WILDFIRE RECOVERY: UNRAVELING FOREST AND GRASSLAND DYNAMICS IN WESTERN MONTANA

by

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DEDICATION

To my parents, Daryl and Lisa, and my sister, Ashley – thank you for your unwavering patience and support throughout my educational journey. Your encouragement has meant everything.

A special thanks to my grandfather, Jim Philips, for teaching me what truly matters in life. Your wisdom continues to guide me.

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ABSTRACT

Wildfires are increasingly reshaping landscapes in Western Montana, prompting questions about how vegetation responds to fire across varied environmental conditions. These include differences in topography and fire severity across complex terrain in the Bitterroot National Forest. This study evaluates post-fire vegetation dynamics across four wildfire complexes that burned in 2000, focusing on how fire severity, elevation, slope, and aspect influence the recovery of grasslands and forests. Using data from the Monitoring Trends in Burn Severity (MTBS) program and the National Land Cover Database (NLCD), vegetation change was assessed from 2001 to 2020. Spatial analysis in a geographic information system and logistic regression modeling were used to quantify grassland and forest gain, loss, and persistence. I found that grasslands consistently expanded following fire, with high persistence and minimal loss, whereas forests experienced limited recovery and substantial decline, particularly in high severity burn areas. Environmental gradients strongly influenced outcomes, with grassland gain more responsive to fire severity and elevation, and forest recovery constrained across much of the landscape. My findings highlight divergent recovery pathways and underscore the value of spatially explicit models for informing post-fire management. This work provides a foundation for anticipating vegetation shifts under changing fire regimes and supports the development of targeted restoration strategies in fire-affected ecosystems.

CHAPTER ONE

INTRODUCTION

Wildfire is a key ecological process in Western Montana, shaping landscapes through cycles of disturbance and recovery. By influencing ecosystem composition and structure, fire drives transitions between forested and grassland states, with outcomes mediated by burn severity, climate, and site conditions. However, as climate change exacerbates wildfire activity through rising temperatures, prolonged droughts, and altered precipitation patterns, the resilience of post-fire ecosystems is increasingly uncertain (Halofsky et al., 2020). In Western Montana, earlier snowmelt and extended dry seasons have already amplified fire risk, raising questions about the long-term stability of these landscapes (Pederson et al., 2010). While some forests regenerate after disturbance, others fail to reestablish. Forest regeneration failure can result in conversion to grass-dominated systems (Staver et al., 2011). Understanding the environmental factors that drive these divergent trajectories is essential for predicting long-term vegetation dynamics and for identifying conservation strategies aimed at preserving ecosystem services such as carbon storage, hydrologic regulation, and wildlife habitat (Kelly et al., 2020; Pellegrini et al., 2018).

Fire severity is a primary driver of post-fire outcomes, with high severity burns associated with delayed or unsuccessful tree establishment (Bartels et al., 2016; Chen et al., 2011; Lydersen et al., 2017). Yet recovery trajectories are not uniform across landscapes; they are further mediated by variation in climate, elevation, and soil conditions (Halofsky et al., 2020). For example, lower elevations with drier soils may favor grassland persistence, while higher elevations with cooler temperatures and greater moisture availability may support forest

regeneration (Bond & Keeley, 2005; Körner, 2007). Although many studies have documented general post-fire trends, no studies have examined these processes at the spatial resolution needed to explain why forests regenerate in some places but not others. Tepley et al. (2018), for example, used landscape-scale models to explore how fire and vegetation feedbacks shape long-term vulnerability to regime shifts, but their work did not account for patch-level variation or spatially explicit predictors. Despite these contributions, a critical knowledge gap remains in identifying how spatial and environmental interactions shape the fine-scale competitive dynamics between trees and grasses following fire. This gap is especially evident in Western Montana, where pronounced topographic and climatic heterogeneity drives highly variable recovery outcomes. A long-term study paired with fine-scale imagery or targeted field sampling could offer the spatial and temporal resolution needed to clarify these dynamics and explain patterns of forest persistence and grassland expansion.

My study aims to identify the mechanisms driving post-fire forest regeneration versus grassland expansion in Western Montana. To address this knowledge gap, I examined vegetation recovery patterns across four wildfire complexes in the Bitterroot National Forest, each representing distinct compositions of burn severities, vegetation zones, and environmental characteristics (Fig. 1, Table 1). By leveraging remotely sensed datasets from the National Land Cover Database (NLCD) and the Monitoring Trends in Burn Severity (MTBS) program, this study provides a spatially explicit assessment of vegetation change from 2001 to 2020, a 20-year period following fire (Dewitz, 2023; U.S. Geological Survey, USDA Forest Service, and Nelson, 2021). To achieve these objectives, this study employs a combination of raster-based geospatial analysis and statistical modeling to assess post-fire vegetation trajectories. Zonal statistics were

used to summarize trends in grassland and forest gain, loss, and persistence across burn areas, while raster overlay analysis was applied to map spatial relationships between burn severity and vegetation transitions. These geospatial methods were complemented by generalized logistic models, which quantify the influence of environmental variables, including aspect, elevation, slope, and fire severity, on the likelihood of vegetation gain. By integrating these approaches, the study aims to uncover the mechanisms driving post-fire ecological transitions, from forest regeneration to persistent grassland expansion, and to consider their implications for long-term landscape resilience under changing climate conditions.

The core objective of this study is to identify the environmental thresholds that determine whether forest regenerates or is replaced by grassland following fire. By linking spatial data with ecological modeling, the results offer land managers new tools to prioritize restoration, particularly in areas with limited moisture availability or high burn severity. In contrast, areas with favorable conditions for natural recovery may be best left unmanaged. These distinctions can help optimize the use of limited resources and align restoration efforts with site-specific conditions (Noss et al., 2006).

The findings of this work help to bridge ecological theory and practical management. By disentangling the roles of climate, fire, and terrain, this study helps advance fundamental knowledge of disturbance-driven change, which can be particularly critical as warming temperatures and intensified fire regimes alter ecological responses to fire. Practically, the results can help inform adaptive strategies to bolster landscape resilience, such as identifying areas where grassland expansion is irreversible or where proactive interventions could accelerate forest recovery.

Beyond local land management, the study's findings have broader implications for regional and national wildfire policy. By pinpointing the environmental factors associated with forest loss and grassland expansion following high severity fires, this work can guide strategic interventions, such as reforestation programs or fuel reduction efforts to mitigate ecological degradation (Rogers et al., 2020). The results may also inform climate adaptation planning, which could help policymakers anticipate cascading impacts of changing fire regimes on biodiversity and to water availability. Ultimately, this research underscores the need for science-driven frameworks to navigate the ecological and socioeconomic challenges posed by wildfires in an era of climatic uncertainty.

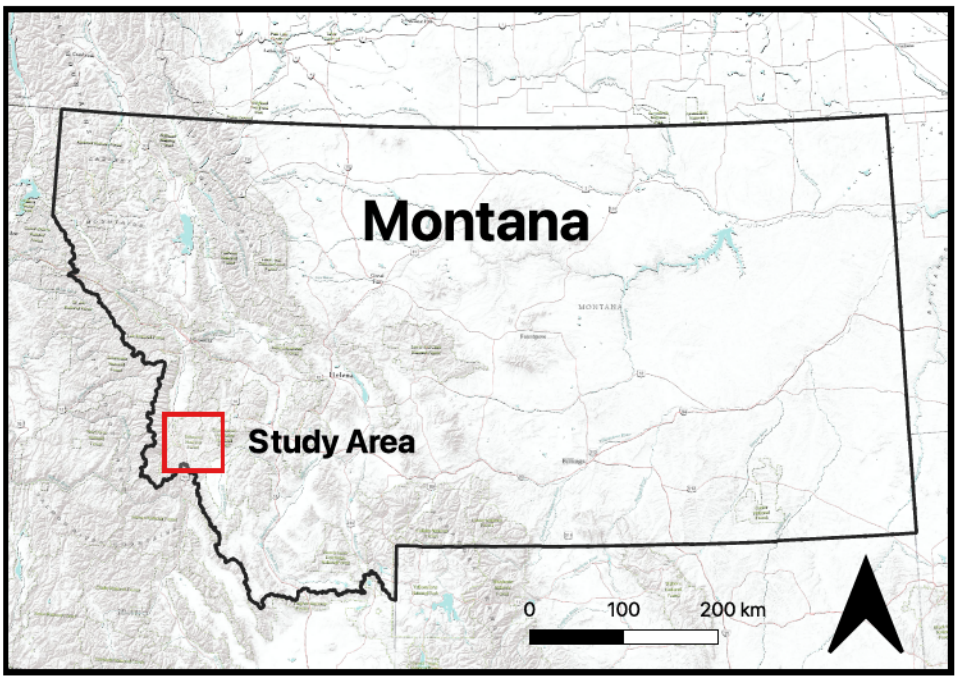


Figure 1. Reference map of study area in Western Montana.

