Assessing Fuels and Vegetation Following Forest Fire and Reburns in the Western Cascade Range of Oregon

by

Niamh M. Houston

A thesis accepted and approved in partial fulfillment of the

requirements for the degree of

Master of Science

in Geography

Thesis Committee:

Dr. Daniel Gavin, Chair

Dr. Melissa Lucash, Member

University of Oregon

Spring 2026

© 2026 Niamh M. Houston

This work is licensed under a Creative Commons Attribution–NoDerivatives 4.0 International License (CC BY-ND 4.0).

https://creativecommons.org/licenses/by-nd/4.0/

THESIS ABSTRACT

Niamh M. Houston

Master of Science in Geography

Title: Assessing Fuels and Vegetation Following Forest Fire and Reburns in the Western Cascade Range of Oregon

Since the 2003 B&B Fire, which burned 368 km^2 in the subalpine forests of the Oregon High Cascade Range, wildfire activity has increased in the lower elevation forests of the Western Oregon Cascade Range, converting large areas of mature forest into early successional vegetation. In the historically moist forests of Oregon's Western Cascade Range, rapid regrowth of shrubs and herbaceous vegetation combined with abundant dead fuels may increase the likelihood of repeated burning. However, the extent to which reburns influence vegetation recovery, fuel accumulation, and future flammability remains poorly understood.

To evaluate how repeated fires shape post-fire vegetation and fuel development, I surveyed 60 plots across four watersheds in Oregon's Western Cascade Range spanning gradients of burn history (one to three fires in the last 23 years), time-since-fire (1 to 7 years), moisture regime, and elevation (~400 to 1500 m). At each site, I quantified vegetation composition, seedling recruitment, shrub structure, live and dead tree density, surface fuel loads, and soil carbon to evaluate patterns of post-fire recovery and ecosystem structure following single and repeated fires.

Repeated fires reduced residual live tree basal area by killing remaining live trees from the antecedent fire, and generally reduced seedling density and fine fuel loads, while responses in

coarse woody debris were mixed, with increases occurring primarily at lower elevations. Time-since-fire strongly influenced live fuel loads, which in turn were the primary driver of modeled fire behavior. Rapid fuel accumulation during the early post-fire period produced peak flame lengths and rates of spread 2–3 years following fire, with both metrics declining slightly thereafter. In contrast, reburns had relatively limited effects on modeled fire behavior. This pattern reflects rapid accumulation of fine, continuous fuels and herbaceous cover during early succession followed by changes in fuel structure and continuity through time. Elevation further constrained these dynamics, with high-elevation sites (>1200 m) exhibiting limited vegetation recovery, reduced fuel accumulation, and minimal modeled fire behavior. Similarly, for the 135 species individually identified among the 60 plots, elevation, rather than time-since-fire or number of reburns, was the most significant driver of vegetation composition as revealed by an ordination analysis.

Overall, these results suggest that reburns primarily altered fuel structure and composition, reducing live tree basal area, seedling density, and fine fuels while in some cases increasing coarse woody debris. Despite these structural changes, reburned sites did not consistently exhibit higher modeled fire behavior than once-burned sites. Instead, time since fire appeared to exert a stronger influence on modeled fire behavior, with flame length and rate of spread increasing rapidly within the first several years after fire and remaining relatively elevated through time. Because these patterns are inferred from a chronosequence, they should be interpreted with caution; however, they suggest that post-fire stands may experience a relatively short-term period of elevated fire potential before stabilizing as fuels continue to develop. Understanding these temporal dynamics is critical for predicting future fire regimes and informing management in increasingly fire-prone landscapes of the western Cascade Range.

ACKNOWLEDGMENTS

This research would not have been possible without the help and company of many individuals and organizations. I wish to express my deepest appreciation to my field assistants — Joey Vierra, Jessie Brodrick, Ben Adams, Gracie Minnix, and Violet Wade — for their incredible support and energy throughout this project. They each possess an innate talent for creating fun, and their ability to uplift even the most miserable of sites is a true gift. I am profoundly grateful for every moment we shared in the field. Their friendship, humor, and dedication have brought me so much happiness. I will cherish our stories forever.

I am also grateful to my advisor, Dr. Dan Gavin, who gave me the opportunity of a lifetime with this project. His patience, invaluable feedback, and extraordinary investment of time have shaped both this research and my growth as a scientist. I also wish to thank my committee member, Dr. Melissa Lucash, and collaborators Andres Holz, Steve Perakis, Halima Najihi, Buzz Nanavati, Robert Scheller and Alan Tepley for their guidance and wealth of knowledge.

TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 11

1.1 Changing wildfire regimes in the Western Cascades 11

1.2 Historical forest structure and recent megafires 11

1.3 Knowledge Gaps in Postfire Fuel Succession and Reburn Dynamics 12

1.4 Research Questions 13

1.4.1 Vegetation Composition and Regeneration 14

1.4.2 Fuels and Fire Behavior 14

II. METHODS 15

2.1 Study Area 15

2.2 Sampling design and site selection 18

2.3 Plot establishment 19

2.4 Vegetation Composition and Regeneration 21

2.4.1 Vegetation sampling 21

2.4.2 Shrub abundance 21

2.4.3 Seedling survey 22

2.4.4 Tree inventory 22

2.5 Fuel Assessment and Fire Behavior 22

2.5.1 Fuel Sampling 22

2.5.2 Fire behavior modeling 22

2.6 Soil sampling and laboratory analysis 23

2.7 Statistical analysis 24

Chapter Page

III. RESULTS 25

3.1 Vegetation Recovery and Diversity 25

3.1.1 Vegetation Composition and Structure (H1) 25

3.1.2 Regeneration (H1, H2) 30

3.1.3 Species Diversity (H4) 33

3.1.4 Soils 35

3.2 Fuels and Fire Behavior 37

3.2.1 Fuel Structure and Loads (H5, H6) 37

3.2.2 Modeled Fire Behavior (H7) 43

IV. DISCUSSION 46

4.1 Vegetation and Regeneration 46

4.1.1 Effects of Repeated Fire 46

4.1.2 Temporal Dynamics 48

4.1.3 Elevation Effects 48

4.1.4 Vegetation Composition and Alternative States 49

4.1.5 Integration of Vegetation, Fuels, and Fire Behavior 50

4.2 Fuels and Fire Behavior 51

4.2.1 Temporal Dynamics 51

4.2.2 Effects of Repeated Fire on Fuels 53

4.2.3 Elevation Effects on Fire Behavior 54

4.4 Significance 56

4.5 Limitations 56

V. CONCLUSION 58

APPENDIX: ALL SPECIES IDENTIFIED 60

REFERENCES CITED 64

LIST OF FIGURES

Figure Page

1. Map of 60 study site locations across four watersheds in the western Cascade Range of Oregon, showing fire history and elevation classes. 17

2. Sampling plot design showing transects, quadrats, seedling belts, shrub sampling, and fuel sampling scheme. 20

3. NMDS ordination of post-fire vegetation composition with environmental gradients and species associations. 27

4. Boxplots of seedling density (all seedlings and Pseudotsuga menziesii) across fire frequency and elevation classes. 31

6. Basal area (live and dead) for all species and Pseudotsuga menziesii across fire frequency and elevation classes. 33

7. Species richness across fire frequency and time-since-fire classes. 34

8. Soil total organic carbon (TOC) across fire frequency and time-since-fire..... 35

9. Soil carbon-to-nitrogen (C:N) ratios across fire frequency and time-since-fire. ... 36

10. Fuel loads by fuel class (1-hr, 10-hr, 100-hr, herbaceous, woody) across fire frequency and elevation 38

11. 1000-hour fuel loads across fire frequency and elevation 39

12. Fuel loads across time-since-fire classes for all fuel classes and elevation groups..... 41

13. 1000-hour fuel loads across time-since-fire classes and elevation groups. 42

14. Modeled flame length across time-since-fire, elevation, wind speed, and fuel moisture scenarios..... 44

15. Modeled rate of spread across time-since-fire, elevation, wind speed, and fuel moisture scenarios..... 45

LIST OF TABLES

Table Page

1. Indicator species analysis of plant species that are statistically significant with site types..... 29

1. INTRODUCTION

1.1 Changing wildfire regimes in the Western Cascades

Wildfire regimes across the western United States are undergoing rapid transformation, with increasing fire frequency, size, and severity reshaping forested landscapes (Moritz et al. 2012; Halofsky et al. 2018; McDowell et al. 2020). In the Western Cascade Range of Oregon, a region historically characterized by infrequent, high-severity and mixed-severity fire (Agee 1993; Teensma 1987; Morrison and Swanson, 1990; Tepley et al. 2017; Johnston et al. 2023), recent decades have seen a rise in large wildfires and subsequent reburns within short intervals (Reilly et al. 2022; Buma et al. 2020; Abatzoglou et al. 2021). These changes raise fundamental questions about how forest ecosystems respond to repeated disturbance and whether post-fire recovery processes are being fundamentally altered (Kitzberger et al. 2012; Tepley et al. 2017).

1.2 Historical forest structure and recent megafires

Moist, productive forests of Oregon's western Cascade Range have traditionally been considered resilient to fire due to long return intervals and the dominance of fire-resistent *Pseudotsuga menziesii* (Douglas-fir) and late-successional *Tsuga heterophylla* (western hemlock) (Franklin and Dyrness 1988; Agee 1993). However, beginning with the 368 km² 2003 B&B Fire in subalpine forests and culminating in the large 2020 Labor Day megafires across the western Cascade Range (Archie Creek 530 km², Beachie Creek 783 km², Holiday Farm 700 km², Lionshead 830 km², and Riverside 558 km²), extensive early-successional landscapes have been created, characterized by dense shrub and herbaceous vegetation, standing dead trees, and accumulating surface fuels (Burke 1979; Abatzoglou et al. 2021; Reilly et al. 2022).

In these systems, post-fire vegetation recovery plays a critical role in shaping future fire behavior (Pausas et al. 2017; Schwilk et al. 2009). Fine fuels, including grasses, forbs, and small woody vegetation, can accumulate rapidly following disturbance, combined with the loss of the microclimate effects of mature forests (i.e., canopy shading and wind buffering), greatly increasing the likelihood of fire spread and intensity (Agee and Huff 1987; Keane and Dickinson 2007). At the same time, coarse woody debris derived from fire-killed trees may contribute to longer-duration burning and increased fire severity (Brown et al. 2013; Keane et al. 2008). The interaction between these fuel components, vegetation structure, and environmental gradients ultimately determines the flammability of post-fire landscapes (Archibald et al. 2018; Pausas et al. 2017). There is precedent for positive fire-fuel feedback in the wet forests of the Pacific Northwest. For example, multiple reburns occurred after the 1902 Yacolt Fire in the Washington Cascade Range and after the 1933 Tillamook Fire in the Oregon Coast Range (Hoadley 2001). Both fire events were human-ignited and occurred during strong east wind events, just as the 2020 Labor Day fires in Oregon's western Cascade Range.

1.3 Knowledge Gaps in Postfire Fuel Succession and Reburn Dynamics

While previous studies have documented changes in vegetation and fuels following single fire events, the effects of repeated fires—particularly in moist forest systems—remain less well understood (for exceptions see Tepley et al. 2017; Buma et al. 2020). Reburns may alter successional trajectories, reduce conifer regeneration, and promote alternative vegetation states (Kitzberger et al. 2012; Tiribelli et al. 2023), yet their influence on fuel accumulation and fire behavior is complex and potentially nonlinear (Kennedy et al. 2021; Landesmann et al. 2021).

Additionally, much of the existing work has focused either on vegetation dynamics or fire behavior in isolation (Keane et al. 2001; Cruz and Alexander. 2010). Fewer studies integrate field-based measurements of vegetation and fuels with modeled fire behavior to evaluate how ecological changes translate into differences in flammability (Finney 2004; Scott and Burgan 2005). The role of environmental gradients, particularly elevation and moisture, in mediating these relationships also remains an important but underexplored dimension (Crockett and Hurteau 2024; Dobrowski et al. 2009). Understanding how repeated fires reshape vegetation and fuels is critical for predicting future fire regimes in the western Cascades (Halofsky et al. 2018; Higuera et al. 2021; Dye et al. 2024). As climate change and altered disturbance patterns continue to increase fire frequency, landscapes that were historically resilient may transition into new ecological states with different fuel structures and fire behavior characteristics (McWethy et al. 2013; Hoecker et al. 2023)

1.4 Research Questions

This study provides a comprehensive, field-based assessment linking vegetation recovery (tree, shrub and forb regeneration), fuel development, and modeled fire behavior across multiple environmental gradients in the western Cascade Range of Oregon. It focuses on early post-fire recovery (i.e., 1-7 years post- fire) across 60 sites spanning four watersheds, capturing variability in fire history, elevation and regional climate. To clearly examine these linked processes, this thesis is organized into two complementary parts; the first focus is on vegetation recovery and diversity, including patterns of regeneration, species composition and successional dynamics; the second addresses fuels and fire behavior, encompassing fine and coarse fuel accumulation, fire behavior modeling and implications for post-fire flammability.

1.4.1 Vegetation Composition and Regeneration:

How do repeated, short-interval, fires, and time since fire influence post-fire vegetation composition and regeneration trajectories across environmental gradients in the western Cascade Range of Oregon?

