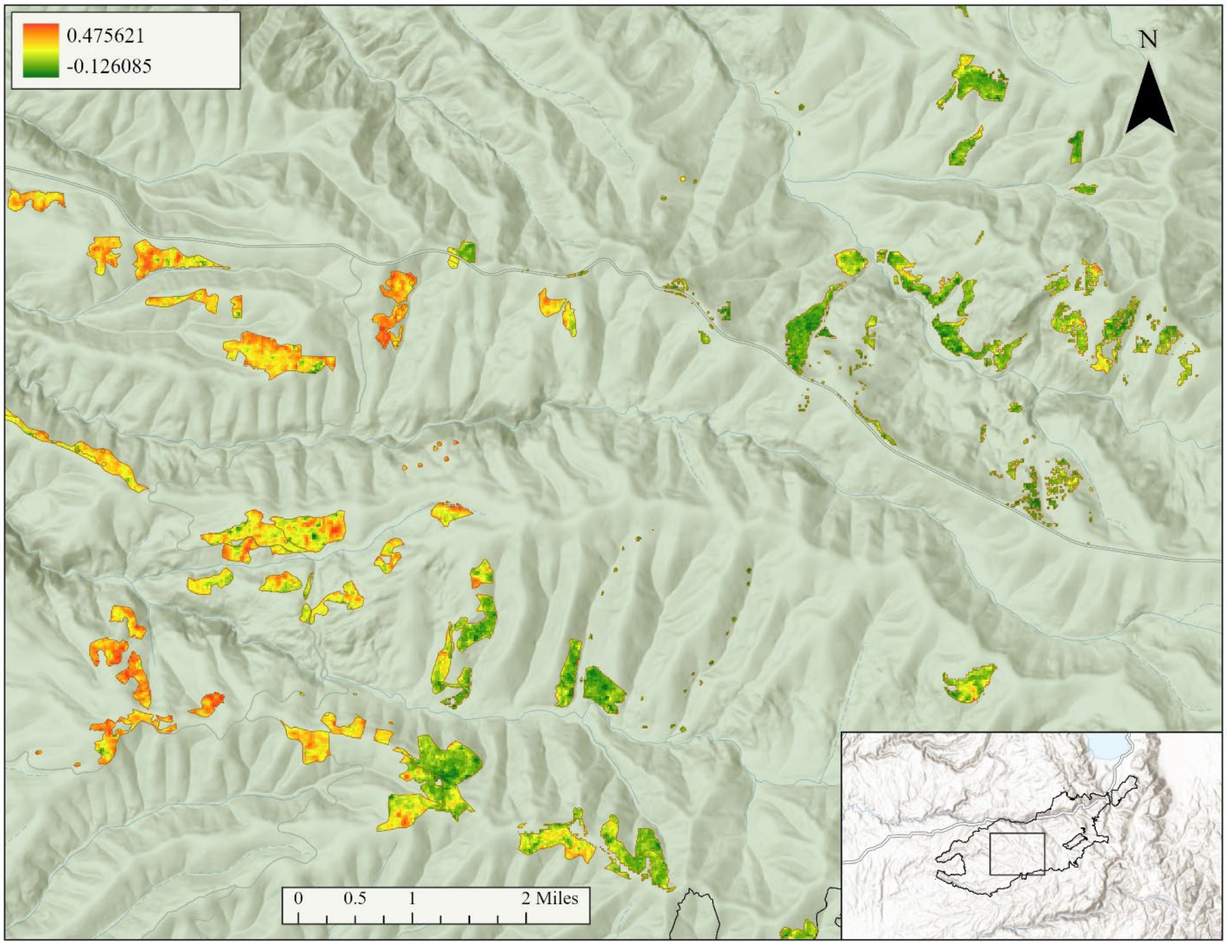

Figure 12. dNBR extracted to the Thinning and Prescribed Fire treatment type

The untreated control, Unmanaged/untreated, was the most prevalent category within the study area (Figure 13). It occurred primarily in the western half of the study area and displays a large proportion of high dNBR values.

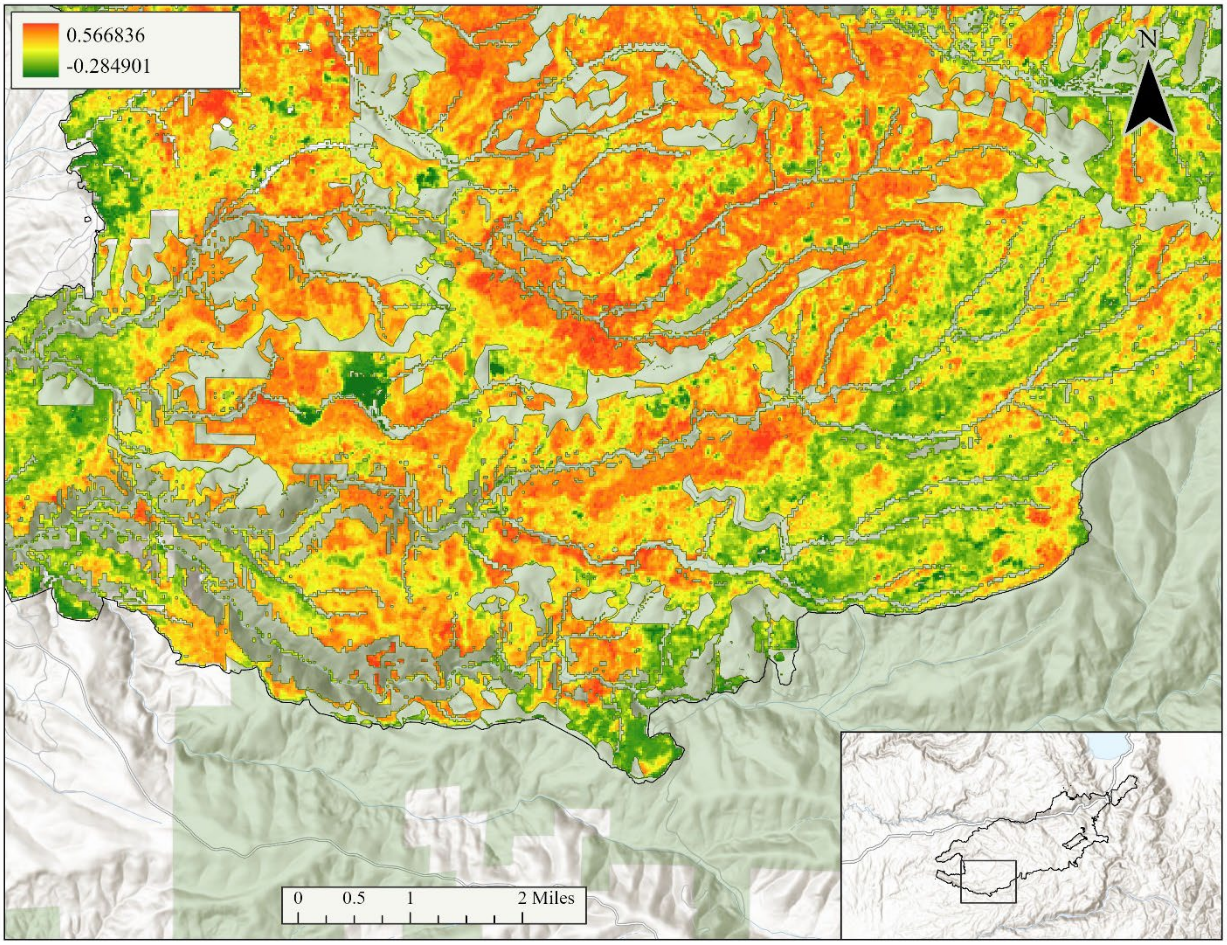

Figure 13. dNBR extracted to the Unmanaged/untreated treatment control

4.2.2 Comparison of 10- and 15-year Treatment Datasets

Each of the treatment types experienced unique distributions of burn severity for both the 10- and 15-year treatment datasets. For the 10-year treatment dataset, the Thinning Only treatment had the lowest mean dNBR, followed by Thinning and Prescribed Fire and Prescribed Fire Only (Figure 14). The untreated control displayed the highest dNBR.

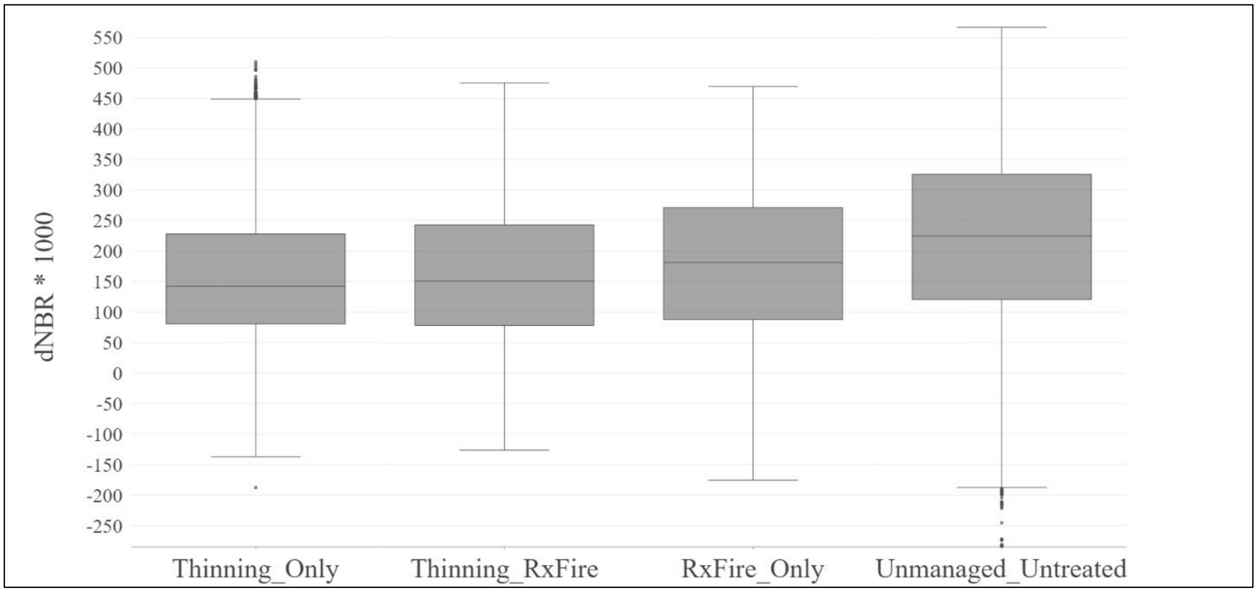

Figure 14. Distribution of dNBR for the 10-year treatment dataset

The results for the 15-year Treatment dataset are similar to the 10-year treatment dataset, except Thinning and Prescribed Fire had the lowest mean dNBR, just slightly under the mean dNBR of Thinning Only. Prescribed Fire Only had the highest dNBR of the three treatments, followed by the untreated control, which showed the highest dNBR (Figure 15).

