Post-Fire Vegetation Recovery Dynamics of the Rim Fire in California, 2013-2021

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ABSTRACT

The increasing severity and frequency of wildfires have heightened the need for comprehensive analyses of their ecological impacts. This research conducts a temporal analysis of the 2013 Rim Fire, one of California's most severe wildfires. The data was calculated and summarized in Google Earth Engine (GEE). Firstly, burn severity maps were obtained from the RAVG program, and CBI was selected as the index to classify severity. High-severity patches were defined as pixels surrounded by eight immediate neighbors, each with a Composite Burn Index (CBI) of 4, where the patch size exceeded 0.5 hectares. A USGS Digital Elevation Model (DEM) was used to examine topographical effects, comparing south-facing slopes to north-facing slopes where the slope exceeded 15%. Finally, the Wang 2022 dataset was used to derive maps of fragmented land cover types. The results indicate that tree cover declined significantly more in areas of high burn severity. Most of the pixels were converted to shrubs, and bare fields decreased after a significant increase in the immediate year after the fire. Furthermore, south-facing slopes had a higher decrease in tree cover and increased shrubs. Finally, areas of high-severity patches had a significantly higher decrease in tree cover and bare fields, with shrubs taking over in these areas. Herbaceous pixels increased equally regardless of patch presence. This research underscores the critical need for targeted post-fire restoration strategies that consider the heterogeneity of burn severity, landscape features, and the impact of high-severity patches to facilitate effective recovery and resilience of fire-affected ecosystems.

KEYWORDS

Burn Severity, High-Severity Patch, Slope, Aspect, Land Cover Change Analysis

INTRODUCTION

California, known for its diverse ecosystems, has experienced an alarming rise in large, high-severity wildfires. Several quantitative studies have shown that climate change is increasing the frequency and severity of wildfires throughout California (Dennison et al. 2014, Goss et al. 2020). Annual burned areas have increased fivefold during 1972-2018 and are likely to increase due to anthropogenic warming (Williams et al. 2019). California was the leading state in terms of total burned acres and total number of fires in both 2020 and 2021, according to NICC annual reports (NICC. 2020, 2021). In 2022, California still had the highest total wildfires and ranked 6th across US states in burned acres (NICC, 2022). Mega-fires, classified as fires burning more than 100,000 acres, are increasing. Furthermore, recent research demonstrates an increasing frequency of extreme weather events such as drought and heatwaves in California (Hulley et al. 2020, Diffenbaugh et al. 2016), which lead to increased frequency and intensity of megafires across California. Burn severity is one of the most significant variables that affect vegetation recovery (Röder et al. 2008). Therefore, evaluating the impact of fires of this magnitude is crucial for developing effective post-fire restoration strategies.

Moreover, the ecological diversity of California has profound potential in assessing the impacts of wildfires and the factors that affect recovery across contrasting ecosystems. Vegetation recovery after wildfires is a complex process, and past research has shown that at the landscape level, post-fire vegetation recovery relies on the initial state of vegetation types and climatic and terrain characteristics (Pausas and Vallejo. 1999, Wittenberg. 2007). Therefore, it is imperative to analyze site-level characteristics to inform post-fire management strategies. With the increasing severity and frequency of wildfires, it is vital to understand which vegetation types exhibit resilience and how terrestrial features impact their recovery patterns. Aspect significantly influences a region's microclimate, hydrological variations, and soil properties, affecting the conditions for the area's susceptibility to wildfires and vegetation regrowth (Karaman et al. 2011). For example, studies have suggested differences in vegetation recovery patterns in north and south-facing slopes (Fox, 2008. Ireland et al. 2015), with higher elevation and slopes also being documented to impact vegetation recovery (Viana-Soto et al. 2017). Furthermore, vegetation types and species significantly impact vegetation recovery patterns (Meng et al. 2015, Casady et al. 2010, Yang et al. 2017). Therefore, understanding how site-level characteristics affect vegetation recovery and how trends play out in the larger, higher-severity wildfires increasingly impacting California's ecosystems is crucial.

Another essential factor to consider while assessing vegetation recovery is the existence of high-severity patches within the burn scar area. Some studies show an inverse relationship between fire severity and seedling densities in California's coniferous ecosystems (Crotteau et al. 2013, Welch et al. 2016). While high burn severity is a significant influence, patches play a critical role in seedling re-establishment, and insufficient dispersal can lead to shifts in vegetation type. A "high-severity patch" is defined in this paper as "high burn severity pixels (CBI = 4) with high-severity neighboring cells and patch size over 0.5 hectares." Similar studies use this definition to investigate the role of high-severity patches (Stephens et al. 2022, Collins and Stephens. 2010). For example, distance to unburned patches and seed sources significantly influences dry mixed-conifer forest recovery (Donato et al. 2009, Kemp et al. 2016). Findings suggest an inverse relationship between distance to seed sources and vegetation recovery (Chambers et al. 2010). For example, studies show Ponderosa Pine seeds rarely travel more than 30m and, therefore, have limited regeneration capabilities in the middle of high-severity patches >200m further than surviving forests/seed sources (Oliver and Ryker, 2010). Furthermore, recovery varies across different species within the interior of burn patches (Donato et al. 2016). These findings suggest a resilient capacity for natural forest regeneration, contingent upon seedlings' survival and the size and severity of patches. Therefore, it is vital to consider burn severity and closely examine these patches, as high-severity patch presence can substantially affect recovery dynamics. The Rim Fire presents a compelling case study due to its significant impact and scale. It provides diverse ecosystems and severities within the burn scar area that are essential for analyzing the influence of burn severity, topography, and high-severity patches on vegetation recovery. Furthermore, the temporal scale offers a unique advantage in evaluating long-term recovery patterns through a time series analysis, given that a decade has elapsed since the fire. While extensive research has been conducted on wildfires and their immediate effects, there is limited information on how topography, vegetation types, burn severity, and high-severity patch presence affect vegetation recovery, especially for a single mega-fire. Such analysis can be pivotal in understanding the underlying factors influencing post-fire vegetation recovery and developing targeted fire management decisions.

This study analyzes vegetation recovery in the burn scar area of the Rim Fire. The central research question is how the fire has affected vegetation recovery patterns across the landscape. The first subquestion explores the influence of burn severity on vegetation cover types across the burn scar area. Secondly, this paper examines how topographical indices (e.g., slope, aspect, elevation) influence post-fire vegetation cover. Finally, the paper explores the role of high-severity patches on recovery dynamics. Such information can predict particularly vulnerable areas and land cover types and impact landscape management and restoration policy-making. Furthermore, the framework established in this research is applicable to all wildfires for which data is available, and these studies can be compared and contrasted to enhance understanding of post-fire vegetation recovery dynamics and influencing factors such as burn severity, topography, and patch presence.

METHODS

Study site

The selected study area is the region impacted by the Rim Fire, which started in the Stanislaus National Forest and burned in the Sierra Nevada between August and October 2013. The fire was one of the largest and most devastating in the history of California, burning an estimated 257,314 acres. This included over 150,000 acres of National Forest System (NFS) lands in Tuolumne County and Mariposa County, impacting several national forests, including the Stanislaus National Forest and Yosemite National Park. The fire's footprint covers a topographically complex area, with a range of elevations from 60 to 2400m and slopes up to 90%. The fire burned various vegetation types, including grassland, chaparral, hardwood habitats, and mixed conifer forests. A more detailed description of the study area can be found in Casas et al. (2016).

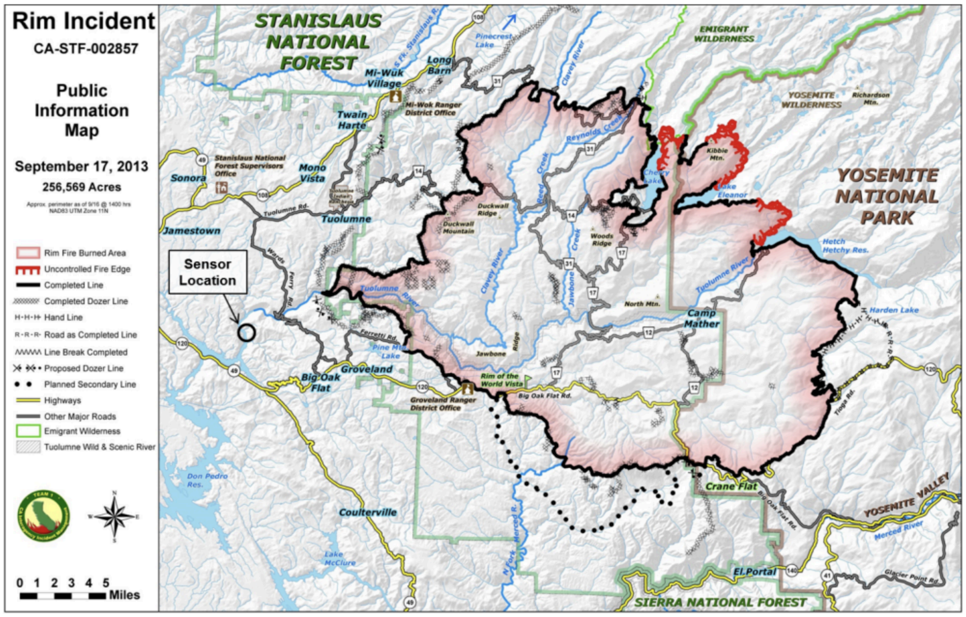

Figure 1: Location of the Rim Fire by the California Water Science Center (2013).

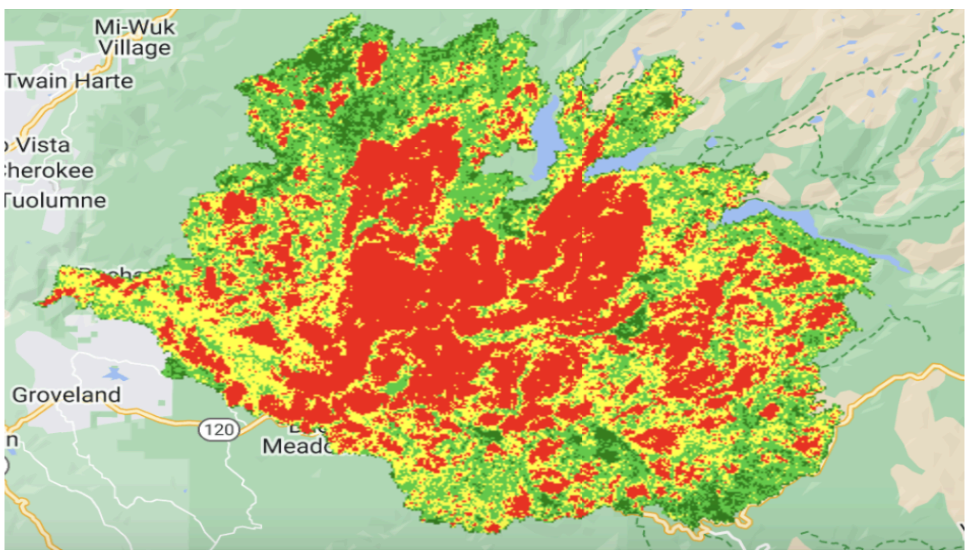

Figure 2: The burn severity footprint of the Rim fire in the Sierra Nevada Mountains, California, USA. Data was downloaded from the USDA Forest Service Geospatial Technology and Applications Center's (GTAC) Rapid Assessment of Vegetation Condition after Wildfire (RAVG) program (2013).

Data collection

To analyze how vegetation recovery has progressed following the fire, I obtained the burn severity map from the USGS's burn severity portal created by the RAVG program. I selected the CBI-4 thematic product to classify the burn scar area into 4 different burn severity categories I will obtain slope and aspect information on each pixel in the area from the USGS digital elevation model (DEM) for the impacted area using the USGS Earth Explorer. All of the data was in 30m spatial resolution. To get total and fractional vegetation cover data, I downloaded the publicly available maps derived in Wang (2022), which is Landsat derived and contains fractional cover for four land types for each year in California from 1985-2021.

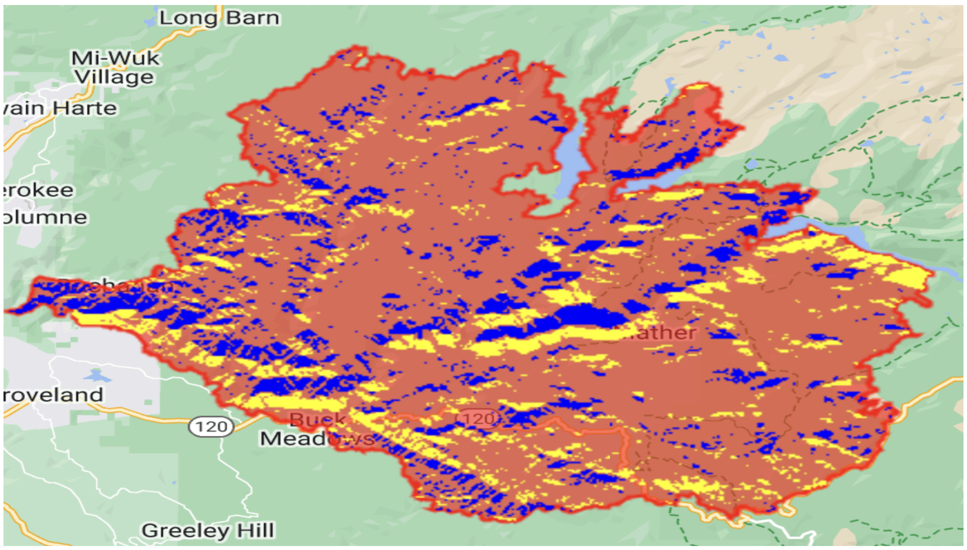

Figure 3: North and South Facing Slopes > 15% Indicated by Yellow (North) and Blue (South)