H1. Plant community composition will differ significantly with increasing burn frequency, even when accounting for differences in time-since-fire, differences among watersheds, and across elevations. At an equivalent time-since-fire, reburned sites will be characterized by lower relative abundance of conifer species and greater abundance of resprouting and disturbance-adapted species.

H2. Tree regeneration in reburned sites will be more strongly limited by seed availability and fire intensity than in single-burn sites.

H3. Species diversity will increase with time-since-fire over the first seven years post-fire, driven by continued colonization of early-successional and disturbance-adapted species.

H4. Soil carbon and nitrogen concentrations, as well as carbon-to-nitrogen (C:N) ratios, will differ significantly based on fire history, with reburned sites exhibiting lower total carbon and reduced C:N ratios. In contrast, soil nitrogen will show weaker or minimal change across fire histories. These differences are expected to be more strongly associated with fire history (number of fires) than with time since fire over the short (~7-year) recovery window.

1.4.2 Fuels and Fire Behavior:

How do repeated fires and time-since-fire alter fuel accumulation, fuel structure, and potential fire behavior across environmental gradients in the western Cascade Range of Oregon?

H5: Repeated burns will alter fuel structure by reducing coarse woody debris and increasing the abundance of fine fuels.

H6: Total fuel loads will be lower in recently reburned sites but will accumulate more rapidly over time due to increased herbaceous and shrub productivity relative to once-burned sites.

H7: Fire behavior models derived from reburned sites will produce higher modeled fire behavior (rate of spread, flame length, fireline intensity) compared to single-fire sites.

While this study captures a broad range of environmental and disturbance conditions, it is limited to short-term post-fire dynamics following severe fire (crown fire and crown scorch) and does not address longer-term successional processes beyond initial stages of recovery.

2. METHODS

2.1 Study Area

This research was conducted across post-fire landscapes in the western Cascade Range of Oregon, spanning four watersheds from the North Santiam to the North Umpqua rivers. The region is characterized by a montane climate with cool, wet winters and warm, dry summers. Mean January temperatures average approximately 2.7 °C, while mean July temperatures reach ~15 °C. Annual precipitation averages ca. 40.8 inches, falling primarily between October and April.

Sites spanned an elevational gradient from ~400 to 1500 m (1,300–5,000 ft), capturing transitions from mixed conifer forests dominated by *Pseudotsuga menziesii* and *Tsuga heterophylla* at lower elevations to upper montane forests including *Abies amabilis, Abies procera,* and *Tsuga mertensiana* (Franklin and Dyrness 1988; Agee 1993). Soils are derived from volcanic parent material and include andic ash-cap soils typical of the Cascade Range (Franklin and Dyrness 1988).

The broader landscape has experienced multiple large wildfires in recent decades, including the 2003 B&B Fire and subsequent fires that have reburned portions of the landscape. As a result, the study area contains a mosaic of post-fire conditions across environmental gradients. including areas that have burned once, twice, or three times since the early 2000s.

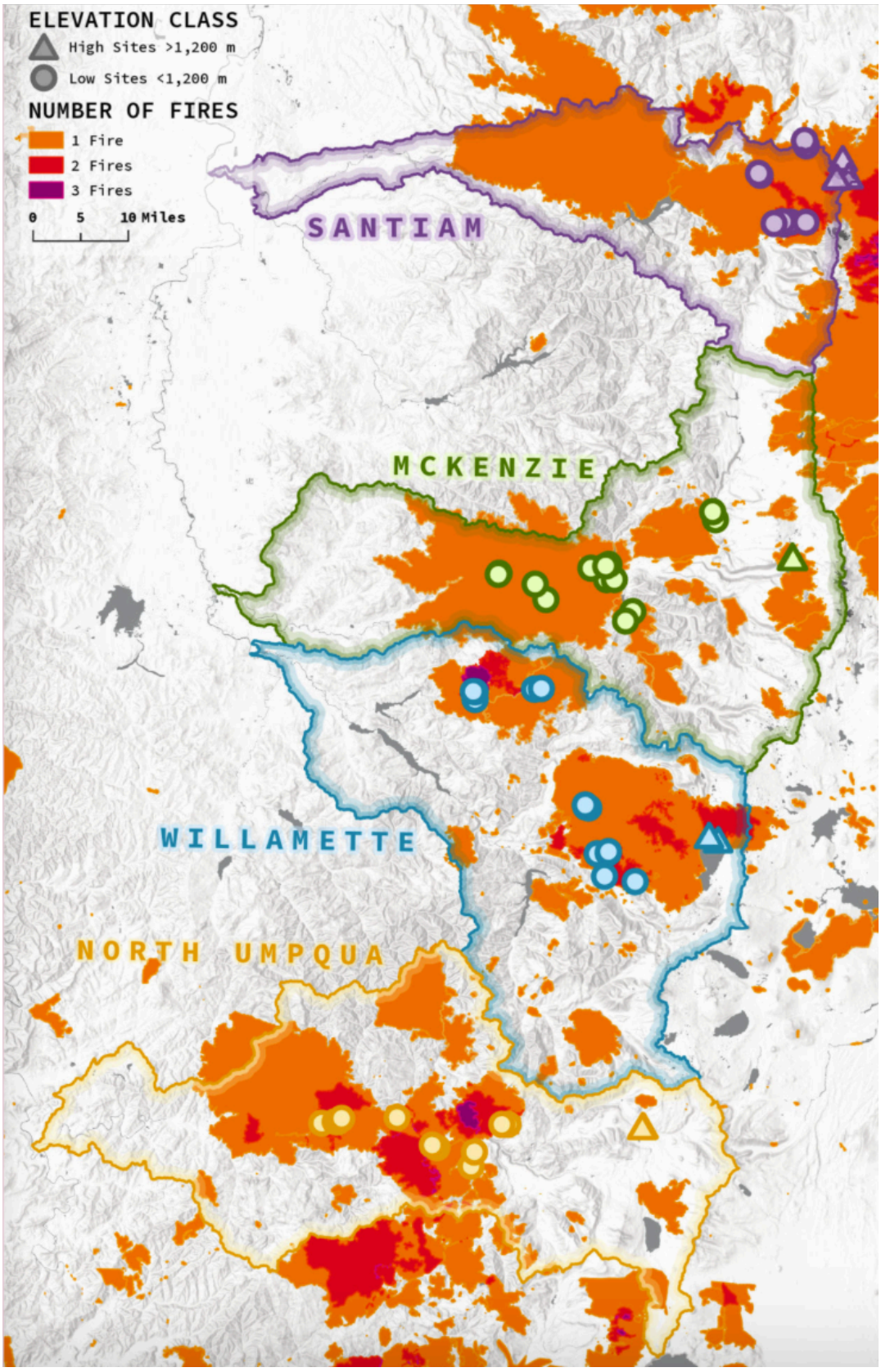

ELEVATION CLASS
High Sites >1,200 m
Low Sites <1,200 m
NUMBER OF FIRES
1 Fire
2 Fires
3 Fires
0 5 10 Miles
SANTIAM
MCKENZIE
WILLAMETTE
NORTH UMPQUA

Figure 1. *Map of 60 study site locations across four watersheds in the western Cascade Range of Oregon (Santiam:Purple, Mckenzie: Green, Willamette: blue North Umpqua: Yellow). Sites occur within burn scars that have experienced one (orange), two (red), or three (magenta) fires within the past decade and span an elevational range of approximately 400 -1500 m. High sites (>1200 m) are labeled with triangles and low sites (<1200 m) are labeled with circles.*

2.2 Sampling design and site selection

Field work was conducted during the summers of 2024 and 2025. Sixty sampling sites were selected to capture variation in fire history (one, two, or three fires), time since fire (1-7 years), elevation (~400 to 1500 m), regional moisture conditions and other environmental and disturbance related factors including slope, aspect, and fire intensity. Sites were in the Willamette National Forest and Umpqua National Forest, distributed across four watersheds (Santiam, McKenzie, Willamette and North Umpqua) to incorporate geographic and climatic variability and to represent the diversity of post-fire conditions across the study region. Sites were only located in high-intensity fire areas where more than 70% of trees were burned and dead. Pre-fire tree stands were consistent with stand ages of at least 50 years since any prior logging. We did not sample sites with recent thinning prior to the fire, or salvage logging after the fire.

Because sites were accessed by foot from public roads, accessibility was a major consideration. Distance from roads or trailheads was not a strict limiting factor; however steep slopes, hazardous terrain, impassable landscapes, and misfortunate skunk encounters influenced final site placement.

In each watershed, sampling included both high (>1200-1500 m)- and low (400-1200 m)-elevation sites to ensure representation across climatic gradients. A minimum of three high-

elevation sites were established in each watershed. These sites were characterized by upper montane vegetation including *Tsuga mertensiana* (mountain hemlock), *Abies amabilis* (Pacific silver fir), and *Abies procera* (noble fir), and are associated with persistent winter snowpack and cooler climatic conditions. A minimum of ten low-elevation sites were also sampled per watershed, dominated by *Pseudotsuga menziesii* and *Tsuga heterophylla*, and occurring in warmer conditions with more seasonal variation and reduced snowpack.

Across all watersheds, sites were distributed among burn scars that had experienced one, two, or three fires in the two past decades. This sampling framework allowed comparison of vegetation recovery and fuel accumulation across gradients of fire frequency and environmental conditions.

2.3 Plot establishment

At each sampling site, the geographic coordinates of the plot center were recorded using a handheld GPS unit. From this central point, four 20-meter transects were established radiating outward in the four cardinal directions (north, south, east, and west), forming a cross-shaped sampling layout (Figure 2). This configuration provided standardized vegetation, fuel, and soil measurements across all plots while capturing spatial variation within each site.

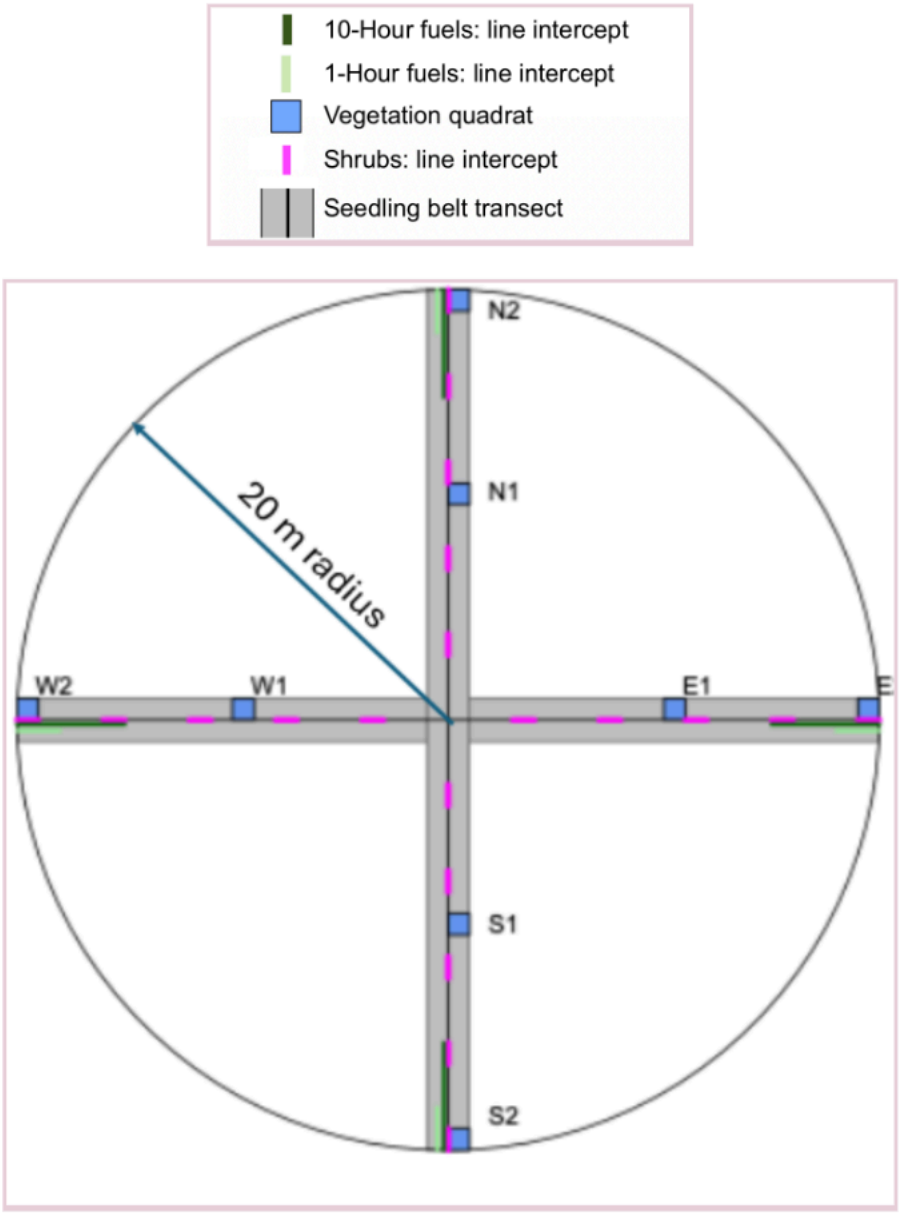


Figure 2. *Sampling plot design. Four 20 m transects extended in the cardinal directions from the plot center. Seedling sampling was conducted within a 1m belt (gray belt) on either side of each transect line. 1 m² Vegetation quadrats (blue squares) were placed at the midpoint (10 m) and endpoint (20 m) of each transect, where soil samples were also collected. Shrub cover was sampled at transect intercepts on every other square meter of the transect (pink lines). 1000- and 100-hr fuels were sampled along the full length of the transect. 10- hr fuels were*

sampled along the final 5 meters of each transect (dark green line) and 1-hr fuels were sampled along the last 2 meters of each transect (light green line).