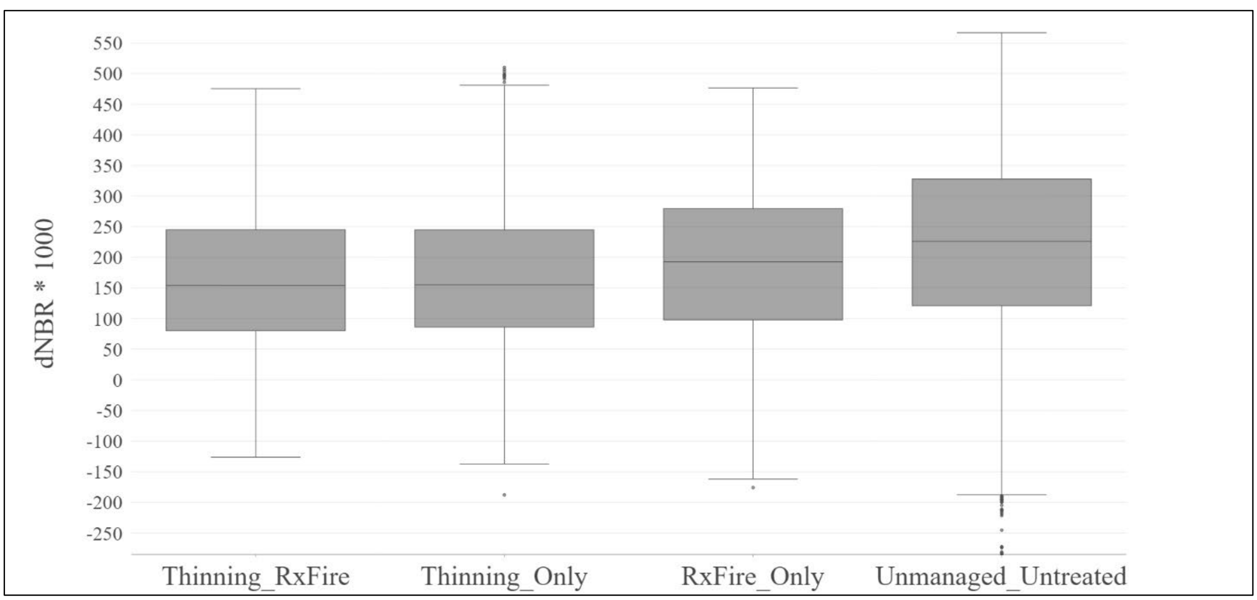

Figure 15. Distribution of dNBR for the 15-year treatment dataset

Table 4 presents the mean dNBR, standard deviation, and pixel count for each treatment type for the 10- and 15-year treatment datasets. For all of the treatment types, mean dNBR is lower in the 10-year treatment dataset compared to the 15-year treatment dataset.

Table 4. Statistics for each treatment type in the 10- and 15-year treatment datasets

Treatment type	Treatment cutoff	Mean dNBR	Standard deviation	Pixel count
Thinning Only	10-year 15-year	0.159 0.170	0.100 0.105	44,125 55,540
Thinning and Prescribed Fire	10-year 15-year	0.164 0.167	0.102 0.102	16,848 27,769
Prescribed Fire Only	10-year 15-year	0.183 0.191	0.114 0.111	6,768 8,672
Unmanaged/untreated	10-year 15-year	0.223 0.224	0.120 0.120	455,490 434,179

For both the 10- and 15-year Treatment datasets, the ANOVA test p-value was less than 0.001, indicating that the distribution of dNBR exhibits statistically significant differences between treatment types. This confirms the hypothesis that different treatment types experienced unique patterns in burn severity. Furthermore, the Tukey HSD test revealed which specific treatment comparisons were statistically significantly different. For the 10-year treatment dataset, statistically significant differences in burn severity were observed for all of the treatment comparisons. Table 5 shows the treatments of comparison, indicated by Treatment 1 and Treatment 2. The mean dNBR is displayed, along with the p-value. P-values less than 0.05 indicate statistically significant differences in dNBR, with three asterisks indicating very high levels of statistical significance.

Table 5. Comparisons of dNBR within treatments for the 10-year dataset

Treatment 1	Treatment 2	Treatment 1 mean dNBR	Treatment 2 mean dNBR	p-value
RxFire and Thinning	RxFire Only	0.164	0.183	0.000***
Thinning Only	RxFire Only	0.157	0.183	0.000***
Unmanaged/Untreated	RxFire Only	0.223	0.183	0.000***
Thinning Only	RxFire and Thinning	0.157	0.164	0.000***
Unmanaged/Untreated	RxFire and Thinning	0.223	0.164	0.000***
Unmanaged/Untreated	Thinning Only	0.223	0.157	0.000***

The results for the 15-year treatment dataset show that all treatment comparisons were statistically significantly different except for the Thinning and Prescribed Fire and Thinning Only treatments, which had mean dNBRs of 0.167 and 0.168, respectively. This means that for the 15-year treatment dataset, the Thinning and Prescribed Fire and Thinning Only treatment types did not experience statistically significant differences in burn severity. Table 6 displays the results of the Tukey HSD test. P-values less than 0.05 indicate statistically significant differences in dNBR, with three asterisks indicating very high levels of statistical significance.

Table 6. Comparisons of dNBR within treatments for the 15-year dataset

Treatment 1	Treatment 2	Treatment 1 mean dNBR	Treatment 2 mean dNBR	p-value
Thinning and RxFire	RxFire Only	0.167	0.191	0.000***
Thinning Only	RxFire Only	0.168	0.191	0.000***
Unmanaged/Untreated	RxFire Only	0.227	0.191	0.000***
Thinning Only	Thinning and RxFire	0.168	0.167	0.923
Unmanaged/Untreated	Thinning and RxFire	0.227	0.167	0.000***
Unmanaged/Untreated	Thinning Only	0.227	0.168	0.000***

4.3 Post-fire Forest Change Analysis

Maps for the one-year and two-year changes in brightness, greenness, and wetness were created to illustrate the temporal response of the variables across the entire Caldor Fire. Graphical plots displaying the relationship between the forest condition variables, burn severity, and the treatment types were also created.

4.3.1 Distribution of Forest Change Variables B, G, W

The one-year change in brightness from 2021 to 2022 is shown in Figure 16. Positive values shown in yellow indicate an increase in brightness, and negative values shown in dark purple indicate decreasing brightness. The areas of increasing brightness correspond to soil, ground, and rock exposure, and are coincident with the areas of high dNBR.

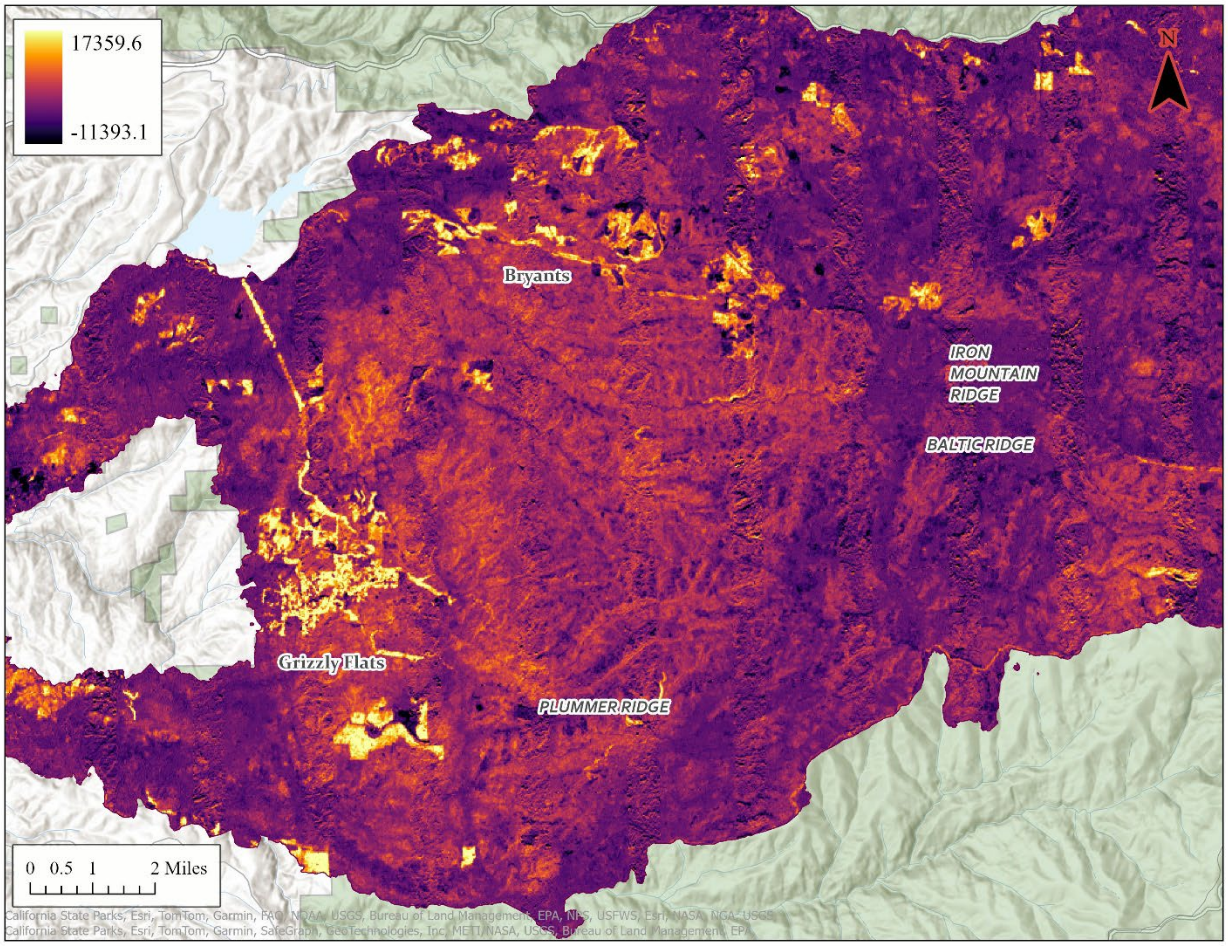

Figure 16. One-year change in brightness

The two-year change in brightness from 2021 to 2023 is shown in Figure 17. Across the study area, patches of increasing brightness are enhanced. This increase in brightness could be due to the decomposition of burned vegetation or debris being hauled off site by maintenance crews. Two large patches of increasing brightness correspond to the exposed, bare ground remnants of the Grizzly Flats and Bryants neighborhoods. Linear features emerge from the neighborhoods that likely correspond to temporary roads used for the transport of rescue goods and services.