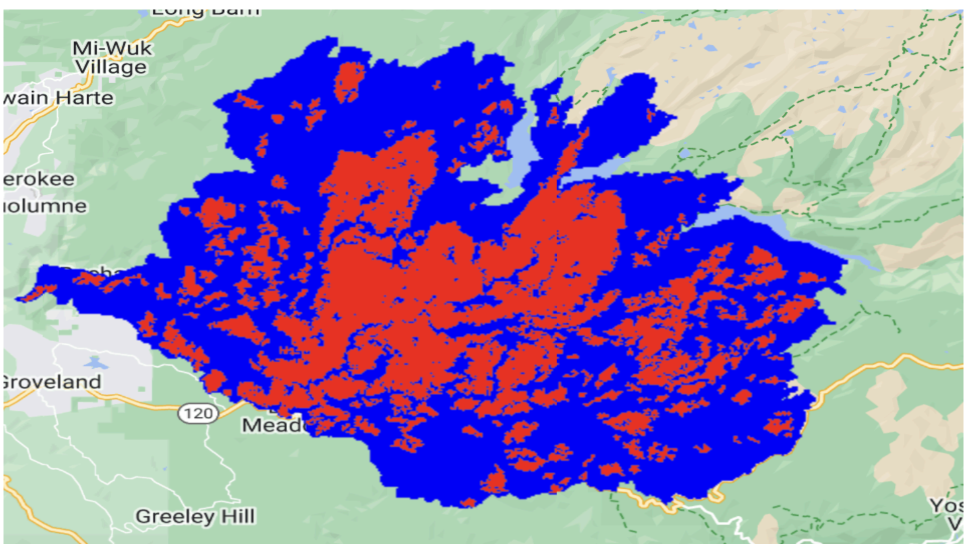

Figure 4: High-Severity Patches Indicated by Red (1) and Blue (0)

Data analysis

I conducted a raster analysis in Google Earth Engine to analyze the impact of the Rim fire and how various variables affect vegetation recovery trends. First, I delineated the landscape based on fire severity using the burn severity map obtained from RAVG. I chose the Composite Burn Index (CBI) developed by Key and Benson (2006). Using RAVG's description of CBI classes, pixels that are CBI class 4 will be referred to as areas of "high severity," CBI class 3 as "moderate severity," CBI class 2 as "low severity," and class 1 as "unchanged." To research the effects of slope and aspect, I overlaid a DEM map from USGS and masked out any areas facing North or South by deriving aspect. Afterward, I masked out any pixels with slopes < 15%. Finally, I used the RAVG burn severity map to derive a binary patch presence indicator. Firstly, I selected pixels with CBI values of 4. I removed any pixels with an immediate neighbor that was not high-severity and then filtered out patches with sizes less than 0.5 hectares. After delineating the entire region for all three variables, I conducted a raster analysis of land cover change between 2014 and 2021.

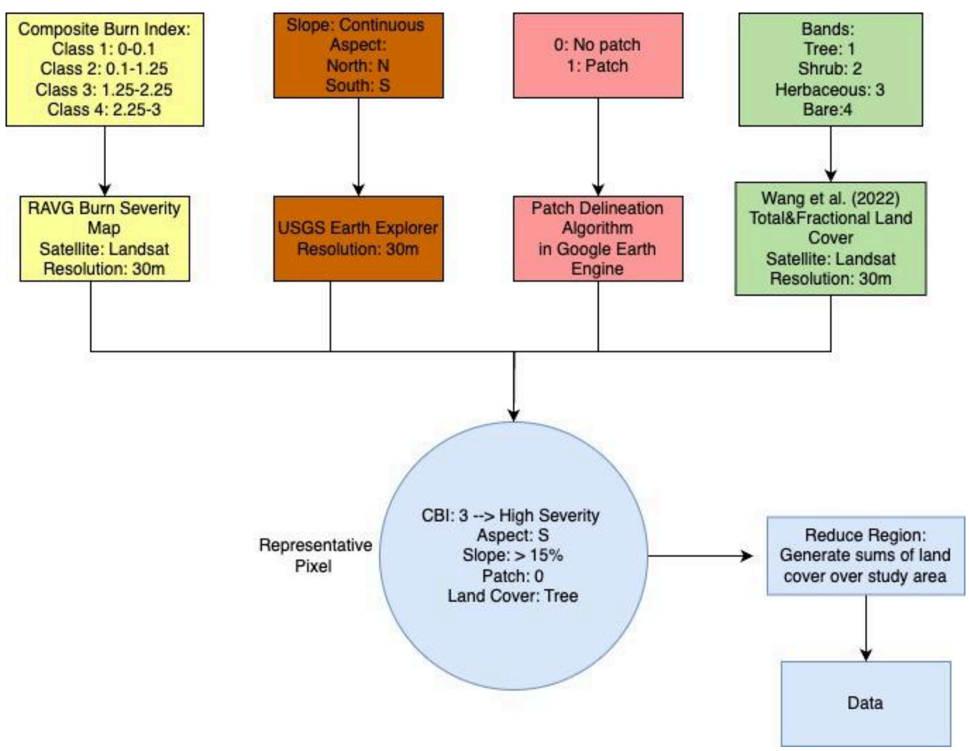

Figure 5: Workflow of Delineation and Raster Analysis

RESULTS

In the rest of the paper, I calculated the percent change with the following formula:

$$(New\ Cover\ Percentage\ -\ Old\ Cover\ Percentage)\ /\ Old\ Cover\ Percentage$$

This means that when there is a percentage increase, the value refers to the percentage increase relative to the older cover percentage. When the percentage is negative, it refers to how much of the original cover percentage was lost to other land cover types.

General Trends in Land Cover Change and Vegetation Type Shifts

There was a consistent trend between 2012 and 2013, followed by significant changes in land cover from 2013 to 2014 due to the fire. Initially, tree covers slightly decreased, and shrubs decreased more pronouncedly. The significant decrease in shrubs makes intuitive sense as they fuel wildfires, while it is more difficult to burn down trees completely. The land lost from trees and shrubs was converted to herbaceous and bare fields. However, after 2014, tree cover significantly decreased, and shrub cover increased substantially. The total percentage of tree cover fell from 63.9% in 2014 to 35.3% in 2021. The total tree cover lost accounted for 28.6% of the area. In contrast, shrub percentage increased by 129.7%, with pixels converted from trees representing 50.9% of total shrub pixels, or 80.6% of converted pixels coming solely from trees. By 2021, shrub cover comprised 47.8% of the total area. The total change in herbaceous plants and bare fields was more marginal relative to the area, but the percent change was still significant; herbaceous plants increased by 55.3%, and bare fields decreased by 48.5%. However, relative to the total area, herbaceous plants made up 8.7% of the area to 13.5%, while bare fields went from 6.6% to 3.4% of the area. In the following sections, I explore how this change reflected across different burn severities and topographies and whether the area was in a high-severity patch. I examined two periods: the immediate effects of the wildfire from 2013 to 2014 and long-term trends between 2014-2021.

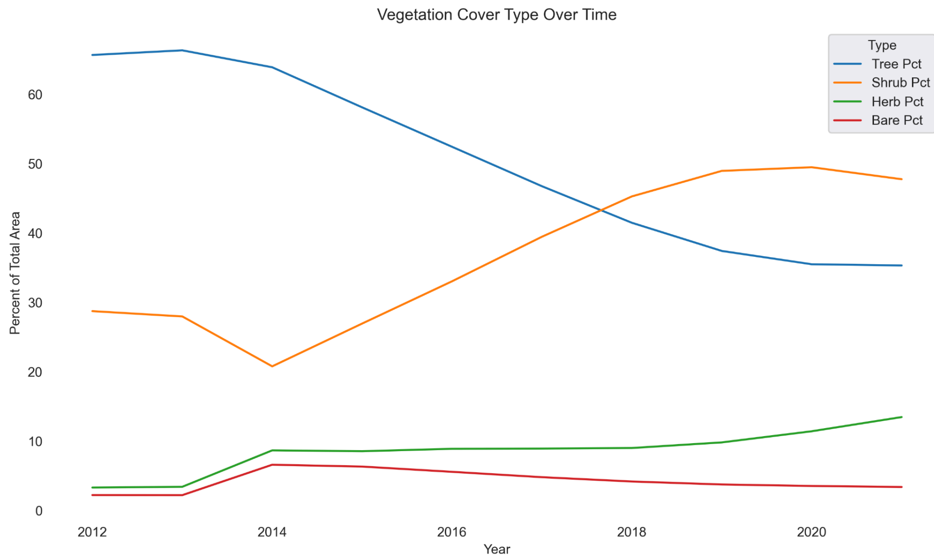

Figure 6: Land Cover Change Trends From 2012-2021.

Immediate Post-Fire Changes (2013-2014)

Tree cover change was not significantly different overall but varied across severity levels. The smallest changes occurred in unchanged and high-severity areas, with decreases of 0.46% and 0.67%, respectively (Figure 7). However, while unchanged areas remained relatively stable, 17.04% of tree cover in high-severity areas was converted to other land cover types. A large portion of this loss, 92.42%, was offset by shrub conversion to trees. Low-severity areas showed a decrease of 5.66%, and moderate-severity areas exhibited the largest decrease at 7.15%. There was an increase in shrub cover in unchanged and low-severity areas by 3.93% and 18.21%, respectively (Figure 8). In contrast, shrub cover declined by 5.74% in moderate-severity areas and by 55.37% in high-severity areas. Within the pixels converted in high-severity areas, 38.72% became trees, 45.42% became herbaceous species, and 15.86% became bare fields.

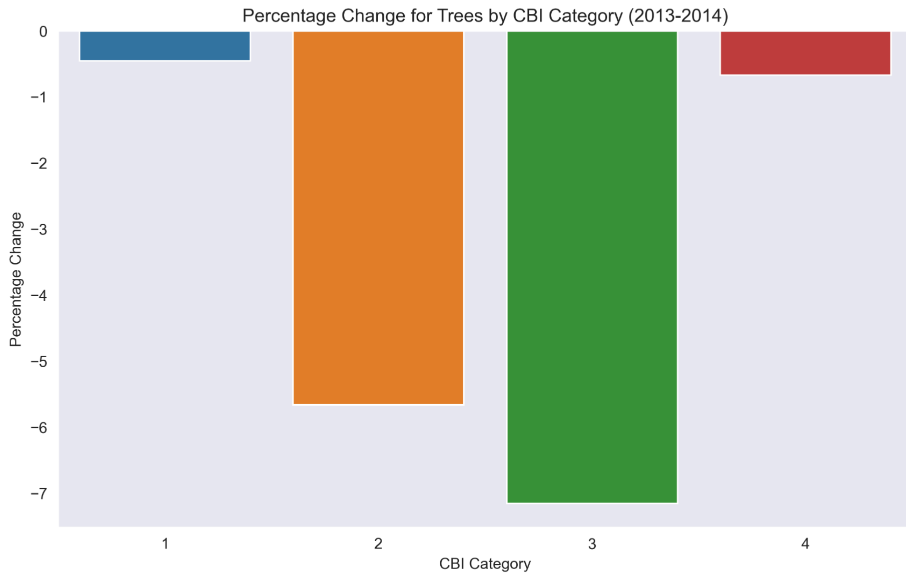

Figure 7: Percent Change in Tree Cover from 2013 to 2014 Across CBI Categories

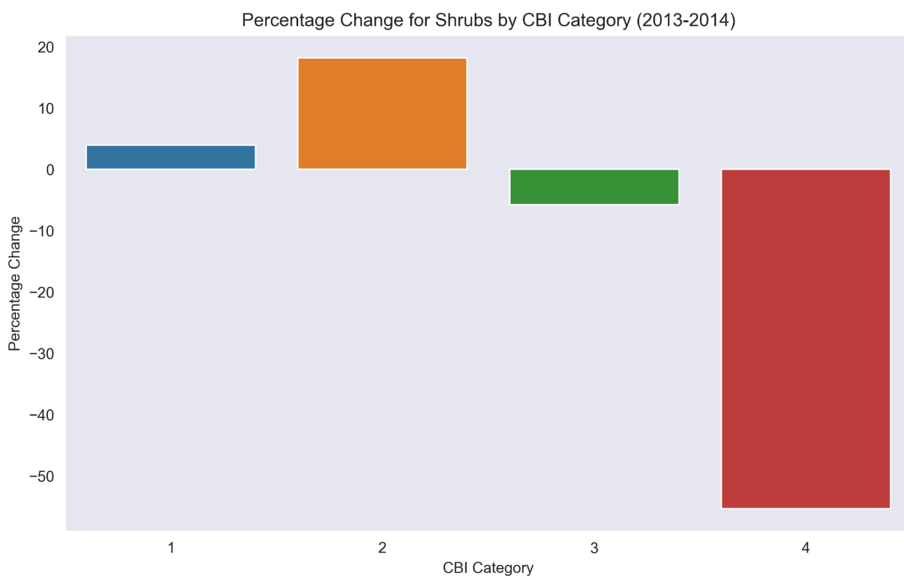

Figure 8: Percent Change in Shrub Cover from 2013 to 2014 Across CBI Categories

Land cover change trends in herbaceous species were pronounced in high-severity areas, with a significant increase of 332.33% (Figure 9). Of the pixels that converted to herbaceous cover, 77.80% came from shrubs. Moderate-severity areas showed an increase of 49.55%, followed by low-severity areas at 32.08% and unchanged areas at 1.11%. These results demonstrate a positive correlation between severity levels and short-term herbaceous succession. Similarly, bare fields followed a comparable trend, with larger increases at higher severity levels

(Figure 10). Unchanged areas experienced a marginal decrease of 0.66%, and low-severity areas saw a slight increase of 8.43%. In contrast, moderate-severity areas increased by 163.57%, and high-severity areas surged by 1591.66%. Thus, there is a clear association between the rise in bare cover and higher severity levels. In high-severity areas, 55.16% of the pixels that converted to bare fields originated from trees, 29.32% from shrubs, and 5.51% from herbaceous cover.