2.4 Vegetation Composition and Regeneration

2.4.1 Vegetation sampling

Vegetation composition and ground cover were quantified using 1 m² quadrats placed at 10 m and 20 m along each of the four transects, resulting in eight quadrats per plot. Within each quadrat, all vascular plant species, except graminoids, were identified using USDA PLANTS codes. Percent cover was estimated using ordinal cover classes (0-1%, 1-5%, 5-25%, 25-50%, 50-75%, 75-100%). Because these classes represented ranges rather than continuous values, in subsequent analyses they were converted to percent cover by assigning the midpoint of each class (e.g., 1-5%=3%, 25-30% = 37.5%). For each species, percent cover values were averaged across all eight quadrats to produce plot-level estimates of mean cover. Cover values for ground and litter components were estimated along with species. Total vegetative cover was calculated as the complement of the estimate of bare ground and litter cover.

Live herbaceous and shrub fuel loads in each quadrat were estimated using visual estimation techniques and photoload comparisons (Keane and Dickinson 2007). Herbs and shrubs taller than 30 cm could not be estimated using the photoload method; therefore, fuel model classifications were assigned using reference photographs from Scott and Burgan (2005) and visual assessment of photographs taken at the plot center and of each quadrat.

2.4.2 Shrub abundance

Shrub abundance was quantified using a planar intercept (Brown 1974) in 1-m transect segments placed every four meters along each transect (n=20 1-m segments per plot). For each segment,

shrub species, intercept length and maximum height were recorded. A unitless shrub abundance index was calculated as the product of intercept length and height and standardized by the cross-section area surveyed up to 2 m height (i.e., 40 m^2).

2.4.3 Seedling survey

Seedling abundance was quantified within 2 m-wide belt transects centered on each of the four main transects, resulting in a total sampled area of 160 m^2 per plot. All tree seedlings were counted and identified to species, and densities were scaled to individuals per hectare. We did not attempt to count seedlings that germinated in the current year.

2.4.4 Tree inventory

All trees > 1.37 m tall within a 20 m radius of the plot center were measured for diameter at breast height (DBH), species identity, live/dead status, and height to live crown when applicable. These measurements were used to calculate basal area and categorize overstory structure and mortality.

2.5 Fuel Assessment and Fire Behavior

2.5.1 Fuel Sampling

Surface fuel loads were quantified using the planar intercept method (Brown 1974), a standardized approach for estimating down woody fuel loads. Intersects of woody fuels and transects were tallied by size class (1-,10-,100-, and 1,000-hour fuels). 1,000-hour fuels, greater than 7.6 cm diameter, were recorded along the full length of each transect, and recorded for species identity (when discernible), diameter, decay class, and location along transect. Fine woody fuels were tallied in progressively smaller size classes along shorter sampling distances along the transect: 100-hour fuels (2.5-7.6 cm diameter) were recorded along the full transect length, 10-hour fuels (0.6 to 2.5 cm diameter) were tallied along the outer 5 m of each transect,

and 1-hour fuels (<0.6 cm diameter) were tallied along the outer 2 m of each transect. Fuel loads were calculated in tonnes per hectare using established equations (Brown; 1974).

2.5.2 Fire behavior modeling

Fuel and vegetation data were used to parameterize fire behavior simulations in BEHAVE Plus 6.0 (Scott and Burgan 2005). Modeled outputs included rate of spread and flame length under a range of wind and fuel moisture scenarios. Simulations were designed to evaluate relative differences among sites rather than predict absolute fire behavior and therefore focused on consistent input conditions across all plots. Custom fuel models were built by starting with the sh2 model, the moderate-load dry-climate shrub model, replacing fuel loads and fuel depth with values estimated from the plot transects and setting slope to 10% (a typical value among the sampled plots). Fuel bed depth was estimated as 63.3% of the average shrub height measured in the shrub planar intercept measurements. Output for each plot was estimated for three moisture levels (moderate, very dry or extremely dry) and two wind speeds (average and high). Moisture levels were set to moderate (9, 10, 11, 90, and 120% for 1-hr, 10-hr, 100-hr, live herbaceous, and live woody moisture, respectively), very dry (6, 7, 8, 60, and 90%), or extremely dry (3, 4, 5, 60, and 90%). Wind speeds were set to 2.2 m/s and 8.9 m/s (5 and 20 miles per hour).

2.6 Soil sampling and laboratory analysis

Soil samples were collected at the 10 m and 20 m points along each transect using a bulb planter to maintain consistent sampling depth and volume across all sites. Eight subsamples collected within each plot were combined into a single composite sample representing overall site conditions.

Composite samples were sealed and transported to the U.S. Geological Survey laboratory for analysis. Laboratory analyses quantified total carbon (%C) and total nitrogen (%N)

concentrations using an elemental analyzer. Additional analyses included soil carbon-to-nitrogen ratios (C:N) and stable isotope composition ($\delta^{13}C$ and $\delta^{15}N$).

These measurements were used to characterize soil nutrient conditions and examine potential relationships between fire history, soil biogeochemistry, and post-fire vegetation responses.

2.7 Statistical analysis

All analyses were conducted in R (v4.5.3; R Core Team 2026).

Vegetation, fuel, and fire behavior variables were evaluated across gradients of the four watersheds, number of fires, time-since-fire, and elevation. Community composition was summarized using species richness and the Shannon diversity index. Differences in vegetation composition among sites were further explored using ordination analyses. Vegetation dissimilarity among plots was estimated using the Bray distance applied to square-root transformed species percent cover. Non-metric multidimensional scaling (NMDS) was applied using the metaMDS function in the vegan package (Oksanen et al. 2026). NMDS was limited to species occurring in at least five plots. Overall species compositional difference among watersheds, number of fires, elevation, and time-since-fire was tested using the full set of species using PERMANOVA (adonis2 function in vegan; Anderson 2001; Warton et al. 2012). The correlation between environmental gradients and vegetation gradients was assessed using the Bray distance calculated for the full set of species using envfit in the vegan package. Environmental variables related to temperature, rainfall, vapor pressure deficit, and solar exposure, were obtained at each site as normals for the 1991-2020 period. Indicator species, those more likely to occur in a particular habitat (here, as watershed, high vs low elevation,

number-of-fires, or time-since-fire) were estimated using the IndVal approach (De Cáceres et al, 2010) as calculated in the indicspecies package.

Statistical analysis of seedling data was performed on raw count data as equal areas were surveyed in each plot. Due to overdispersion of the count data, differences in seedling counts between number-of-fires and time-since-fire were tested using negative binomial models with a significance test using a likelihood ratio compared to a null model. Seedling counts were compared to dead and live tree basal area using negative binomial regression.

3. RESULTS

Post-fire vegetation structure, fuel dynamics, and modeled fire behavior varied across gradients of fire history, time since fire, and elevation. Broadly, the number of fires and elevation exerted strong control over fuel accumulation and vegetation structure, while time-since-fire influenced short-term dynamics and modeled fire behavior. Meanwhile, little differences were found among watersheds, suggesting the results are robust over a large area.

3.1 Vegetation Recovery and Diversity

3.1.1 Vegetation Composition and Structure (H1)

Among all quadrats at the 60 sites, 135 vascular plant taxa were identified (Table S1). Ordination analysis of the 49 species occurring in at least five plots using NMDS onto two axes results in an ordination with a stress of 0.22. Despite this relatively high variability in species composition, the ordination revealed strong environmental controls on species composition (Figure 3). Elevation is the most important gradient correlated with NMDS axis 1 (envfit, r^2=0.66). Many other environmental variables cover with elevation (e.g., mean temperature, r^2=0.70,

precipitation, r^2=0.28). NMDS axis 2 appears to represent a gradient associated with fire intensity, i.e. live tree basal area (ba_live, r^2= 0.13). Sites higher on axis 2 scores are associated with higher live tree basal area and/or lower fire intensity, and are characterized by shade-tolerant, mesic forest species such as *Dicentra formosa* (Pacific bleeding heart), *Oxalis oregana* (redwood sorrel) and *Polystichum munitum* (sword fern). In contrast, lower axis 2 scores are associated with higher fire intensity and are dominated by resprouting shrubs and trees and fire adapted or drought-tolerant species, including *Prunus emarginata* (bitter cherry), *Rhododenderon macrophyllum* (Pacific rhododendron), *Chrysolepis chrysopylla* (golden chinkapin), *Pteridium aquilinum* (bracken fern) and *Xerophyllum tenax* (bear grass) at high elevations. In addition, total solar irradiance onto a sloped surface (solslope, r^2=0.16) is significantly correlated with a vector orthogonal to the elevation vector, suggesting that aspect is also an important control of fire intensity.

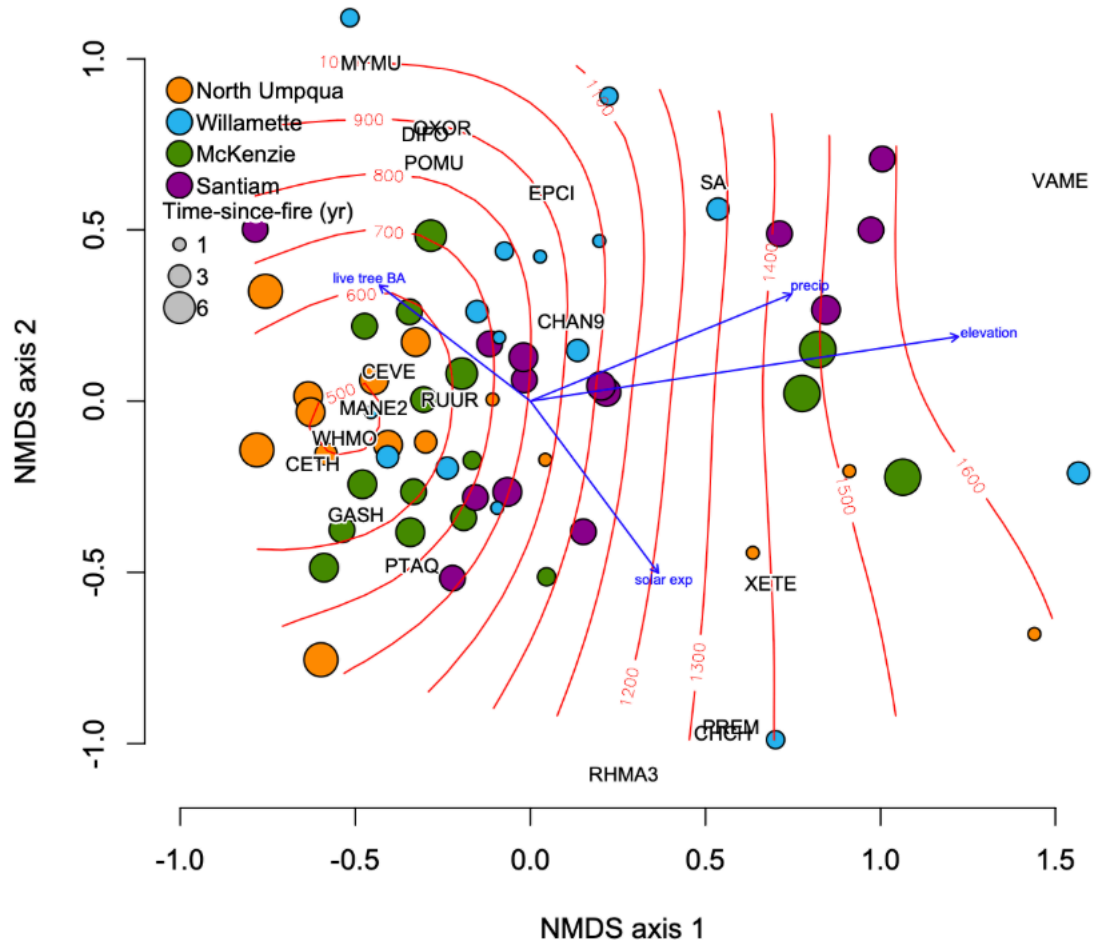


Figure 3. *Ordination of post-fire vegetation composition across study sites. Points represent individual sites and are sized according to time-since-fire. Contour lines indicate elevation. Species codes from the USDA PLANTS database show species occurrences relative to sites (see Table S1), limited to abundant species and species strongly correlated with the two axes. Blue vectors show environmental gradients passively correlated with the ordination space. ppt=April-August precipitation, soltotal=total solar irradiance at the site, ba_live=live tree basal area.*

Permutational multivariate analysis of variance with marginal tests showed that elevation had the strongest unique effect on community composition ($F_{1,55} = 7.09$, $p < 0.001$), followed by watershed ($F_{1,55} = 2.46$, $p = 0.0018$) and time-since-fire ($F_{1,55} = 1.62$, $p = 0.043$), each evaluated while controlling for the other predictors. In contrast, the number of fires did not explain significant additional variation after accounting for the other variables ($F_{1,55} = 1.46$, $p = 0.087$).

