Impacts of Prescribed Burning on Landscapes and Species in the California Sierra Nevada

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ABSTRACT

The California Sierra Nevada is an ecologically fire-dependent, historically fire-excluded ecoregion that is a common candidate for prescribed burns (i.e., mixed-severity, managed fire events) to minimize wildfire risk. Treatments benefit biodiversity and forest structure, but also negatively impact species richness and vegetation composition through alien plant invasion. To understand the behavior and magnitude of degradation on a system-wide scale, I conducted the first spatial review of prescribed burns in the California Sierra Nevada ecoregion using CAL FIRE and LANDFIRE data, quantifying change in vegetation composition characteristics and vegetation departure across 154 initial treatments from 2017 to 2020. Additionally, I assessed the risk to conservation value on land selected to burn with permutation tests of four key metrics from the California Department of Fish and Wildlife. My results revealed a 324% average increase in exotic plants after 18% of treatments. Plant species richness did not generally increase as expected, and was characterized by unexpected variability. Burned vegetation most commonly shifted to chaparral and invasive grassland. Vegetation departure changed insignificantly after treatment, indicating additional management is needed to revert landscapes to their pre-European conditions. Every measured conservation value metric – species biodiversity, habitat connectivity, significant habitat, and climate resilience – was significantly different between land selected to burn and the greater ecoregion ($p = 0.000$). My findings suggest that a single treatment generally did not yield positive landscape change, and sometimes introduced highly impactful plant invasion. Ecosystem-specific strategies must be further refined for Sierra prescribed burning to be effective and ecologically responsible.

KEYWORDS

Rx burns, invasive plant dynamics, conservation planning, remote sensing, fire ecology

INTRODUCTION

Prescribed burning is an effective modern fuel treatment method that has been used indigenously for centuries to reduce wildfire risk (Anderson 2006). Through mixed-intensity burning, managed fire events reduce understory vegetation and prevent high-severity wildfires from reinforcing similarly high-severity conditions (Schmidt et al. 2006). Prescribed burn treatments in coniferous-dominated, seasonally dry forests have been experimentally proven to meet fuel reduction goals and create forest structures more resilient to disturbance (Youngblood and Stephens 2009). Furthermore, prescribed burn effectiveness at the management level, determined by setting a target of fuel reduction and taking pre-burn and post-burn assessments, has been widely confirmed. Firefighter resources and the extent of tree injury is lower after fires preceded by prescribed burning, and remains so after 5 years (Fernandes and Botelho 2003). Additionally, substantial effort of annual treatment rates greater than 5% of the landscape can effectively control the extent of wildfires in forests (Fernandes 2015). Human-centric benefits of wildfire risk reduction and reduced cost are attractive aspects of prescribed burning, but they also produce several environmental advantages.

Treatments encourage higher biodiversity in the California Sierra Nevadas, a region which historically thrives when exposed to frequent low-severity wildfires (Stephens et al. 2021). By depleting excess fuel, the prescribed burns push ecosystems towards native fire regimes (Keeley et al. 2021). Furthermore, treated forests have a greater pyrodiversity (variability in fire severity, season, fire, and frequency) which increases landscape heterogeneity and biodiversity (Stephens et al. 2021). Pyrodiversity is associated with higher bees and understory plant diversity in Yosemite's Illilouette and Sugarloaf (Ponisio et al. 2016, Ponisio 2020, Wilkin et al. 2021), and higher mammal, bird, bat and tree biodiversity in other Sierra Nevada regions (Roberts et al. 2015, Tingly et al. 2016, Blomdahl et al. 2019, Steel et al. 2019). The mixed severity of prescribed burning improves ecosystem health in contrast to high-severity wildfires which homogeneously burn (DellaDalla et al. 2017). Despite these positive environmental co-benefits, applying prescribed burns to the Sierra also has a degradative capacity – particularly through introductions of invasive species when fire is reintroduced to the landscape.

Prescribed burns are intended to reintroduce historical fire regimes and restore forest structures, but occur on landscapes that now may contain diverse alien species poised to take advantage of such disturbances (Keeley 2006). If invasive species colonize treated land, they can change the fuel structure of the forest and set back natural regeneration of dominant trees (Brooks et al. 2004). The effects of fire on invasive plant spread is notable in the Sierra, where unburned conifer forests are mostly free of invasive species and burning has led to significant populations (Keeley et al. 2003). Such invasion is illustrated through the 2002 Sequoia-Kings Canyon National Parks prescribed fire management program, which was stopped after it promoted a vigorous invasion of cheatgrass (Keeley 2002). Under modern political and scientific pressure, prescribed burning in the Sierra is set to grow to 400,000 acres a year by 2025. While fire management practices become more commonly utilized, research has not been conducted to quantify the vulnerability of existing ecosystems at a system-wide scale. A detailed performance review of the entire Sierra Nevada ecoregion will allow prescribed burn planners to better understand potential ecological drawbacks of treatment when they pursue decreased wildfire risk.

I determined how landscape ecosystem components in the California Sierra Nevada were impacted from prescribed fire treatment by burn planners (e.g., CAL FIRE, U.S. Forest Service). I studied the extent that prescribed burns alter existing vegetation types, landscape heterogeneity, and vegetation transitions; if prescribed burns disproportionately impacted areas of conservation priority; and whether treatment disrupted vegetation departure of landscapes from pre-European reference conditions. I expected that prescribed burns will introduce invasive plant species while simultaneously fulfilling expected managed fire behavior on understory fuels and tree canopies. Prescribed burns were expected to occur in areas significantly more important to conservation and ecosystem health, particularly in native plant species richness and endemism, mirroring Calhoun et al. 2021 findings for wildfire events. Lastly, vegetation departure was expected to decrease because treatments convert landscapes closer to estimated, pre-European states of vegetation. Data across the Sierra Nevada ecoregion was acquired using advancements in satellite imagery and remote sensing, modeling efforts by LANDFIRE, and conservation planning metrics created by the California Fish and Wildlife's *Area of Conservation Emphasis* program (ACE). ACE metrics of terrestrial native species biodiversity, climate resilience, habitat connectivity, and significant habitat summaries were spatially clipped onto treatment areas and permutation tested. When calculating metrics of landscapes shortly before and shortly after a burn, existing vegetation types illustrated alien plant invasion and ecosystem health risk.

METHODS

Study site

I studied 154 prescribed burns that began and concluded at any point within 2017 and 2020 and occurred within the California Sierra Nevada (Figure 1). To determine this area, I used spatial boundaries from the Environmental Protection Agency's Ecoregion 5. Ecoregions are defined as "areas of general similarity in ecosystems and in the type, quality, and quantity of environmental resources" (Bryce et al. 2023). An Ecoregion is intended to be a spatial framework for research and management, making its use particularly relevant in my geospatial study. Prescribed burns were selected if their entire boundaries were within Ecoregion 5 and treatment type was "1", indicating a prescribed burn instead of alternative management practices (e.g., mechanical thinning). This also excludes overlapping with any historical treatment in the dataset which began in 1976, ensuring that treatments are the first ones applied for at least 41 years.