Table 1. Wildfire complexes included in study, with area and central coordinates in the Bitterroot National Forest, Montana (fires ignited on July 31, 2000).

Fire Name	Size (acres)	Latitude	Longitude
Mussigbrod Complex	64,810	45˚53'N	113˚36'W
Sula Complex	62,967	45˚47'N	113˚57'W
Valley Complex (Bear)	118,045	46˚00'N	114˚04'W
Valley Complex (Coyote)	20,601	46˚05'N	113˚50'W

METHODS

Study Area

My study focuses on four wildfire-affected landscapes within the Bitterroot National Forest near Sula, Montana. Located in the northern Rocky Mountains, the Bitterroot National Forest spans a diverse range of elevations, from approximately 3,000 to 10,000 ft (914 to 3,048 m). The selected fire complexes, including Valley Complex Coyote (20,601 ac), Valley Complex Bear (118,045 ac), Sula Complex Maynard (62,967 ac), and Mussigbrod Complex (64,810 ac), were all ignited on July 31, 2000 (Table 1, Fig. 2, Appendix Figures A1-A4). These complexes represent grassland, shrubland, and forested vegetation cover classes. In addition, these focal fires complexes capture a broad spectrum of post-fire vegetation changes and are characterized by diverse elevation gradients and vegetation communities. The four fire complexes also differed in their burn severity composition, with the Mussigbrod Complex containing the highest proportion of high-severity burns, while the Valley Complex Bear exhibited a relatively even mix of low- and moderate-severity burns. The Valley Complex Coyote had the largest extent of

moderate-severity burns, and the Sula Complex included the highest proportion of low-severity areas (Fig. 3, Table 5).

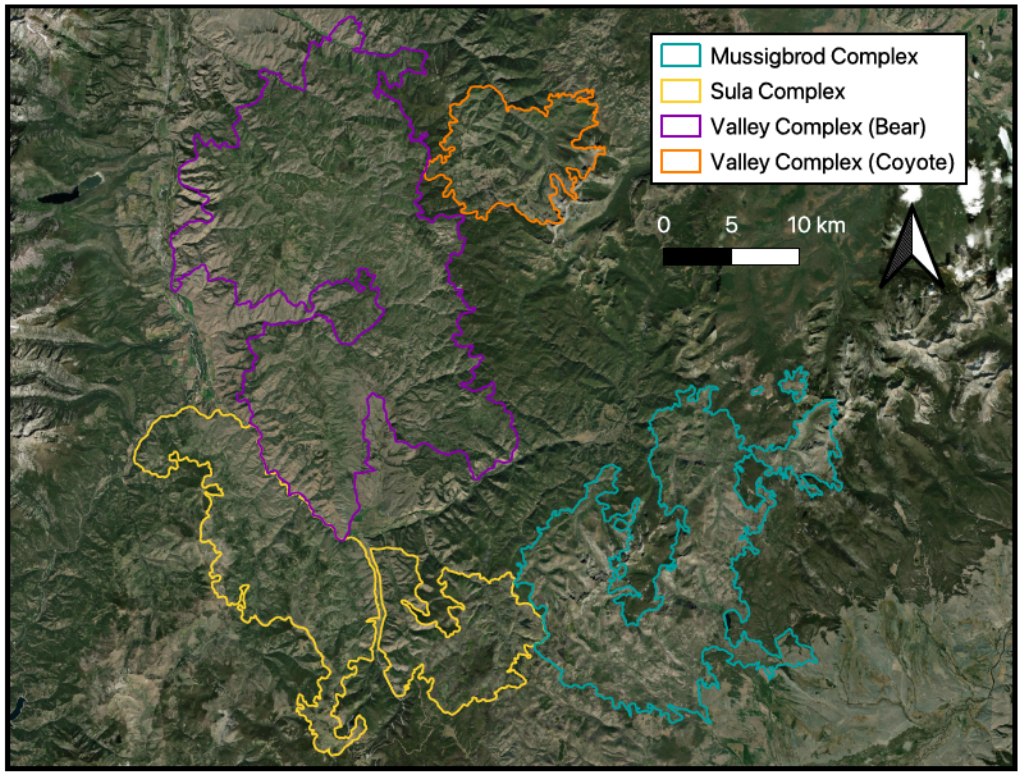


Figure 2. Wildfire perimeters and study area in the Bitterroot National Forest, Montana. Map created by the author.

The study area lies within a semi-arid climate, typical of the intermountain West, with significant variability in precipitation and temperature. Mean annual precipitation ranges from approximately 12 to 20 inches (305 to 508 mm), with most precipitation occurring as winter snow and spring rains (NOAA, 2023). Summer months are typically dry, contributing to the region's high wildfire risk. Mean annual temperatures range from 40 °F to 45 °F (4.4 °C to 7.2 °C), with summer highs averaging 80 °F to 85 °F (26.7 °C to 29.4 °C) and winter lows often dropping below freezing. These climatic conditions, combined with the region's complex

topography, create a dynamic environment for post-fire vegetation recovery (see Results; Table 4).

The Bitterroot National Forest supports a variety of vegetation types, including fire-adapted species such as ponderosa pine (Pinus ponderosa Douglas ex C. Lawson), Douglas fir (Pseudotsuga menziesii (Mirb.) Franco), lodgepole pine (Pinus contorta Douglas ex Loudon), and mixed grasslands. Common grass species in the area include bluebunch wheatgrass (Elymus spicatus (Pursh) Gould), a drought-tolerant perennial grass that plays a key role in stabilizing soils, and Idaho fescue (Festuca idahoensis Elmer), a cool-season grass that dominates many grassland ecosystems in the region. This diversity of vegetation, along with the area's history of frequent wildfires, makes it an ideal location for studying post-fire recovery dynamics. The forest also plays a critical ecological role, providing habitat for wildlife such as elk (Cervus canadensis Erxleben, 1777), mule deer (Odocoileus hemionus (Rafinesque, 1817)), and grizzly bears (Ursus arctos horribilis Ord, 1815). Additionally, the forest is a vital component of the region's watersheds, influencing water quality and availability for downstream communities.

The four fires studied within the Bitterroot National Forest near Sula occurred across terrain with varying slope, aspect, elevation, and burn severity, offering an ideal setting to examine post-fire regeneration in semi-arid ecosystems. This landscape’s complex topography, climatic variability, and diverse plant communities create distinct environmental gradients that help reveal the drivers of vegetation change following wildfire.



Figure 3. McColgan, J. (2000, August 6). Elk in the Bitterroot River [Wildlife photograph]. Alaska Fire Service, Bureau of Land Management.

Analytical Approach

My study examines post-fire vegetation recovery dynamics across four wildfire complexes in the Bitterroot National Forest, Montana. I used a combination of geospatial data and analytical tools to assess changes in vegetation cover over time. Pre-fire (2001) and post-fire (2020) vegetation conditions were derived from the NLCD, focusing on grassland and forest classifications. Fire perimeters and burn severity data were obtained from MTBS program, which provided both the spatial extent of the fires and the differential normalized burn ratio (dNBR) to quantify burn severity.

The NLCD classification scheme was simplified to focus on two primary land cover categories: grassland and forest. Grasslands included herbaceous and shrub-dominated areas, while forests encompassed both deciduous and coniferous tree cover. This reclassification

allowed for a more straightforward comparative analysis of vegetation recovery patterns across the study area. For this study, the 2000 and 2020 NLCD datasets were used to represent pre-fire and post-fire vegetation conditions, respectively. These datasets were chosen because they align with the study's temporal scope and provide a reliable baseline for assessing vegetation change. The NLCD provides spatially explicit, 30-m resolution land cover data for the United States, derived from Landsat satellite imagery and other ancillary data sources. The database includes various land cover classes, including forests, grasslands, shrublands, wetlands, and urban areas. All NLCD classifications use a consistent methodology to ensure that data are comparable across time and space. While the NLCD data have demonstrated high accuracy, typically exceeding 80% for most land cover classes, some limitations remain, particularly in areas with complex vegetation structures or mixed land cover types (Wickham et al., 2017). These factors may necessitate additional validation for localized studies.