Indicator species analysis (Table 1) showed clear compositional differences associated with watersheds, time-since-fire, and reburn history. At the watershed scale, the North Umpqua was associated with more xeric-adapted species such as *Toxicodendron diversilobum* (Pacific poison oak) and *Rosa californica (*California wildrose) indicating comparatively drier sites and conditions. The Willamette watershed showed an association with invasive *Senecio vulgaris* (old-man-in-the-spring), reflecting early successional disturbance responses. The McKenzie watershed was associated with *Pseudotsuga menziesii,* consistent with higher seedling recruitment there, as well as *Corylus cornuta* (beaked hazelnut), a widespread resprouter. The Santiam watershed exhibited strong affinity with high elevation indicator species, including *Anaphalis margaritacea* (western pearly everlasting), *Pseudognaphalium canescens* (Wright's cudweed) and *Pinus contorta* (lodgepole pine) which suggests a distinct high-elevation vegetation composition relative to the other watersheds.

Patterns across time since fire highlight successional trajectories. One-year post-fire sites were exclusively associated with invasive species, including *Geranium robertianum* (Robert geranium), Cardamine *hirsuta* (Hairy bittercress) and *Senecio spp.*, suggesting rapid early post-disturbance colonization. In contrast, sites six to seven years since fire had indicator species typical of mature west-side forests, including *Fragaria vesca* (woodland strawberry), *Prosartes hookeri* (drops-of-gold), *Stachys bullata* (california hedgenettle) and *Vaccinium scoparium* (grouse whortleberry) at high elevations. Together, these patterns suggest a trajectory of recovery towards mature, mesic forest understory communities following initial post-fire invasion and early establishment.

Single-burn histories showed strong associations with several species, most notably *Rosa nutkana* (bristly nootka rose), *Galium aparine* (cleavers) and *Hypochaeris radicata* (common cat's ear). Sites that experienced two or three fires had no indicator species.

Table 1. *Plant species that are statistically associated with site types in burned areas of the western Cascade Range. Significant associations were determined using the indVal method of DeCesare and Legendre, 1997.*

NUMBER OF FIRES

Code	Species	Common name	IndVal	P value
One fire:				
GAAP2	*Galium aparine*	cleavers	0.639	0.013 *
HYRA3	*Hypochaeris radicata*	common cat's ear	0.628	0.048 *
RONUH	*Rosa nutkana*	bristly nootka rose	0.493	0.018*
Two or Three Fires:				
None				

WATERSHED

Code	Species	Common name	IndVal	P value
North Umpqua:				
TODI	*Toxicodendron diversilobum*	Pacific poison oak	0.447	0.036 *
ROCA2	*Rosa californica*	California wildrose	0.447	0.035 *
Willamette:				
SEVU	*Senecio vulgaris*	old-man-in-the-spring	0.672	0.004 **
LEAU2	*Scorzoneroides autumnalis*	fall dandelion	0.516	0.009 **
McKenzie:				
PSME	*Pseudotsuga menziesii*	Douglas-fir	0.752	0.017 *
OXOR	*Oxalis oregana*	redwood sorrel	0.528	0.037 *
COCO6	*Corylus cornuta*	Beaked hazelnut	0.488	0.039 *
Santiam:				
ANMA	*Anaphalis margaritacea*	western pearly everlasting	0.798	0.001 **
PSCAT	*Pseudognaphalium thermale*	wright's cudweed	0.754	0.001 **
PICO	*Pinus contorta*	lodgepole pine	0.436	0.010 *

TIME SINCE FIRE

Code	Species	Common name	IndVal	P value
1 year:				
SEVU	*Senecio vulgaris*	old-man-in-the-spring	0.673	0.012 *
CAHI13	*Cardamine hirsuta*	hairy bittercress	0.447	0.041 *
CLPE	*Claytonia perfoliata*	miner's lettuce	0.447	0.037 *
GERO	*Geranium robertianum*	Robert geranium	0.447	0.043 *
LOUNU	*Lotus unifoliolatus*	American bird's-foot	0.447	0.037 *

SESY	*Senecio sylvaticus*	woodland ragwort	0.447	0.043 *
2-3 years:				
LEAU2	*Scorzoneroides autumnalis*	fall dandelion	0.535	0.011 *
LIBO3	*Linnaea borealis*	twinflower	0.463	0.045 *
4-5 years:				
ANMA	*Anaphalis margaritacea*	western pearly everlasting	0.558	0.028 *
RULE	*Rubus leucodermis*	whitebark raspberry	0.500	0.038 *
6-7 years:				
FRVE	*Fragaria vesca*	woodland strawberry	0.574	0.004 **
PRHO2	*Prosartes hookeri*	drops-of-gold	0.540	0.014 *
STBU	*Stachys bullata*	california hedgenettle	0.500	0.017 *
VASC	*Vaccinium scoparium*	grouse whortleberry	0.493	0.015 *

3.1.2 Regeneration (H1, H2)

Seedling density declined with repeated fires (Figure 4). Across all sites, both total seedlings and *Pseudotsuga* seedlings decreased significantly in reburned areas (P=0.012 for all seedling taxa; P=0.039 for *Pseudotsuga*). At low elevations, declines were modest, while at high elevations, total seedling density decreased, but not significantly due to low sample size; *Pseudotsuga* seedlings were absent at high elevation due to climatic constraints.

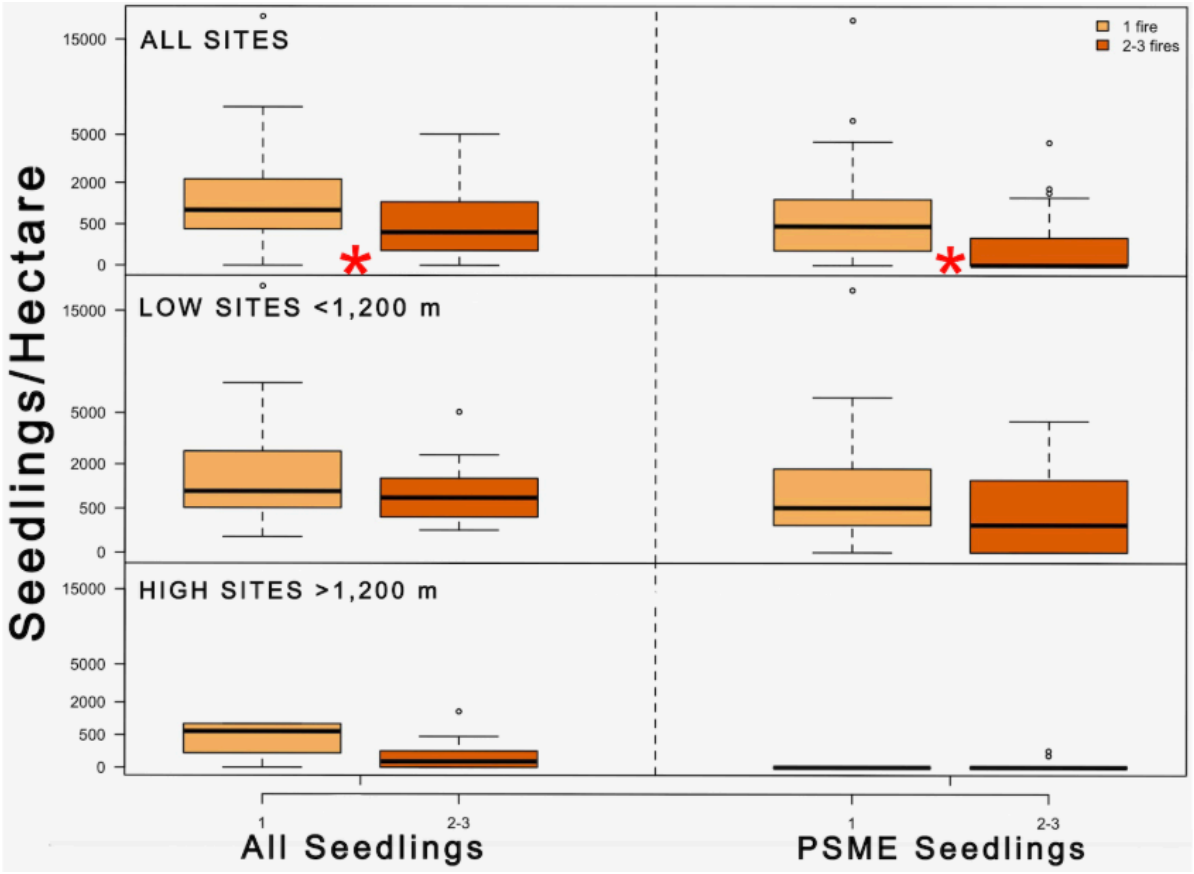


Figure 4. *Boxplots of seedling density (tonnes per hectare) for all seedlings (left) and Douglas-fir (Pseudotsuga menziesii, PSME) seedlings (right) across sites with one fire versus 2–3 fires. Panels are stacked by elevation: top, all sites; middle, low elevation (<4,000 ft); bottom, high elevation (>4,000 ft). Both total seedlings and PSME seedlings generally decrease with repeated fires. PSME seedlings are absent at high elevations due to climatic constraints.*

Seedling density generally increased with time since fire, peaking at 4–5 years and declining slightly at ≥ 6 years (Figure 5). This pattern was statistically significant (P<0.001) at low elevations for all seedlings and for *Pseudotsuga*. At high elevations, total seedling density increased significantly with time-since-fire (P<0.001); *Pseudotsuga* was absent at the high elevation sites.

Basal area patterns of live and dead trees further reflected strong effects of fire history (Figure 7). Total live basal area declined substantially with repeated fires across all sites, while total dead basal area also decreased. *Pseudotsuga menziesii* live basal area remained near zero across all conditions, while dead *Pseudotsuga* basal area increased slightly in reburned sites, particularly at high elevations.

At low elevations, total basal area was already low and declined further with repeated fires. At high elevations, total dead basal area decreased significantly with reburns, while *Pseudotsuga* dead basal area increased.

Both shrub (live woody) and herbaceous cover decreased significantly with increasing elevation across all watersheds.

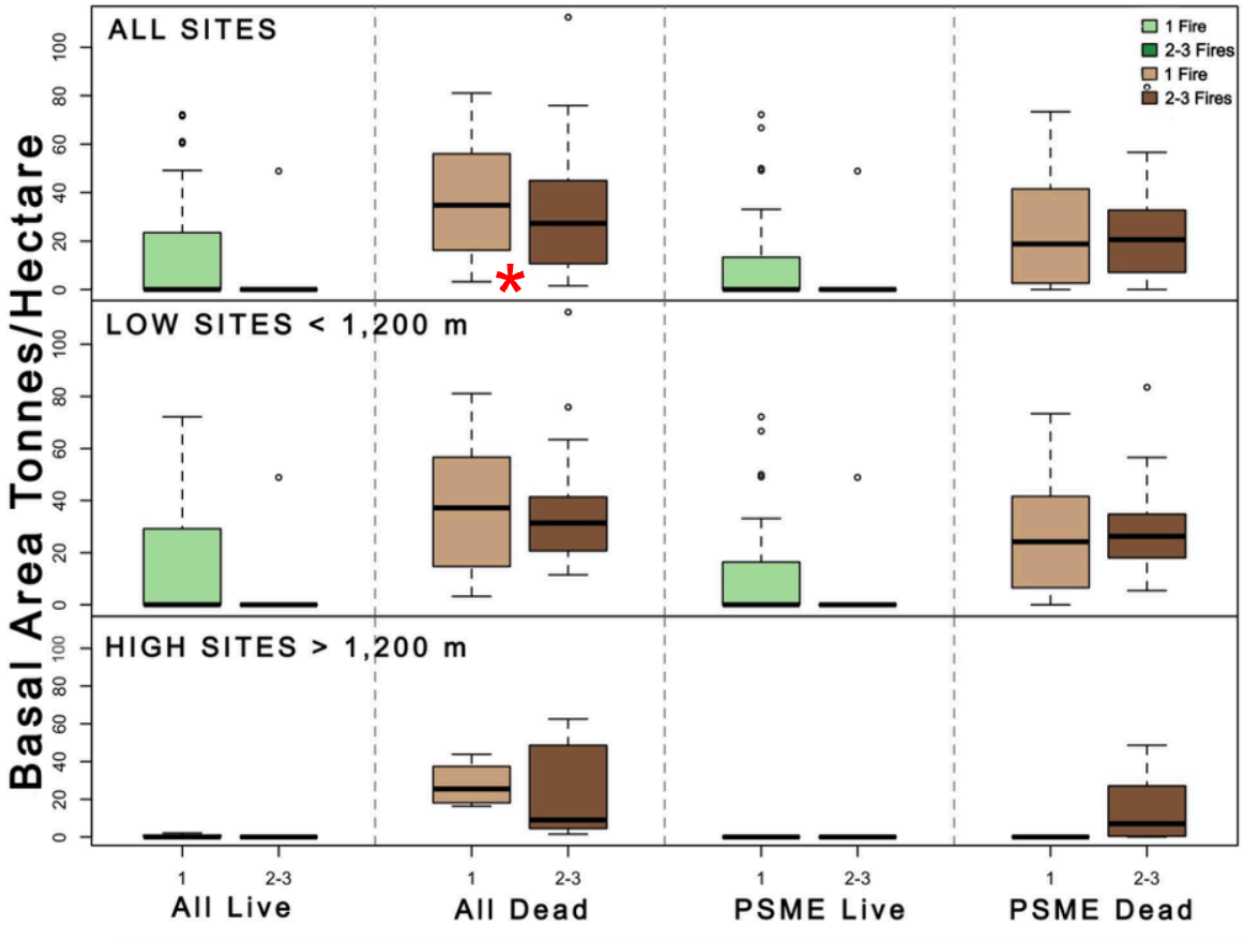


Figure 5. *Boxplots of basal area (m²/ha) for live and dead trees, for all species and Douglas-fir (Pseudotsuga menziesii, PSME) components, across sites with one fire versus sites with 2–3 fires. Panels are stacked by elevation class: top, all sites; middle, low elevation (<4,000 ft); bottom, high elevation (>4,000 ft). Each scenario includes two boxplots representing 1 fire (left) and 2–3 fires (right). Live tree basal area is shown in green, and dead tree basal area in brown. Total live basal area declines with repeated fires, while PSME live basal area remains near zero across sites. Dead basal area responses vary with species and elevation, with PSME dead basal area increasing slightly in reburned sites, particularly at high elevations.*

3.1.3 Species Diversity (H4)

Species richness showed modest responses to fire history (Figure 8). Across all sites and at low elevations, richness decreased significantly with repeated fires (P=0.02). Species richness across

time since fire showed high variability and no consistent trend across elevations, indicating that diversity responses are not strongly structured by time since fire within the observed range.