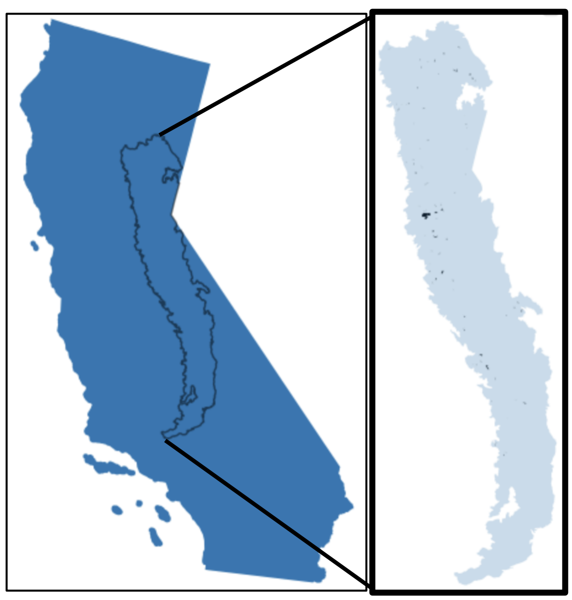

Figure 1. Bird's-eye view of study site. California Sierra Nevada Ecoregion 5 inside California (left), and prescribed burn sample overlaid on Ecoregion 5 (right).

Determining change in existing vegetation composition

In order to quantify how prescribed burns changed existing vegetation composition, I aggregated remote-sensed existing vegetation types (EVT) from each prescribed burn sample, resulting in two profiles for each burn. The profiles are from 2016 and 2020 and represent field data from before and after a treatment. The 154 burns were collected from a dataset actively managed by the California Natural Resources Agency and the California Department of Forestry and Fire Protection (CAL FIRE 2019). EVT data was downloaded from LANDFIRE's Vegetation data collection program. LANDFIRE constructed the EVT layers by labeling complexes of plant communities following NatureServe's terrestrial ecological ecosystems classification (USDA Forest Service, Department of the Interior). Each record within the EVT layer represents a modeled output for a 30 meter by 30 meter plot of land captured by the Landsat 8 observation satellite. I used Python libraries Rasterio and GeoPandas to project each EVT layer into the EPSG:3310 coordinate reference system (NAD 1983 USGS California Albers) which is recommended to state-level analysis and kept relevant records in the Pandas DataFrame by clipping each layer to prescribed burn geometry. During clipping, only records that were fully within a burn were kept.

Vegetation heterogeneity was first calculated by counting the number of unique EVTs in each prescribed burn area in 2016 and 2020, and then subtracting the difference. These outputs were collected for all burns and the mean, standard deviation, and median of the resulting distribution were calculated. Next, I created two metrics in order to measure both the proportional change and spatial change of landscape vegetation. I calculated the proportion change of each EVT from 2016 to 2020 and aggregated the results by physical group (e.g., Grassland, Conifer, Shrubland). In the special case that an EVT did not exist in the area in 2016 and then appeared in 2020, I designated the proportion as 1 to represent a 100% increase. This was done to avoid a bias in the event that a large fire had a new EVT (e.g., an increase in 587 plots is a proportion increase of 587). In addition to proportional change, spatial change was collected by calculating EVT transitions in each unique 30 x 30 meter plot of land from 2016 to 2020. For each EVT transition, the most common final EVT determined by highest total plots of land was used to find the most common post-treatment EVTs. I created a histogram to visualize the skew of vegetation heterogeneity across the sample; a table containing proportion change, physical groups, standard deviation, number of fires, and number of unique EVTs to perform detailed analysis; and a heatmap using log-transformed EVT transition counts to illustrate the effects of prescribed burn treatments.

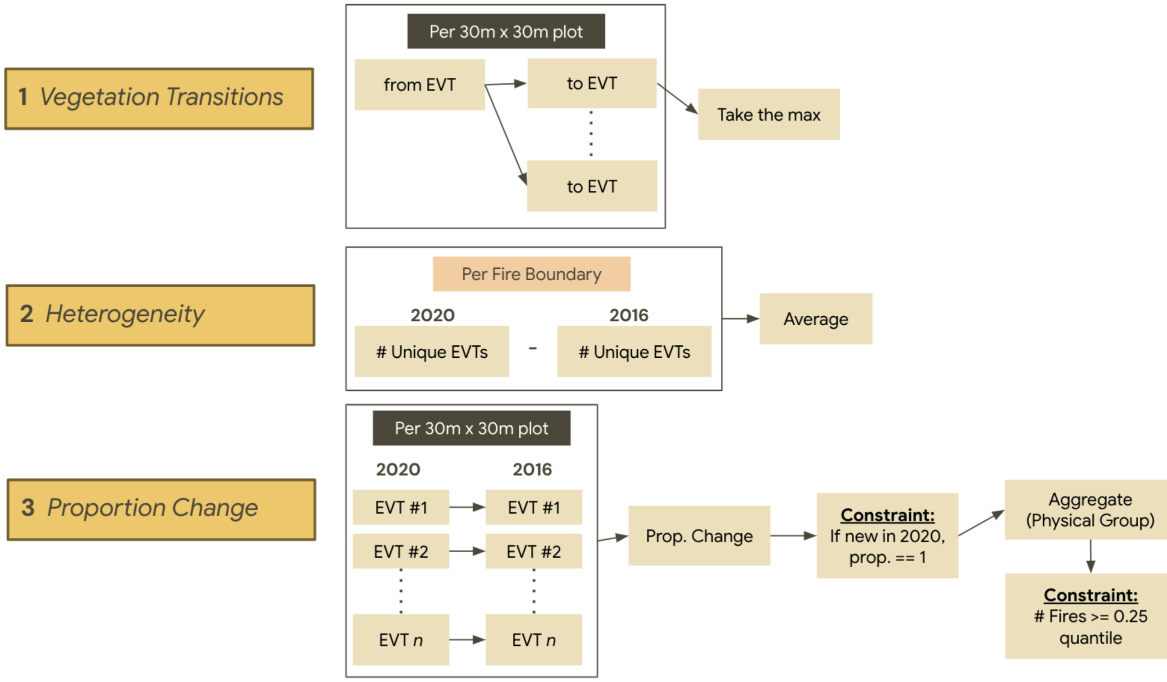

Figure 2. Methodology flowchart for the three components of existing vegetation type (EVT) analysis. This chart displays the step-by-step logic to determine vegetation transition, heterogeneity, and proportion vegetation change across the sample of prescribed burns. All remotely sensed data are in 30 meter by 30 meter plots.