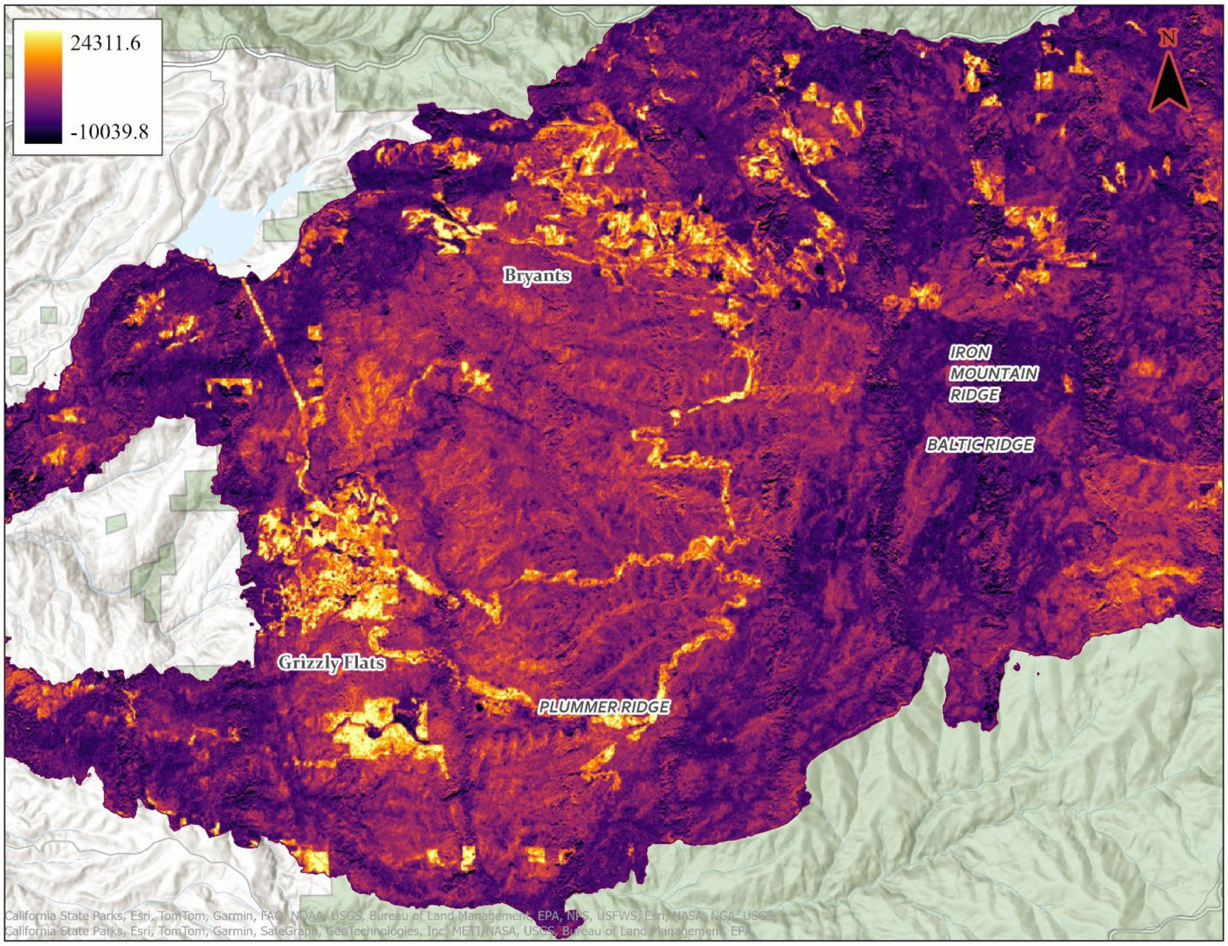

Figure 17. Two-year change in brightness

The one-year change in greenness from 2021 to 2022 is shown in Figure 18. Negative values shown in brown represent areas of decreasing greenness, suggesting loss of vegetation. Positive values shown in green represent areas of increasing greenness, suggesting a growth of vegetation. The large brown region of decreasing greenness on the western side of the Caldor Fire corresponds to the large region of high dNBR shown in Figure 8.

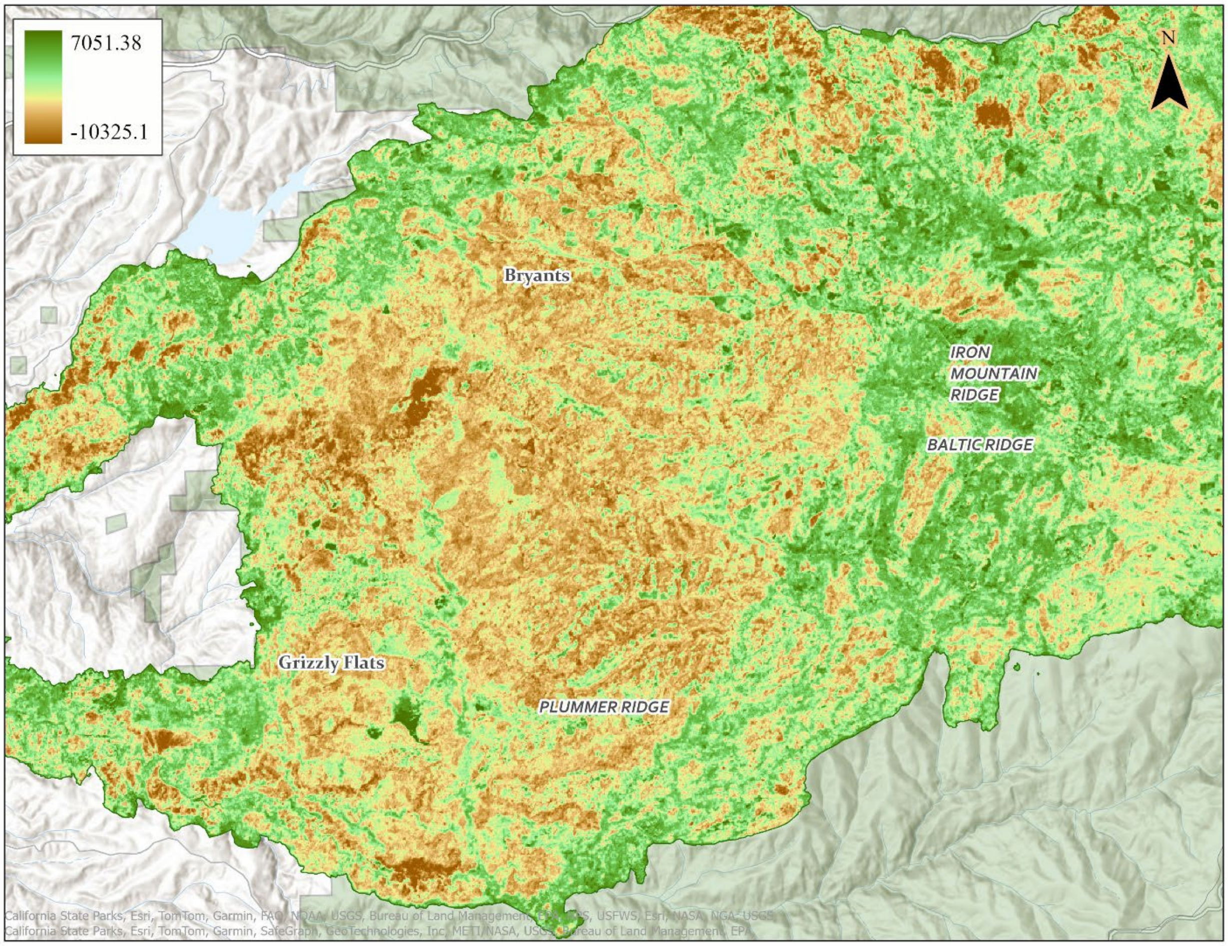

Figure 18. One-year change in greenness

The two-year change in greenness is shown in Figure 19. Brown areas of greenness decrease are less pronounced. The prevalence of yellow coloration suggests that dG values are returning to pre-fire values due to the recovery of vegetation in burned areas. Generally, the distribution of dG is similar between the one-year and two-year changes.

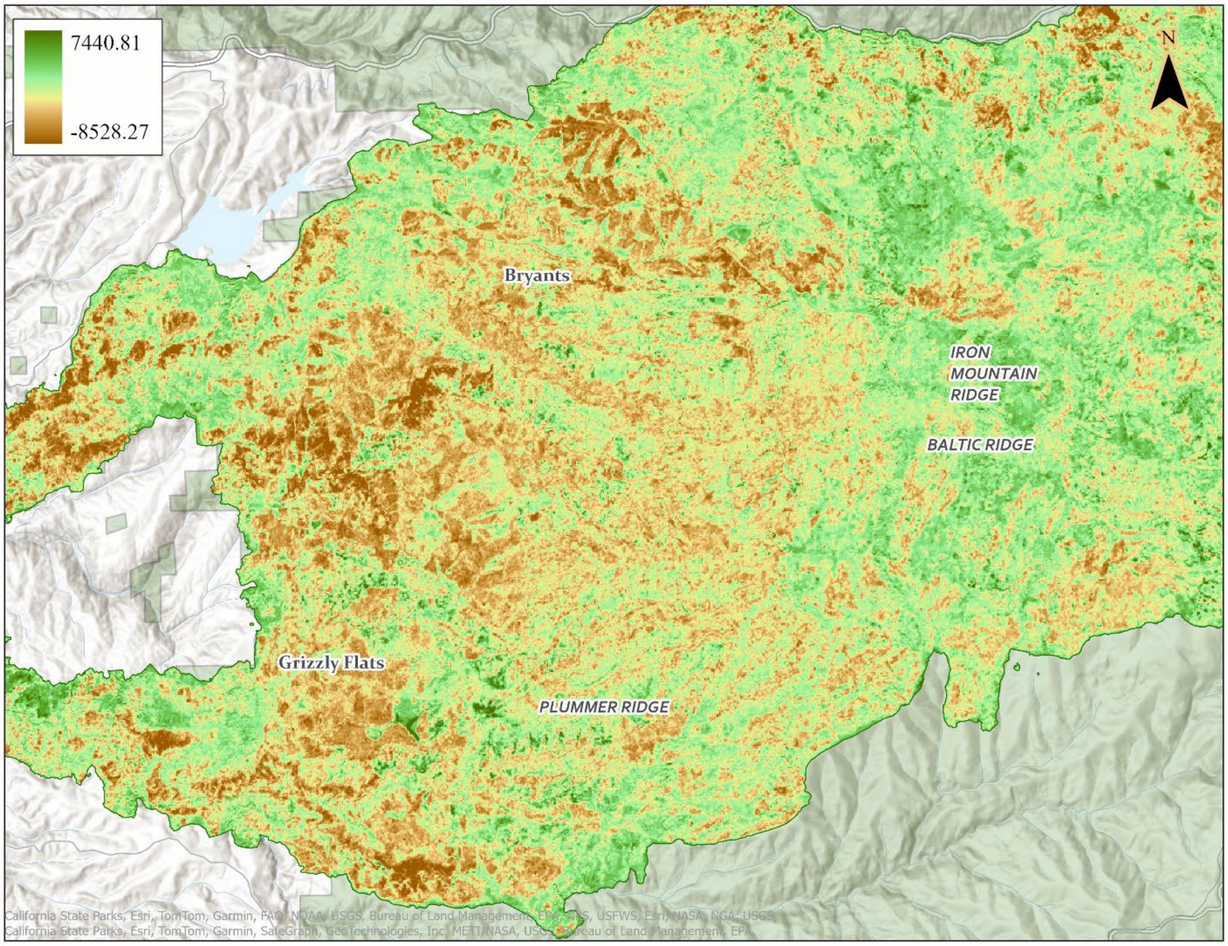

Figure 19. Two-year change in greenness

The one-year change in wetness is shown in Figure 20. Negative values shown in brown represent areas of decreasing wetness, suggesting loss of vegetation and soil moisture. Positive values shown in blue represent areas of increasing wetness, suggesting an increase of vegetation and soil moisture. The large brown region of decreasing wetness on the western side of the Caldor Fire corresponds to the large region of high dNBR shown in Figure 8.