All geospatial analyses were conducted using QGIS, an open-source geographic information system, to manage, visualize, and analyze spatial data (QGIS Development Team 2025). Datasets were standardized to a uniform coordinate reference system (NAD83, Montana) and resampled to a spatial resolution of 30 m to ensure consistency across layers. Post-fire vegetation change was assessed using the raster calculator to identify gain, loss, and persistence of grasslands and forests within fire perimeters. Gain was defined as the transition from non-vegetated to either grass or forest, or from one land cover type to another (e.g., forest to grassland or grassland to forest). Loss was defined as the transition from grassland or forest to other types, and persistence as areas that retained their original classification. Zonal statistics

were applied to summarize these vegetation dynamics at the fire complex level, enabling comparisons between fire complexes at a landscape scale.

Environmental predictor variables, including slope, elevation, aspect, and burn severity, were also summarized using zonal statistics. These variables were reclassified into categorical bins using general groupings selected to balance ecological interpretation with data simplification. To evaluate how these conditions influenced vegetation recovery, logistic regression models were developed using R statistical software (R Core Team 2022). Separate models were constructed for grassland gain and forest gain as binary response variables. The models estimate the probability of vegetation gain based on the extracted environmental conditions.

To interpret and present the results, maps were generated in QGIS to illustrate the spatial distribution of grassland and forest gain, loss, and persistence within each fire perimeter (Fig. 4). Bar graphs were used to summarize vegetation change by fire complex and burn severity class, allowing for visual comparisons across study sites (Fig. 5). This study is limited by the availability of high-resolution, long-term vegetation data and does not incorporate other factors that may influence recovery, such as soil properties or seed availability. These limitations highlight opportunities for future research.

Burn Severity

Burn severity was assessed using classifications from the MTBS dataset, which categorizes areas based on changes in vegetation and surface conditions following fire events (Appendix Figure A5). In contrast to fire intensity, which measures the energy released during a fire, burn severity mapping reflects the loss of organic matter in the soil and the conversion of

aboveground vegetation to ash (Keeley, 2009). This approach provides a broader understanding of post-fire impacts by using satellite imagery to assess changes in both vegetation and surface characteristics. Although it does not directly measure soil properties, burn severity mapping captures spectral signals associated with vegetation loss, charring, and exposed soil, which often correspond to soil degradation. Classifying the landscape into burn severity levels helps identify areas most affected by fire and supports restoration and land management decisions (Veraverbeke et al., 2012). These assessments often rely on multi-temporal satellite imagery and bi-temporal image differencing techniques, which compare pre- and post-fire conditions to calculate indices such as the differenced Normalized Burn Ratio (dNBR) and differenced Normalized Difference Vegetation Index (dNDVI) (Key and Benson, 2006; Chu and Guo, 2014). Among these, the Normalized Burn Ratio (NBR) and dNBR have been shown to provide the most accurate estimates of post-fire burn severity (Epting et al., 2005; Parks et al., 2014).

Topographic Variables

To evaluate post-fire vegetation recovery across the four wildfire-affected complexes, we categorized slope, elevation, and aspect using standardized classification methods in GIS. These variables were derived from a Digital Elevation Model (DEM) using QGIS tools, ensuring consistency across the study area. Slope data were obtained from the DEM using the slope analysis tool in QGIS. Slopes were categorized into five classes to capture terrain steepness variability: Flat (0–5°), Gentle (6–15°), Moderate (16–30°), Steep (31–45°), and Extreme (46–67°) (see Appendix Figure A6). These slope categories reflect terrain variability and help assess the influence of slope steepness on post-fire vegetation recovery.

Elevation data were also extracted from the digital elevation model (DEM) and divided into five classes using evenly spaced elevation intervals to provide a general representation of terrain variation across the study area (Appendix Figure A7). Although the thresholds are not based on statistical clustering, the resulting classes reflect broad gradients in moisture and temperature that may influence vegetation recovery. The five elevation classes were defined as follows: Very Low (1160–1495 m), Low (1496–1826 m), Moderate (1827–2159 m), High (2160–2491 m), and Very High (2492–2824 m). These elevation bands capture a transition from lowland to montane environments and represent a range of ecological conditions that may influence vegetation recovery. Dividing the terrain into five categories provides a structured way to examine how post-fire vegetation patterns vary along elevation-driven moisture and temperature gradients.

Aspect, indicating the cardinal direction of slope exposure, was classified into four primary categories to capture differences in solar exposure: North, East, South, and West (Appendix Figure A8). These directional categories are essential for assessing how sunlight exposure and microclimate variability influence post-fire vegetation patterns. By systematically categorizing these variables, we aimed to evaluate how topographic factors shape vegetation recovery after wildfires.

RESULTS

Post-fire vegetation change was assessed by calculating gain, loss, and persistence of grassland and forest cover across four fire complexes in Western Montana. All vegetation change was measured relative to pre-fire land cover, derived from classified satellite imagery. Changes were quantified by comparing pre- and post-fire classifications over a 20-year period, providing

a basis for evaluating long-term vegetation dynamics. Vegetation conditions at the beginning (2000) and end (2020) of the study period are summarized by fire complex (Appendix Tables A1 and A2).

Vegetation Recovery

Grasslands exhibited substantial net gains across all complexes, indicating widespread expansion into areas previously classified as forest, shrubland, or non-vegetated land cover (Table 2). Gains ranged from 13.26% with 42,418 acres (17,163 hectares) in the Valley Complex Bear to 19.96% with 46,357 acres (18,760 hectares) in the Mussigbrod Complex. The Valley Complex Coyote and Sula Complex also demonstrate considerable grassland expansion, with gains of 19.2% (9,572 acres or 3,873 hectares) and 17.55% (29,073 acres or 11,765 hectares), respectively. Grassland losses were relatively minor, ranging from 0.29% (685 acres or 277 hectares) in the Mussigbrod Complex to 0.82% (2,631 acres or 1,065 hectares) in the Valley Complex Bear. Persistence of pre-existing grassland cover varied across sites. These low rates of decline suggest that grasslands largely remained intact across the study area. The Valley Complex Bear retained the highest amount of intact grassland at 25,960 acres (10,505 hectares), or 8.12%, while the Valley Complex Coyote retained the least at 1,242 acres (503 hectares), or 2.49%. The Sula and Mussigbrod Complexes fell in between, with persistence values of 6,996 acres (2,831 hectares), or 4.22%, and 4,520 acres (1,829 hectares), or 1.95%, respectively.

Forest cover demonstrated limited recovery and substantial reductions across all four complexes when measured relative to pre-fire extent (Table 3). Forest gains were minimal, with the Mussigbrod Complex showing the lowest increase at 0.34% (881 acres or 357 hectares) and the Valley Complex Bear the highest at 0.67% (2,680 acres or 1,084 hectares). These low gains indicate slow or failed reestablishment of forest in many burned areas. In contrast, forest losses

were extensive, especially in the Mussigbrod Complex, where 44,289 acres (17,926 hectares) were lost, representing 17.12% of its total pre-fire forest area. The Valley Complex Bear also experienced substantial forest loss, with 41,775 acres (16,906 hectares) lost, or 10.43%. Forest persistence, defined as the area that remained classified as forest throughout the study period, ranged from 4.74% (12,258 acres or 4,962 hectares) in the Mussigbrod Complex to 11.10% (44,472 acres or 17,998 hectares) in the Valley Complex Bear. Forest persistence was similar for the Valley Complex Coyote and Sula Complex at 10.87% and 10.15%, respectively.

Table 2. Post-fire grassland gain, loss, and persistence (2000 - 2020).

	Grass Gain Area (acres)	Grass Loss Area (acres)	Grass Persist Area (acres)	Total Grass Area (acres)	% Grass Gain	% Grass Loss	% Grass Persist
MUSSIGBROD COMPLEX	46357.15	685.09	4519.70	51561.94	19.96	0.29	1.95
SULA COMPLEX	29072.68	706.40	6995.89	36774.97	17.55	0.43	4.22
VALLEY COMPLEX (BEAR)	42418.21	2630.70	25960.24	71009.14	13.26	0.82	8.12
VALLEY COMPLEX (COYOTE)	9571.53	251.53	1242.09	11065.15	19.20	0.50	2.49

Table 3. Post-fire forest gain, loss, and persistence (2000 - 2020).