Impact on areas of conservation priority

To determine if prescribed burns were disproportionately applied to areas of conservation priority, I performed permutation testing between the prescribed burns sample and the entire California Sierra Nevada (Ecoregion 5) using *Terrestrial Connectivity*, *Terrestrial Significant Habitat*, *Terrestrial Native Species Richness*, and *Climate Resilience* metrics from the California Department of Fish and Wildlife's *Area of Conservation Emphasis* (ACE) program. The ACE program gathers best available spatial data on wildlife, vegetation, and habitats in the state to inform conservation planning (Biogeographic Data Branch, California Department of Fish and Wildlife 2019), and was last updated in 2018. The four metrics I am using are the key components of the program's suite of terrestrial conservation information, determined within a 2.5 square mile-hexagon grid format. Metric values are calculated using predictive species modeling and occurrence data.

I used Rasterio and GeoPandas to project each metric into the EPSG:3310 coordinate reference system (NAD 1983 USGS California Albers) and kept relevant hexagons (records in the

DataFrame) by clipping each layer to prescribed burn landscapes. Unlike the EVT heterogeneity, proportion change and transition calculations, hexagons could intersect prescribed burns instead of being entirely within them. This was allowed because the hexagons are much larger in size than the 30 meter by 30 meter Landsat 8 satellite imagery used by LANDFIRE, and enforcing a *within* constraint would be unrealistic given the average size of my sample prescribed burns.

Permutation testing was used to determine if there is an statistically significant association between the land being selected for treatment and conservation priority. This method was used instead of one-tailed t-test because the distribution of data was unknown and the assumption of equal variances may not hold. I used the null hypothesis that the difference in means of prescribed burns and the ecoregion was 0. A positive difference suggests that the prescribed burn landscape has higher mean rankings than the ecoregion, and vice versa. Finally, I calculated the p-value with threshold $p \leqslant 0.05$.

Historical vegetation departure

Finally, to investigate if prescribed burns impacted the departure of landscapes from estimated pre-European composition, I used LANDFIRE's Fire Regime Vegetation Departure values from 2016 and 2020 to compare burns before and after completion. Vegetation Departure (VDep) is based on changes to vegetation composition, structural stage, and canopy closure (Biogeographic Data Branch, California Department of Fish and Wildlife 2019). VDep is also modeled for 30 meter by 30 meter, remotely-sensed plots of land. Similar to previous data cleaning, I used Rasterio and GeoPandas to project each metric into the EPSG:3310 coordinate reference system (NAD 1983 USGS California Albers) and kept relevant records in the Pandas DataFrame by clipping each layer to prescribed burn landscapes. During clipping, only records that were fully within a burn were kept. I saved the resulting values from 2016 and 2020 for all burns to get two sample population distributions. Using these distributions, I determined whether there was a change in departure using descriptive statistics on mean burn departures. Additionally, I created two overlaid histograms and kernel density estimates to visually explain the impact of treatment.

RESULTS

Change in existing vegetation types

On average across all prescribed burns in the sample (*n* = 154), Exotic Herbaceous, Grassland and Riparian physical groups increased after a treatment by 169%, 19%, and 17%, respectively. Developed-Roads and Developed (which includes urban vegetation types) groups also increased, but were not a subject of this study. Hardwood, Conifer-Hardwood and Sparsely Vegetated vegetation types changed insignificantly. Conifer and Shrubland physical groups decreased on average by 12% and 15%, respectively (Table 1).

Table 1. Overall net vegetation proportion changes. Average proportion change from 2016 to 2020 of Existing Vegetation Type (EVT) Physical Groups within prescribed burns. Developed physical groups are not a subject of my study.

Physical Group	$\bar{X}_{\textbf{prop. change}}$
Developed-Roads	1.86
Exotic Herbaceous	1.69
Developed	0.32
Grassland	0.19
Riparian	0.17
Developed-Low Intensity	0.07
Hardwood	0.0070
Sparsely Vegetated	0.00
Conifer-Hardwod	-0.013
Conifer	-0.12
Shrubland	-0.15

Table 2. Overall positive vegetation proportion changes. Positive average proportion change in Existing Vegetation Type (EVT) Physical Groups from 2016 to 2020, with respective standard deviation, number of unique EVTs and number of unique fires. Developed physical groups are not a subject of my study.

Physical Group	$\bar{X}_{\textbf{prop. change}}$	σ	**EVTs**	**Fires**
Grassland	10.00	18.83	1	6
Exotic Herbaceous	3.24	4.44	1	29
Developed-Roads	2.10	2.62	1	44
Shrubland	2.08	3.84	5	47
Developed	1.35	1.74	8	73
Developed-Low Intensity	1.11	0.33	1	9
Developed-Medium Intensity	1.00	0.00	1	3
Riparian	0.85	1.30	3	16
Conifer	0.47	1.11	9	105
Hardwood	0.40	0.34	1	7
Conifer-Hardwood	0.01	0.00	1	3

Table 3. Overall negative vegetation proportion changes. Negative average proportion change in Existing Vegetation Type (EVT) Physical Groups from 2016 to 2020, with respective standard deviation, number of unique EVTs and number of unique fires.

Physical Group	$\bar{X}_{\textbf{prop. change}}$	σ	**EVTs**	**Fires**
Grassland	-1.00	0.00	3	40
Developed-Low Intensity	-0.98	0.07	1	9
Shrubland	-0.74	0.41	8	64
Developed	-0.64	0.35	8	55
Conifer	-0.50	0.0.47	10	144
Exotic Herbaceous	-0.19	0.40	1	6
Riparian	-0.19	0.28	3	14
Hardwood	-0.15	0.14	1	8

In certain prescribed burns, Grassland, Exotic Herbaceous, Developed and Shrubland physical groups increased significantly (Table 2). For each of these physical groups, only one existing vegetation type (EVT) changed: Mediterranean California Subalpine Meadow, California Ruderal Grassland and Meadow, and Developed Roads, respectively. Likewise, the Grassland, Shrubland, and Conifer physical groups experienced a dramatic decline in other unique burn events (Table 3). The three unique Grassland EVTs which declined were Recently Logged-Herb and Grass Cover; Recently Burned-Herb and Grass Cover; and Recently Disturbed Other-Herb and Grass Cover. The most common of unique shrubland EVTs were Recently Logged-Shrub Cover (32 fires); Recently Burned-Shrub Cover (22 fires); and California Montane Woodland and

Chaparral (13 fires). Similarly, the three most common of ten unique conifer EVTs were Recently Logged-Tree Cover (63 fires); Mediterranean California Mesic Mixed Conifer Forest and Woodland (53 fires); and Recently Burned-Tree Cover (32 fires).

Table 4. Comparison of landscape vegetation composition based on invasive plant disruption. Landscape composition of entire prescribed burn sample (n = 154), subsample disturbed by exotic plant species, and subsample undisturbed by exotic plant species.

Physical Group	All (%)	Disturbed (%)	Undisturbed (%)
Conifer	78.2	78.6	69.7
Shrubland	10.8	9.62	19.35
Grassland	3.21	4.89	2.88
Riparian	1.85	1.74	0.45
Exotic Herbaceous	1.76	2.26	–
Exotic Tree-Shrub	0.002	0.002	–
Hardwood	1.13	0.80	0.93
Sparsely Vegetated	0.82	0.24	1.85
Conifer-Hardwood	0.40	0.24	4.13

Prescribed burns with preexisting exotic plant species had similar vegetation composition to the entire sample of 154 burns (Table 4). Prescribed burns that were undisturbed prior to burning had less conifer and more shrubland vegetation, with other physical groups remaining generally constant.