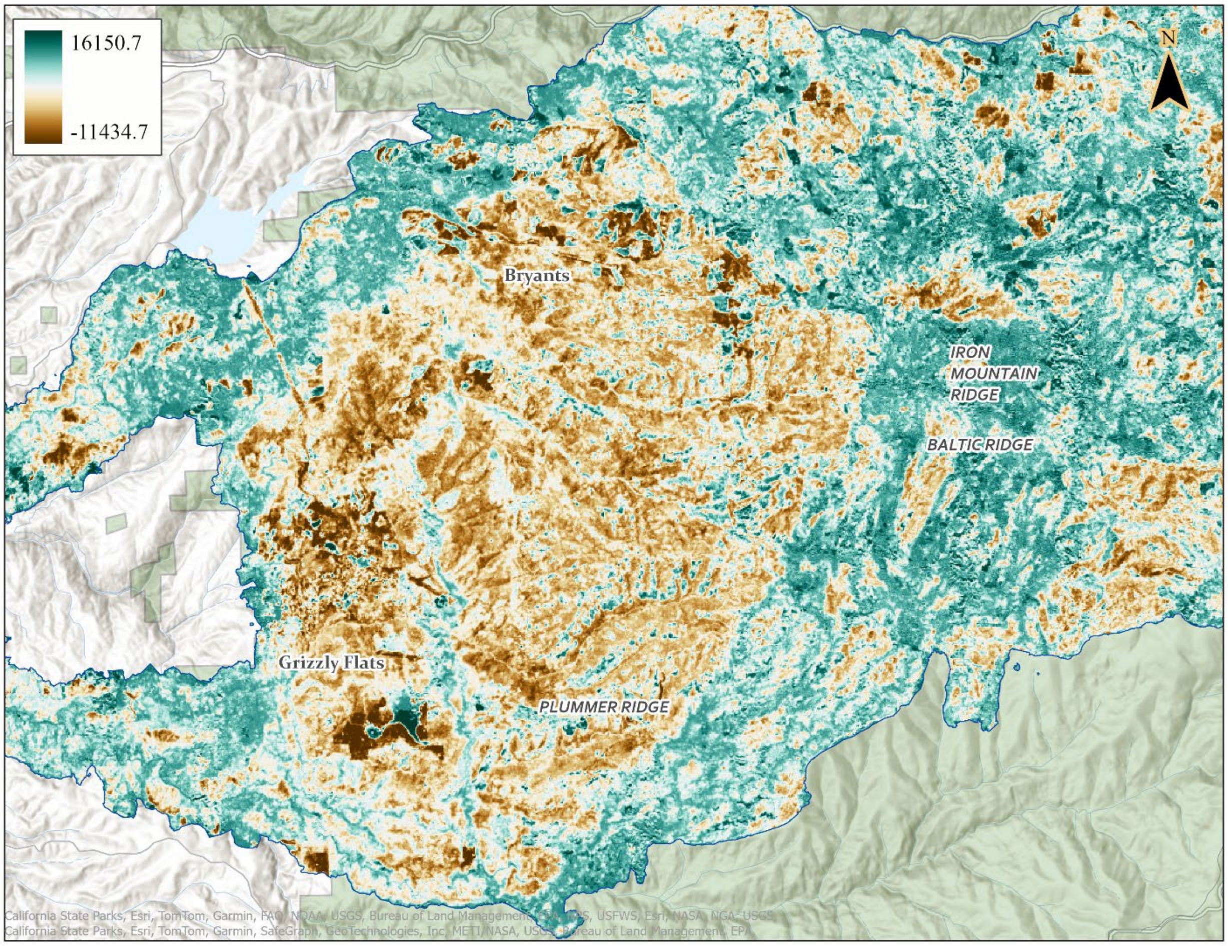

Figure 20. One-year change in wetness

The two-year change in wetness is shown in Figure 21. Areas of wetness decrease are less pronounced, as indicated by the prevalence of white coloration. This suggests that dW values are returning to pre-fire values. Generally, the distribution of dW is similar between the one-year and two-year changes.

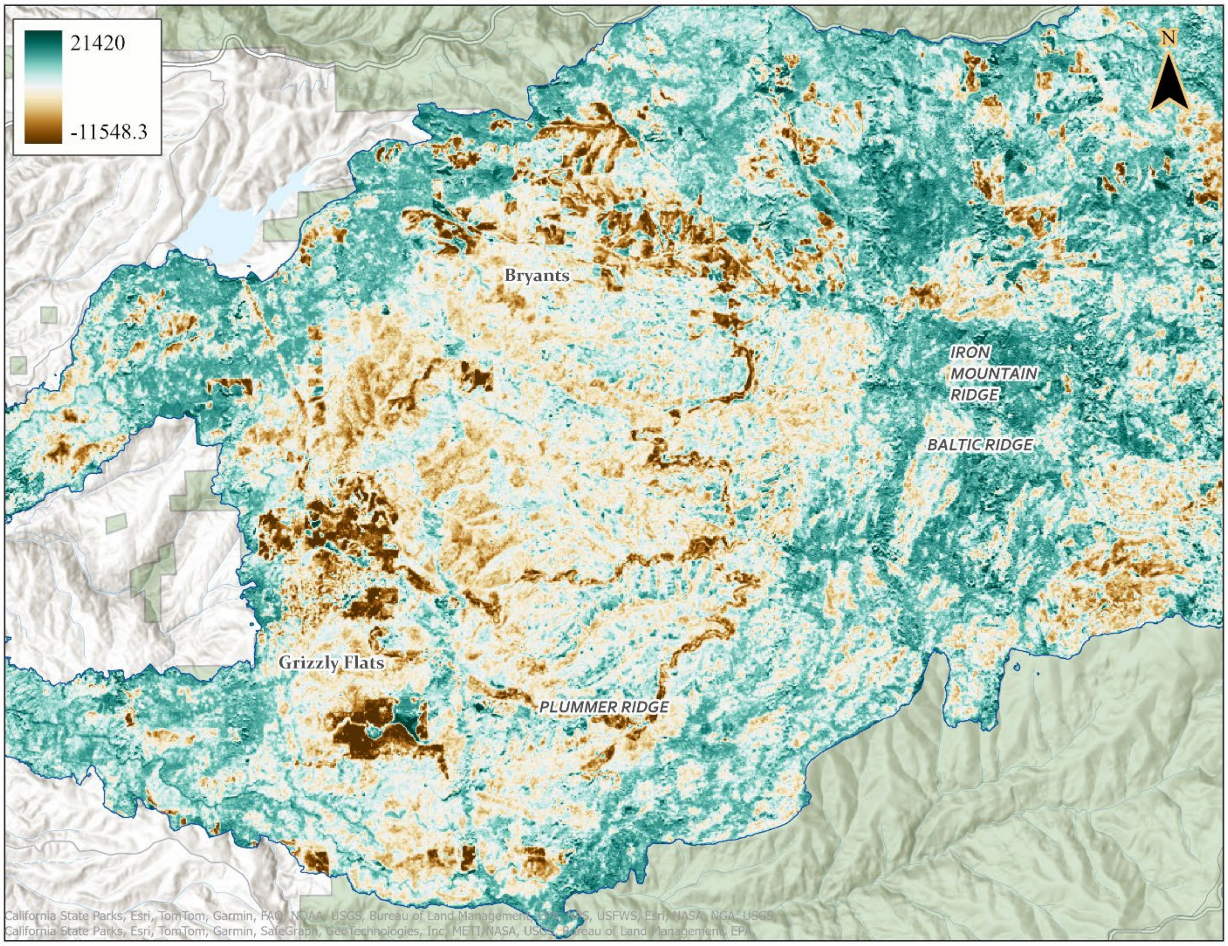

Figure 21. Two-year change in wetness

4.3.2 Relationships between dNBR, Forest Change Variables, and Treatments

The results of the analysis reveal strong relationships between dNBR and the forest condition variables. The relationship between dNBR and brightness is positive, and negative for greenness and wetness. For brightness, the R2 for the relationship with dNBR is 0.3. There is a greater range of dB values with higher dNBR values, showing large increases at dNBR values between 0.2 and 0.4 (Figure 22).

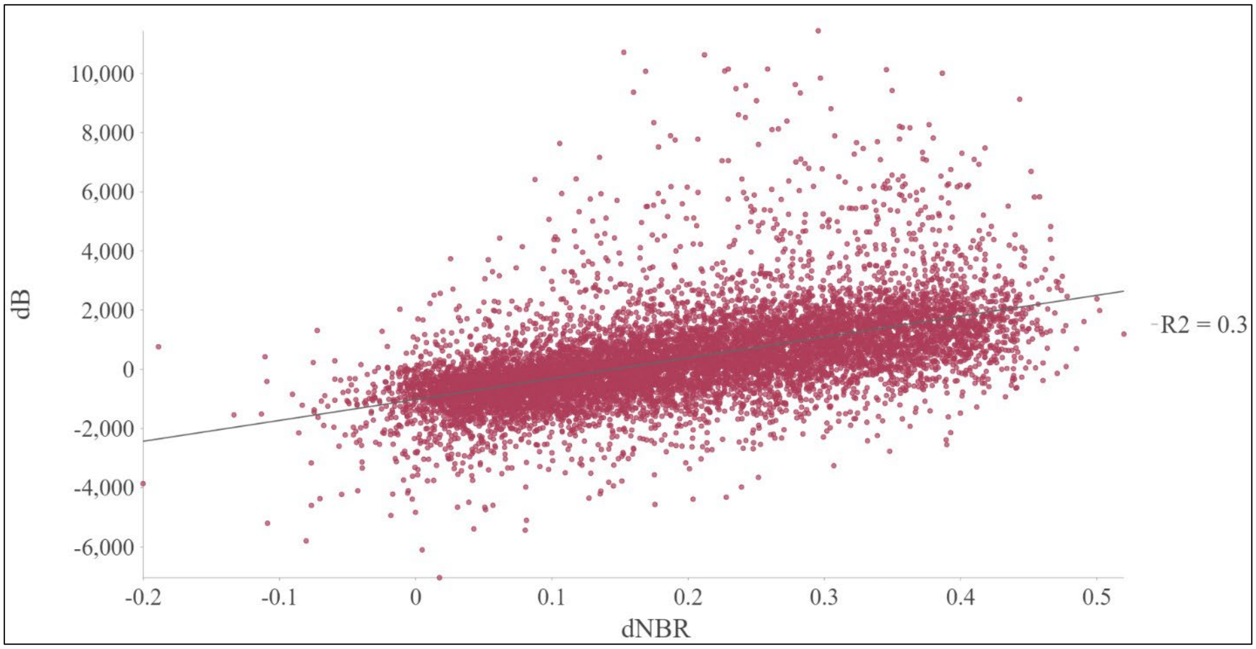

Figure 22. Relationship between dNBR and forest change in brightness

dNBR has strong linear negative relationships with greenness. Figure 23 illustrates how increasing burn severity is correlated with a decrease in greenness. The relationship is very strong with an R2 of 0.9.