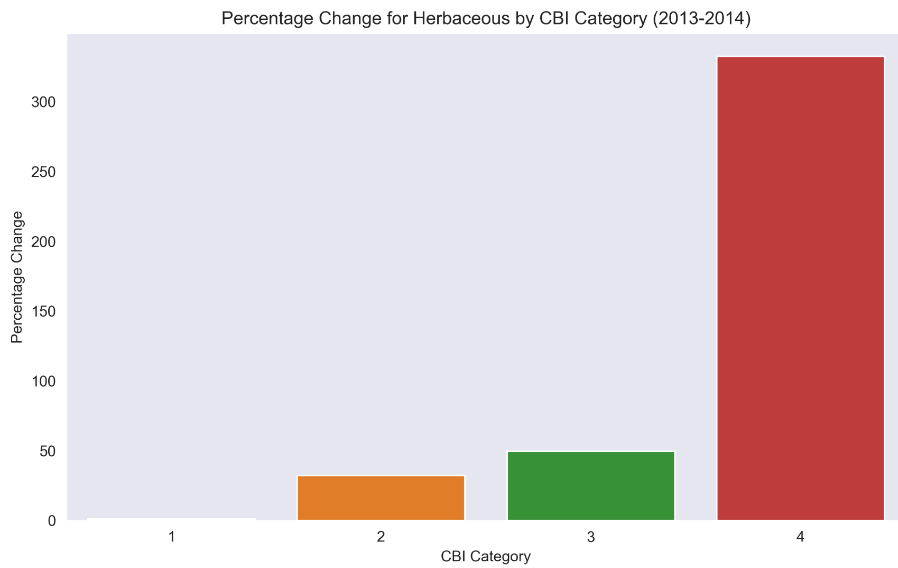

Figure 9: Percent Change in Herbaceous Cover from 2013 to 2014 Across CBI Categories

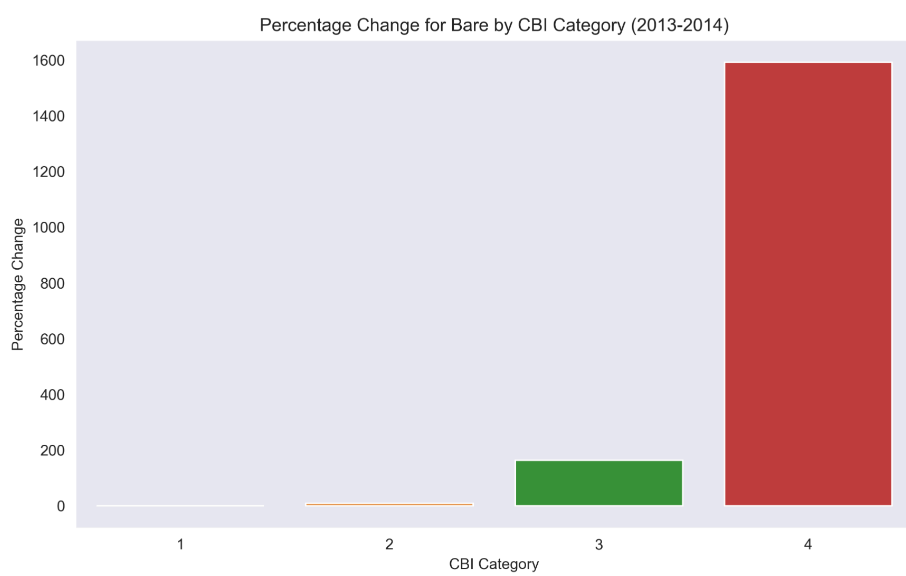

Figure 10: Percent Change in Bare Cover from 2013 to 2014 Across CBI Categories

Long-Term Land Cover Shift Trends (2014-2021)

Tree cover change significantly differed across CBI categories (Figure 11). While there were decreases in all categories, the magnitude of change increased as burn severity increased. The conversion of tree cover to other land cover types in 2014 varied by burn severity: 6.9% in unchanged areas, 21.7% in low severity, 36.1% in moderate severity, and 75.7% in high-severity areas. In unchanged areas, 91.4% of converted tree pixels transformed into shrubs. This figure was 94.1% for low-severity areas, 87.7% for moderate-severity areas, and 71% for high-severity areas.

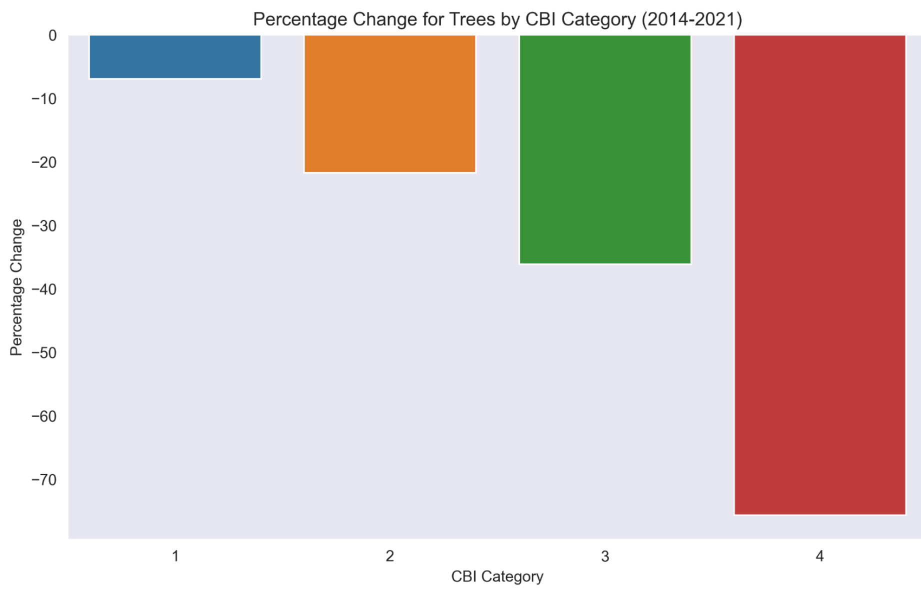

Figure 11: Percent Change in Tree Cover from 2014 to 2021 Across CBI Categories

There was a relatively constant trend in land cover change with no lines intersecting and ordered by severity level (Figure 12). Tree cover loss increased faster between 2014 and 2019 and slowed down in the following two years. This observed pattern indicates a significant stratification of tree cover loss directly correlated with the intensity of the fire damage, emphasizing the impact of burn severity on tree survival.

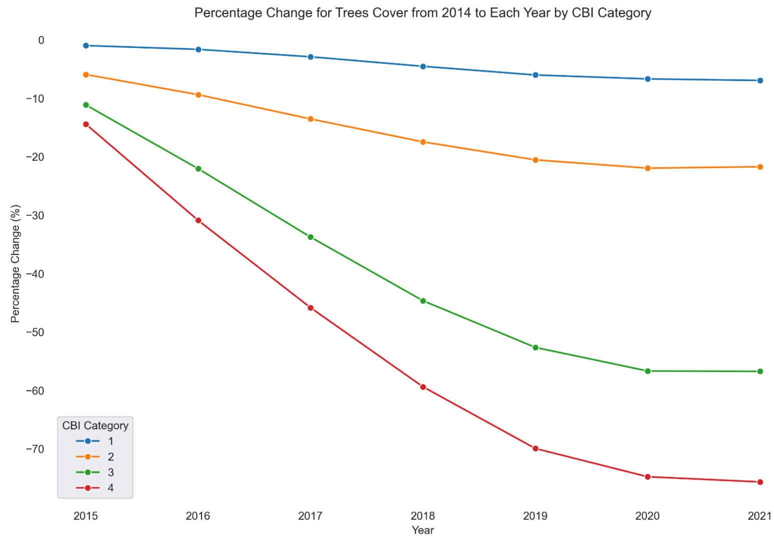

Figure 12: Cumulative Percent Change in Tree Cover From 2014 to 2021 Across CBI Categories

There was an increase in shrub cover across all categories, ordered by burn severity levels. Shrub cover in unchanged areas increased by 53.6%, low-severity areas by 67.2%, moderate severity areas by 103.9%, and finally, high-severity areas by 235.5% (Figure 13). For all categories, the majority of the increase came from tree cover conversion. Shrub cover that was lost differed across categories, with more shrubs being converted to tree cover in unchanged and low-severity areas but more shrub cover being classified as herbaceous in moderate to high-severity areas.

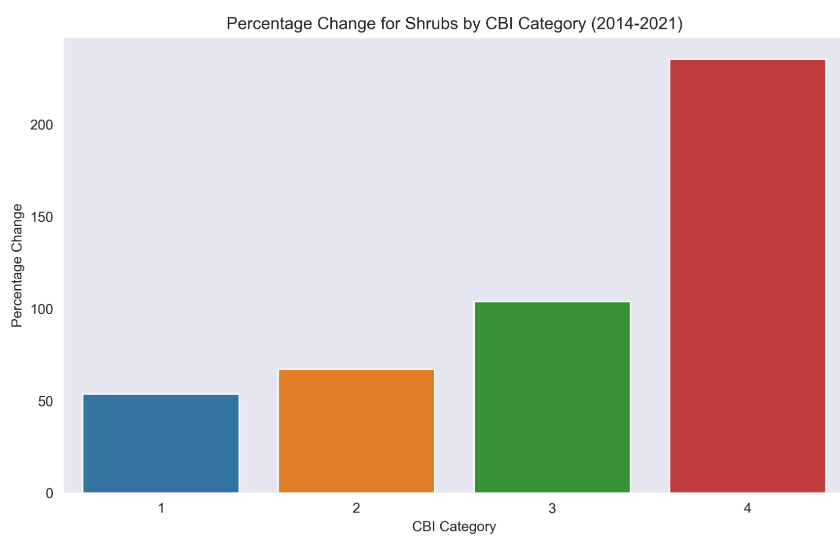

Figure 13: Percent Change in Shrub Cover from 2014 to 2021 Across CBI Categories

Furthermore, the increase in shrub cover in high-severity areas reached a peak of 255.8% in 2019 (Figure 14). For the highest severity pixels, there was an increase in shrub percentage at a much higher pace than other classes. Furthermore, the increase leveled off after 2019. These findings demonstrate a clear trend of increased shrub species correlating with higher burn severity levels, with the most severe category (CBI 4) showing an exceptional increase. This pattern demonstrates that out of the land cover types considered, shrubs succeed in areas most damaged by the wildfire.

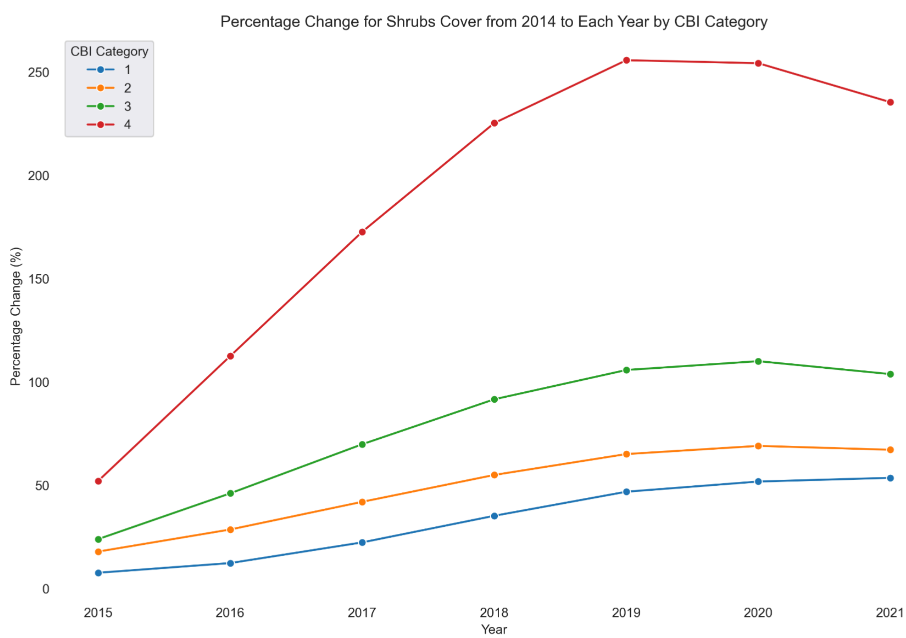

Figure 14: Cumulative Percent Change in Shrub Cover from 2014 to 2021 Across CBI Categories

Land cover trends for herbaceous species also differed across different burn severities (Figure 15). However, the change with the highest magnitude was not in high-severity areas but in moderate-severity areas with 68.0%. High-severity areas increased by 55.7%, low-severity areas by 29.7%, and finally, unchanged areas by 19.3%. The increase across all categories shows that regardless of severity levels, herbaceous plants were increasing after the fire. Furthermore, across all categories, the majority of conversions to herbaceous species originated from shrubs, accounting for 61.2% in unchanged areas, 77.8% in low-severity areas, 88.2% in moderate-severity areas, and 90.3% in high-severity areas. Thus, conversions from shrubs to herbaceous species occurred at higher rates in areas of greater burn severity.

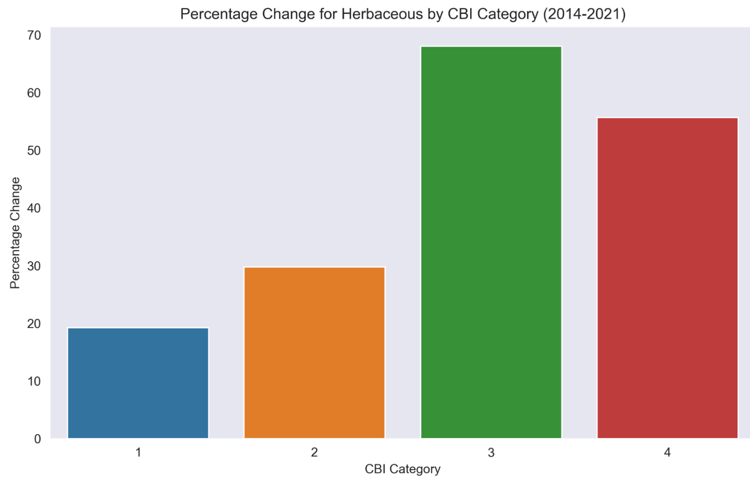

Figure 15: Percent Change in Herbaceous Cover from 2014 to 2021 Across CBI Categories

There was an initial loss of herbaceous plants in high-severity areas as the line plot started below 0 in 2015 (Figure 16). All classes increased after 2015, followed by a relatively stable period until 2018. The period from 2018 to 2021 was completely different, with higher severity classes depicting significant increases from 2018 to 2019 and faster increases for the following years. The cumulative change changed from -0.7% in 2018 to 55.7% in 2021. For the same years, the land cover increased from 13% to 68% for moderate severity areas, so both areas showed a similar pace of change. While low severity and unchanged areas still demonstrated increases, the magnitude of change was much lower. Since shrub increase had leveled off after 2019, suggesting that herbaceous plants started expanding in the landscape after 2019 or other land cover types were converted into herbaceous species during this period. This data indicates a notable expansion of herbaceous plants post-fire, particularly in moderate to high-severity areas. However, the emergence of herbaceous plants typically did not occur immediately post-fire but emerged several years later. Despite variations in the rate of increase, the overall trend confirms a general resilience and adaptability of herbaceous species in the post-fire landscape across all burn severity levels.