	Forest Gain Area (acres)	Forest Loss Area (acres	Forest Persist Area (acres)	Total Forest Area (acres)	% Forest Gain	% Forest Loss	% Forest Persist
MUSSIGBROD COMPLEX (MUSSIGBROD)	881.34	44288.78	12257.73	57427.85	0.34	17.12	4.74

SULA COMPLEX (MAYNARD)	863.14	28623.35	24852.68	54339.16	0.35	11.69	10.15
VALLEY COMPLEX (BEAR)	2679.76	41774.85	44472.37	88926.98	0.67	10.43	11.10
VALLEY COMPLEX (COYOTE)	392.05	9072.92	9082.91	18547.88	0.47	10.86	10.87

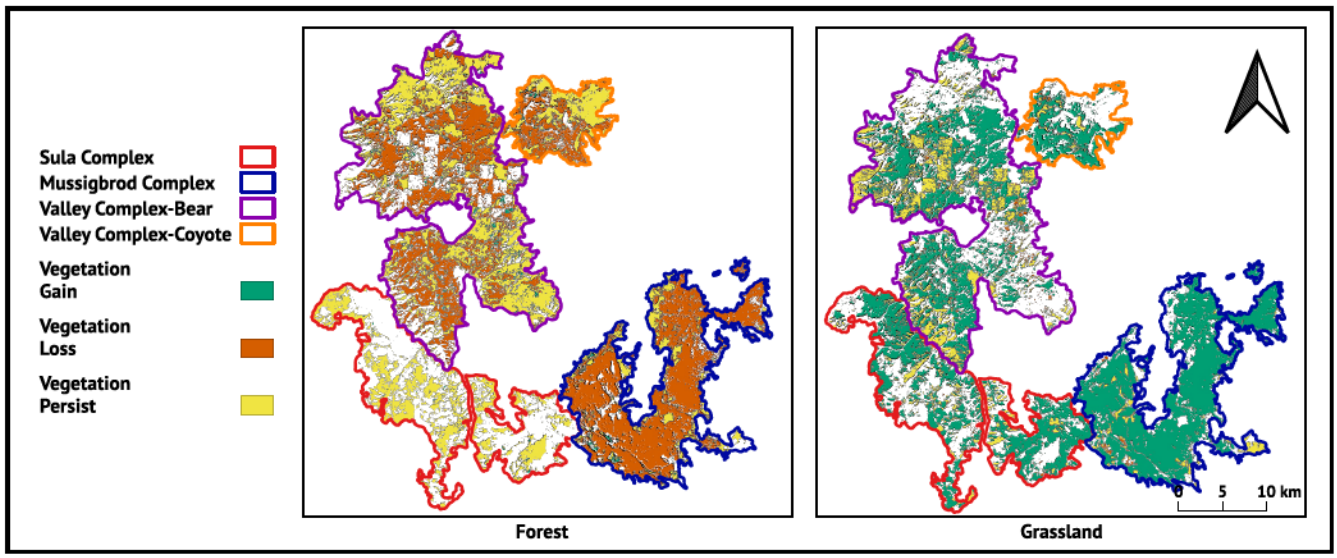


Figure 4. Spatial distribution of post-fire vegetation recovery across four wildfire-affected complexes in Western Montana (2000–2020).

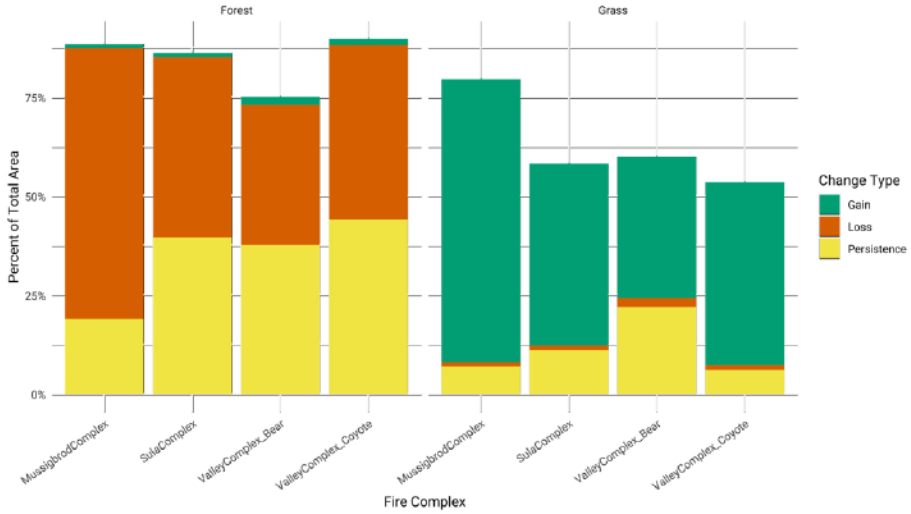


Figure 5. Comparison of post-fire vegetation recovery (forest vs. grass) across four wildfire-affected complexes in Western Montana (2000–2020)

Burn Severity

The analysis of environmental variables revealed clear differences in fire severity and terrain characteristics across the four wildfire-affected complexes in Western Montana (Table 4). High-severity burns were most extensive in the Mussigbrod Complex, covering 40.41% of the area, and were least common in the Valley Complex Bear at 10.10%. Moderate-severity burns were most frequent in the Valley Complex Coyote (10.23%) and least represented in the Mussigbrod Complex (2.23%). Low-severity burns were most common in the Sula Complex (8.03%) and lowest in the Mussigbrod Complex (1.83%). The unburned-low severity category was relatively consistent across Mussigbrod, Sula, and Bear (13.93% to 14.88%), while it dropped to 8.62% in the Valley Complex Coyote. Although increased greenness was recorded, its extremely low percentages suggest it had limited ecological significance in this context.

Environmental Variables

Elevation patterns varied considerably among the complexes, which likely influenced post-fire vegetation potential through associated moisture and temperature gradients. The Valley Complex Bear had the highest proportion of low elevation area, with 54.87% classified as low and 13.94% as very low (Table 4). In contrast, the Mussigbrod Complex had no very low elevation zones and was dominated by high (51.07%) and moderate (37.08%) elevations, with an additional 6.97% in very high terrain. Medium elevation was most prevalent in the Valley Complex Coyote (59.30%), suggesting transitional site conditions. The Sula Complex had a more even distribution across elevation bands, with notable representation in both low (33.79%) and moderate (28.98%) categories.

Slope patterns highlight further contrasts. The Valley Complex Bear had the highest proportion of moderate slopes at 57.77%, while Mussigbrod had a near even distribution

between gentle (42.25%) and moderate slopes (41.16%). Flat terrain was most prominent in Mussigbrod (10.03%) and least common in Bear (3.48%). Steep slopes were most frequent in the Valley Complex Coyote and Sula Complex (both around 10.28%), while extreme slopes were nearly absent across all sites.

Aspect distributions were similarly variable. North-facing slopes were most common in the Sula Complex (28.28%) and Valley Complex Coyote (26.66%), offering potentially cooler and moister microclimates. East-facing aspects were most extensive in Sula (30.49%), while west-facing slopes were most prevalent in the Valley Complex Coyote (31.63%) and Valley Complex Bear (29.84%). South-facing aspects, typically associated with warmer and drier conditions, were most frequent in the Valley Complex Bear (26.36%), potentially influencing patterns of reduced forest recovery and enhanced grassland persistence in that complex.