Transition of existing vegetation types

242 transitions occurred from one EVT value to another, but this was a small proportion of total possible transitions (Figure 3). 27 unique EVTs transformed into developed roads (Value 7299). Although this was the most common transition, they occurred at very small magnitudes and developed categories were not a focus of my study since it involves non-living classification. Inversely, recently logged-tree cover (Value 7193) experienced the greatest transitions to other unique EVTs at 15. The transition from type 7192 to 7105 – recently logged-shrub cover to Northern and Central California dry-mesic chaparral – was the largest change by surface area (Figure 3 & Table 5). The second-largest was from type recently logged-herb and grass cover to

California ruderal grassland and meadow. This was also the largest transition to exotic plant species.

Table 5. Most common vegetation transitions. The five largest transitions from one EVT to another, and their respective counts.

Name From	Name To	Count
Recently Logged-Shrub Cover	Northern and Central California Dry-Mesic Chaparral	3059
Recently Logged-Herb and Grass Cover	California Ruderal Grassland and Meadow	2834
Recently Logged-Tree Cover	Mediterranean California Mesic Mixed Conifer Forest	2557
Recently Burned-Herb and Grass Cover	California Ruderal Grassland and Meadow	1977
Mediterranean California Mesic Mixed Conifer Forest	Developed-Roads	1101

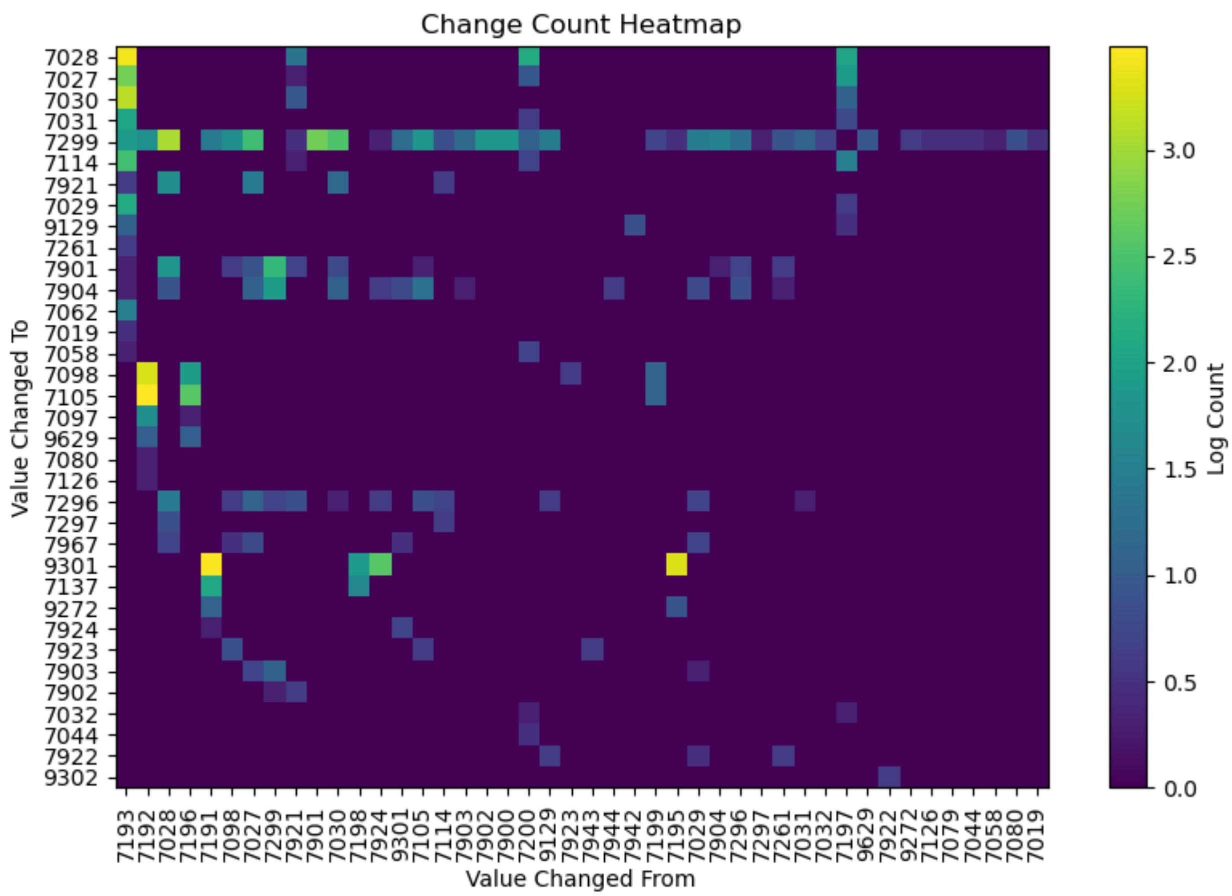

Figure 3. Transition of vegetation types after treatment. Heatmap of log-transformed counts of 30 meter by 30 meter remotely-sensed land plots within prescribed fires that changed from one EVT to another.