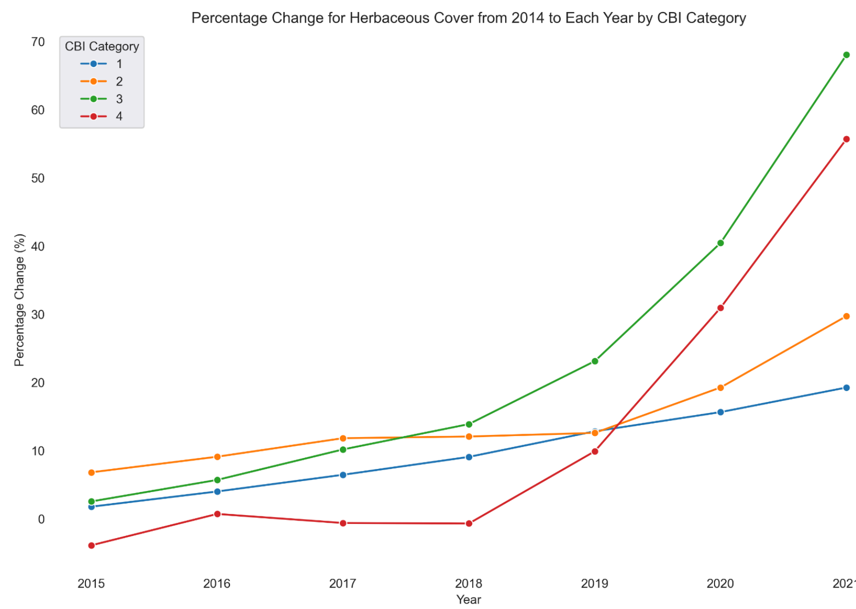

Figure 16: Cumulative Percent Change in Herbaceous Cover from 2014 to 2021 Across CBI Categories

There was a significant difference between severity levels (Figure 17). Unchanged and low-severity areas displayed marginal differences, with a slight decrease of -3.5% for unchanged and -1.8% for low-severity areas. In contrast, moderate severity areas displayed a decrease of -47.1% in bare fields, followed by high severity areas with a decrease of 68.1%. In moderate-severity areas, 62.8% of lost bare fields were converted to shrubs, and in high-severity areas, 53.5% were converted to shrubs. Therefore, there is a pattern of shrub emergence in bare fields left by the wildfire.

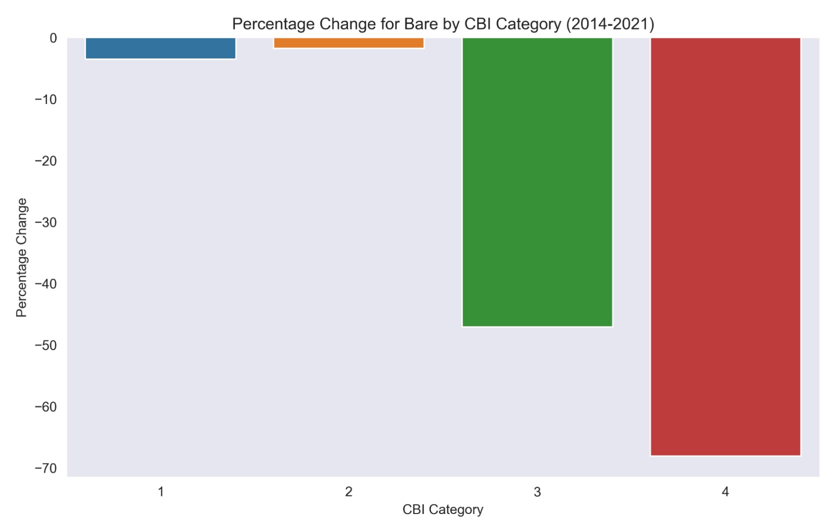

Figure 17: Percent Change in Bare Cover from 2014 to 2021 Across CBI Categories

There was no significant change across the post-fire time period for unchanged and low-severity areas (Figure 18). However, there was a pronounced decrease in bare fields for moderate and high-severity areas. In addition, there was a sharp decrease from 2015 to 2018 for moderate to high-severity areas. However, this change slowed down in the years that followed.

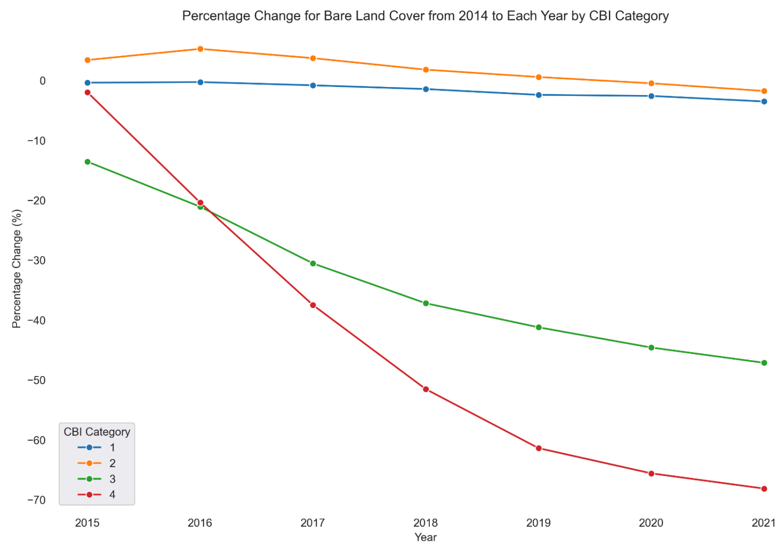

Figure 18: Cumulative Percent Change in Bare Cover from 2014 to 2021 Across CBI Categories

Steep North/South Facing Slopes

Immediate Post-Fire Changes (2013-2014)

Tree cover change was marginal across both categories, with a small decrease of 0.87% in steep north-facing slopes and an increase of 0.99% in south-facing slopes (Figure 19). In shrubs, however, land cover change was more pronounced, with north-facing slopes displaying a decrease in shrub cover percentage by 7.23% and south-facing slopes displaying a decrease of 36.97% (Figure 20). In all shrub pixels converted in north-facing slopes, 82.43% were classified as trees in 2014. The trend was completely different in south-facing slopes, with 61.40% of converted pixels changing to herbaceous cover, 22.31% to tree cover, and 16.28% to bare fields.

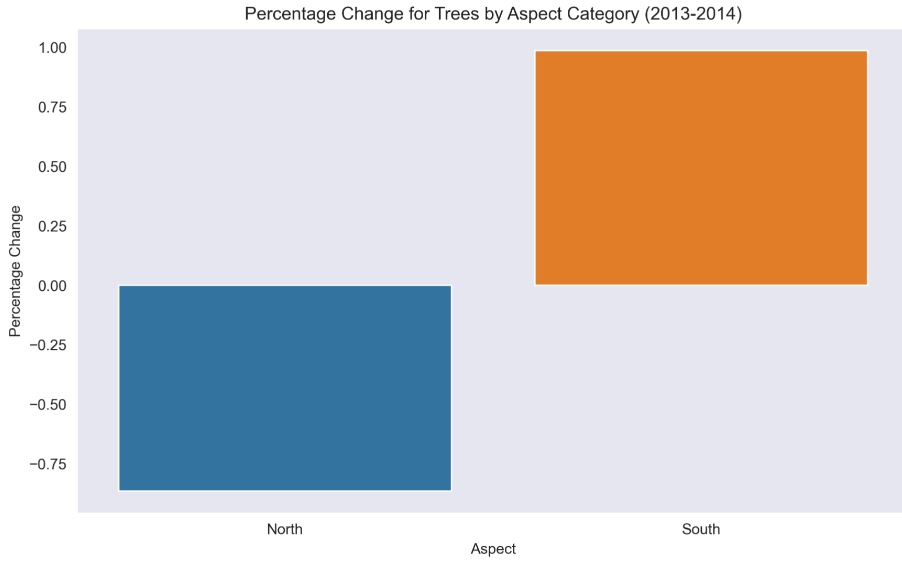

Figure 19: Percent Change in Tree Cover from 2013 to 2014 by Aspect

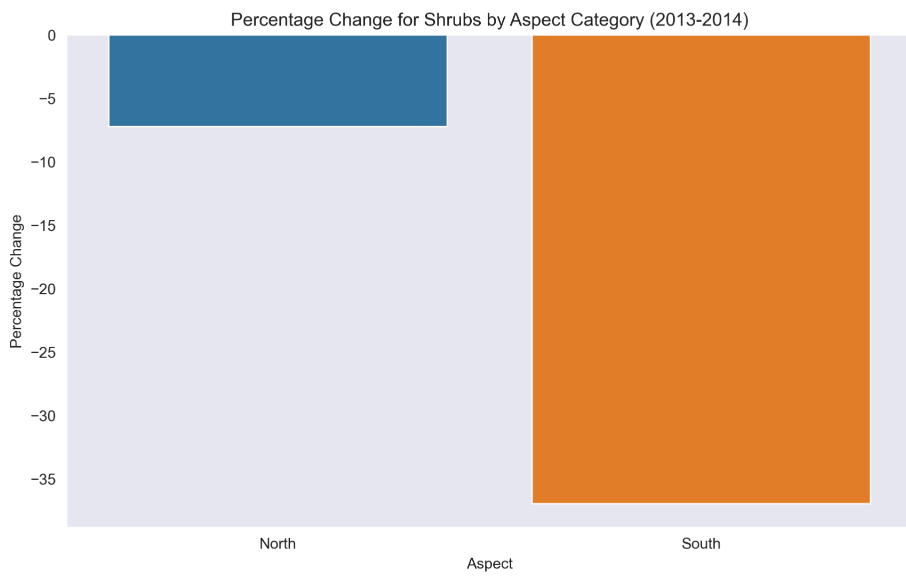

Figure 20: Percent Change in Shrub Cover from 2013 to 2014 by Aspect

Examining herbaceous cover trends, both north-facing and south-facing steep slopes displayed remarkably similar changes, with an increase of 164.69% and 164.81%, respectively (Figure 21). However, it is important to note that pixel totals were significantly different across both categories, with herbaceous pixels increasing from 456 to 1,207 in north-facing slopes and 17,021 to 45,074 in south-facing slopes. The majority of the conversion came from shrubs in both categories. Furthermore, trends in bare cover change varied significantly between categories. Although both categories showed an increase, the change was substantially more pronounced on south-facing slopes, with increases of 39.71% on north-facing slopes compared to 223.97% on south-facing slopes (Figure 22). Although the majority of conversions on north-facing slopes originated from trees, on south-facing slopes, shrubs were the primary source of conversions.

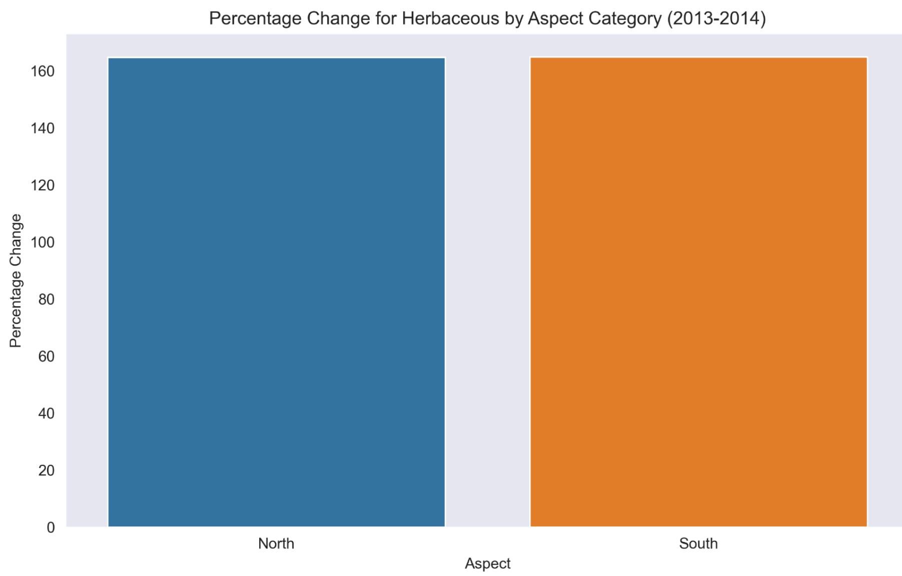

Figure 21: Percent Change in Herbaceous Cover from 2013 to 2014 by Aspect

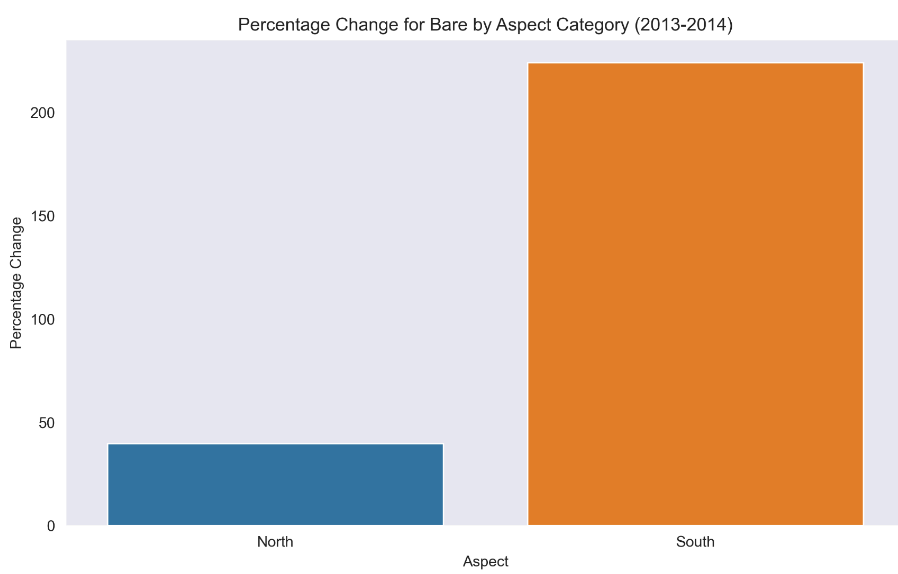

Figure 22: Percent Change in Bare Cover from 2013 to 2014 by Aspect

Long-Term Land Cover Shift Trends (2014-2021)

Tree loss was significantly higher on south-facing slopes, with 74.8% of tree pixels converted to other land cover types (Figure 23). Steep north-facing slopes also depicted a decreasing trend, with 34.3% of the area in 2014 being converted to other classes. However, it is important to note that there were 127,516 north-facing pixels compared to 38,172 south-facing pixels. From 2014 to 2021, 97.6% of tree pixels reclassified on north-facing slopes were converted to shrubs. In contrast, on south-facing slopes, the figure was 81.4%. Although both percentages are significant, the conversion to shrubs is particularly pronounced on north-facing slopes.