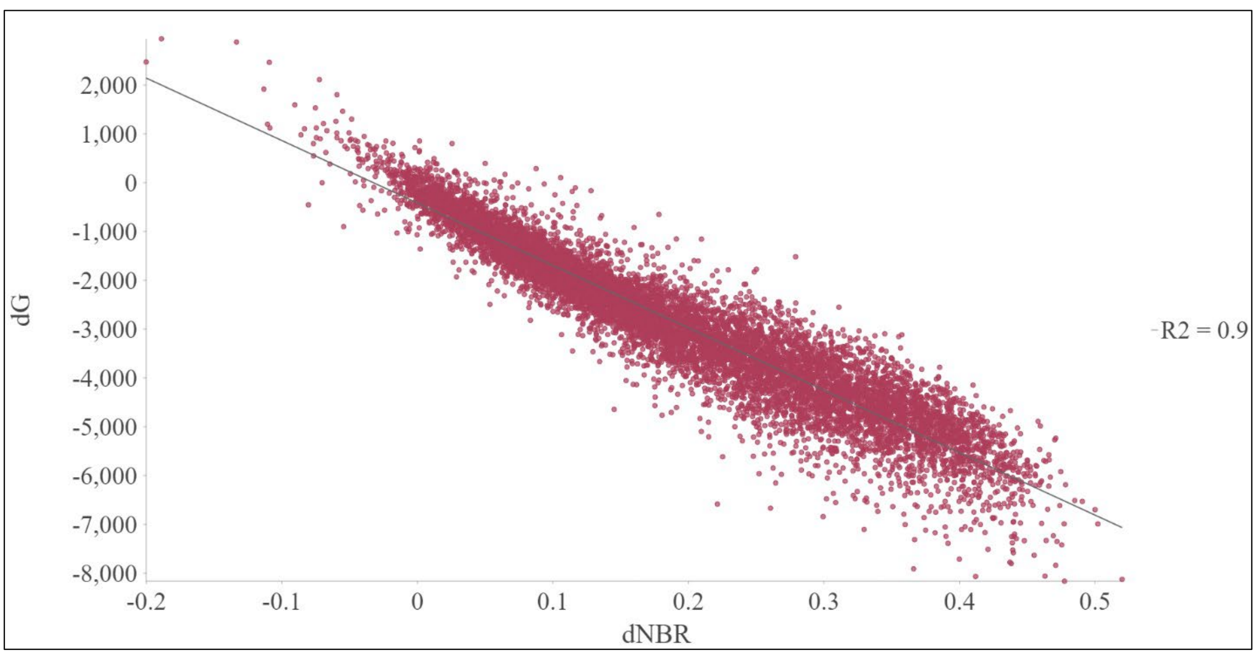

Figure 23. Relationship between dNBR and forest change in greenness

dNBR has strong linear negative relationships with wetness. Figure 24 illustrates how increasing burn severity is correlated with a decrease in wetness. The relationship is very strong with an R2 of 0.9. At dNBR values between 0.2 and 0.5, the values for dW spread out, indicating that there are some areas that experienced an extreme loss of wetness post-wildfire.

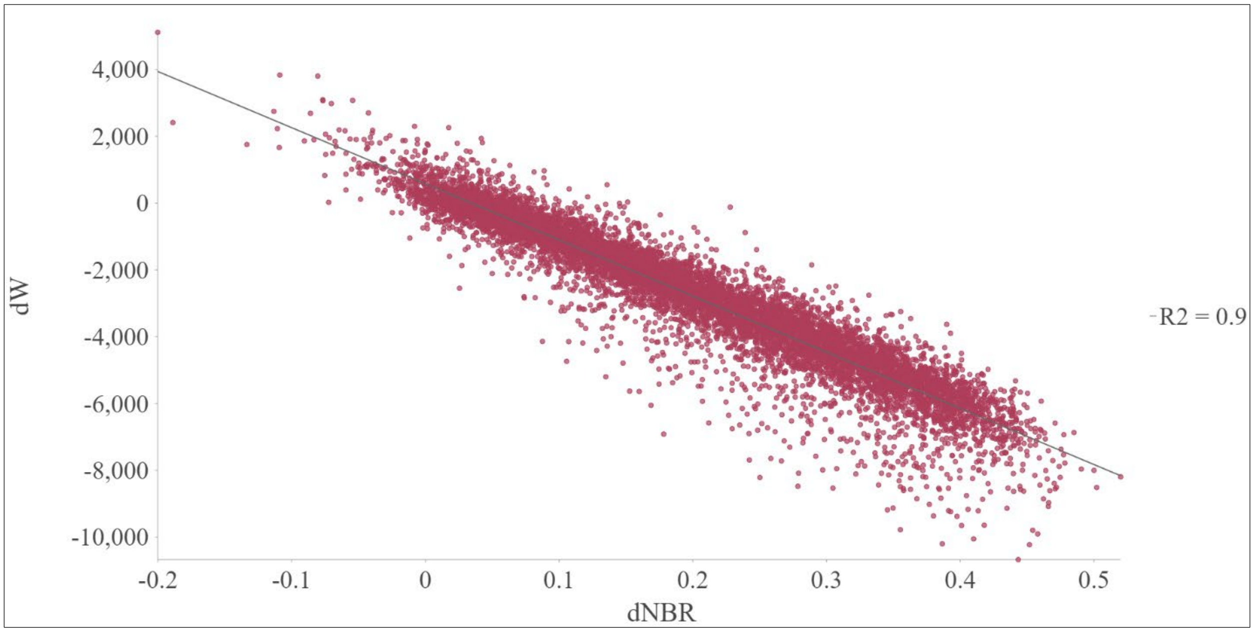

Figure 24. Relationship between dNBR and forest change in wetness

The forest change variables displayed unique temporal responses for each of the burn severity groups. For brightness, the Low/unburned and Low burn severity groups showed a slight dip after one year and approached the pre-fire baseline by 2023 (Figure 25). The Moderate and High burn severity groups show significant increases in brightness after one-year and two-years.

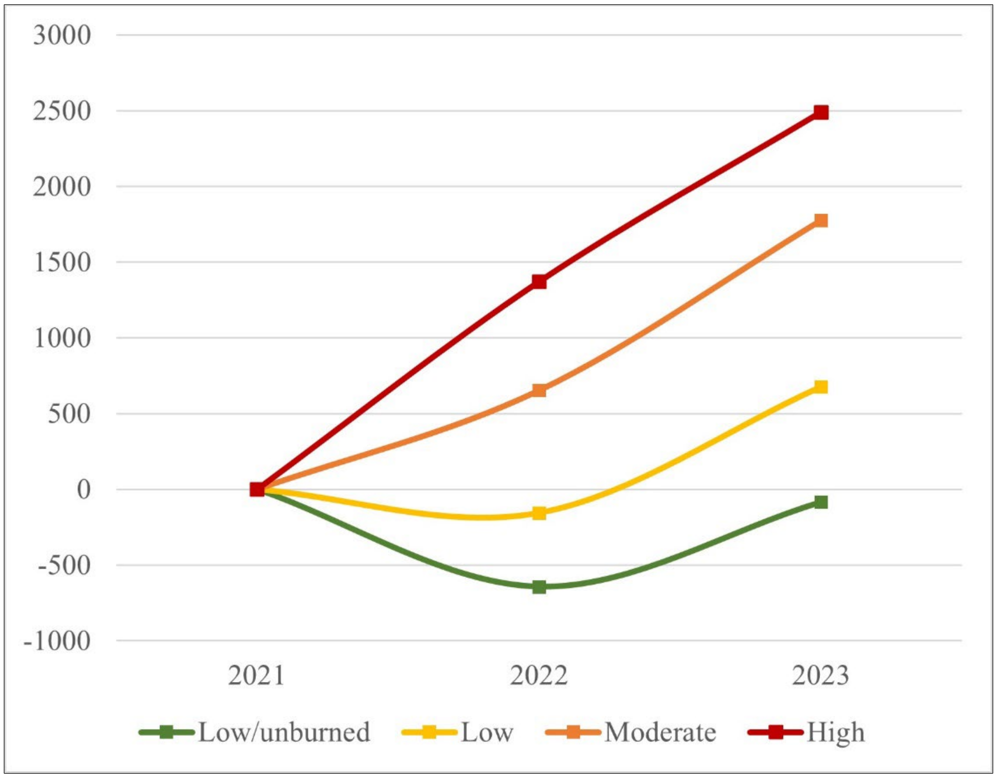

Figure 25. Median values of the temporal change of brightness for each burn severity group

For greenness, the Low/unburned burn severity group experienced the small decline in greenness. The High burn severity group experienced the sharpest decrease in greenness in 2022, and by 2023 was similar to the Moderate burn severity group (Figure 26). After two years, median dG values for the Low, Moderate, and High burn severity groups started to converge.