Change in landscape heterogeneity

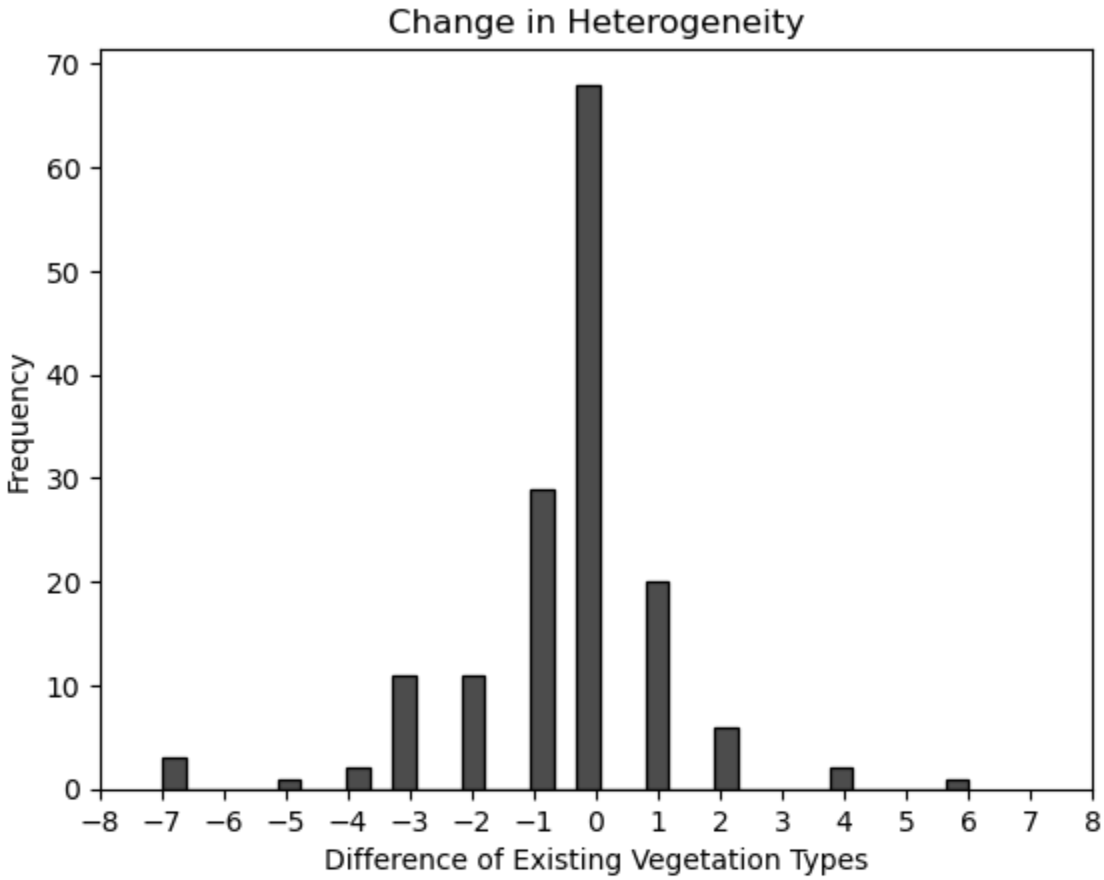

Figure 4. Landscape heterogeneity change. Histogram of change in landscape heterogeneity (difference of unique EVTs from 2016 to 2020 for each prescribed burn).

The change in landscape heterogeneity was roughly normally distributed (Figure 4), with an average decrease of -0.47 existing vegetation types (EVTs), a median of 0 EVTs, and a standard deviation of 1.72 EVTs. The maximum positive change in heterogeneity was +6 EVTs, and the maximum negative change was -7 EVTs. The distribution was skewed towards a decrease in heterogeneity, and a majority of landscapes experienced no change.

Impact on areas of conservation priority

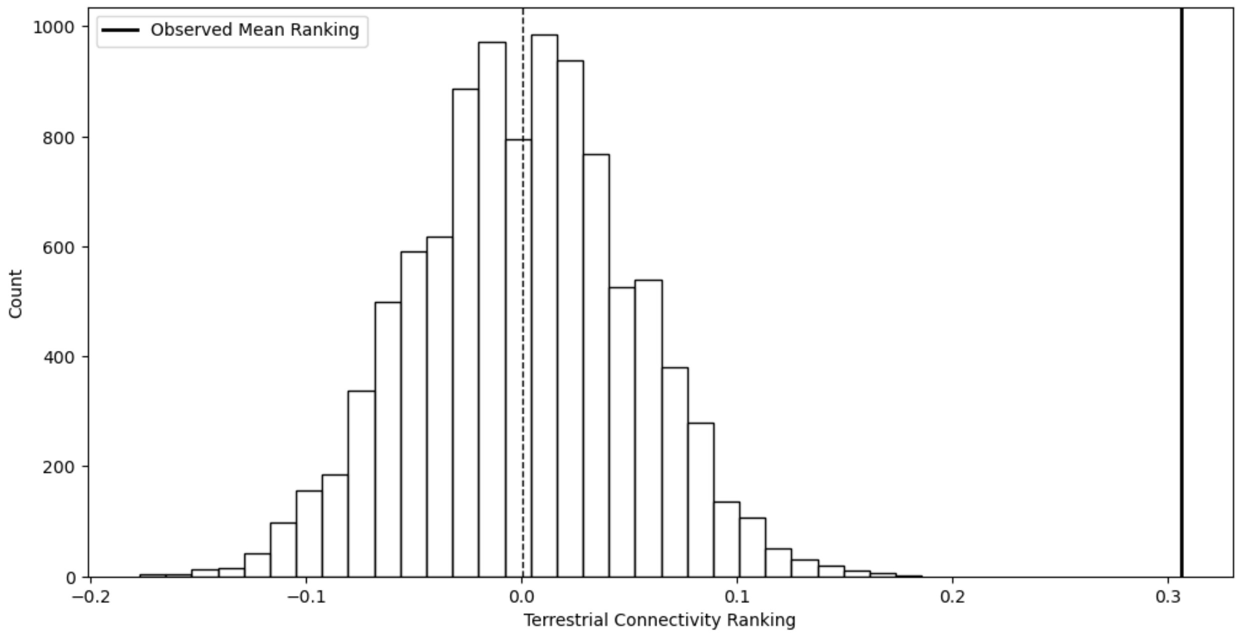

Figure 5. Terrestrial connectivity. Permutation test of terrestrial connectivity rankings between the entire Sierra Nevada and prescribed burn area ($p = 0.000$).

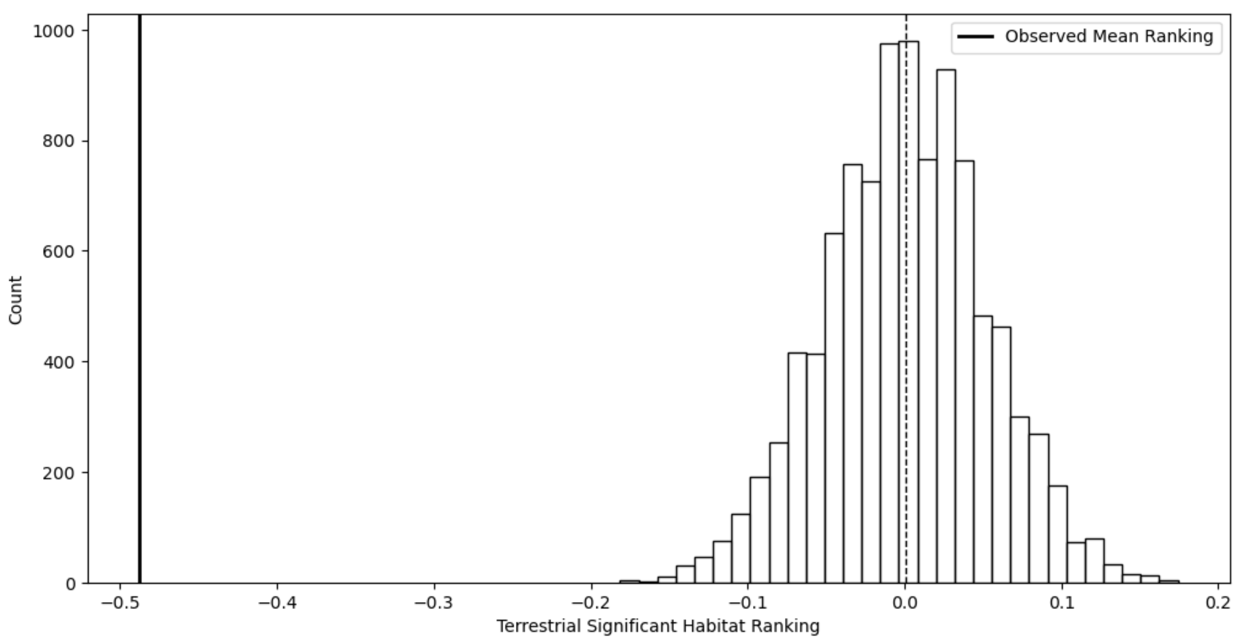

Figure 6. Terrestrial significant habitat. Permutation test of terrestrial significant habitat rankings between the entire Sierra Nevada ecoregion and prescribed burn area ($p = 0.000$).