Table 4: Percentage of area by fire severity, elevation, slope, and aspect across four wildfire-affected complexes in Western Montana

	MUSSIGBROD COMPLEX (% of Area)	***SULA COMPLEX (% of Area)***	***VALLEY COMPLEX (BEAR) (% of Area)***	***VALLEY COMPLEX (COYOTE) (% of Area)***
Fire Severity				
Unburned - Low	13.93	14.08	14.88	8.62
Low	1.83	8.03	7.32	6.02
Moderate	2.23	6.91	6.67	10.23
High	40.41	19.38	10.10	17.66
Increased Greenness	0.00	0.07	0.00	0.01
NA	41.59	51.53	61.03	57.46
Elevation				
Very Low (1160 - 1495 m)	0.00	12.43	13.94	0.00
Low (1496 -1826 m)	3.64	33.79	54.87	8.48
Moderate (1827 - 2159 m)	37.08	28.98	28.28	59.30
High (2160 -2491 m)	51.07	22.12	0.20	28.38
Very High (2492 - 2824 m)	6.97	0.16	0.00	2.11
Slope				
Flat (0 - 5˚)	10.03	5.13	3.48	3.53
Gentle (6 - 15˚)	42.25	28.62	31.82	32.86
Moderate (16 - 30˚)	41.16	55.96	57.77	53.31
Steep (31- 45˚)	6.50	10.29	6.93	10.28
Extreme	0.06	0.00	0.01	0.01

(46 - 67˚)				
Direction				
North	22.08	28.28	22.59	26.66
East	26.59	30.49	21.21	20.28
South	23.75	15.88	26.36	21.43
West	27.58	25.35	29.84	31.63

Logistic Regressions

The relative importance of environmental predictors differed substantially between the grassland and forest gain models. Although all predictors were statistically significant ($p < 0.001$), fire severity emerged as the strongest driver in both models. Its influence was far more pronounced in the grassland model, where it accounted for the largest share of deviance (LR Chi-square = 41,157; Table 5). In comparison, fire severity explained considerably less variation in the forest gain model (LR Chi-square = 1,488), indicating a weaker association with burn intensity. Elevation and aspect also contributed more to explaining grassland gain (LR Chi-square = 2,926 and 1,506, respectively) than forest gain (176 and 186, respectively), while slope had a relatively modest but consistent effect in both models. These patterns highlight that, despite statistical significance across variables, the strength of association with vegetation recovery outcomes differed notably between grassland and forest responses.

Table 5. Likelihood Ratio Chi-square (LR Chi-square) statistics and p-values from Type II ANOVA comparing the effects of fire severity, elevation, aspect, and slope on the probability of post-fire grassland and forest gain.

Variable	Grassland Model (LR Chi-sqare)	Forest Model (LR Chi-sqare)	p-values
Fire Severity	41,157	1,488	< 0.001
Elevation	2,926	176	< 0.001

Aspect	1,506	186	< 0.001
Slope	92	141	< 0.001

Two separate logistic regression models were fitted to examine the influence of environmental factors, including categorized slope, elevation, aspect, and fire severity, on the likelihood of post-fire vegetation recovery for forests and grasslands. The grassland recovery model (n = 100000 sampled pixels) identified fire severity as the strongest predictor, with additional contributions from elevation, aspect, and to a lesser extent, slope. All categorical predictors were interpreted relative to the following reference levels: unburned low-severity (fire severity), very low (elevation), gentle (slope), and north-facing (aspect).

Predicted probabilities of grassland gain increased markedly with burn intensity. In unburned low-severity areas (the reference category), the probability of grassland recovery was approximately 4.5%. This probability increased to 19% in low-severity burns, 53% in moderate-severity burns, and 88% in high-severity burns, assuming all other predictors were held at their reference categories ($p < 0.001$). These increases reflect a clear positive trend in recovery likelihood with increasing burn severity.

Topographic variables also influence recovery, although patterns appear less pronounced. In the lowest elevation categories, predicted probabilities of grassland gain remain below 4%. These rise significantly to 13% in high elevation zones and 12% in very high zones ($p < 0.001$ for both), suggesting elevation-related moisture or temperature gradients may support recovery, and that this increase in probability may occur at a threshold elevation. Mid-elevation categories, by contrast, show no significant differences from the reference. Slope exerts a modest nonlinear effect. Moderately steep slopes reduce predicted probability from 5% in gentle terrain to about

4% ($p < 0.001$), while flat and steep slope categories show no significant deviation from the reference. Aspect influences recovery probabilities relative to north-facing slopes, with predicted values increasing to 10% on east-facing slopes, 13% on south-facing slopes, and 14% on west-facing slopes.

The grassland gain model explains 35.2% of the deviance in the data (McFadden's pseudo-R squared = 0.352), with a residual deviance of 89688 and an AIC of 89720. The model reaches convergence after five Fisher scoring iterations. A few sparsely populated categories produce large standard errors, yet overall model fit and stability remain strong. Simulated residuals indicate no significant deviation from uniformity (Kolmogorov-Smirnov test: $p = 0.26$), supporting acceptable model performance.

The second logistic regression model (n = 100000 sampled pixels) evaluated factors influencing post-fire forest recovery across the same environmental gradients used in the grassland analysis. All categorical predictors were interpreted relative to the following reference levels: unburned low-severity (fire severity), very low (elevation), gentle (slope), and north-facing (aspect). Compared to the grassland model, the forest model exhibited lower explanatory power, with more modest predictor effects. Predicted probabilities of forest gain was low across all burn severities and decreased with increasing burn severity. In unburned, low-severity areas (reference), the probability of forest recovery was approximately 2.3%. This declined to 1.5% in low-severity burns, 0.6% in moderate-severity burns, and 0.2% in high-severity burns. a strong negative association between burn severity and forest regeneration.

Elevation effects follow a unimodal pattern, with mid-elevation categories showing the highest recovery probabilities. Compared to the reference category (very low elevation, 1.6%

probability), the probability of forest gain rises to 5.4% in lower mid elevations, 6.8% in upper mid elevations, and 5.3% in high elevation zones. Very high elevations display a predicted probability of 4.9%, still significantly higher than the reference ($p < 0.001$), although slightly lower than mid-elevation zones. Slope effects appear more pronounced at steeper gradients. The probability of forest gain drops from 2.3% in gentle slopes to 1.9% on moderately steep terrain and falls further to 0.3% on the steepest slopes ($p < 0.001$). Other slope categories show no significant differences from the reference. Aspect influences forest recovery in the opposite direction of grassland gain. Predicted probabilities of forest gain decline to 1.6% on south-facing slopes, 1.2% on west-facing slopes, and 1.0% on east-facing slopes, relative to north-facing slopes (2.3%).

The model explains 10.6% of the deviance in the data (McFadden's pseudo-R squared = 0.106), with a residual deviance of 15810 and an AIC of 15842. The model reaches convergence after twelve Fisher scoring iterations. Simulated residuals indicate no significant deviation from uniformity (Kolmogorov-Smirnov test: $p = 0.73$), supporting acceptable model fit.

DISCUSSION

My study examined post-fire vegetation recovery across four wildfire-affected complexes in Western Montana: Mussigbrod, Sula, Valley (Bear), and Valley (Coyote). The analysis revealed clear differences in post-fire outcomes between grasslands and forests. Grasslands exhibited substantial gains and persistence in all four complexes, while forests show more limited recovery, often marked by substantial losses in areas that experienced high severity fire. Burn severity varied widely across the landscape. The key findings from this work suggest that grassland and forest recovery patterns following fire are influenced by burn severity and

environmental factors in predictable ways. These patterns reflect how disturbance intensity, combined with local environmental variation, shapes contrasting recovery trajectories for grassland and forest ecosystems.

The ability of grasslands to rapidly expand following fire likely stems from adaptive traits such as quick germination and efficient seed dispersal, which allow fast colonization of disturbed areas (Pausas and Keeley, 2014). In contrast, forest recovery was more constrained, particularly in areas that experienced higher severity burns, where seed sources may have been lost and soil conditions altered. The divergence in recovery responses underscores the central role of fire severity in driving vegetation change. Higher intensity burns were consistently associated with reduced forest cover but greater grassland expansion, suggesting that fire acts not only as a disturbance to woody vegetation but also as a catalyst for herbaceous dominance (Higgins et al., 2000).

Topographic gradients, particularly elevation, played an important role in shaping vegetation outcomes. Higher elevation zones were associated with greater grass gain, likely due to cooler temperatures and higher moisture availability. Forest recovery peaked at intermediate elevations, suggesting that these zones provide more favorable conditions for tree recruitment and survival. Slope and aspect also influenced outcomes. Steep slopes were generally less likely to support either forest or grassland gain, likely due to reduced soil stability and water retention. North-facing slopes, which tend to retain more moisture and experience less solar exposure, were more strongly associated with forest regeneration, while grassland gain was more common on south- and west-facing slopes. These findings show that post-fire vegetation recovery is shaped not only by fire severity but also by fine-scale topographic features that affect local

microclimate. While slope and aspect provided useful proxies, some environmental drivers of vegetation response may remain undetected due to limitations in the spatial resolution of available data (Lembrechts et al., 2019).

One important limitation of this study is that interactions among environmental variables were not explicitly modeled. Although factors such as elevation, aspect, and slope may modify the effects of fire severity on vegetation recovery, the model evaluated only the main effects of each predictor relative to a shared set of reference conditions. Specifically, the estimated effect of a variable such as elevation reflects its influence when fire severity was low, slope was gentle, and aspect was north-facing, rather than in isolation. As a result, some baseline interactions are already reflected in the results using reference categories. However, without formally modeling interaction terms, it is not possible to determine whether the influence of elevation, aspect, or slope shifts under different fire severity conditions. For instance, elevation effects could vary between high- and low-severity burns, but this study could not explicitly assess that possibility. Identifying such interactions could reveal important contingencies in post-fire recovery patterns, offering a more nuanced understanding of vegetation responses and refining management strategies to account for the combined influence of multiple environmental factors.