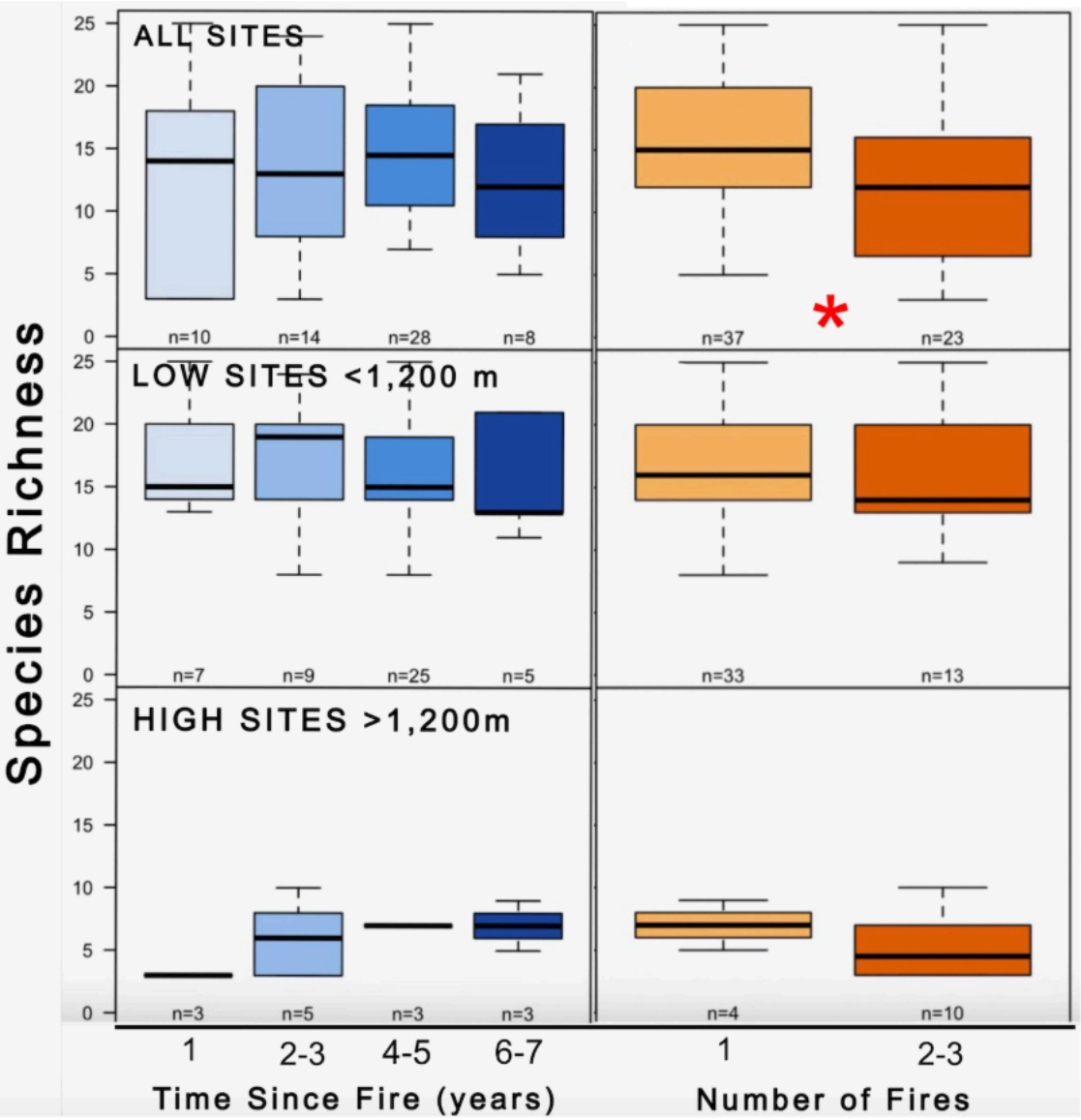


Figure 6. *Boxplots of species richness across four time-since-fire classes and across sites with one fire versus 2–3 fires. Panels are stacked by elevation: top, all sites; middle, low elevation (<1200 m); bottom, high elevation (>1200 m). Species richness decreases slightly with repeated fires at all sites and low elevations. No significant change in species richness occurred with time-since-fire.*

3.1.3 Soils

Soil carbon and nitrogen concentrations varied across number of fires (Figure 9). Total carbon (%C) ranged from 0.96 to 9.75 %. Carbon content decreased in reburned sites, consistent with the expected loss of organic matter through combustion during fire, which reduces soil carbon pools through direct volatilization and consumption of surface organic material.

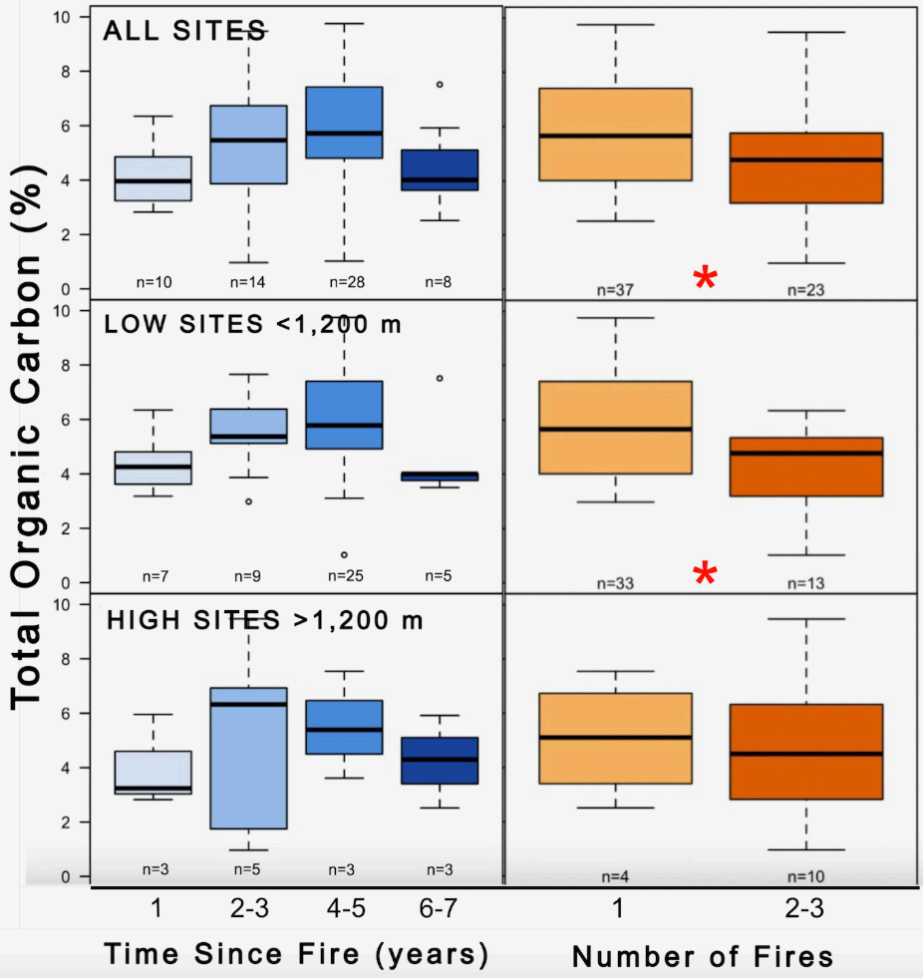


Figure 7. *Boxplots of total organic carbon (TOC) across sites with one fire versus 2–3 fires and across four time-since-fire classes. Panels are stacked by elevation: top, all sites; middle, low elevation (<1200 m); bottom, high elevation (>1200 m). TOC decreases in sites that have experienced multiple fires, consistent with carbon loss through combustion and reduced organic matter inputs following reburns. No consistent trend in TOC is observed across time-since-fire classes over the 7-year sampling window.*

Total nitrogen (%N) ranged from 0.036 to 0.56 % and remained relatively consistent across fire histories. This pattern is consistent with the tendency for nitrogen to be more resilient in mineral soil than carbon during fire events, as it is often less directly volatilized at the soil depths sampled and can be partially retained or replenished through post-fire inputs such as ash deposition and biological fixation.

Carbon-to-nitrogen (C:N) ratios ranged from 14.75 to 32.56. C:N ratios were generally lower in reburned sites, reflecting the proportional decline in carbon relative to nitrogen following fire. This shift indicates a change in soil organic matter quality, with reburned soils showing comparatively reduced carbon availability relative to nitrogen.

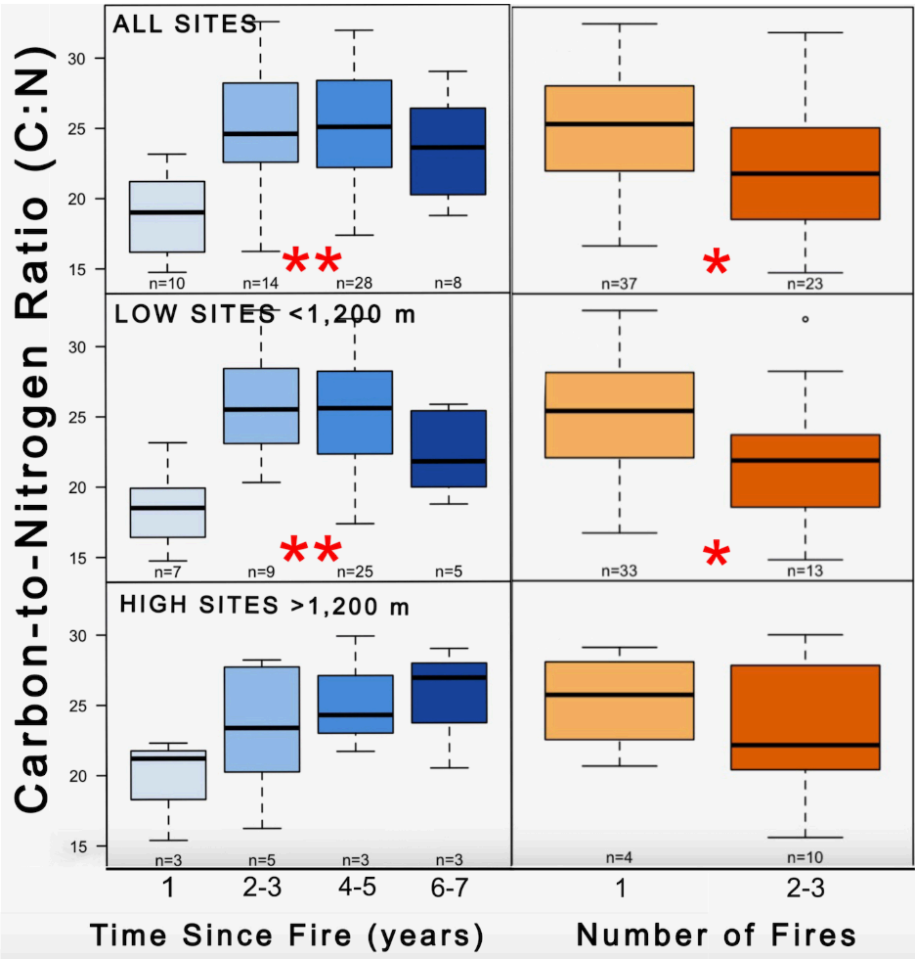


Figure 8. *Boxplots of carbon-to-nitrogen (C:N) ratio across sites with one fire versus 2–3 fires and across four time-since-fire classes. Panels are stacked by elevation: top, all sites; middle, low elevation (<1200 m); bottom,*

high elevation (>1200 m). C:N ratios are generally lower in reburned sites, reflecting a proportional decline in carbon relative to nitrogen following repeated fire. No consistent trend in C:N ratio is observed across time-since-fire classes over the 7-year sampling window.

Time since fire was not a meaningful explanatory variable for soil chemistry patterns over the relatively narrow (~7-year) sampling window, as changes in soil carbon and nitrogen pools at this temporal scale are minimal compared to the immediate and legacy effects of fire history itself.