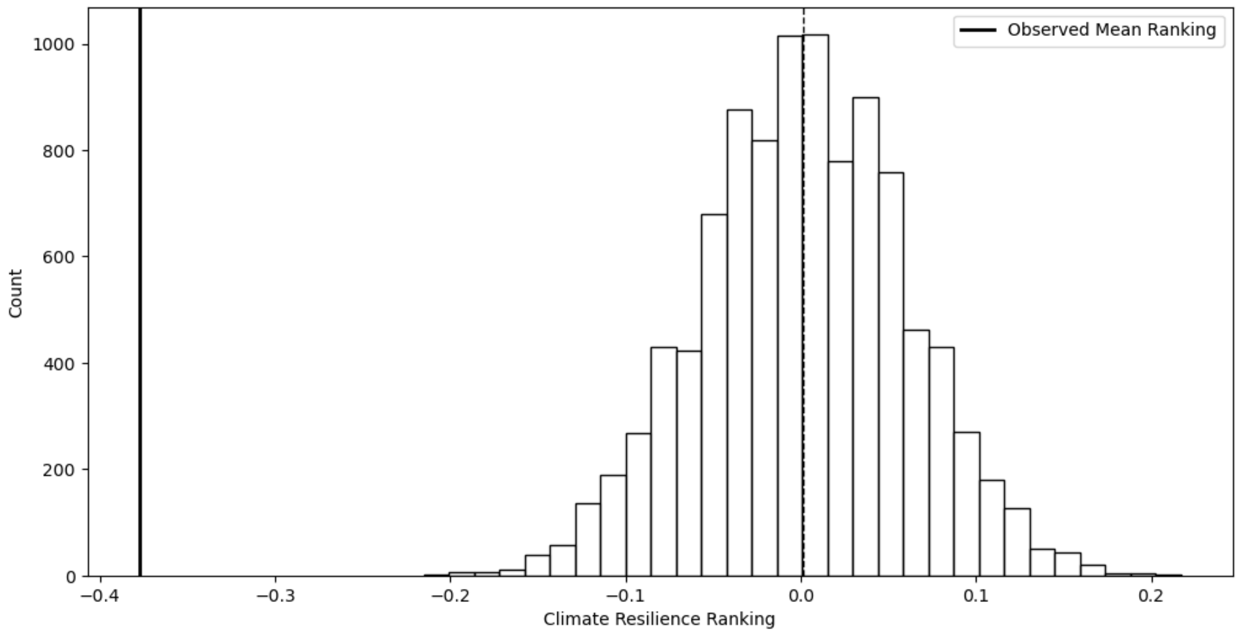

Figure 7. Climate resilience. Permutation test of climate resilience rankings between the entire Sierra Nevada and prescribed burn area ($p = 0.000$).

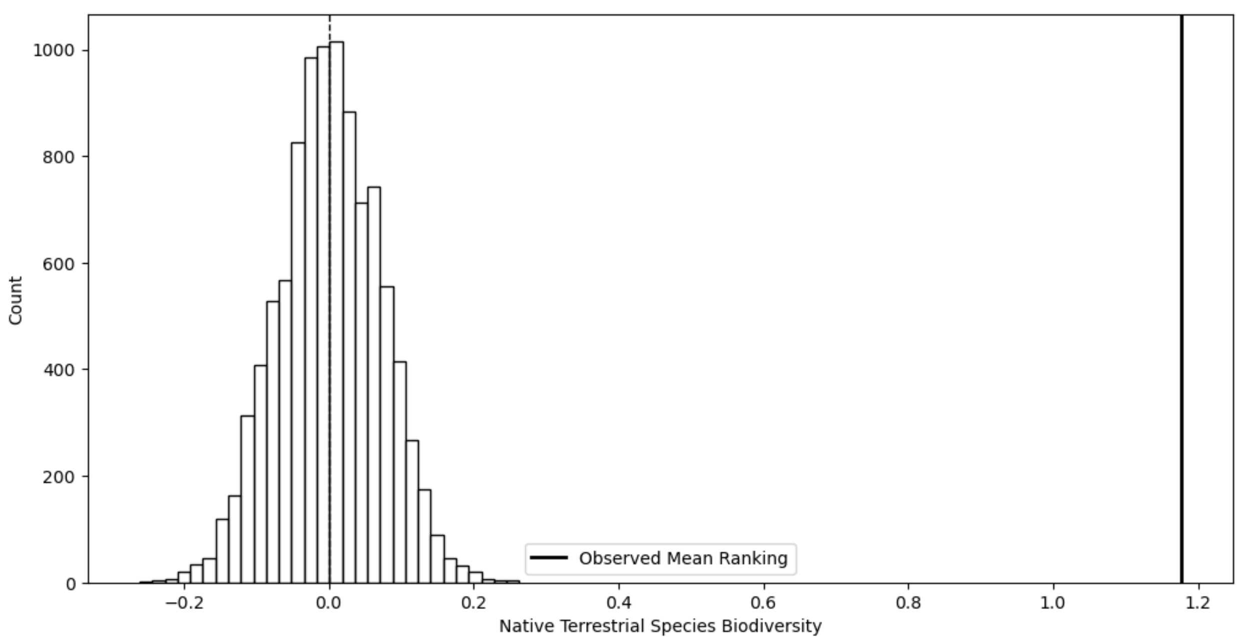

Figure 8. Terrestrial species biodiversity. Permutation test of terrestrial species biodiversity rankings between the entire Sierra Nevada and prescribed burn area ($p = 0.000$).

The null hypothesis that the difference of metric means between the ecoregion and prescribed burn areas is 0 was rejected for all four measurements: terrestrial connectivity, significant habitat, climate resilience, and species biodiversity. A statistically significant association exists between land chosen for treatment and all metrics (*$p = 0.000$)*. Relative to the spread of the distribution, Native Terrestrial Species Diversity was the most different between the two populations (Figure 8). Conversely, Climate Resilience was the least different between the two populations (Figure 7). Prescribed burns occurred on land that had more habitat connectivity, less significant habitat, less climate resilience, and more terrestrial native biodiversity.

Historical vegetation departure

The average vegetation departure (VDep) of prescribed burn areas in 2016 was 40.2%, and the standard deviation was 11.3%. The average VDep in 2020 was 40.5%, and the standard deviation was 9.3% (Table 6). Therefore, departure viewed collectively actually increased after burning. The distribution of mean vegetation departure shifted slightly higher after burning, with maximum departure increasing to 93.8% from 88.0%. Respective kernel density estimates are essentially identical (Figure 9).