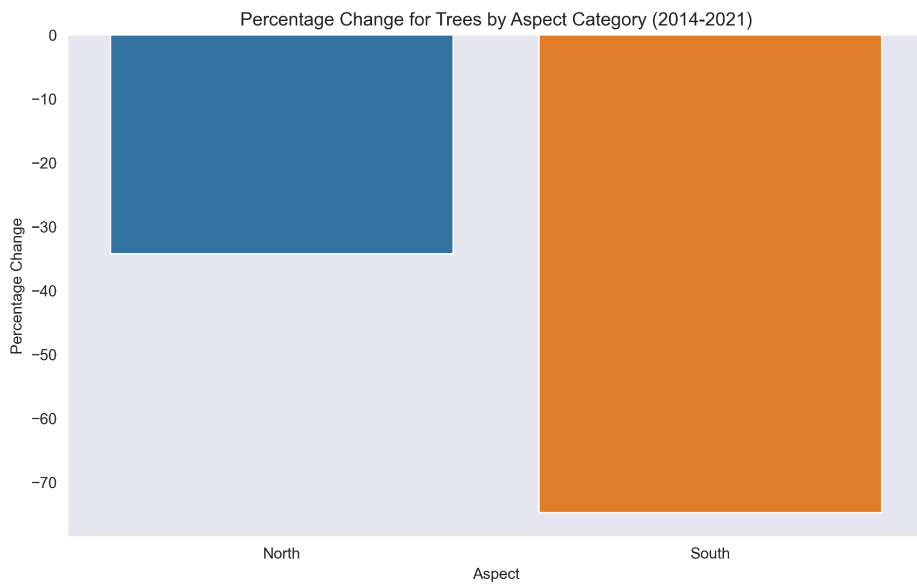

Figure 23: Percent Change in Tree Cover from 2014 to 2021 by Aspect

Observing tree cover loss on a year-to-year temporal scale, there was a sharper drop in the initial years following the fire, with south-facing slopes starting lower in the graph in 2015 and conveying a sharp decrease until 2018 compared to steep north-facing slopes (Figure 24). The decrease leveled off in both categories after 2019.

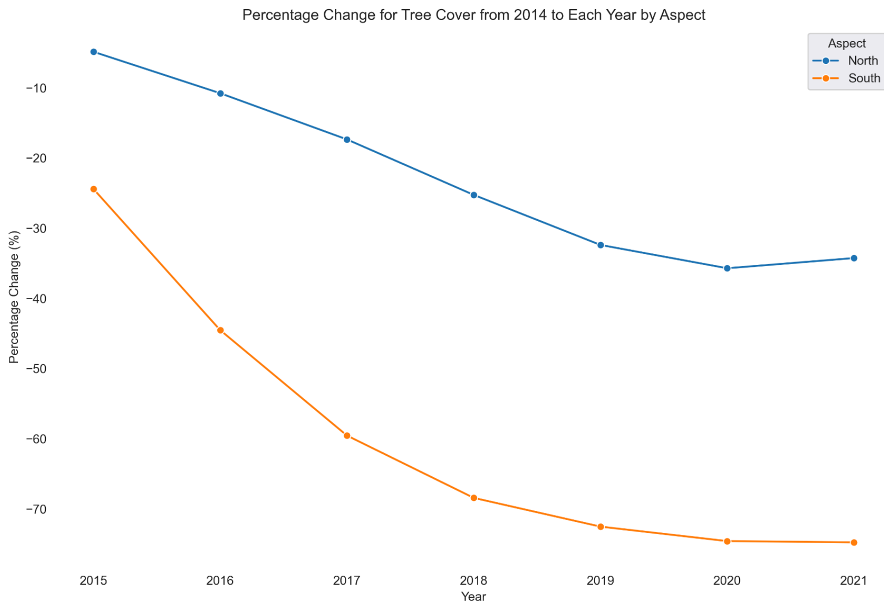

Figure 24: Cumulative Percent Change in Tree Cover from 2014 to 2021 by Aspect

The number of shrub pixels on steep north-facing slopes increased significantly by 255.5% from 2014 to 2021, from 17,518 to 62,280 pixels (Figure 25). For south-facing slopes, the increase was 67.5%, from 65,221 to 109,263 pixels. There was a clear variation in shrub cover expansion in percentage across the two different aspect categories, with north-facing slopes experiencing a significantly higher increase than south-facing slopes. Most new shrub pixels came from trees in both categories, but there were significant differences when compared to other land cover types. Firstly, while 96.1% of all new shrub cover came from trees in north-facing slopes, this figure was 47.1% for south-facing slopes, 41% from herbaceous species, and 11.9% from bare cover. Furthermore, 46,018 tree pixels were converted to shrubs in north-facing slopes, significantly higher than the 14,394 pixels classified as shrubs in 2014 and 2021. In contrast, this difference was less pronounced in south-facing slopes, as 23,923 tree pixels become shrubs, but already 58,433 pixels were classified as shrubs in both years.

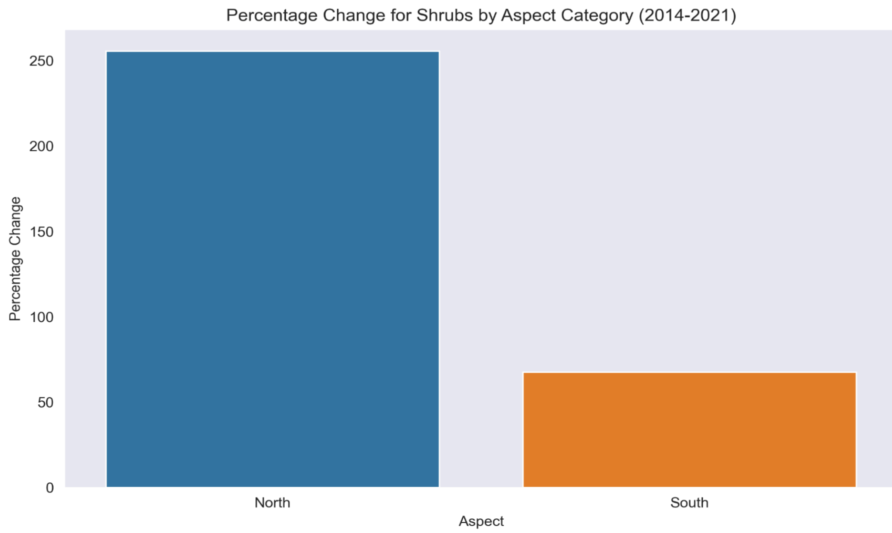

Figure 25: Percent Change in Shrub Cover from 2014 to 2021 by Aspect

Examining the trajectory of shrub cover change, both categories started at a similar positive increase from 2014 to 2015, at 35.8% for north-facing and 26.9% for south-facing slopes (Figure 26). However, while there was an increasing trend until 2018, which leveled off in the subsequent years for south-facing slopes, north-facing slopes had a much higher magnitude of increase, observed until 2020, followed by a marginal decrease in 2021.

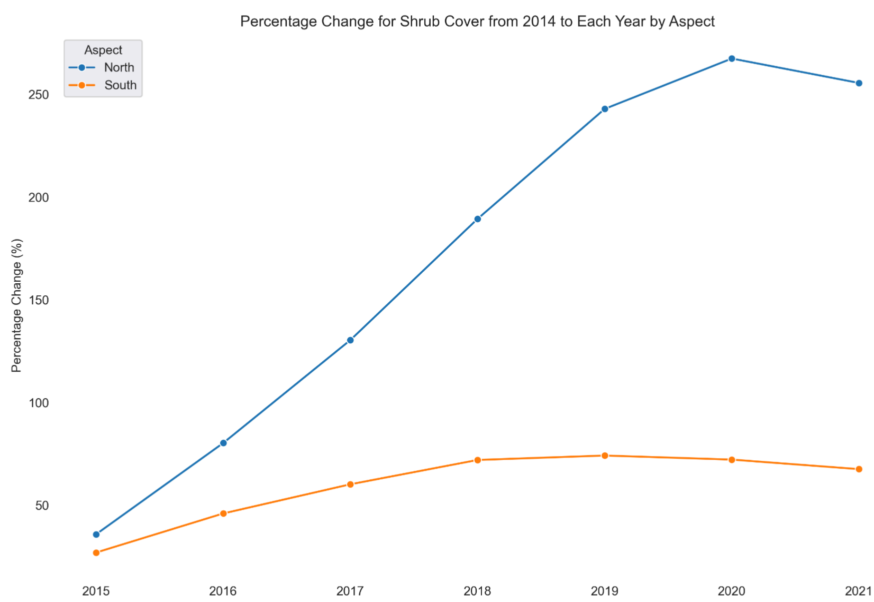

Figure 26: Cumulative Percent Change in Shrub Cover from 2014 to 2021 by Aspect

For herbaceous cover, there was a 5.1% increase in north-facing slopes (Figure 27). In contrast, 23.2% of herbaceous pixels in 2014 were converted to other land types by 2021. Notably, only 1,207 pixels were classified as herbaceous in north-facing slopes, while 45,074 pixels were classified as such in south-facing slopes in 2014. The change was 62 pixels in north-facing slopes and 10,444 in south-facing slopes. Therefore, while herbaceous species are rarely observed in north-facing slopes, they are much more common in south-facing slopes in the Rim Fire burn scar area, and the magnitude of change was much more significant for south-facing slopes. Furthermore, 90.6% of herbaceous pixels that change were converted to shrubs.

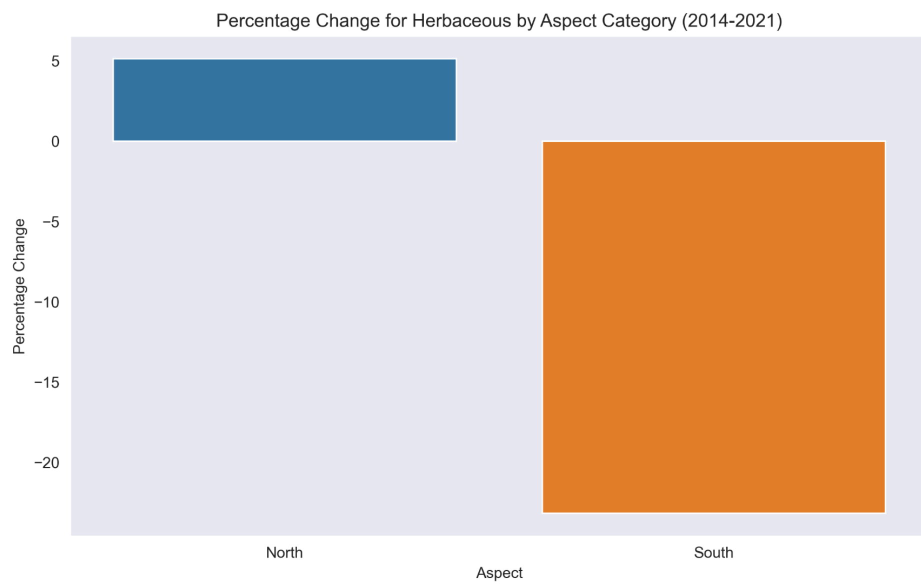

Figure 27: Percent Change in Herbaceous Cover from 2014 to 2021 by Aspect

Herbaceous cover change trends in both categories started with a decreasing trend, with steep north-facing slopes having a higher decrease in magnitude until the year 2017 (Figure 28). The decrease was less in magnitude for steep south-facing slopes, and the land cover percentage decreased till 2018. After this time period, both categories depicted increasing percentages of herbaceous species. North-facing slopes demonstrated a larger increase, with an especially pronounced change from 2020 to 2021. However, it is important to recognize that the number of herbaceous pixels was limited in north-facing slopes.