3.2 Fuels and Fire Behavior

3.2.1 Fuel Structure and Loads (H5, H6)

Fuel loads varied substantially by fuel class, fire history, and elevation. Across all sites, most fuel classes (1-hr, 10-hr, 100-hr, and woody fuels) decreased in sites that experienced 2–3 fires compared to sites that burned once (Figure 9). Herbaceous fuels remained relatively stable, while shrub biomass showed a slight increase at low elevations. At high elevations, all fuel classes generally declined with repeated fires, with minimal change in shrub fuels.

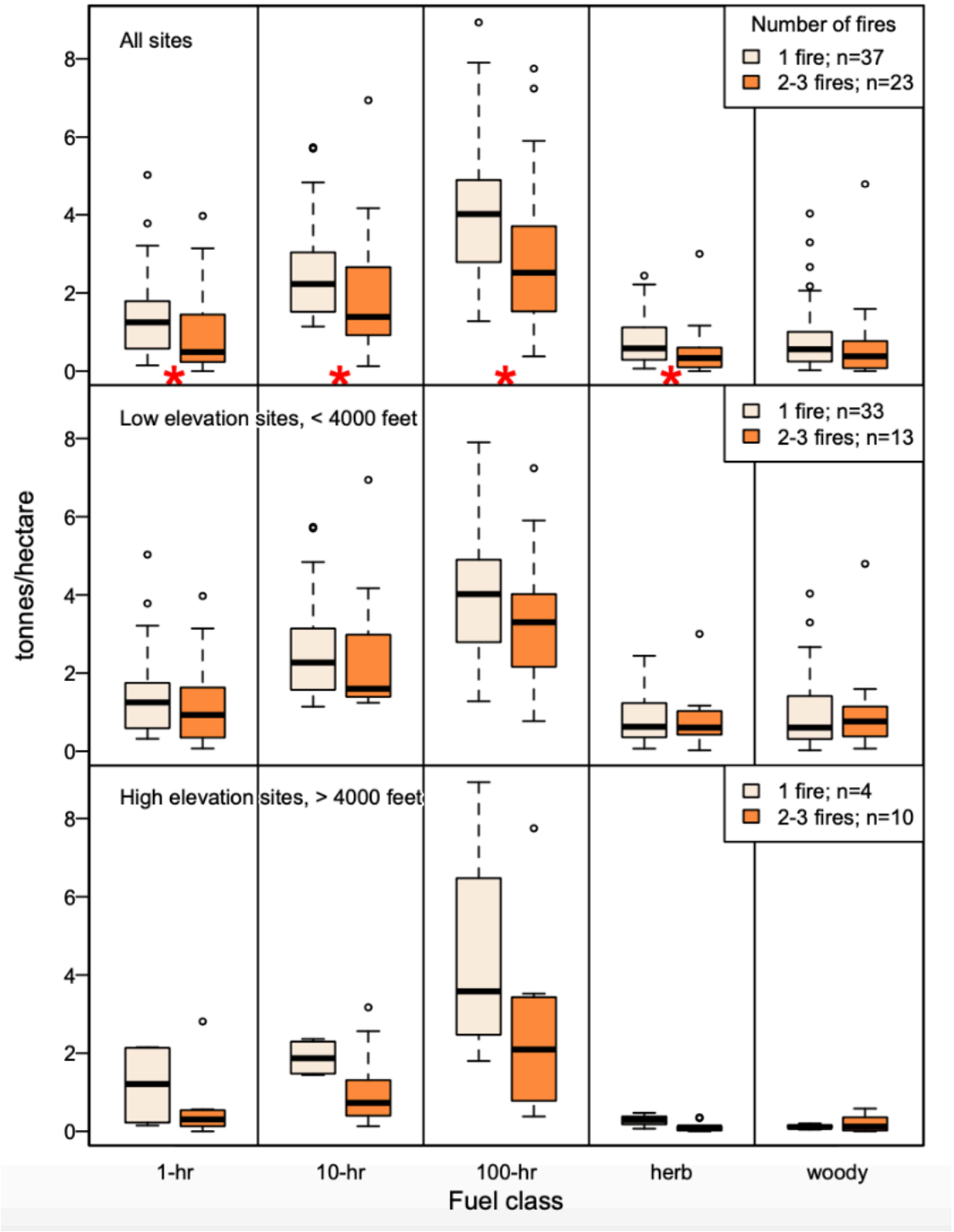


Figure 9. *Boxplots of fuel loads (tonnes per hectare) by fuel class (1-hr, 10-hr, 100-hr, herbaceous, and woody) across sites with one fire versus sites with 2–3 fires. The figure is divided into three stacked panels: top, all sites;*

*middle, low elevation sites (<1200 m); bottom, high elevation sites (>1200 m). Fuel loads generally decrease with repeated fires across most classes, with notable exceptions including slight increases in shrub biomass at low elevations and stable herbaceous fuel at low elevations. *=P<0.05 by Kruskal-Wallis test.*

In contrast, 1,000-hour fuels showed a different response to repeated burning. Across all sites, 1,000-hour fuels increased slightly in reburned areas, with a more pronounced increase at low elevations and a slight decrease at high elevations, although these differences were not statistically significant (Figure 10).

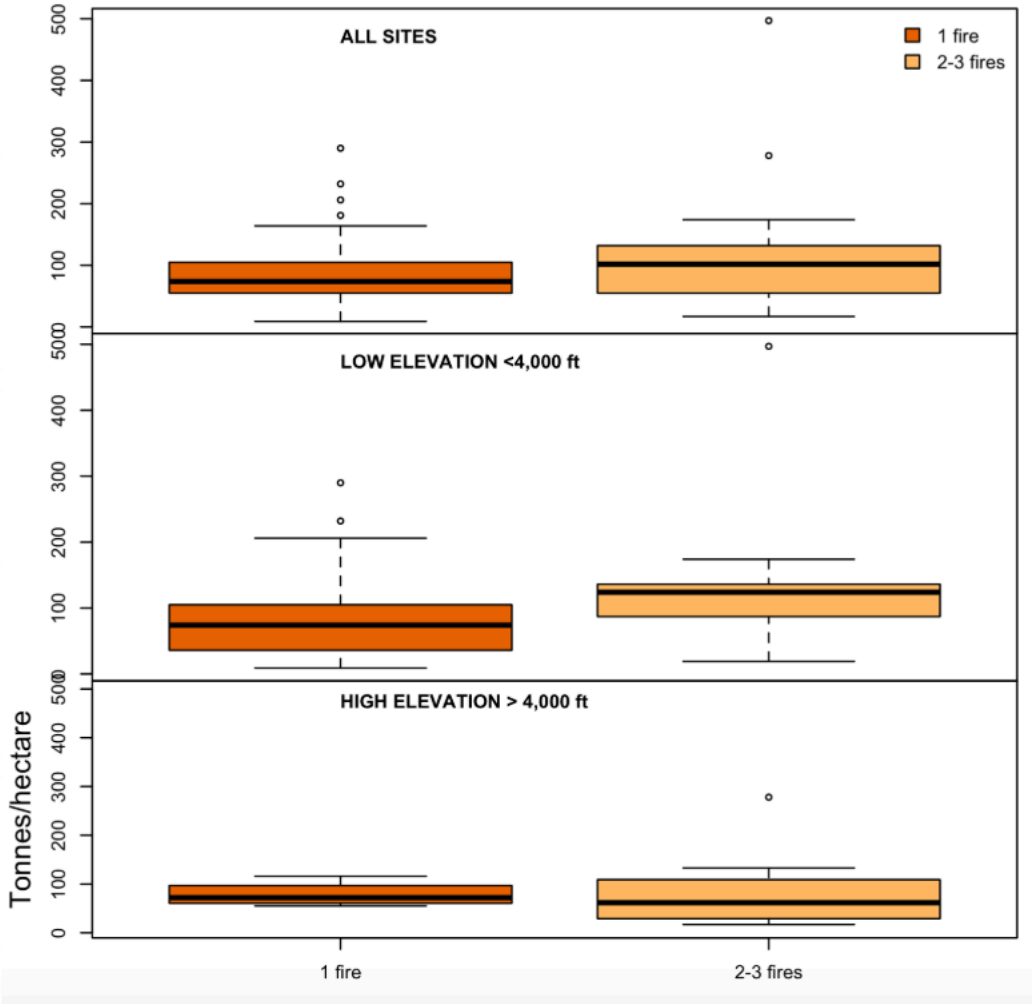


Figure 10. *Boxplots of 1000-hour fuel loads (tonnes per hectare) for sites with one fire versus sites with 2–3 fires. Panels are stacked by elevation class: top, all sites; middle, low elevation (<4,000 ft); bottom, high elevation*

(>4,000 ft). Sites with multiple fires show a slight overall increase in 1000-hour fuels, particularly at low elevations, whereas high-elevation sites exhibit a slight decrease. There were no significant differences among groups by Kruskal-Wallis tests.

Fuel dynamics over time since fire exhibited strong size-specific patterns (Figure 11). Across all sites, fine fuels (1-hr) showed a cyclical pattern, increasing at 2–3 years, decreasing at 4–5 years, and increasing again at ≥6 years. Ten-hour fuels increased steadily, while 100-hour fuels showed an initial jump followed by gradual increases. Herbaceous fuels remained relatively stable, while shrub biomass showed a pronounced increase at intermediate time periods.

At low elevations, fuels exhibited similar but more pronounced fluctuations, while high-elevation sites showed steadier increases in larger fuels and declines in shrubs.

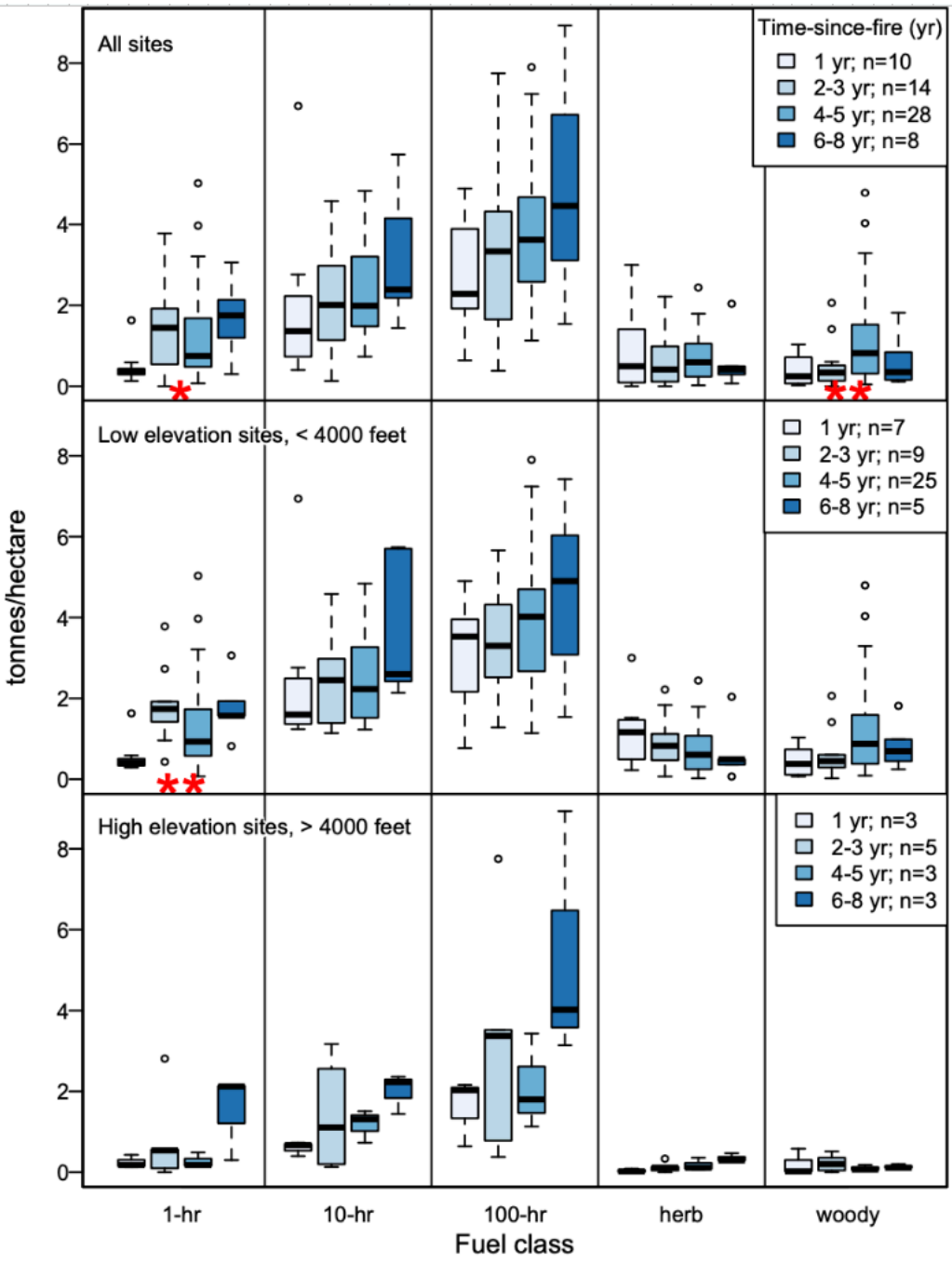


Figure 11. *Boxplots of fuel loads (tonnes per hectare) for each fuel class (1-hr, 10-hr, 100-hr, herbaceous, and woody) across time since fire (1, 2–3, 4–5, and ≥6 years). Panels are stacked by elevation class: top, all sites; middle, low elevation (<1200 m); bottom, high elevation (>1200 m). Fuel classes exhibit distinct temporal patterns: 1-hr fuels show pronounced fluctuations, 10-hr fuels generally increase over time, 100-hr fuels show stepwise*

*increases with some variability, herbaceous fuels are largely stable, and shrub biomass varies by elevation with notable spikes at intermediate time bins. *=P<0.05; **=P<0.01 by Kruskal-Wallis tests.*

Patterns of 1,000-hour fuels over time since fire further highlighted elevation-dependent responses (Figure 12). Low-elevation sites showed delayed accumulation following an initial decline, whereas high-elevation sites exhibited an early increase followed by variability. Across all sites, patterns were muted and reflected a combination of these opposing trends.