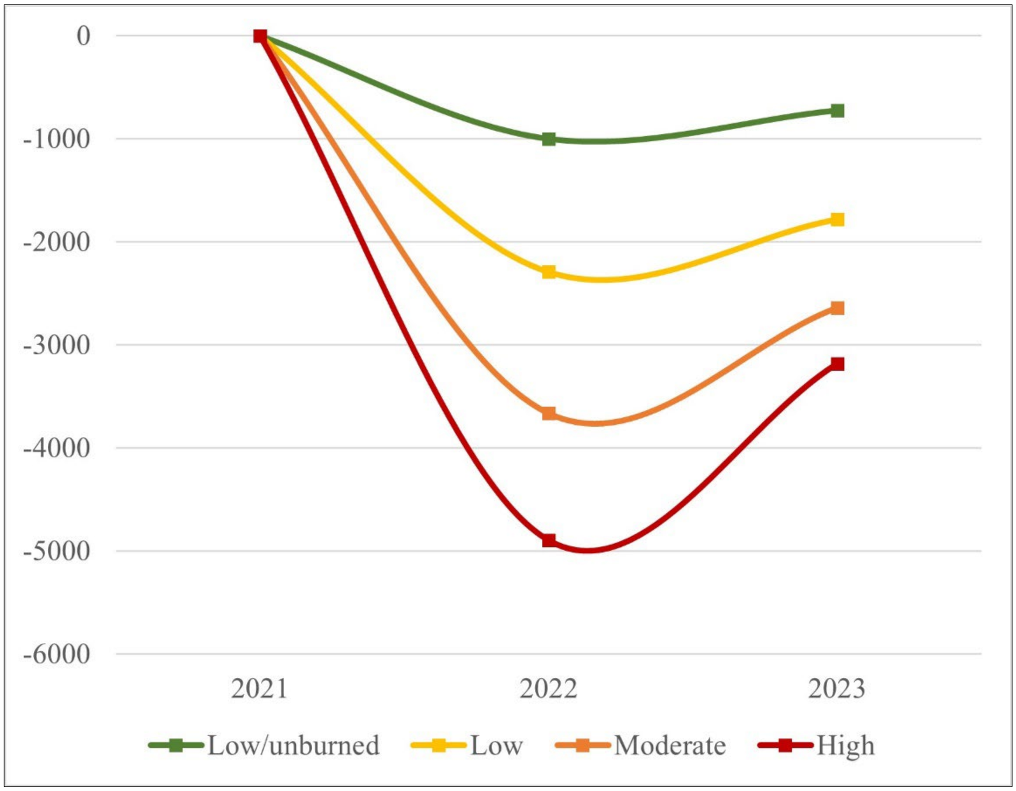

Figure 26. Median values of the temporal change of greenness for each burn severity group

For wetness, the Low/unburned burn severity group did not experience a significant change in 2022 or 2023 (Figure 27). The Moderate and High burn severity groups experienced significant decreases in wetness and begin to recover after two years. After two years, the median dW values for the burn severity groups are more spread out than the dG values after two years.

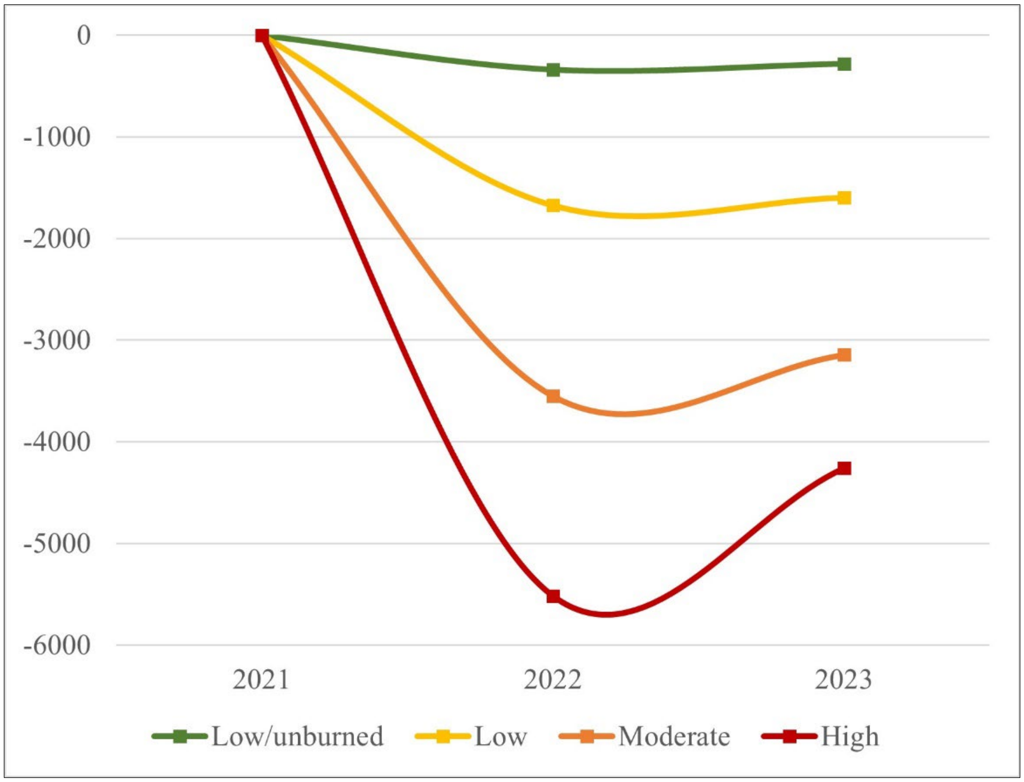

Figure 27. Median values of the temporal change of wetness for each burn severity group

Treatment types exhibited distinct temporal response patterns in the median forest condition variables when compared to the pre-fire baseline. For brightness, all of the treatments, including Unburned, showed an increase from 2021 to 2023 (Figure 28). Untreated/unmanaged, which had the highest dNBR, has a similar trajectory to Prescribed Fire Only. Prescribed Fire and Thinning had a larger increase in brightness than Thinning Only, although their similar slopes indicate a shared trend.

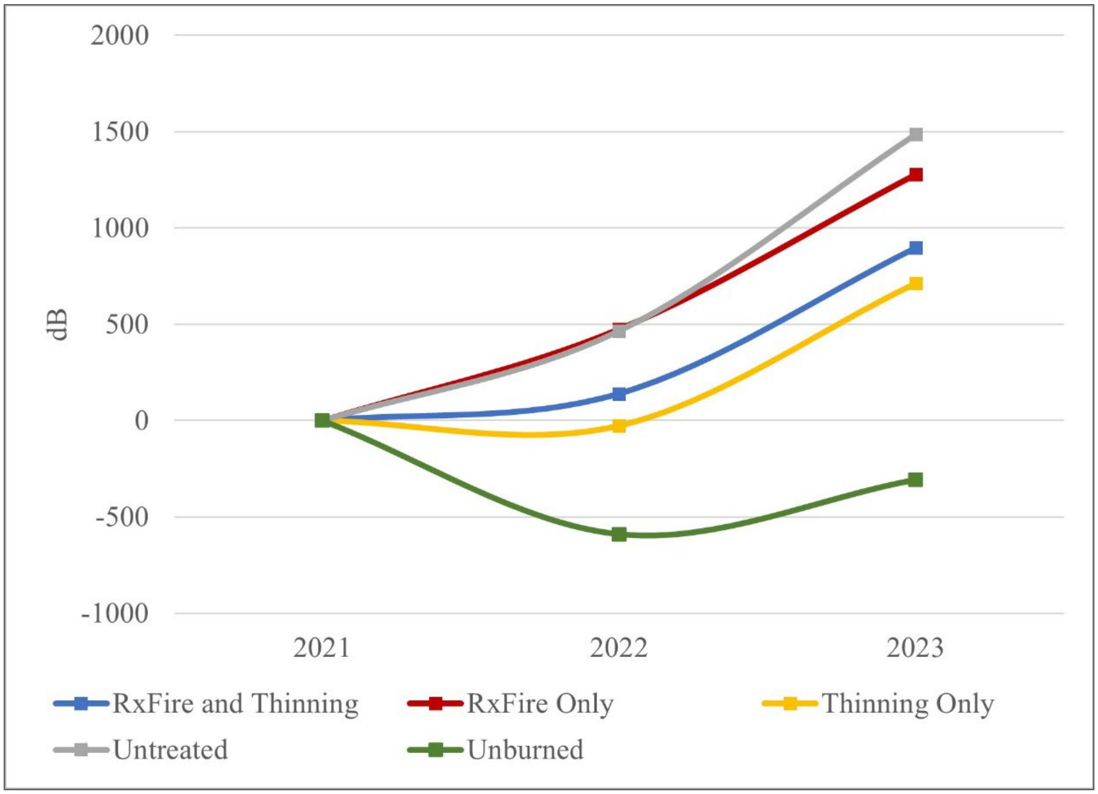

Figure 28. Median values of the temporal change of brightness for each treatment type

For greenness, Thinning Only and Thinning and Prescribed Fire displayed similar trends in greenness decrease and increase over the timespan from 2021 to 2023. Prescribed Fire Only showed a steeper decrease in greenness in 2022, but by 2023 its greenness had approached Prescribed Fire and Thinning. Untreated/unmanaged had the greatest decrease in greenness, with values remaining the lowest in 2023. By 2023, Thinning Only, Prescribed Fire Only, and Prescribed Fire and Thinning had similar dG values between -1500 and -2000.

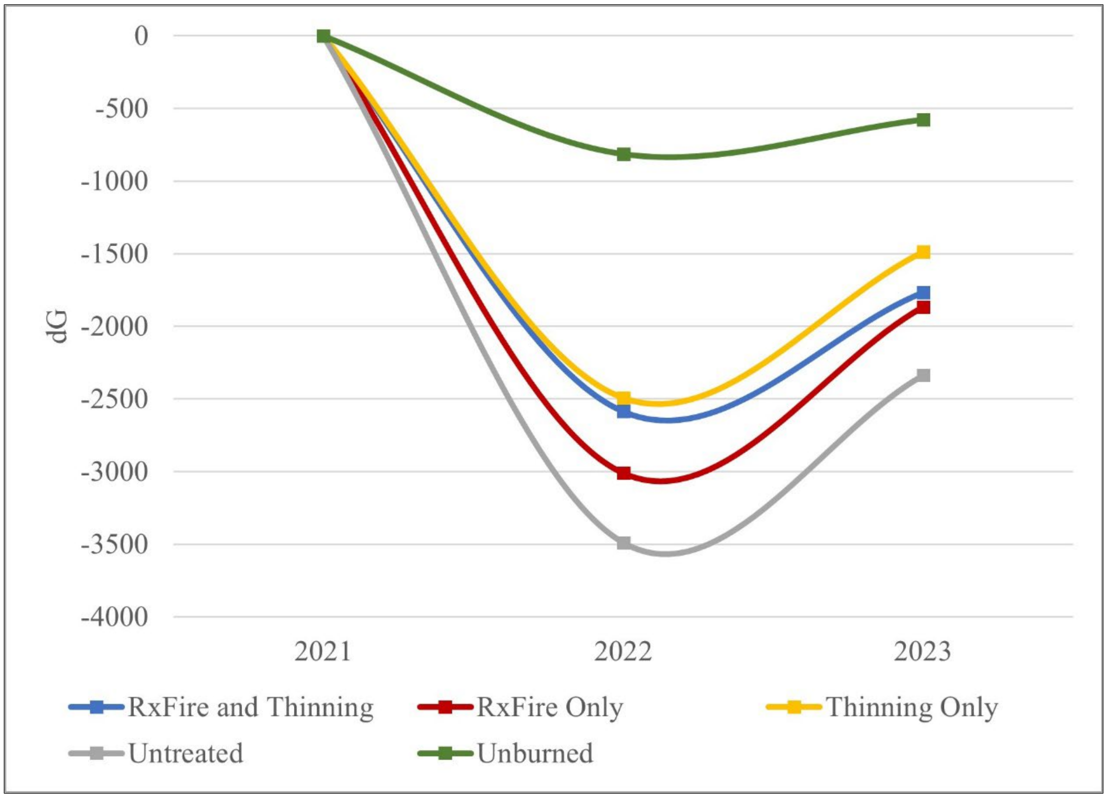

Figure 29. Median values of the temporal change of greenness for each treatment type

For wetness, the trends followed greenness, meaning that the order of treatments for decreasing wetness was the same as for greenness (Figure 30). However, by 2023, the distribution of dW values was much more spread out than dG values. Thinning Only showed the lowest decrease in wetness, followed by Prescribed Fire and Thinning and Prescribed Fire Only. Unmanaged/Untreated showed the greatest loss in wetness.