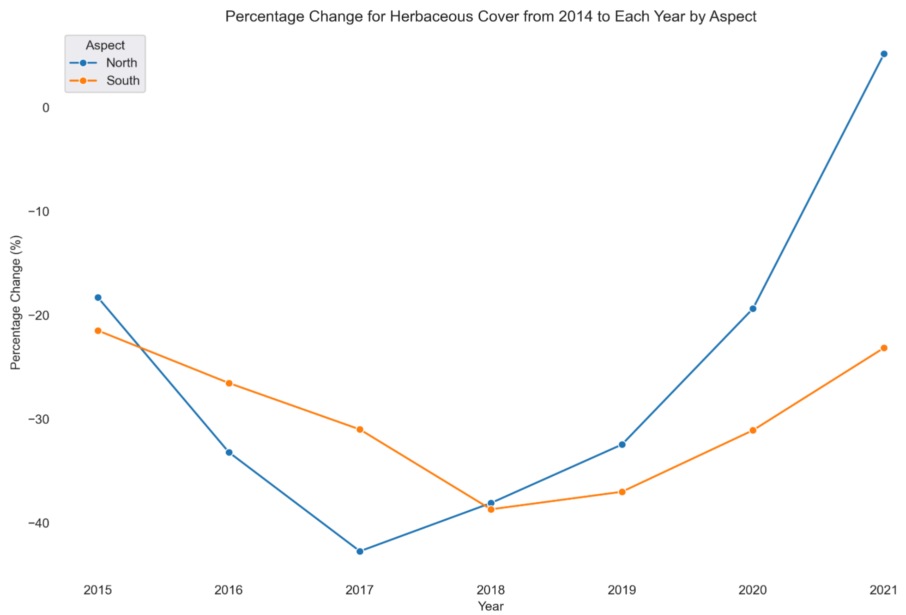

Figure 28: Cumulative Percent Change in Herbaceous Cover from 2014 to 2021 by Aspect

A decrease in bare cover was observed in both categories, but the magnitude of change was higher in south-facing slopes, with a decrease of 35.5%, compared to a decrease of 18.5% in north-facing slopes (Figure 29). Most bare cover was converted to shrubs in both areas, with 72.5% of converted pixels becoming shrubs in south-facing slopes and 66.5% for north-facing slopes. This makes sense, considering shrub cover significantly increased in both categories.

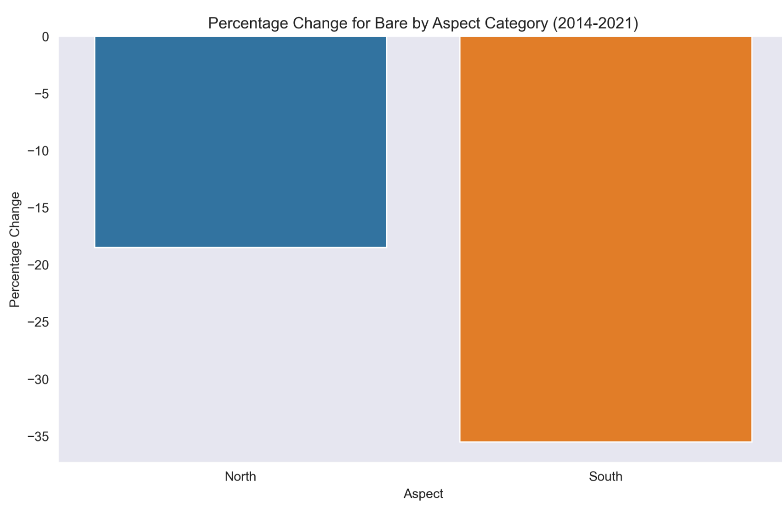

Figure 29: Percent Change in Bare Cover from 2014 to 2021 by Aspect

Bare cover in both categories increased from 2014 to 2015 and consistently declined until 2021 (Figure 30). The decrease was most rapid from 2015 to 2017 for south-facing slopes and from 2016 to 2019 for north-facing slopes.

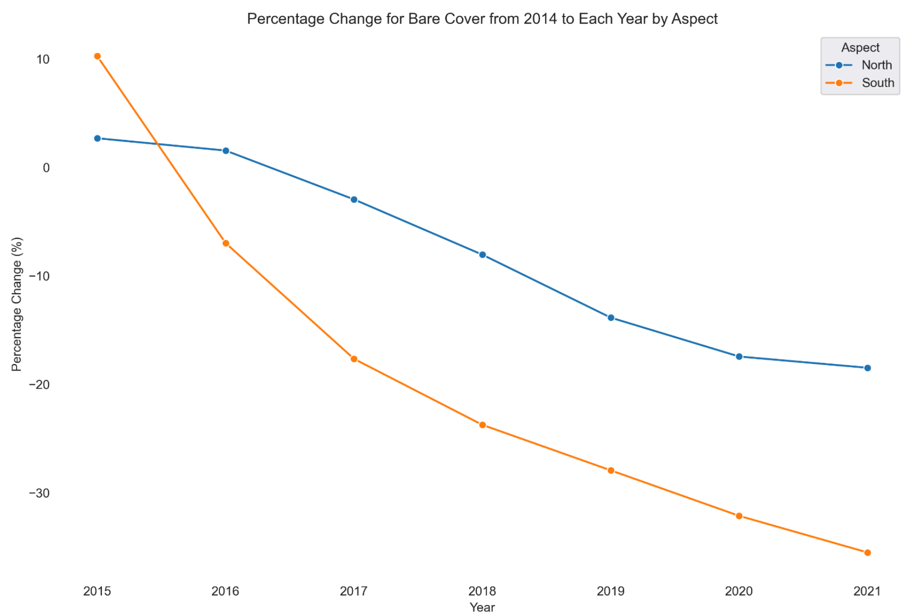

Figure 30: Cumulative Percent Change in Bare Cover from 2014 to 2021 by Aspect

Patch Presence

Immediate Post-Fire Changes (2013-2014)

Examining tree cover change, there was a 0.70% decrease in high-severity patches and a 4.94% decrease in non high-severity patches (Figure 31). Compared to high-severity areas (CBI = 4), the decrease in tree cover was 4.27% higher, signifying a more pronounced effect due to patch presence. Similar to the trends observed in high-severity areas, while some tree pixels convert to other types, mainly to bare fields, this change was neutralized by areas classified as shrubs in 2013 as trees in 2014. In contrast, most converted tree pixels in non-high-severity areas were classified as shrubs in 2014. Furthermore, there was a significant difference in shrub cover trends across both categories, with high-severity patches demonstrating a decrease of 55.99% and non-high-severity patch areas displaying an increase of 2.18% (Figure 32). Compared to high-severity areas, the decrease in shrub cover was 0.62% higher, much more marginal than the difference across both tree categories. Shrub cover was mainly converted to tree and herbaceous cover within high-severity patches and contributed significantly to the new bare cover observed in 2014.

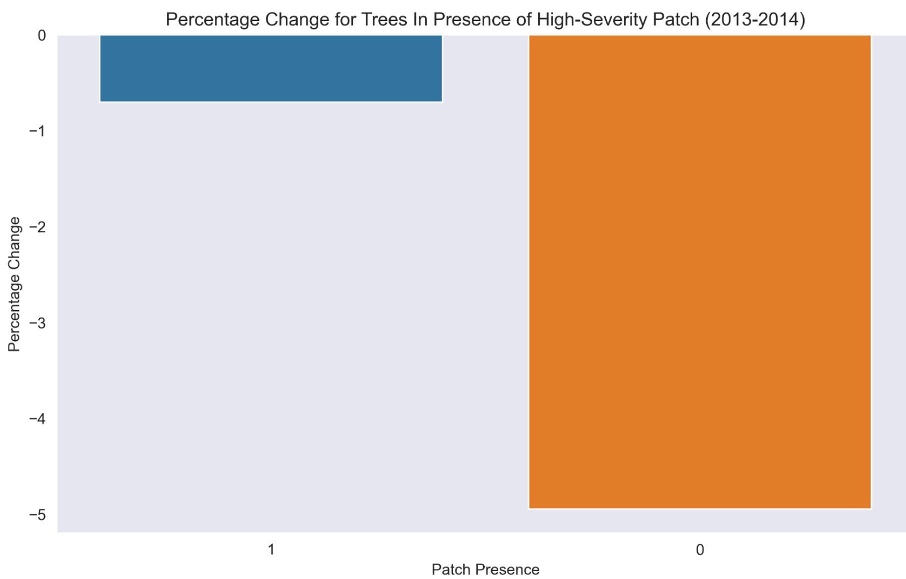

Figure 31: Percent Change in Tree Cover from 2013 to 2014 by Patch Presence

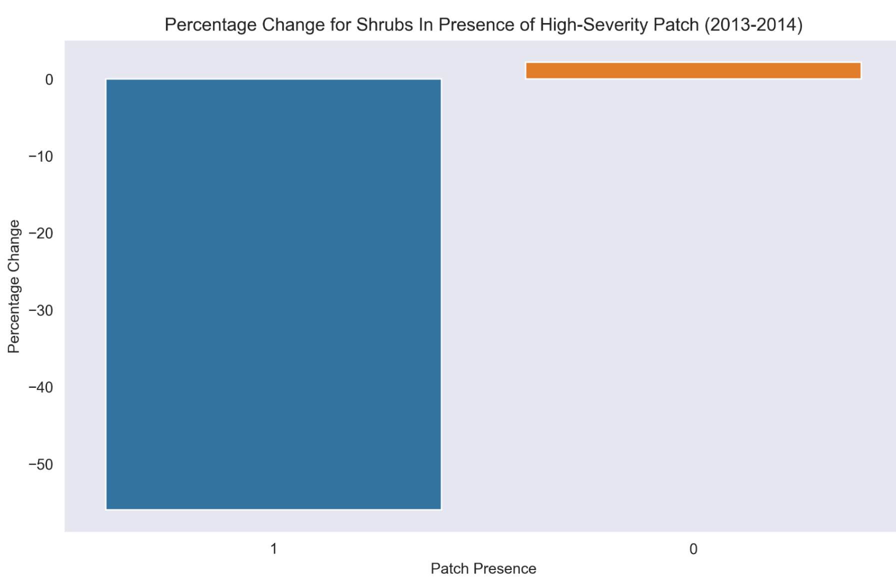

Figure 32: Percent Change in Shrub Cover from 2013 to 2014 by Patch Presence

Herbaceous cover showed a significant increase of 356.71% in high-severity patches and an increase of 38.34% in the remaining area (Figure 33). Compared to high-severity areas (CBI =

4), the increase in herbaceous cover was 24.38% higher. In both categories, the majority of conversion to new herbaceous pixels came from shrubs. However, this trend was more pronounced in high-severity patches, with 77.80% of newly converted pixels coming from shrubs, compared to 63.40% in non-high-severity patches. Therefore, herbaceous species performed positively immediately following the fire, especially in high-severity patches impacted by severe wildfires. However, the land cover type that demonstrated the difference of the highest magnitude between high-severity patches and the remaining area was bare fields; while there was a 55.60% increase in areas outside high-severity patches, areas within these patches displayed an increase of 1938.89% in bare fields (Figure 34). This change was 347.23% higher compared to high-severity areas, indicating that more bare fields remained in high-severity patches, with less vegetation able to expand into these areas. The majority of land converted to bare fields came from trees and shrubs.

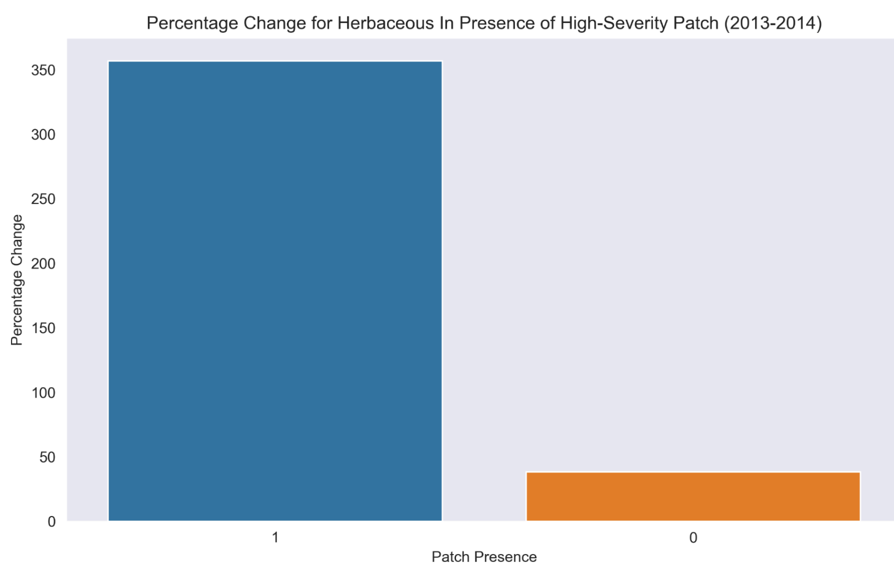

Figure 33: Percent Change in Herbaceous Cover from 2013 to 2014 by Patch Presence

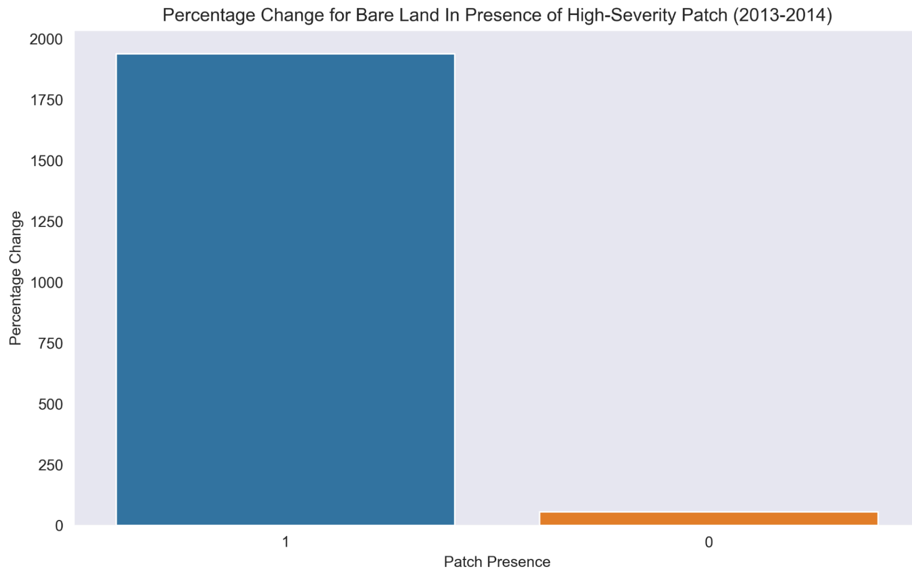

Figure 34: Percent Change in Bare Cover from 2013 to 2014 by Patch Presence

Long-Term Land Cover Shift Trends (2014-2021)

Since there is a significant overlap between high-severity pixels (CBI = 4) and those considered to be within a high-severity patch, vegetation recovery trends were parallel. The decrease was much more pronounced for tree cover loss in high-severity patches, with 75.96% of the original tree pixels being lost to other types (Figure 35). The loss was 30.86% for non-high-severity patches. This difference between loss across high-severity areas and high-severity patches was marginal, with an extra 0.33% loss within patches. Furthermore, there was a consistent decrease from 2014 to 2019, which slowed down in the following years across both categories (Figure 36). For shrubs, high-severity patches displayed a significant emergence of shrub pixels with an increase of 239.15%, compared to 86.34% (Figure 37). The increase in shrub percentage was 3.65% higher in high-severity patches compared to high-severity areas. Furthermore, while shrub increase hit a peak in 2019 for both high-severity patches and high-severity areas, the maximum was higher in high-severity patches with a value of 260.0%, which was 4.2% higher than the maximum peak for high-severity areas (Figure 38).