Another limitation of this study is the coarse spatial resolution of the soil and climate datasets used, which may have masked important interactions between environmental conditions and vegetation response. Soil properties such as moisture availability and nutrient content are key determinants of post-fire recovery, but their variability is often underestimated in broad-scale models (Andrade et al., 2021; Switzer et al., 2012). Future research would benefit from integrating high-resolution soil and climate data, combined with long-term field sampling, to

better understand how fine-scale environmental gradients affect vegetation dynamics following fire.

These findings offer useful guidance for land management in fire-prone areas like Western Montana. In the Mussigbrod Complex, where high severity burns dominated, recovery strategies could prioritize assisted seed dispersal and the protection of remnant forest patches to support regeneration, especially in mid elevation zones where forest recovery was more likely. Management actions that promote native grassland persistence at higher elevations, where grass gains were concentrated, may help maintain native plant composition over the long term in the Valley Complex (Bear), which experienced lower fire severity. In the Valley Complex (Coyote), where moderate severity burns were more prevalent, restoration may require a balanced approach that supports both grassland recovery and potential forest regeneration depending on slope, aspect, and elevation. Tailoring management strategies to elevation bands as well as fire severity patterns and vegetation responses will be essential for sustaining resilient and diverse landscapes. Continued research that integrates finer scale environmental data and emphasizes interactions among fire, topography, and soil conditions will improve our capacity to guide post-fire recovery under evolving climate and fire regimes.

CONCLUSION

This study examined post-fire vegetation dynamics across four wildfire complexes in Western Montana, integrating geospatial analysis and statistical modeling to assess differences in recovery between grasslands and forests. Grasslands show strong post-fire recovery, with high gain and persistence and relatively low loss. In contrast, forests exhibited limited recovery, particularly in areas affected by high severity burns and likely constrained by seed source

availability. These patterns underscore the importance of localized environmental factors, such as fire severity, elevation, and soil moisture, in shaping vegetation outcomes. The findings provide useful insights for land managers, supporting the development of targeted restoration strategies and adaptive management practices in fire-prone landscapes. More broadly, this work contributes to our understanding of post-fire ecological dynamics and highlights the need for continued research that improves predictive models of vegetation change under future climate conditions.

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APPENDIX

Supplementary Data

Table A1. Initial vegetation conditions (2000) by fire complex. Forest and grassland areas are reported in acres and as a percentage of the total fire perimeter area.

Fire Complex	Forest Area (acres)	Grassland Area (acres)	Total Area (acres)	Forest %	Grassland %
MUSSIGBROD COMPLEX	56544	5204	61749	92	8
SULA COMPLEX	53469	7706	61174	87	13
VALLEY COMPLEX (BEAR)	86243	28600	114842	75	25
VALLEY COMPLEX (COYOTE)	18154	1495	19648	92	8

Table A2. Vegetation conditions (2020) by fire complex. Forest and grassland areas are reported in acres and as a percentage of the total fire perimeter area.

Fire Complex	Forest Area (acres)	Grassland Area (acres)	Total Area (acres)	Forest %	Grassland %
MUSSIGBROD COMPLEX	13138	50875	64013	21	79
SULA COMPLEX	25721	36063	61784	42	58
VALLEY COMPLEX (BEAR)	47160	68373	115532	41	59
VALLEY COMPLEX (COYOTE)	9470	10818	20288	47	53

Table A3. Grass Gain, Loss, Persist

	Grass Gain (Pixels)	Grass Loss (Pixels)	Grass Persist (Pixels)	Total Grass (Pixels)	% Grass Gain	% Grass Loss	% Grass Persist
MUSSIGBROD COMPLEX	208816	3086	20359	232261	89.91	1.33	8.77
SULA COMPLEX (MAYNARD)	130958	3182	31513	165653	79.06	1.92	19.02
VALLEY COMPLEX (BEAR)	191073	11850	116938	319861	59.74	3.70	36.56
VALLEY COMPLEX (COYOTE)	43115	1133	5595	49843	86.50	2.27	11.23

Table A4. Forest Gain, Loss, Persist

	Forest Gain (Pixels)	Forest Loss (Pixels)	Forest Persist (Pixels)	Total Forest (Pixels)	% Forest Gain	% Forest Loss	% Forest Persist
MUSSIGBROD COMPLEX	3970	199499	55215	258684	1.53	77.12	21.34
SULA COMPLEX	3888	128934	111949	244771	1.59	52.68	45.74
VALLEY COMPLEX (BEAR)	12071	188175	200326	400572	3.01	46.98	50.01
VALLEY COMPLEX (COYOTE)	1766	40869	40914	83549	2.11	48.92	48.97

Table A5. Dominant Topographic and Fire Severity Characteristics Across Fires

	Slope Categories (Mode)	Elevation Categories (Mode)	Aspect Categories (Mode)	Fire Severity Categories (Mode)
MUSSIGBROD COMPLEX	2	4	4	4
SULA COMPLEX	3	2	2	4
VALLEY COMPLEX	3	2	4	2
VALLEY COMPLEX	3	3	4	3