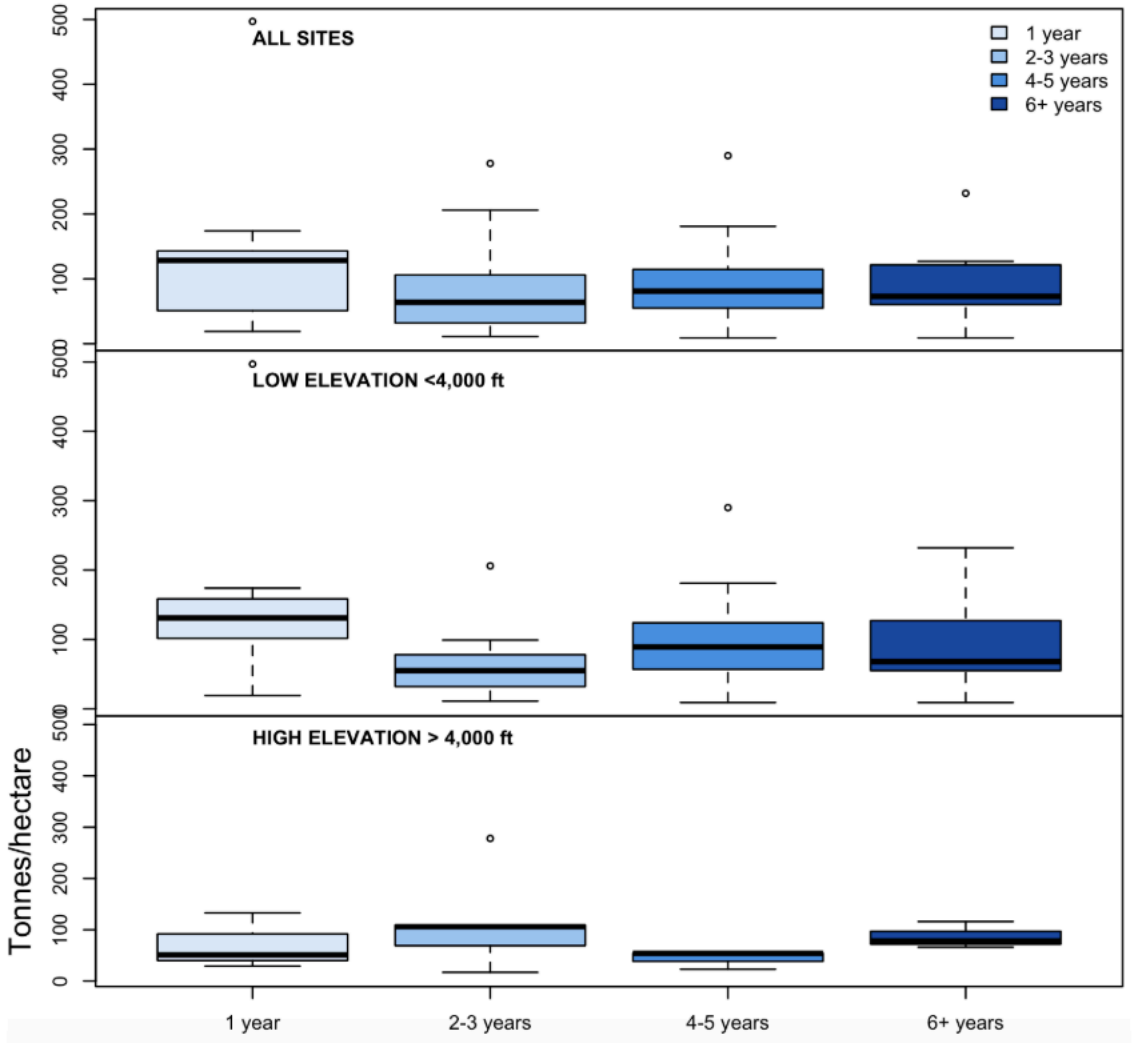


Figure 12. *Boxplots of 1,000-hour fuel loads (tonnes per hectare) across time since fire, binned into 1, 2–3, 4–5, and ≥6 years. Panels are stacked by elevation class: top, all sites; middle, low elevation (<4,000 ft); bottom, high elevation (>4,000 ft). Low-elevation sites show an initial drop at 2–3 years followed by increases, whereas high-*

elevation sites exhibit the opposite pattern. All-sites patterns reflect a combination of these trends, with slight decreases after 1 year, gradual increases at 4–5 years, and minor declines at ≥6 years. There were no significant differences among groups by Kruskal-Wallis tests.

Overall, number of fires appeared to exert a stronger influence on coarse fuel accumulation than time since fire, likely due to increased tree mortality and subsequent inputs of large woody debris following reburns.

3.2.2 Modeled Fire Behavior (H7)

Modeled flame length increased with time since fire and peaked at 2–3 years post-fire, particularly under high wind (8.9 m s^{-1}) and dry conditions (Figure 13). This pattern was most pronounced at low elevations, while high-elevation sites showed consistently low flame lengths with minimal variation. Sites with moderate moisture conditions exhibited more gradual increases in flame length without a strong peak.

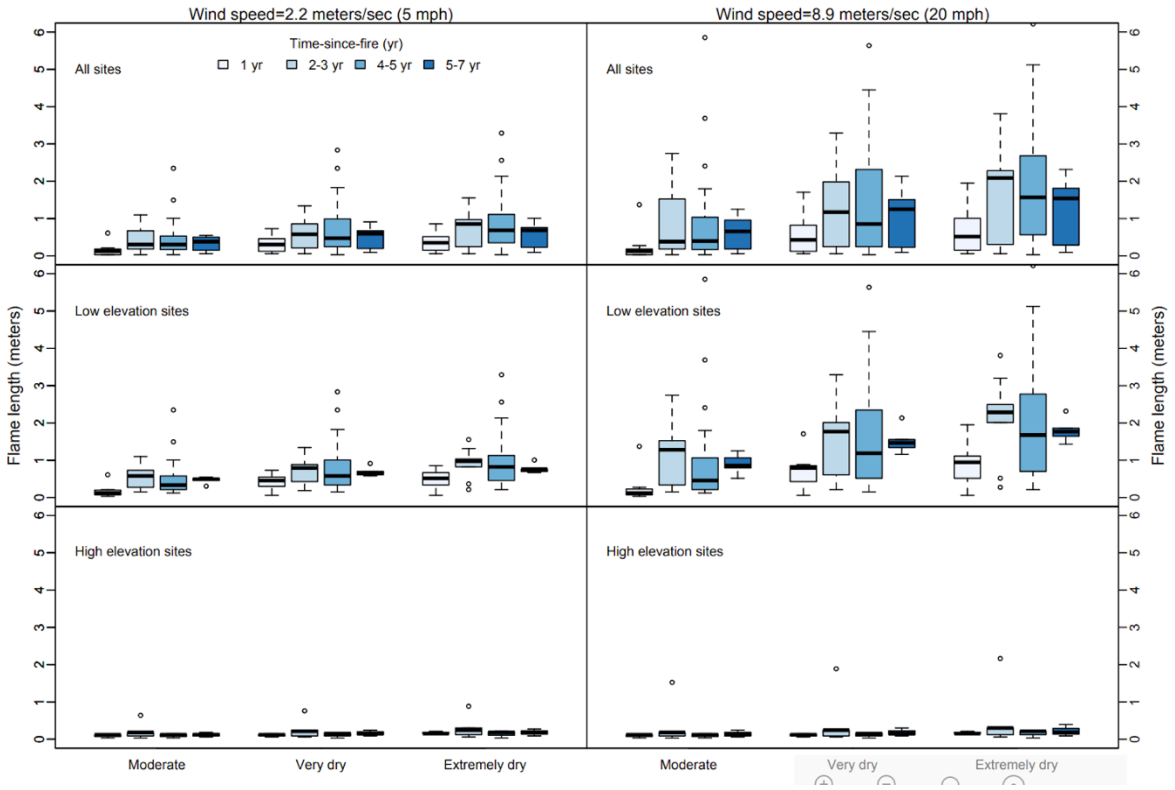


Figure 13. *Boxplots of modeled flame length across time since fire (1 year, 2–3 years, 4–5 years, ≥6 years), stratified by elevation (top: all sites; middle: low elevation <4,000 ft; bottom: high elevation >4,000 ft), wind speed (2.2 m s⁻¹ and 8.9 m s⁻¹), and fuel moisture conditions (moderate, very dry, extremely dry). Flame length generally increases with time since fire and peaks at 2–3 years, particularly under high wind (8.9 m s⁻¹) and dry conditions at low elevations. High-elevation sites exhibit consistently low flame lengths with minimal variation. No significant effect of number of fires is observed.*

Modeled rate of spread exhibited similar patterns (Figure 14). Across all sites, the rate of spread increased with time since fire and peaked at 2–3 years, especially under very dry and extremely dry conditions and high wind speeds. Low-elevation sites showed strong increases, whereas high-elevation sites remained low and relatively unchanged.

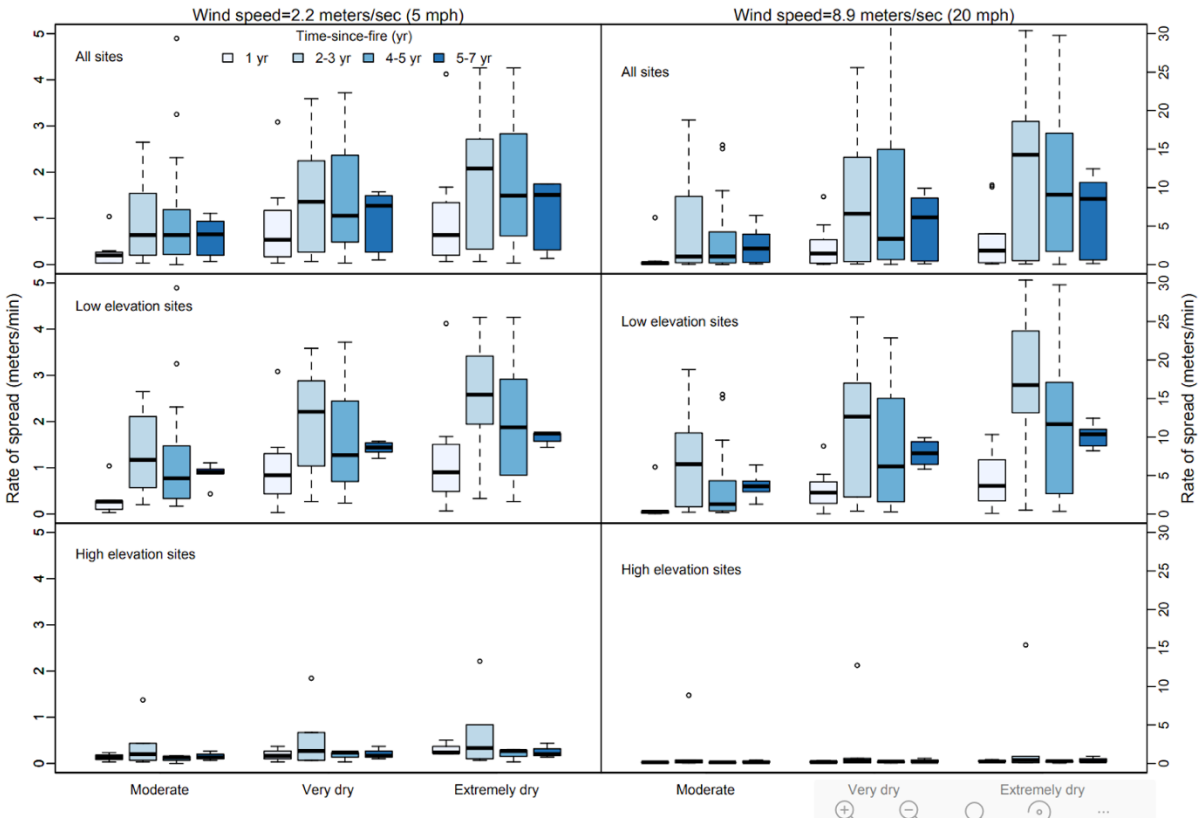


Figure 14. *Boxplots of modeled rate of spread across time since fire (1 year, 2–3 years, 4–5 years, ≥6 years), stratified by elevation (top: all sites; middle: low elevation <4,000 ft; bottom: high elevation >4,000 ft), wind speed (2.2 m s^{-1} and 8.9 m s^{-1}), and fuel moisture conditions (moderate, very dry, extremely dry). Rate of spread generally increases with time since fire and peaks at 2–3 years, particularly under very dry and extremely dry conditions and higher wind speeds. Low-elevation sites show pronounced increases, while high-elevation sites exhibit consistently low values.*

Across both modeled outputs, the number of fires did not show a significant effect on fire behavior, whereas time since fire, fuel moisture, and wind speed were the primary drivers. The consistent peak at 2–3 years suggests a window of elevated flammability, likely associated with increased herbaceous fuel availability during early post-fire succession.