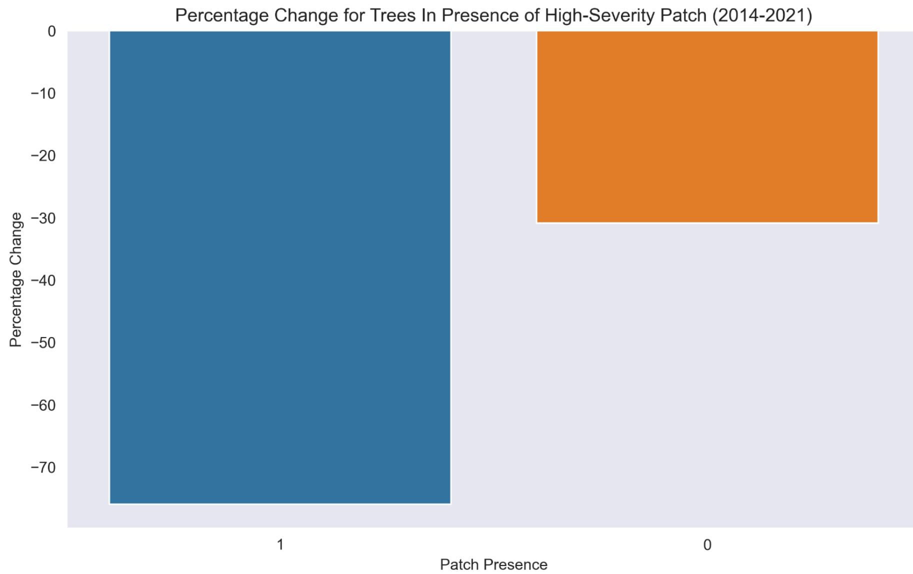

Figure 35: Percent Change in Tree Cover from 2014 to 2021 by Patch Presence

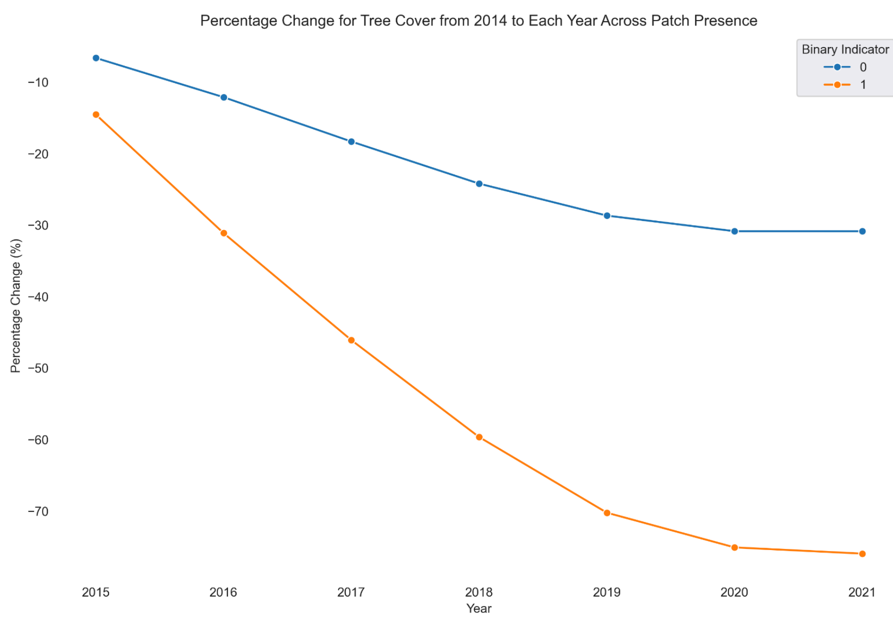

Figure 36: Cumulative Percent Change in Tree Cover from 2014 to 2021 by Patch Presence

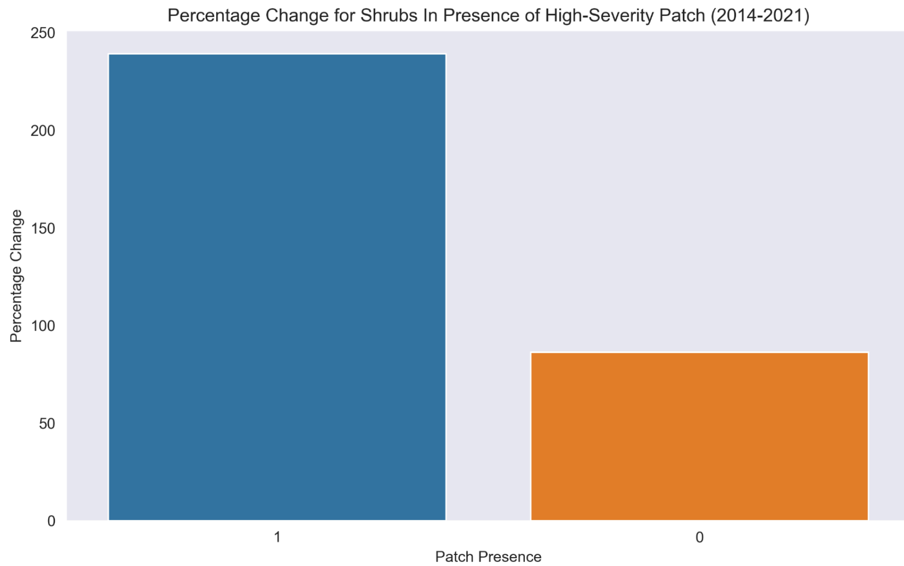

Figure 37: Percent Change in Shrub Cover from 2014 to 2021 by Patch Presence

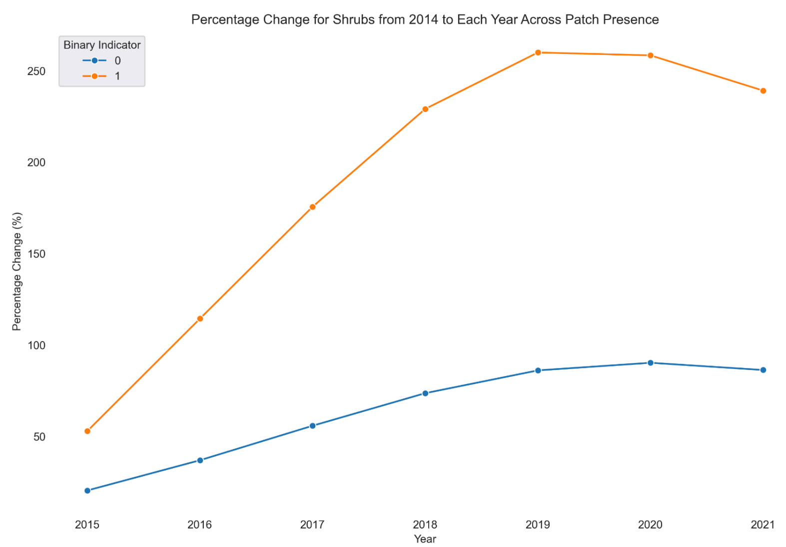

Figure 38: Cumulative Percent Change in Shrub Cover from 2014 to 2021 by Patch Presence

Herbaceous cover change trends were similar regardless of whether the pixel was in a high-severity patch. Moderate severity areas displayed the highest increase in herbaceous pixels, followed by high-severity, low-severity, and unchanged areas (Figure 39). The patch presence results are sensible as their average converges to similar percentages. In high-severity patches, there was an increase of 55.5%, compared to 55.0% in the remaining area. The difference between patches and high-severity areas was 0.2%, with patches displaying a lower increase. Comparing yearly cumulative change trends, while herbaceous cover increase is higher in non-high-severity patches from 2014 to 2020, the rapid increase starting in 2018 in high-severity patches eventually caught up in 2021 (Figure 40).

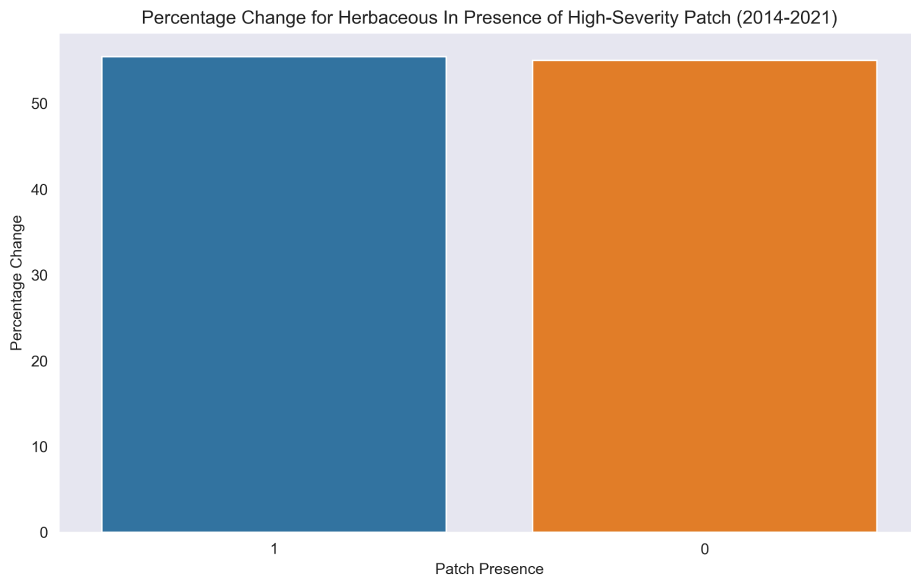

Figure 39: Percent Change in Herbaceous Cover from 2014 to 2021 by Patch Presence

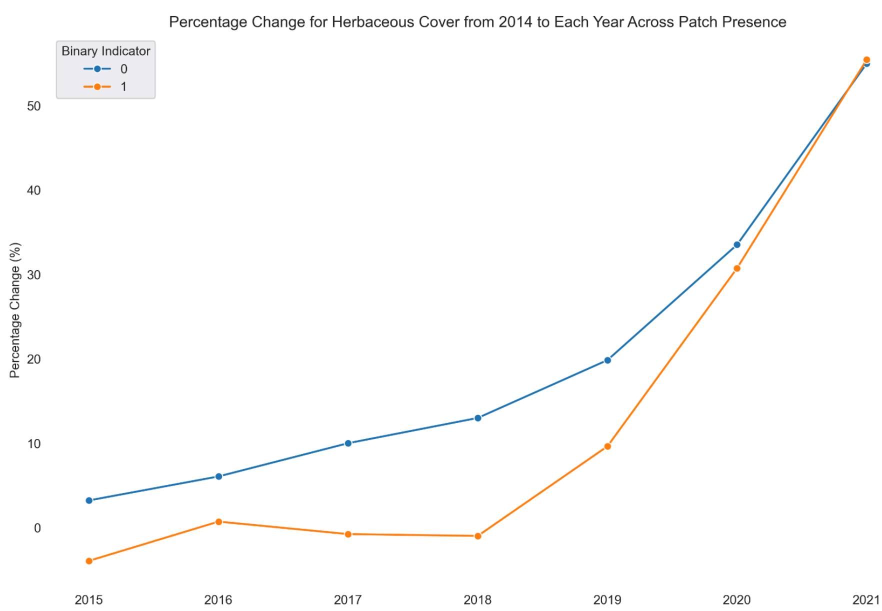

Figure 40: Cumulative Percent Change in Herbaceous Cover from 2014 to 2021 by Patch Presence

Finally, while bare fields decreased in both categories, the reduction was more substantial in high-severity patches, where bare cover decreased by 68.82%, compared to a 26.92% decrease in non-high-severity areas (Figure 41). This decrease was 68.12% in high-severity areas, so there was a slightly higher loss within patches. In 2015, bare cover loss started at -1.5% in high-severity patches (Figure 42). In contrast, this value was -6.6% in non-high-severity patches. This demonstrates that the conversion of bare fields created by the fire is initially slower in high-severity patches. However, the change accelerated in high-severity patches in the following years, and the decrease in high-severity patches overtook non-high-severity patches in the next year. A rapid decrease was observed from 2015 to 2019 in high-severity patches, which slowed down in the following years, demonstrating the emergence of other land cover types within the bare areas left by the high-severity burns. In contrast, the decrease was relatively consistent across all years in non-high severity patches.