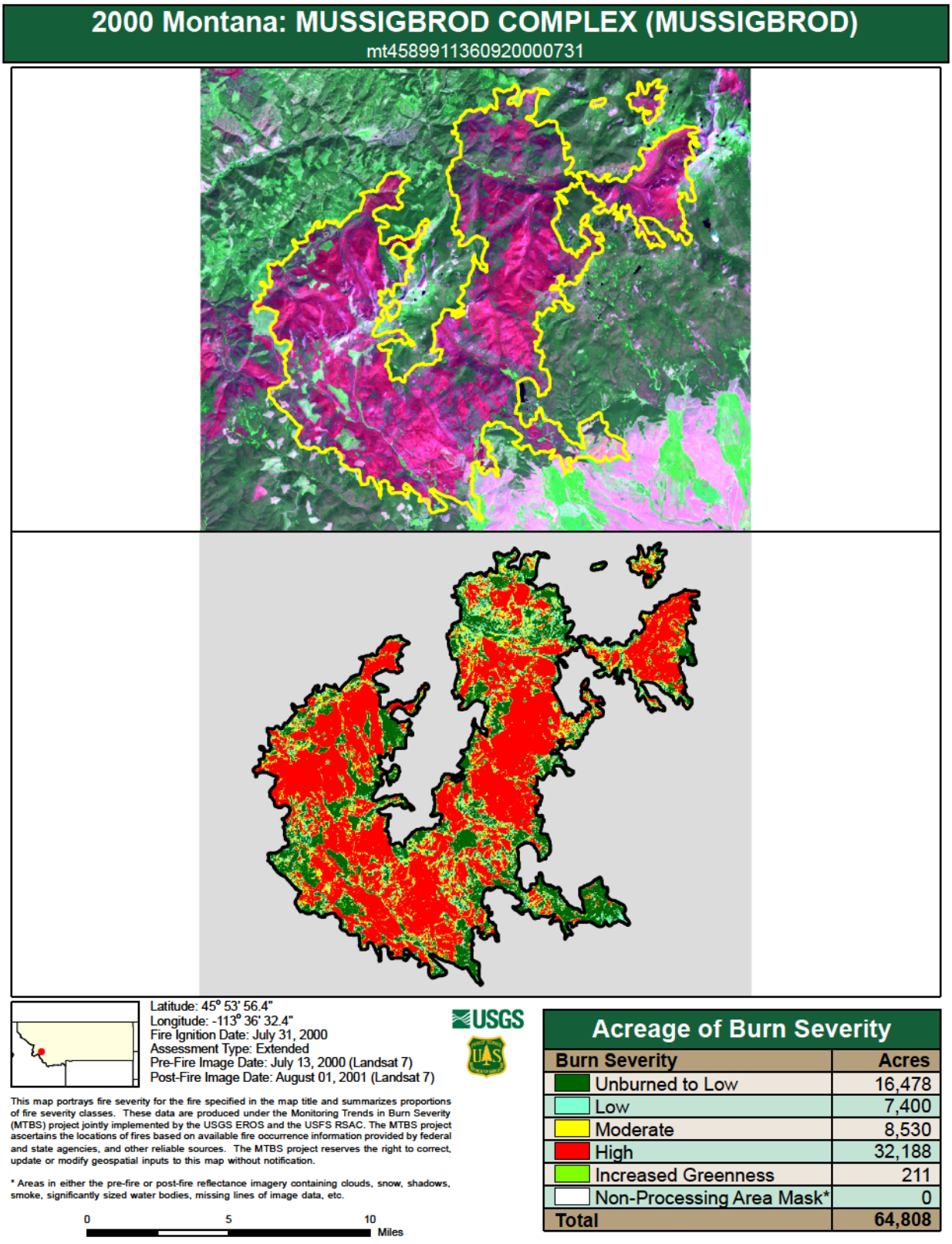


Figure A1. Mussigbrod Fire Complex

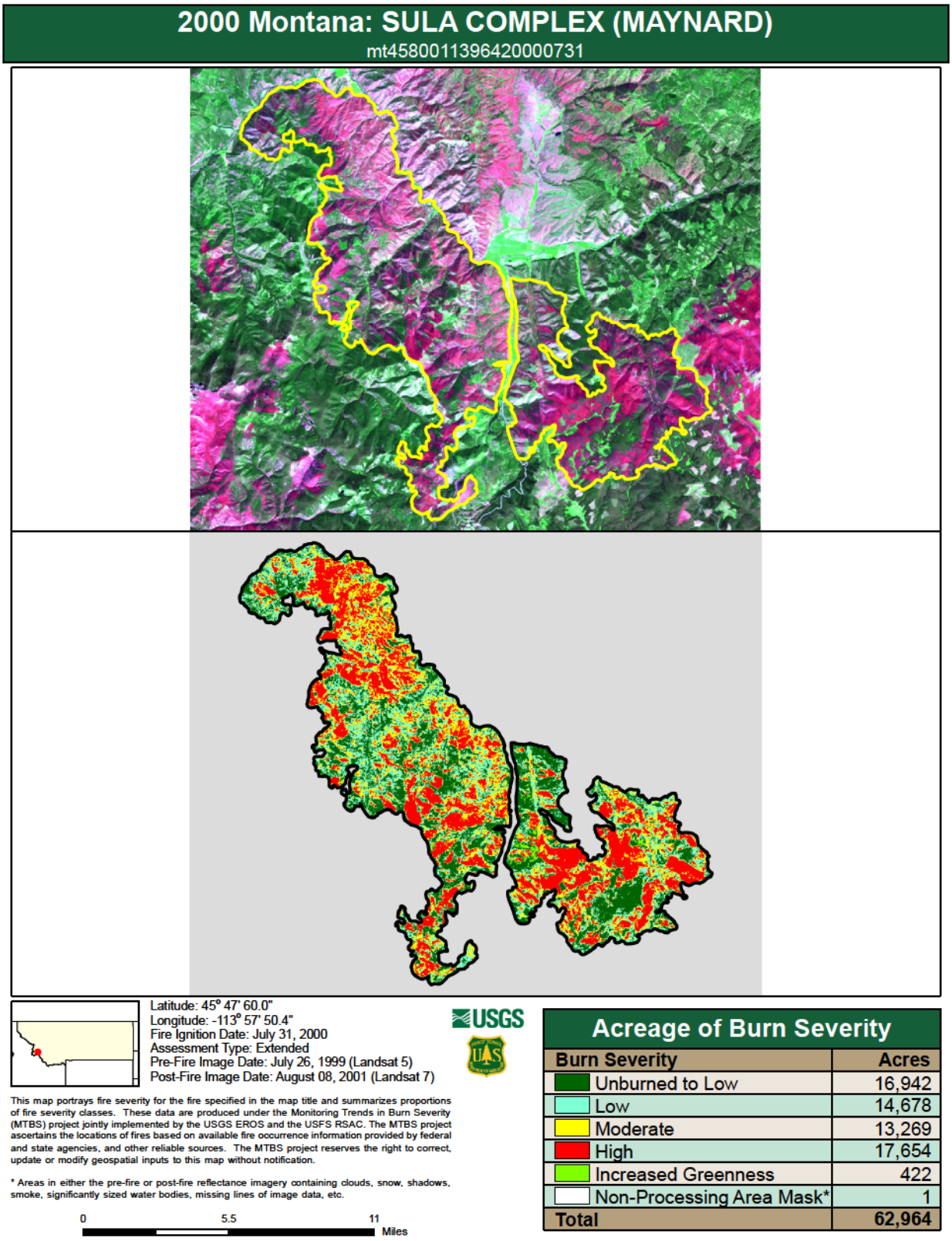


Figure A2. Sula Fire Complex

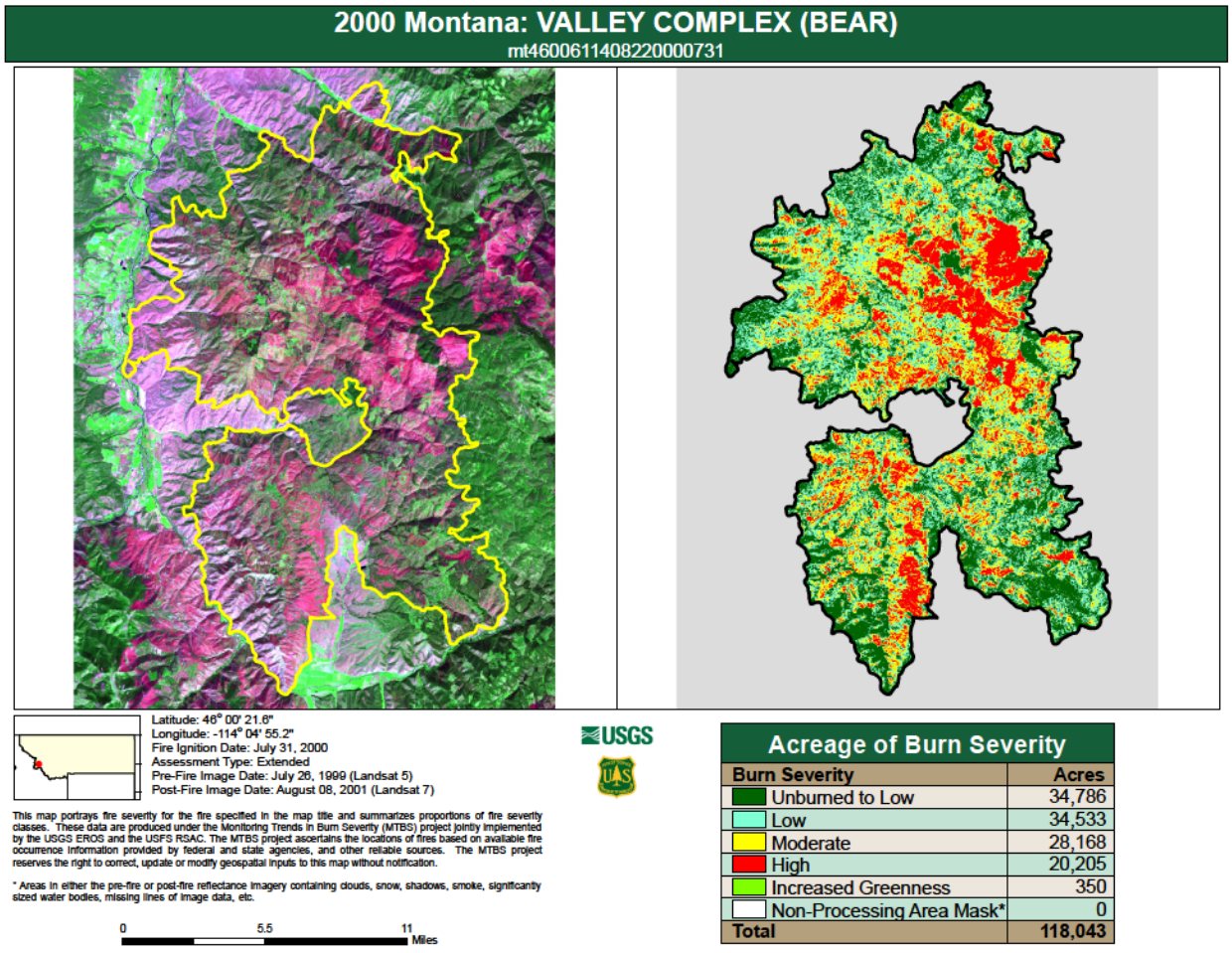


Figure A3. Valley Fire Complex (Bear)