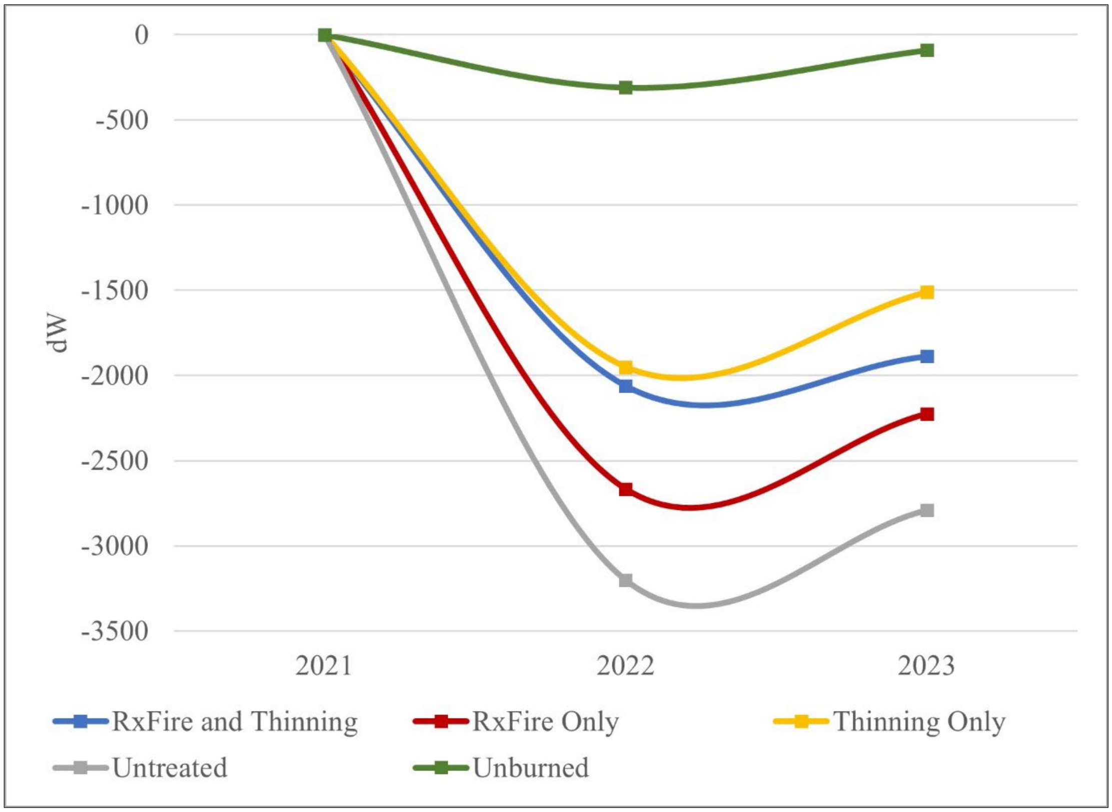

Figure 30. Median values of the temporal change of wetness for each treatment type

Chapter 5 Discussion

The analysis highlights the interactions between fuel reduction treatments, burn severity, and post-fire forest change in the Caldor Fire. The results confirm the utility of treatments for reducing burn severity and how specific treatment types impacted burn severity outcomes. The results also reveal how burn severity and treatment type may impact post-fire forest change and recovery. Although there are some limitations to the conclusions that can be drawn, there are opportunities for future research.

5.1 Burn Severity Analysis

The analysis confirms the hypothesis that the various treatment types experienced statistically significant variations in burn severity. In both the 10-year and 15-year treatment datasets, the untreated control experienced the highest burn severity. Higher burn severity values within the untreated control are expected, as these areas should have a higher density of untreated fuels that can ignite during wildfire. This result confirms the efficacy of treatments as a general practice.

Regarding the efficacy of specific treatment types compared to one another, it is difficult to draw a conclusion. The Thinning Only treatment type performed better than treatments incorporating prescribed fire in both the 10- and 15-year treatment datasets. The Thinning Only treatment type experienced the lowest burn severity in the 10-year treatment dataset and displayed statistically similar burn severity to the Thinning and Prescribed Fire treatment for the 15-year treatment dataset. Prescribed Fire Only displayed the highest burn severity values compared to the other two treatment types in both the 10- and 15-year treatment datasets. The result that the Thinning Only treatment experienced less burn severity than the Thinning and

Prescribed Fire treatment in the 10-year dataset and the Prescribed Fire Only treatment in the 15-year dataset is surprising, although the results concur with the findings of Hanson and Baker's study of the Caldor Fire (2022). Based on existing literature, the expectation is that treatments incorporating prescribed fire would be more effective at reducing burn severity than treatments incorporating thinning alone (Van Wagtedonk 1996). Prescribed fire is more effective than thinning at treating surface fuels, and literature has emphasized prescribed fire's role in mitigating burn severity (Taylor et al. 2022). As the treatment types were controlled for vegetation type and slope, this anomaly cannot be attributed to differences in vegetation composition or terrain. It is possible that other wildfire behavior factors, such as wind or extreme temperature, played a role in determining burn severity. Another factor that could have influenced this result is the date of treatment implementation. The Thinning Only treatment was implemented more recently than the other treatments, with a mean implementation year of 2015. The histogram in Figure 31 shows a large proportion of Thinning Only treatments occurring in 2019 and 2020.

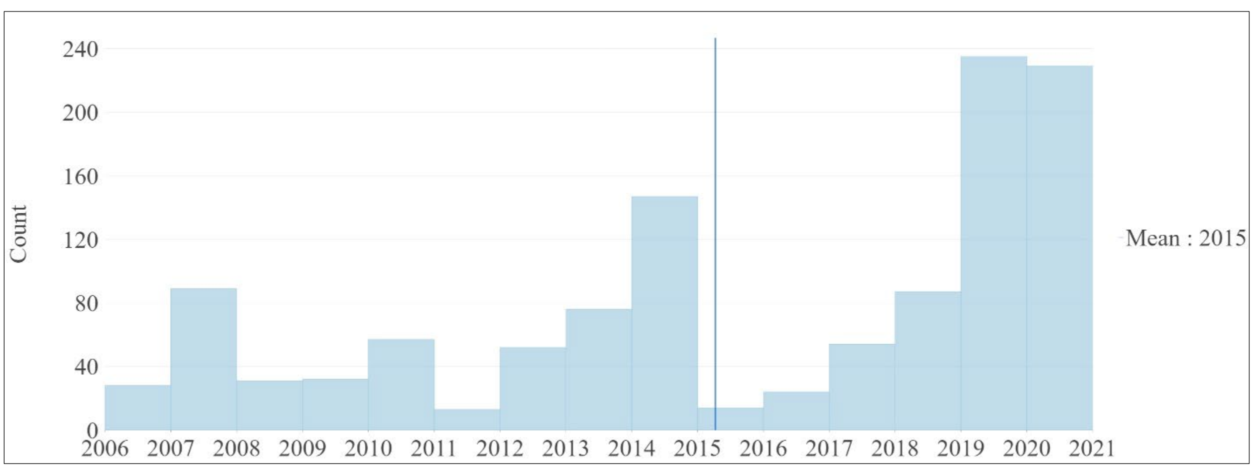

Figure 31. Implementation years for the Thinning Only treatment

The majority of Prescribed Fire Only treatments were implemented between the years of 2010 through 2015, with a mean treatment implementation year of 2012 (Figure 32).

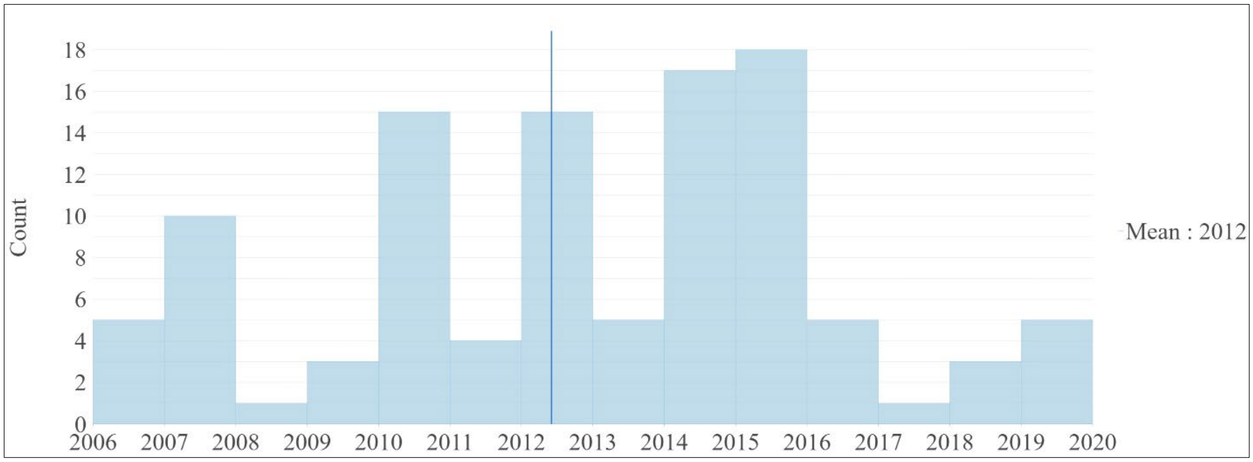

Figure 32. Implementation years for the Prescribed Fire Only treatment

The majority of Thinning and Prescribed Fire treatments were implemented between the years 2010 and 2015, with a mean treatment implementation year of 2012 (Figure 33).