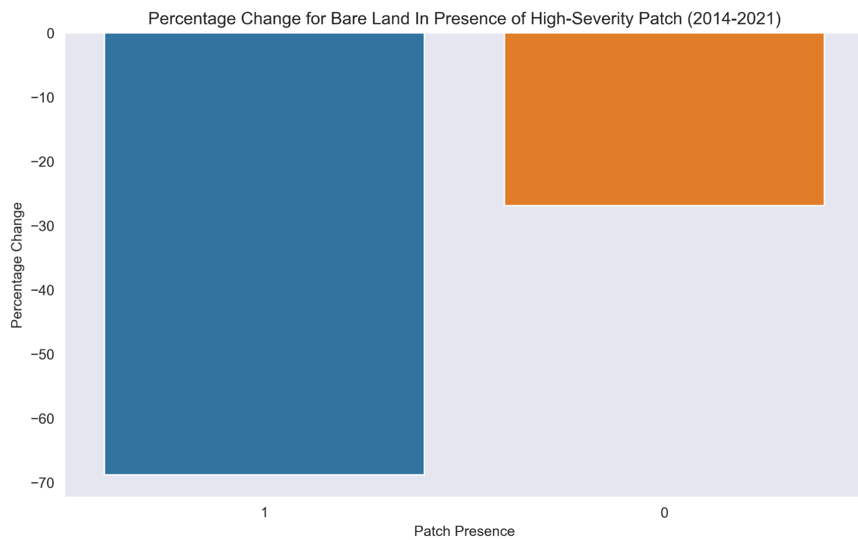

Figure 41: Percent Change in Bare Cover from 2014 to 2021 by Patch Presence

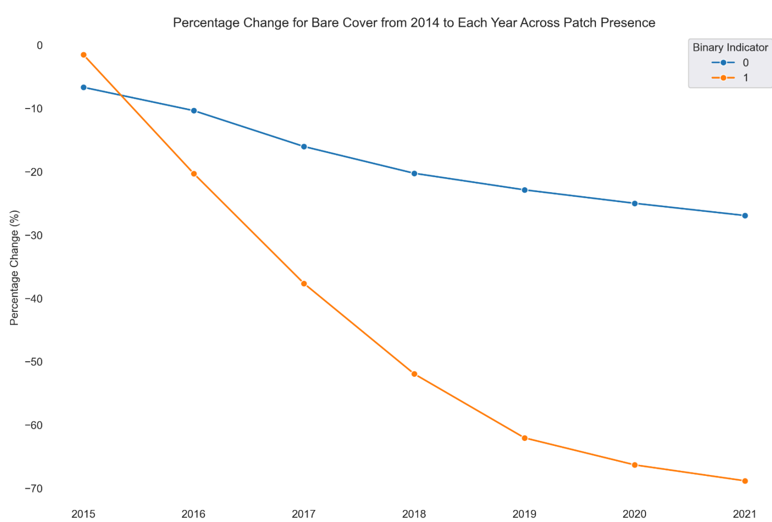

Figure 42: Cumulative Percent Change in Bare Cover from 2014 to 2021 by Patch Presence

DISCUSSION

The devastating effects of the 2013 Rim Fire provide an opportunity to explore the intricacies of vegetation recovery dynamics in response to wildfires. This study has identified significant variations in land cover changes influenced by burn severity, topographical factors (such as slope and aspect), and high-severity patches. Notably, areas with higher burn severity and those located on south-facing slopes significantly decrease in tree cover recovery, indicating less resilience of trees, particularly in these areas. Conversely, the resilience of shrub and herbaceous covers was more pronounced in moderate to high-severity areas, reflecting a shift in vegetation composition post-fire. High-severity patches displayed the same trends as high-severity areas, but the changes were marginally more pronounced. These findings underscore the critical need for tailored post-fire restoration strategies that account for the heterogeneity of fire impact across different landscapes. Specifically, while each wildfire and landscape is a unique and challenging example, post-fire restoration efforts to return the landscape to its pre-fire state should consider areas with high burn severity, south-facing steep slopes, and high-severity patches. This study's insights into the variable recovery rates across different vegetative types and terrains provide a valuable framework for addressing the challenges posed by increasing wildfire frequency and intensity under changing climatic conditions.

General Trends in Land Cover Conversion

The aftermath of the 2013 Rim Fire revealed significant shifts in vegetation composition. The most significant change across the landscape was the decline in tree cover alongside an expansion in shrub species. The tree cover percentage goes from 63.9% in the year after the fire to becoming only the second most common cover type in the burn scar area, leaving the title to shrublands. The initial predominance of tree cover following the fire, followed by its significant decline in subsequent years, can be attributed to dead trees that were initially still classified as tree cover. Over time, these dead trees gradually transitioned into shrublands as the landscape stabilized and the shrubs colonized the areas formerly occupied by trees. The notable increase in herbaceous plants and the reduction in bare fields further underscore the dynamic nature of post-fire recovery, illustrating a progression where more resilient and adaptive species such as shrubs and herbaceous fill the gaps left by tree populations that cannot recover. Furthermore, examining the change between 2013 and 2014, there was a decline in trees and shrubs but an increase in bare fields and herbaceous species. The increase in bare fields most likely results from the initial decimation of other species by the wildfire and herbaceous species capitalizing on the state of the post-fire ecosystem. However, bare fields decreased consistently in the following years, and while herbaceous species stagnated, shrub cover took over. Finally, except for bare fields, none of the classes returned to their pre-fire levels, suggesting the significant impact the wildfire has had on the landscape. Therefore, if there is a goal to return an ecosystem to its original state, there is an absolute necessity for targeted restoration efforts.

Impact of Burn Severity on Vegetation Recovery

By examining a 9-year period, this study aimed to understand the short and long-term resilience of the landscape by analyzing land cover trends. Delineating the landscape across different burn severity classes using the Composite Burn Index (CBI) and analyzing land cover change for each severity class provides a clear framework for assessing the ecological impact of the fire, particularly in terms of shifts in land cover for trees, shrubs, herbaceous species, and bare fields. While there has been some confusion regarding the distinction between fire intensity, fire severity, and burn severity, this study focuses on burn severity as the metric offers a more precise measure of a fire's ecological impact, particularly regarding changes to organic matter (Keeley, 2009). In the immediate aftermath of the fire, while changes in tree-cover classifications were marginal, high-severity areas displayed a much higher decrease in shrubs and a significant increase in herbaceous plants and bare fields. Over time, high-severity areas have consistently demonstrated the greatest transformation, with a significant portion of the landscape transitioning to shrublands. The findings are consistent with past literature, where high-severity fire zones are often associated with significant species composition shifts and biodiversity reduction (Crotteau et al. 2013, Welch et al. 2016). Furthermore, past research has shown that shrubs respond positively in high-severity areas resulting from wildfires (Harold et al. 2017, Liu et al. 2022). This intensive change underscores the significant and potentially irreversible ecological transformations induced by high-severity fires, emphasizing the need for targeted management strategies for areas with varying burn severities to mitigate the impacts on biodiversity and landscape functionality.

Topographical Influences on Post-Fire Vegetation Dynamics

In post-fire vegetation dynamics, the analysis of topographical factors such as slope and aspect has demonstrated significant differences in land cover trends. Studies have suggested the impeding effect of topography on wildfire spread, with topographical features affecting fire spread and often serving as natural boundaries (Holsinger et al. 2016). Further, topographical features such as elevation and slope influence climatic factors such as hydrological variations, soil properties, and moisture availability, affecting the conditions for the area's susceptibility to wildfires and vegetation regrowth (Karaman et al. 2011, Viana-Soto et al. 2017). Land cover trends in the immediate year after the fire differ significantly from those in the following years. This suggests that site-level characteristics influenced by topography play a role in vegetation succession after fire disturbance. In the long term, south-facing slopes have shown a larger decrease in tree cover than north-facing slopes. This disparity is likely due to higher soil temperatures, reduced moisture levels on south-facing slopes, and less favorable conditions for seed germination and plant growth. In contrast to burn severity levels, where there was a higher shrub increase in areas with higher tree cover loss, there was a larger increase of shrubs in north-facing slopes. This demonstrates that north-facing slopes provide a more suitable habitat for shrubs after disturbance. While the limited number of herbaceous pixels did not change in north-facing slopes, we observed a more pronounced decrease in south-facing slopes. The decrease of herbaceous species aligns with findings in past literature, as they are less likely to reproduce in south-facing slopes due to a combination of factors such as low soil moisture during summer, high temperatures, and high irradiance alongside lower temperatures during winter (Warren et al. 2008). Finally, while bare fields decreased in both, this change was more pronounced in south-facing slopes. Observing the general trends in both categories, there was a larger increase in shrub cover and decreases in the other three categories. While the increase in shrubs was more significant in north-facing slopes, the decrease in other land cover types, percentage-wise, was larger in south-facing slopes. These differences are likely to arise from the unique site-level characteristics that are influenced by topographical metrics, demonstrating the necessity of considering topographical factors in wildfire management and restoration efforts and ensuring strategies are tailored to the specific environmental conditions of the landscape.

Impact of High Severity Patches

While many studies analyze the inverse relationship between recovery and burn severity, many fail to consider the distribution of high-severity pixels across the landscape. Whether high-severity pixels are scattered across the landscape or whether they create large patches significantly shapes the trajectory of vegetation recovery. Past studies have shown the importance of distance to unburned patches and seed sources for recovering dry-mixed conifer forests (Donato et al. 2009, Kemp et al. 2016). Furthermore, high-severity patches that are often > 100ha have been increasing, especially in US Ponderosa pine forests (Singleton et al. 2019). Seed dispersal is highly limited in these patches, potentially leading to the conversion of trees to shrubs, herbaceous vegetation, or lasting bare fields. This suggests the importance of the size and severity of patches for the resilience of natural forests. Therefore, looking beyond burn severity and analyzing land cover trends within high-severity patches is crucial. In the first year after the fire, while tree and shrub cover did not differ significantly from high-severity areas, changes in herbaceous species and especially bare fields were more pronounced. Although the long-term differences were marginal - converged closer to areas of high severity - in the following years, trees within high-severity patches exhibited a more pronounced decline than in high-severity areas. This finding agrees with past literature that suggests wildfires with large patches of high severity are expected to cause extensive shifts in plant species (Stevens-Rumann et al. 2018). Furthermore, the increase in shrub cover was slightly higher within high-severity patches, with these areas showing a substantial increase in shrub cover compared to surrounding less affected regions. Considering the significant overlap between high-severity areas and high-severity patches, it is unsurprising to see similar results. However, the magnitude of change is slightly higher in these areas, indicating that patches might play a role in recovery trends.

Limitations

There are a few limitations to this study of note. Firstly, the reliance on NDVI and land cover type as primary measures of vegetation recovery does not fully capture the complexity of ecological responses, such as species compositions or post-fire biodiversity levels. The relatively coarse resolution of Landsat data and the lack of ground-truth data limits the ability to analyze vegetation recovery at the species level. Furthermore, while the land cover data from Wang (2021) has a higher overall accuracy compared to NLCD data (Wang et al. 2021), it is still subject to misclassifications across the landscape, especially as the data was produced at the national scale. The coarser resolution used to generate the data may not fully capture the actual trends of land cover conversion in the burn scar area. Another limitation, or a potential topic to explore further, was the lack of analysis of pre-fire conditions, which significantly affect the trajectory of ecosystem recovery. While pre-fire conditions affect burn severity, topography, and the creation of high-severity patches due to fuel availability and vegetation health and composition, these metrics do not fully capture its effects on subsequent recovery. Finally, I could not get reliable georeferenced data on human intervention and management practices, which introduces a bias to the results that were not accounted for in the study. Up to 8 years after the fire, there have been restoration attempts by the Yosemite Stanislaus Solutions (YSS) collaborative group, which include salvage logging, fuel reduction treatments, and 4,625 acres of tree replantation. These attempts have not been accounted for or masked from the study results.

Future Directions

Future studies should consider integrating very high-resolution (VHR) imagery to improve the spatial accuracy of vegetation and land cover classification. This also opens up the possibility of analyzing vegetation recovery at the species level. However, the collection of consistent VHR imagery of the burn scar area is a difficult task, requiring commercial sources such as Planet or drone-based aerial imagery and yearly revisits at the same seasons to reduce seasonal variability across images. Furthermore, a more in-depth analysis of pre-fire conditions could be integrated into the workflow to integrate pre-fire vegetation health, soil moisture levels, and historical climate data. This will allow for a more comprehensive understanding of the factors driving post-fire recovery dynamics. Additionally, incorporating ground-truth data through systematic field surveys could significantly enhance the accuracy and reliability of remote sensing analyses, offering a robust method to calibrate and validate the interpretations made from satellite imagery. Furthermore, this would allow for the integration of unsupervised and supervised machine learning methodologies to classify the landscape. If researchers can achieve higher accuracies across classes compared to land cover data used in this paper, it would improve the overall accuracy of results and the detection of subtle changes in vegetation cover. One of the study's goals was to provide a standard workflow to analyze the effect of critical variables (burn severity, topographical indices, patch presence) on recovery patterns. Future research should improve and standardize the workflow to provide a framework for analyzing post-fire vegetation recovery in other wildfires. This is necessary as wildfires will continue to increase in frequency and severity.

Broader Implications

Firstly, the study results suggest that burn severity is a critical determinant of post-fire recovery trajectories, with higher severity areas requiring more time and potentially human intervention to recover. Furthermore, the observed recovery patterns underscore the need for targeted restoration strategies, considering the heterogeneity of burn severity across the landscape. Restoration efforts must prioritize high-severity areas for actions such as seedling replantation, invasive species management, and soil stabilization to facilitate recovery and mitigate against the long-term ecological shifts that can arise from such catastrophic wildfires. This shift underscores the critical need for targeted restoration efforts to mitigate the adverse effects of high-severity burns, including soil stabilization and reintroducing native plant species to promote ecological recovery and resilience. The analysis of topographical features demonstrates the importance of considering the unique environmental conditions and microclimates created by varying landscape elements in post-fire recovery efforts. Slope, aspect, and elevation significantly influence moisture availability, sunlight exposure, and temperature regimes, critical for vegetation recovery patterns. Specifically, with their greater exposure to sunlight, south-facing slopes often experience higher evapotranspiration rates and lower soil moisture, challenging the survival and establishment of vegetation post-fire. This variability indicates that restoration strategies should be finely tuned to the specific topographical context of burned areas, requiring different techniques and plant species selections based on aspect, elevation, and slope steepness to achieve intended recovery outcomes. Such precision in restoration planning can enhance the efficiency and effectiveness of efforts to restore fire-affected ecosystems, ultimately contributing to their resilience and sustainability in the face of future wildfires. Finally, the study's findings emphasize the importance of considering the spatial distribution of high-severity patches in post-fire management and restoration planning. These areas must be prioritized first in replantation efforts to ensure recovery of fire-affected ecosystems. This is especially important if the goal is to restore species that rely on seed dispersal for resiliency. Incorporating the spatial context of these patches allows for a more strategic allocation of resources, targeting areas most needing intervention to prevent further degradation and loss of biodiversity.

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