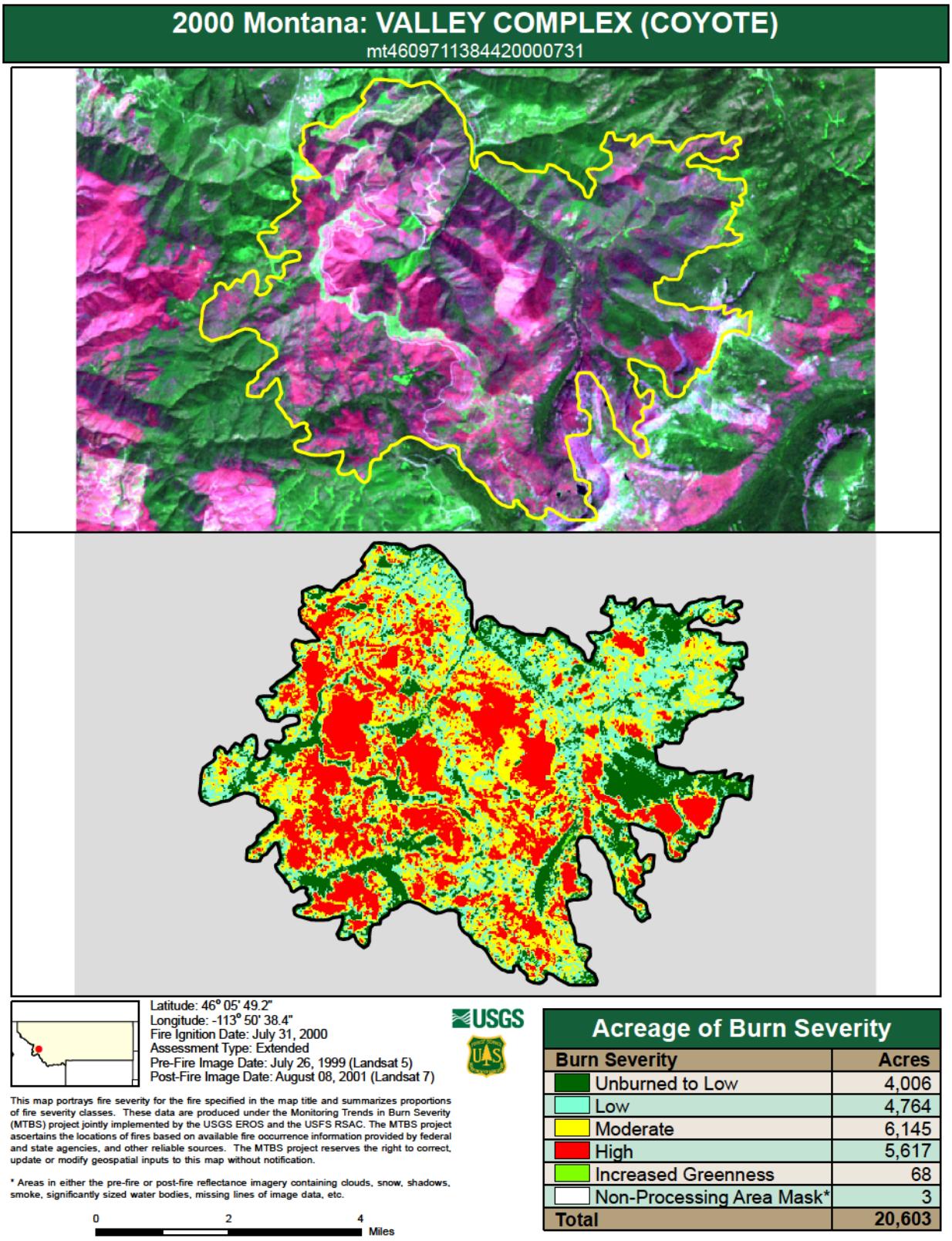


Figure A4. Valley Fire Complex (Coyote)

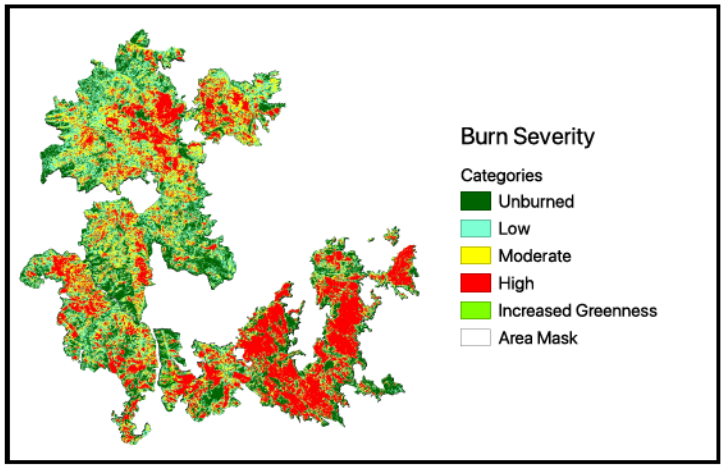


Figure A5. Burn Severity Within Fire Perimeters

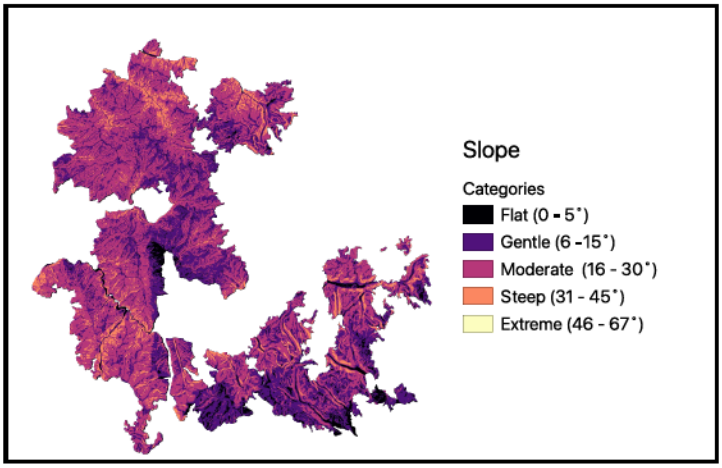


Figure A6. Slope Categories Within Fire Perimeters

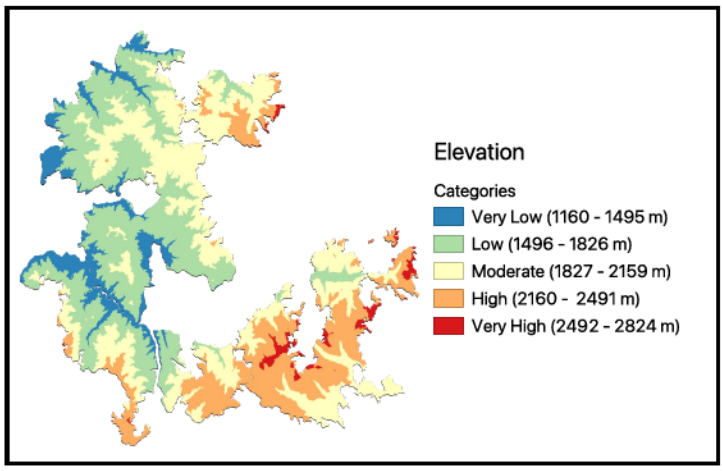


Figure A7. Elevation Categories Within Fire Perimeters

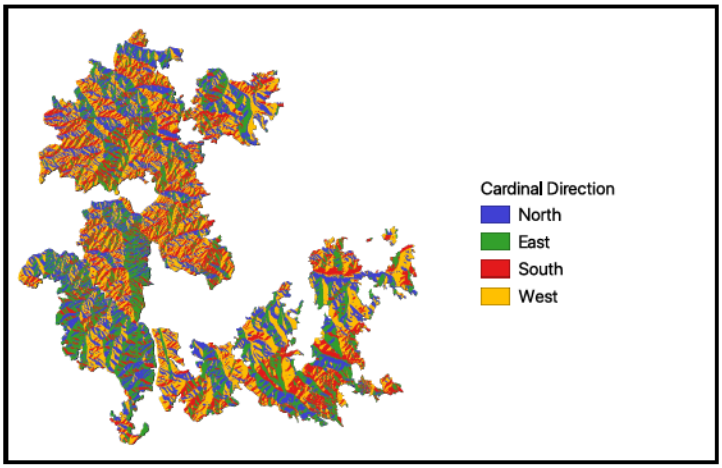


Figure A8. Aspect Categories Within Fire Perimeters