Table 6. Vegetation departure statistics. Descriptive statistics of average vegetation departure in 2016 and 2020 (e.g., mean of means, standard deviation of means).

Statistics	$\bar{X}_{\textbf{VDep 2016}}$	$\bar{X}_{\textbf{VDep 2020}}$
mean	40.209833	40.452837
std	9.348488	11.329495
min	27.000000	23.000000
25%	34.017778	34.064059
50%	38.279029	38.707203
75%	43.718233	45.940471
max	88.076923	93.846154

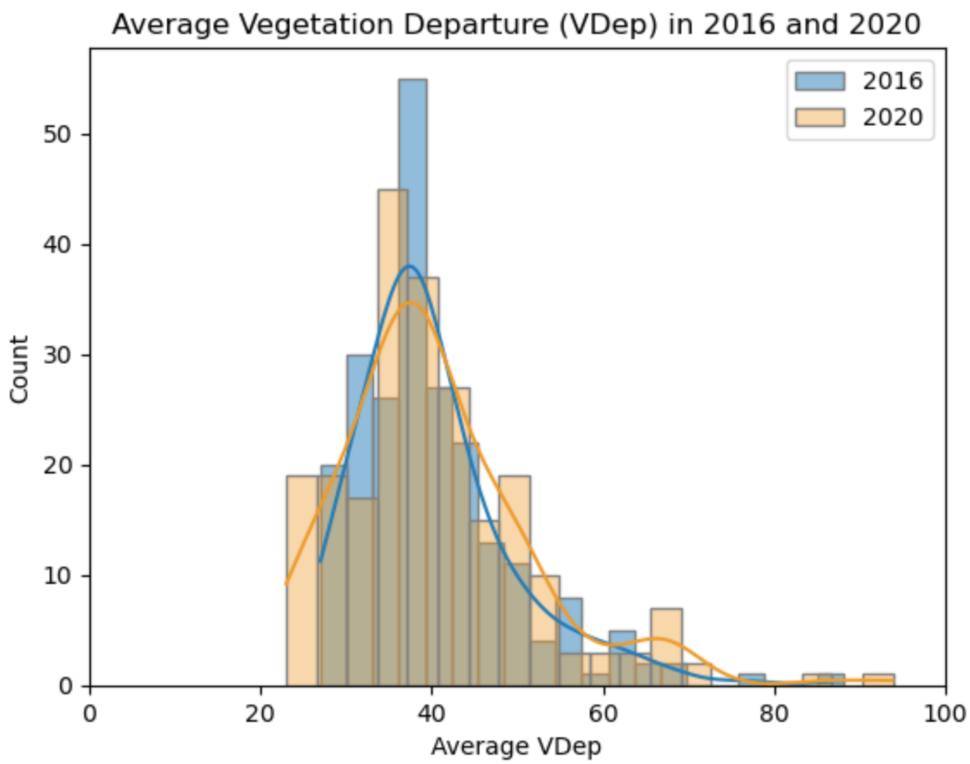

Figure 9. Vegetation departure distribution from 2016 to 2020. Overlaid histograms of burn average vegetation departures (VDep) in 2016 (blue) and 2020 (yellow) with respective kernel density estimate (KDE) curves.

DISCUSSION

Prescribed burn management practices aimed at reducing fuel loads in the California Sierra Nevada are most effective if planners first understand the impacts of fire on local endemism and conservation (Calhoun et al. 2021). I conducted a spatial analysis of prescribed burns in the ecoregion and identified several negative landscape responses associated with reduction in wildfire risk. Burned areas most commonly transitioned to open canopy and exotic, annual forbs and herbs. Changes in grassland, shrubland, conifer and riparian vegetation groups largely followed expectations from literature on other Sierra treatments. Surprisingly, treatments did not meaningfully change vegetation heterogeneity or departure. Landscapes that were selected to burn had a disproportionately greater conservation value in terrestrial species biodiversity and habitat connectivity when compared to the entire Sierra Nevada ecoregion. My findings suggest that prescribed fires induce many landscape changes as intended, but in some cases deteriorate native ecosystems and function as catalysts for an invasion of exotic plants.

Changes in existing vegetation composition

Behavior of treatment

Prescribed burns created significant changes in existing vegetation composition; however, some of these changes were expected. Riparian vegetation and non-exotic grasses increased the most. Conversely, conifer and shrubland vegetation generally decreased after treatment, with coniferous decreases being most diverse and their reduction most widespread. Conifer and shrubland changes post-fire are corroborated by other frequently-treated Sierra landscapes (Boiseramé et al. 2017, Vaillant et al. 2009). California Sierra Nevada riparian vegetation is known to rapidly recover after an initial decline after a fire (Bêche et al. 2005). The recorded increase in riparian vegetation indicates that this recovery happens in less than a year. The nature of this recovery, however, may not be beneficial to endemic species. After prescribed burns in Maryland wetlands, plants thought to benefit from fire experienced little to no effect and plants generally less useful to wildlife saw the largest increase in growth (Flores et al. 2011). While Sierra Nevada riparian ecosystems may not behave similarly, negative changes must be a consideration before planners treat landscapes.

Exotic plant species growth

In almost equal proportions, exotic herbaceous plants increased after a prescribed burn in areas where both none and some were already present. In the case of preexistence, alien plants were in extremely small proportions relative to their final abundance, suggesting that even if prescribed burns do not introduce an exotic plant into the ecosystem, treatment will greatly increase their spread. In landscapes that were burned and had an increase in exotic plants, the study sites were mostly coniferous land. Of these areas, previously uninvaded landscapes had more shrubland and less conifers by area than already-invaded landscapes. This behavior is a surprising departure from understanding that coniferous forests generally have fewer alien plant species than other biomes (Keeley et al. 2010). Current prescribed burn management practices themselves may also be at fault, as fuel breaks can act as invasive highways carrying alien species into uninfested wildland areas and can safely harbor alien seed banks (Keeley 2001). It is essential that prescribed burn managers utilize strategies that minimize plant introduction and colonization, therefore reducing the risk that invasives will change fuel properties of vegetation stands as the landscape recovers (Webster and Halpern 2010).

Vegetation heterogeneity

Vegetation heterogeneity decreased on average after prescribed burns, but the large spread of change centered around a median of zero indicates that prescribed burning of Sierra landscapes causes highly variable disturbance with no clear trend. These results do not support my prediction that landscapes would become more plant species rich after a treatment. The observed spectrum of large positive and negative changes in plant heterogeneity largely follows responses of understory fuels in dry forest ecosystems of southern Australia. There, landscapes that were more diverse pre-fire were homogenized by burning and those that were more homogenous pre-fire differentiated (Holland et al. 2016). Furthermore, the skew towards decreased heterogeneity in the Sierra is at odds with early-season prescribed burning which sees the best vegetation recovery. My findings more closely resemble late-season burning which is typical for natural wildfires and correlates to sudden drops in plant cover and lower species richness (Knapp et. al 2007). The idea that the Sierra prescribed burns may be more similar to wildfire is corroborated by the overall small magnitude of decreased heterogeneity, which aligns with results from intense burns in untouched mixed conifer forests whose species richness remained relatively constant (Huisinga et al. 2005). All sampled prescribed burns in my study were the first treatments to occur on their respective landscapes since at least 1976. Therefore, it is possible that high fuel loading conditions caused by fire exclusion cause first treatments to have higher severity and mitigate any benefits to heterogeneity, even when prescribed burns are intended to boost pyrodiversity (Stephens et al. 2021). In this case, many plant species may be reacting to fire-specific differences in intensity and severity caused by unique landscape conditions (Knapp et al. 2007).