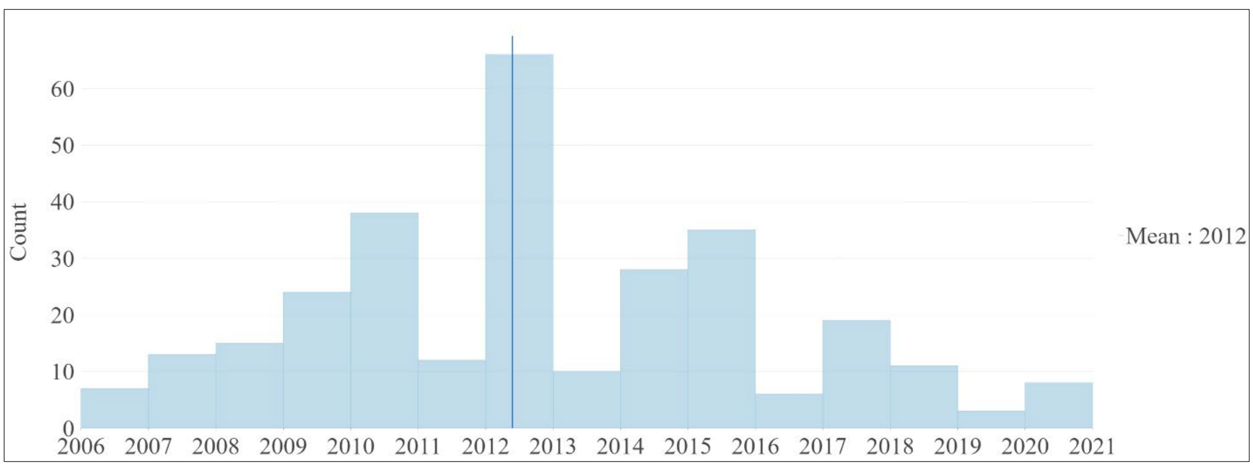

Figure 33. Implementation years for the Thinning and Prescribed Fire Only treatment

It is possible that treatment efficacy decreased with time, and the Thinning Only treatments experienced low burn severity because the activities were implemented more recently than the other two treatments. The potential impact of time on treatment efficacy is further emphasized by a comparison of the 10- and 15-year treatment datasets. For all treatment types, dNBR consistently increased in the 15-year treatment dataset (Table 4) compared to the 10-year dataset, highlighting how the five year difference may have reduced treatment efficacy for mitigating burn severity.

The results of the ANOVA and Tukey-HSD statistical analyses show that different treatment types experienced statistically significant variations in burn severity. Overall, treatments performed better than the untreated control at mitigating burn severity. These findings are promising as they confirm the hypothesis that specific treatments can be effective at reducing wildfire intensity. However, it is difficult to make a concrete conclusion about which treatments were the most effective at reducing burn severity. Future analysis into the influence of time or other wildfire factors, such as wind and temperature, can shed light on this question.

5.2 Post-fire Forest Change analysis

The Post-Fire Forest Change analysis revealed the relationship between burn severity, treatment type, and post-fire forest change over the multi-year study period. The relationship between burn severity and the change in brightness is positive (Figure 22). This relationship is consistent with Petrakis et al.'s assertion that post-fire surfaces with exposed soil, rock, or ash, and reduced vegetation cover are expected to exhibit increased brightness (2018). As burn severity increases, a greater proportion of the landscape will exhibit exposed soil, rock, and ash, resulting in increasing brightness values. The relationship between burn severity and greenness is strongly and negatively correlated (Figure 23). This result is expected, as greenness corresponds to vegetation presence (Crist and Cicone 1984). Additionally, the relationship between burn severity and the change in wetness is strongly and negatively correlated (Figure 24). This is expected, as post-fire surfaces should endure losses to plant and soil moisture (Crist and Cicone 1984).

The temporal response of the forest condition variables for each burn severity group displayed unique patterns. Areas that experienced high burn severity showed the largest increase in brightness (Figure 25). The Low/unburned and Low burn severity groups showed a slight dip in brightness after one year, and then increased after two years. This could be due to the decomposition of burned vegetation exposing bare soil and rock after a longer period of time. For greenness, the High and Moderate burn severity groups showed the largest decrease in greenness (Figure 26). The values for dG for all the burn severity groups begin to converge after two-years, and this could be due to the recovery of vegetation and the colonization of new shrubs and grasses. Regarding wetness, the High and Moderate burn severity groups display the largest decreases in dW after one and two years. Although wetness begins to increase after two-years, the slopes of recovery are flatter than they are for greenness. This suggests that burn severity has a greater impact on wetness than on greenness, and moisture from the soil and plants takes longer to recover than vegetation.

The temporal responses of the forest condition variables within the treatment types provide insight on how the forest changed within different treatment types. The relationship between brightness and burn severity is reflected in the treatment types, as treatments with low burn severity show small increases in brightness and treatments with high burn severity show larger increases in brightness. The temporal response within Prescribed Fire Only and Unmanaged/Untreated followed very similar trajectories in 2022. In 2023, Unmanaged/untreated shows a slightly higher increase in brightness (Figure 28).

The relationship between greenness and burn severity is also reflected in the treatment types, as the treatments with higher burn severity values experienced sharper decreases in greenness. The Thinning Only and Thinning and Prescribed Fire treatments exhibit the smallest decrease in greenness in 2022 and begin to approach pre-fire levels by 2023 (Figure 29). Prescribed Fire Only, which shows a larger decrease in greenness by 2022, approaches the same level of greenness as Prescribed Fire and Thinning. Unmanaged/untreated shows consistently sharper decreases in greenness, with the one-year and two-year values showing the largest decline compared to the treatment types.

Wetness follows the same trend as greenness, with Thinning Only and Thinning and Prescribed Fire showing the lowest decreases in wetness, followed by Prescribed Fire Only and Unmanaged/untreated (Figure 30). However, the two-year changes in wetness show a higher degree of variation, and the slopes of recovery between 2022 and 2023 are flatter than they are for greenness. This trend may be due to early regenerative vegetation, such as shrubs and grasses, that do not necessarily indicate recovery of the same plant species. Similar to the plots of B, G, and W and the burn severity groups (Figure 27), the spread in wetness values in 2023 and the flat recovery slopes indicate that plant and soil moisture captured by wetness takes longer to recover than the vegetation cover captured by greenness.

5.3 Treatment Implications

The first research objective of this thesis project was to compare burn severity within treatment types. The statistically significant variations in burn severity within treatment types indicate that specific treatments did impact burn severity outcomes in the Caldor Fire. Treated areas consistently experienced lower burn severity than non-treated areas, suggesting the efficacy of fuel treatments for mitigating wildfire intensity. In comparisons of individual treatment types, the Thinning Only treatment type performed the best at reducing burn severity; in the 10-year treatment dataset Thinning Only had the lowest burn severity values and was tied with Thinning and Prescribed Fire in the 15-year treatment dataset. However, this conclusion is tentative because the Thinning Only treatments were implemented more recently than Prescribed Fire Only and Thinning and Prescribed Fire.

The second research objective was to compare post-fire forest change within treatment types. The results demonstrate how higher severity burns cause a greater degree of change in the forest condition variables of brightness, greenness, and wetness. Treatments that experienced high burn severity showed associated increases in brightness due to the exposure of bare soil and rock. Treatments that experienced high burn severity showed associated decreases in greenness and wetness due to the loss of vegetation cover and soil moisture. As with the burn severity analysis, the Thinning Only treatment performed the best in mitigating post-fire forest change. The Thinning Only treatment displayed the smallest increase in brightness and the smallest decreases in greenness and wetness. This finding reveals the connection between burn severity and the forest condition variables, as the Thinning Only treatment experienced the lowest burn severity and the smallest magnitude of post-fire forest change. As with the burn severity analysis, this conclusion is tentative because of the recency that the Thinning Only treatments were implemented.

5.4 Limitations of the Study and Opportunities for Future Research

There are a few limitations to the analysis that create opportunities for future research. One limitation is that the analysis relies solely on measurements from remote sensing data. Validation of the results with field observations would support the findings. Field observations can support and enhance the measurements of brightness, greenness, and wetness by providing visual context for their temporal responses. For example, areas with increasing post-fire greenness values can be surveyed to observe what kind of plant species are colonizing the burned areas.

The analysis emphasizes the importance of treatment longevity, as burn severity values consistently increased among treatment types when considering treatments with a 10-year timespan versus a 15-year time span. The higher burn severity values displayed in the 15-year treatment dataset suggest that treatment efficacy begins to decline between 10 and 15 years. A more detailed analysis of treatment longevity can further investigate the timespan of treatment efficacy. Although the schedule of treatments is dependent upon budgetary and logistical constraints, understanding treatment longevity can enable land managers to optimize when treatments are implemented. Future research can utilize a weighting scheme to analyze treatment efficacy based on age, with newer treatments having a larger influence.

The analysis employs a case study of a single wildfire. One promising research path is to analyze multiple wildfires. Automation can enable the adoption of this methodology to rapidly analyze multiple wildfires in a region, drawing comparisons not only between treatment types but also across multiple wildfires. Automation is feasible using ArcGIS Model Builder or ArcPy scripts and can proceed once the input satellite imagery and treatment feature classes are obtained. This analysis could be replicated for wildfires similar to the Caldor Fire such as the Dixie Fire, which occurred earlier in the same year and also burned through various treatment areas.

Another limitation of this study is the lack of consideration of cumulative severity arising from both treatments and wildfire damage. Research on the Caldor Fire has shown that tree mortality arising from fuel reduction treatments and wildfire damage is higher than tree mortality from wildfire alone, indicating that fuel reduction treatments were counterproductive for preserving forest structure (Hanson and Baker 2022). Land managers should consider the possibility that wildfire alone may cause less tree mortality than the combination of wildfire and fuel treatments. Understanding these dynamics is crucial for developing strategies that optimize both the ecological and structural resilience of forests. Incorporating cumulative severity into assessments will provide a more comprehensive understanding of the long-term impacts of treatment and wildfire interactions, informing better management decisions.

5.5 Research Contributions

Using the Caldor Fire as a case study, the research contributes to the field of wildfire risk management in a few ways. First, the analysis provides an evaluation of the fuel reduction treatments implemented in the Caldor Fire. Land management agencies such as the Eldorado National Forest can use these findings to inform future wildfire risk management initiatives in the area. Second, this research confirms the efficacy of treatments for reducing burn severity, as the three treatment types experienced consistently lower burn severity values than the untreated control. This finding contributes an additional case study of fuel treatment efficacy to the scientific literature. Thinning Only was shown to be the most effective treatment method for mitigating burn severity, although this may be due in large part to the recency that those treatments were implemented. Third, the analysis highlights the reality of treatment longevity, as burn severity increased within treatment types when considered at 10- or 15-year intervals. This finding suggests that treatments lose efficacy for reducing burn severity after 10 years. The analysis also highlights the interactions between burn severity and post-fire forest change. Mainly, higher severity burns are correlated with increases in brightness and decreases in wetness and greenness. Increases in brightness are due to the exposure of bare soil and rock.

Decreases in greenness and wetness are due to loss of vegetation cover and soil moisture, respectively. Land managers can use this knowledge to understand the trend of post-fire forest change and recovery. This analysis can be replicated in past and future wildfires, assisting land managers in identifying areas that endured high severity burns and require restoration efforts. Furthermore, this analysis can help land managers study burn severity in more detail, examining specific aspects of post-fire forest recovery related to vegetation cover and soil moisture. This ability is important, as areas that endured a similar level of burn severity may display distinct changes to greenness or wetness that are obscured when only considering dNBR. Finally, the analysis demonstrates how this knowledge can be attained using open-source, publicly available data.

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