Existing vegetation transitions

The most common vegetation transitions inside burned landscapes were from recently logged and burned tree cover to shrub-dominated chaparral and exotic annual and perennial forbs, demonstrating the sensitive balance between reducing wildfire risk and exacerbating alien invasion. Prescribed burns reduce leaf litter and ground cover therefore reducing wildfire risk, but create a sparse landscape that gives exotic herbaceous plants room to dominate (Keeley and McGinnis 2007). Treated landscapes followed this transformation to naturally sparse chaparral, which is susceptible to invasive grassland and forb invasion (Keeley 2001). California chaparral was historically considered resistant to invasion by exotic grasses but has recently undergone substantial conversion (Park and Jenerette 2019). Therefore, the transition towards exotic plants and shrubland after prescribed burns is troubling for ecosystem health.

Areas of conservation priority

Prescribed burn sites have statistically significant differences in species biodiversity, habitat connectivity, significant habitats, and climate resilience from those of the entire Sierra Nevada, highlighting that conservation value is endangered when planners select landscapes for treatment. Areas burned were already the most biodiverse in the Sierra Nevada — all three subcomponents, native species richness, rare species, and irreplaceable species, had statistical distributions that were significantly higher than the greater ecoregion. These behaviors mirror those from California conifer forests burned by wildfire, which often had the highest plant and mammal richness (Calhoun et al. 2021). The similarity between land burned by managed and unmanaged fire may indicate that burn managers are correctly identifying land with similar vegetative profiles to those burned by broadscale wildfires, and thus targeting areas that can successfully reduce wildfire risk. There exists an opportunity that prescribed burn fire breaks can protect the habitats of fire-sensitive species (Pastro et al. 2011), but the impact of changing fire regimes is taxon and biome-dependent – in temperate and boreal forests and shrubland, it is not guaranteed that biodiversity improves after fire (Pastro et al. 2011; Eales et al. 2018).

Treatment areas possessed higher connectivity across mapped corridors or linkages, which promote species persistence (Morelli et al. 2017). In contrast, climate resilience of selected land was much lower than the greater ecoregion, corresponding to a lower probability that these landscapes were already climate refugia. A need for higher resilience offers an opportunity for treatments to directly benefit a natural system by building more resilience to natural disasters such as floods and drought (Boisramé et al. 2016). Finally, the number of significant habitats was lower within burn boundaries, implying that burn managers are successfully avoiding land that harbors focal wildlife species, though not completely. This finding could also be explained by planners creating treatment boundaries outside conserved areas protected by law, which is a major factor of the ACE significant habitat ranking.

Vegetation departure

The mean and median change of vegetation departure before and after treatment was near-zero, suggesting that in the short term, prescribed burns do not meaningfully alter the landscape's vegetative composition from historic, pre-European settlement ecosystem reference conditions. Burned Sierra landscapes remained steady in their change from modeled historical sequences of vegetation succession (Holsinger et al. 2006), which had often already departed above 40%. Furthermore, under the LANDFIRE calculation criteria of vegetation composition, modeled successional stages per biophysical setting, and canopy closure, burned landscapes had nearly unnoticeable changes from their previous departure. These findings challenge the efficacy of burning to return Sierra Nevada land to historical fire regimes, which has been a major goal of burn planners (Keifer et al. 2000). There are three plausible reasons for the lack of departure shift: 1) the burned ecosystems are too altered that mechanical thinning may be necessary before a first burn, 2) regeneration time is greater than the few years of time before I measured Vegetation Departure again, and 3) fire regimes were not evaluated as recommended by the Fire Regime Class Guidebook due to a lack of current fire regimes estimates (Rollins 2009).

Limitations and future directions

My study only considers government-managed burns from 2017 to 2020 that were the first to happen on that land since record-keeping began. This is only a small fraction of available data, constrained by the availability of modeled LANDFIRE remote sensing data that has only become accurate in recent years. Therefore, the three-year time period introduces variation in results that might not exist if I had used all five decades of prescribed burn boundaries. Similarly, fires and landscapes are complex systems that interact differently depending on soil, elevation, and climate. I performed my analysis on my entire sample, extracting trends and characteristics holistically instead of stratifying on the factors above. Data availability also introduced constraints into my methodology. The *Area of Conservation* metrics were not updated since 2018, and LANDFIRE metrics are not calculated annually. Therefore, I was unable to analyze fires at a fixed interval before and after they ended, with some treatments only being reviewed two years after they had completed (i.e., fires which began and ended in 2017 had pre-treatment data from 2016 post-treatment data from 2020).

Without the need for additional LANDFIRE and ACE data, I could add value to this study by exploring taxonomic differences in treatment response to compare with research performed on wildfires and megafires (Calhoun et al. 2021). Alternatively, focusing on a single taxonomic group (e.g., mammals, birds, or reptiles) could introduce the Sierra Nevada as an interesting point of comparison with the dry forests or arid central area of Australia (Pastro et al. 2011). In addition to taxonomy, a point of future study could especially focus on biome and landscape types (e.g., mixed-shrubland, conifer, grassland, riparian).

Broader implications

Even in the Sierra Nevada where prescribed burning for biodiversity and ecosystem health has seen success, current management strategies cannot be a one-size-fits-all solution. In cases of change in existing vegetation and heterogeneity, conservation priority, and vegetation departure, prescribed fires interact with landscapes in a surprisingly diverse manner which reflects the incredible geographic and taxonomic diversity of the ecoregion. In an alarming number of study sites, invasive plants are colonizing post-treatment landscapes with implications that native plant recovery and forest restoration in modern landscapes may require new strategies. Furthermore, regions of higher native species richness and habitat connectivity are being selected to burn, indicating that planners are risking current conservation value for a future benefit. Ultimately, the sheer diversity in both Sierra landscapes and my results reveals that the gap in research of how to protect species from wildfire also extends into managed fire.

To reduce Sierra Nevada wildfire risk, management and planning must take into account the diverse ecosystems that will be burned and their responses. Although my results confirm that prescribed burn treatments are generally working as intended to reduce fuels, they also highlight that commonly understood treatment behavior varies significantly. Fire no longer burns under the laws of old fire regimes or vegetation compositions — their behaviors and impacts are a direct response of modern landscapes that often have anthropogenic signatures like invasive plants and threatened species. Ecosystem-specific, and even location-specific, approaches need to be developed for prescribed burning to minimize the exposure of ecosystems to negative changes while simultaneously reducing wildfire risk.

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