4. DISCUSSION

This study investigated how post-fire vegetation structure, fuel dynamics, and modeled fire behavior vary across gradients of fire history, time since fire, and elevation in the western Cascade Range. Several clear patterns emerged. First, repeated fires generally reduced live biomass, fine fuels, and seedling density, while in some cases increasing coarse woody debris (1,000-hour fuels), particularly at low elevations. Second, time-since-fire strongly influenced early successional fuel dynamics, with many fuel classes and both modeled fire behavior metrics (flame length and rate of spread) peaking at approximately 2–3 years post-fire. Third, elevation consistently mediated these patterns, with high-elevation sites exhibiting reduced vegetation cover, lower fuel loads, and minimal modeled fire behavior. Finally, vegetation composition was structured along strong environmental gradients, particularly elevation and moisture, as well as a fire severity gradient, with shifts between fire- and disturbance-adapted species and shade-tolerant, mesic forest species (e.g., *Pteridium aquilinum* versus *Polystichum munitum*). Taken together, these findings indicate that post-fire ecosystems in this region are shaped by interacting controls, where fire frequency, environmental gradients, and early successional processes collectively determine vegetation recovery, fuel development, and potential fire behavior.

4.1 Vegetation and Regeneration

4.1.1 Effects of Repeated Fire

Repeated fire acts as a strong ecological filter on vegetation structure, driving declines in both live biomass and regeneration potential while reshaping post-fire community trajectories. Reburns removed any persisting live trees, suggesting that multiple fires constrain the persistence of overstory trees and limit structural recovery. These effects are particularly evident

in seedling dynamics, where both total and *Pseudotsuga menziesii* regeneration declined significantly in reburned stands, suggesting that short-interval fires may exceed the recovery capacity of key conifer species. Vegetation responses following short-interval, high-severity reburns emphasize the role of seed availability and nearby surviving trees in driving post-fire conifer regeneration, while repeated burning likely limits recruitment through the loss of these seed sources. Despite these structural and compositional shifts, species richness showed relatively limited response to reburns across most sites, with only modest declines. This apparent resilience of diversity is consistent with broader patterns observed in Smith et al. (2020). Peak plant diversity during early forest development, which demonstrates that early-seral forests often support high levels of plant diversity due to increased resource availability, structural heterogeneity, and the coexistence of disturbance-adapted and residual species (Swanson, 2010).Similar early-seral diversity patterns have also been documented in Pacific Northwest forests more broadly where post-fire environments often maintain or enhance plant diversity through the coexistence of ruderal, resprouting, and early colonizing species during the first decade following disturbance (Swanson, 2010). These studies emphasize that post-fire diversity is strongly shaped by rapid colonization dynamics and local environmental filtering rather than by fire history alone.

In this context, repeated fire may reduce tree regeneration and alter dominance patterns without substantially reducing overall diversity, instead maintaining or even enhancing species richness through the persistence of early-seral and resprouting taxa. Together, these findings suggest that while short-interval fires can fundamentally alter forest structure and inhibit conifer recovery, they do not necessarily lead to immediate declines in plant diversity, highlighting a decoupling between structural recovery and compositional richness in post-fire ecosystems.

4.1.2 Temporal Dynamics

Time-since-fire played a secondary but consistent role in structuring post-fire vegetation, shaping short-term successional trajectories rather than broad compositional patterns, which were more strongly controlled by elevation. Indicator species results show a clear but simplified temporal sequence following fire. One-year sites were dominated by ruderal and invasive taxa such as *Geranium robertianum*, *Cardamine hirsuta*, and *Senecio* spp., reflecting rapid colonization immediately after disturbance. By 2-3 years, early-establishing native species such as *Linnaea borealis* became more common, indicating initial community stabilization.

At 4-7 years post-fire indicator species shift toward later-seral understory taxa including *Fragaria vesca*, *Prosartes hookeri*, and *Stachys bullata*, along with high-elevation species such as *Vaccinium scoparium*. This pattern suggests gradual reassembly toward pre-fire forest understories, though trajectories remain strongly filtered by elevation and moisture conditions. Seedling dynamics follow a similar but weakly structured temporal pattern, increasing with time-since-fire and peaking 4-5 years before declining slightly thereafter, consistent with early recruitment followed by density-dependent mortality. These trends are strongest at low elevations, while high elevation sites show limited and slower regeneration.

Overall, temporal dynamics reflect a general but flexible recovery trajectory, with early colonization, mid-term structural development, and gradual understory reassembly, all modulated by strong environmental filtering.

4.1.3 Elevation Effects

Elevation strongly influenced vegetation, with the primary ordination axis (NMDS1) reflecting elevation and associated climatic controls, High-elevation sites were characterized by reduced

vegetation cover, likely due to cooler temperatures, shorter growing seasons, and higher moisture availability. Recovery in these environments are therefore dominated by species adapted to harsher conditions due to presence of snow, and subsequent shorter growing seasons, resulting in distinct successional trajectories compared to lower elevations.

Low-elevation sites exhibited greater variability and stronger responses to fire history and time-since-fire. Higher productivity at these elevations supports faster fuel accumulation and vegetation recovery, but also increases potential for subsequent fire activity. Pronounced peaks in modeled fire behavior at low elevations suggest heightened vulnerability to short-interval reburns.

4.1.4 Vegetation Composition and Alternative States

Ordination analysis indicated that post-fire vegetation composition was strongly structured by environmental gradients. The secondary axis (NMDS2) appeared to reflect variation in moisture conditions, fire severity, and residual overstory structure. Sites associated with greater live tree basal area generally supported more mesic and shade-tolerant understory communities, whereas sites with reduced overstory structure were more strongly associated with disturbance-adapted vegetation. Together, these patterns highlight the combined influence of environmental conditions and fire effects in shaping post-fire plant communities.

Particularly abundant and ecologically influential species help highlight compositional patterns, even when clear ordinational separation is lacking. Although *Chamerion angustifolium* (fireweed; CHAN9) and *Ceanothus velutinus* (whitebrush ceanothus; CEVE) do not occupy opposite ends of the ordination, field observations indicate that sites where either species dominates are often characterized by near-total cover of one or the other. This pattern, while not

strongly resolved in the ordination itself, suggests a tendency towards locally high dominance by distinct functional groups- herbaceous versus shrub- under certain post-fire conditions. Rather than indicating discrete alternative states, these observations point to variability in early successional trajectories that may be shaped by factors such as moisture availability and fire severity as well as pre-fire community compositions. These differences have important ecological implications; *Ceanothus* species contribute to nitrogen inputs through fixation and may promote longer term-woody succession, whereas *Chamerion angustifolium* is associated with rapidly cycling fine fuels and early-sereal nutrient dynamics. Together, this highlights that post-fire vegetation development is not uniform, but reflects environmentally mediated variation in dominant species and functional strategies, even when such patterns are only partially captured by ordination analysis.

4.1.5 Integration of Vegetation, Fuels, and Fire Behavior

The study's integration of vegetation, fuel, and fire behavior data allows a more holistic understanding of post-fire dynamics. Patterns in seedling density were generally weak, although regeneration was consistently lower in reburned areas. When compared to typical post-planting stocking level (~1000 seedlings per hectare), a large portion of plots fall below this threshold, particularly in reburned sites (e.g., 20 of 23 reburn plots have fewer than 1000 seedlings/ha, compared to 26 of 37 single-burn plots). While these values do not necessarily indicate regeneration failure- given expected mortality and continued recruitment over time- they do suggest that reburns may constrain early tree establishment relative to single-fire conditions.

These findings are broadly consistent with those reported by Busby and Holz (2022), despite Busby and Holz's focus on subalpine forests in Oregon's Cascade Range. Busby and Holz further

demonstrate that rapid reburns increase the size and continuity of high severity patches, thereby amplifying seed limitation and promoting a shift in species composition toward fire-adapted, fast establishing conifers in proximity to surviving seed sources. Where seed sources are absent or distant, regeneration is reduced overall, contributing to a patchy post-fire forest structure composed of low-density conifer regeneration and non-forest vegetation.

These vegetation patterns are reflected in fuel development and modeled fire behavior in this study. Areas with greater post-fire vegetation recovery accumulate fuels more rapidly, increasing modeled fire behavior potential. In contrast, sites with limited regeneration remain fuel-limited, exhibiting lower modeled fire behavior. This spatial coupling between regeneration patterns and fuel development aligns with Busby and Holz (2022), where early-seral vegetation structure and seed limitation jointly influenced post-fire successional pathways and contributed to heterogeneous forest recovery trajectories. The alignment of fine fuel accumulation with modeled fire behavior further emphasizes the role of early post-fire vegetation structure—particularly herbaceous fuels and developing regeneration—in shaping flammability during the early successional period.

Together, these results support a linked interpretation in which repeated fire reduces conifer regeneration primarily through seed limitation, which in turn produces more spatially heterogeneous vegetation and fuel conditions that feed back into divergent fire behavior potential across the landscape.

4.2 Fuels and Fire Behavior

4.2.1 Temporal Dynamics

Time since fire emerged as the strongest and most consistent control on early successional dynamics, with both fuel availability and modeled fire behavior peaking approximately 2–3 years post-fire. This pattern was evident across modeled flame length and rate of spread, particularly under high wind and dry fuel conditions. The observed peak likely reflects the rapid accumulation of fine continuous fuels, especially herbaceous biomass and small woody material. Immediately following fire, fuel loads are sparse and discontinuous, limiting fire spread. As vegetation recovers, increasing fuel continuity promotes more efficient fire transmission across the landscape, resulting in elevated flame lengths and rates of spread. Beyond 2–3 years, the stabilization or slight decline in modeled fire behavior likely reflects shifts in fuel structure, including decomposition, increasing shading, and reduced horizontal continuity. The cyclical patterns observed in 1-hour fuels further support the interpretation of dynamic fuel turnover during early succession.

Although these dynamics occur within a relatively short post-fire window, the magnitude of modeled fire behavior is not trivial. Even within 1–5 years following fire, rates of spread and flame lengths under dry and windy conditions indicate the potential for sustained and ecologically meaningful fire activity. This contrasts with intact forest conditions, where closed canopies reduce wind penetration and maintain higher fuel moisture, thereby limiting fire spread. Similar patterns have been documented in western hemlock/Douglas-fir forests, where canopy loss following disturbance rapidly alters surface fuel dynamics and increases fine fuel accumulation during early succession (Agee and Huff, 1987). Their work showed a marked increase in 1-hour fuels by approximately three years post-fire, with weaker or declining short-term trends in larger fuel classes.

Our results show broadly similar early post-fire behavior, particularly in the persistence of elevated modeled fire potential within the first 1–5 years, but with substantially greater spatial variability and less consistent monotonic fuel trajectories than those reported by Agee and Huff (1987). In our dataset, fine fuels exhibit high variability across sites and time-since-fire, while 100-hour and 1,000-hour fuels do not show simple directional trends, reflecting heterogeneous post-fire recovery pathways and site-specific controls. This variability nonetheless supports the idea that early post-fire environments can maintain or rapidly reestablish flammability relatively quickly, even if the pathways differ from the more structured successional signal documented in earlier work. These findings are also consistent with broader syntheses of Pacific Northwest early-seral ecosystems showing that the first several years following fire are characterized by highly dynamic and spatially heterogeneous fuelbeds, including rapid development of herbaceous and shrub layers that can temporarily increase fine fuel continuity and reburning potential (Friesen and Swanson).

Importantly, this study captures only early post-fire stages. Longer-term successional processes—including canopy closure, shifts in species composition, and continued accumulation of coarse woody debris (Spies et al. 2018)—are likely to further modify fuel structure and fire behavior beyond the observed peak. As such, the 2–3 year window identified here represents a critical but transient stage within a broader trajectory of post-fire ecosystem development.

4.2.2 Effects of Repeated Fire on Fuels

Repeated fires had complex effects on fuels. Fine fuels (1-hour, 10-hour, and 100-hour fuels) generally declined following reburns, while 1,000-hour fuels increased slightly at low elevations, although these differences were not statistically significant. These patterns suggest that repeated

fires alter fuel structure and composition rather than uniformly increasing or decreasing total fuel loads.

At the same time, coarse fuels responded differently than fine fuels. While smaller fuel classes generally declined with repeated fires, 1,000-hour fuels tended to increase at low elevations, likely reflecting increased tree mortality and subsequent snag fall. Repeated fires therefore do not simply reduce total fuel loads but may shift systems toward greater dominance of coarse woody debris. Similar reductions in conifer regeneration and altered post-fire fuel conditions following repeated high-severity fire have been documented across western North American forests, particularly where reburns reduce seed availability and increase distance from surviving trees (Tepley et al. 2017; Sheehan et al. 2015).

This structural transition has important implications for future fire regimes. Fine fuels and herbaceous fuels with low moisture are associated with rapid ignition and fire spread, whereas coarse fuels contribute to longer fire residence times and localized fire intensity. The observed shift toward greater coarse fuel representation therefore suggests that reburned systems may experience changes not only in the likelihood of burning, but also in the characteristics of fire behavior itself.

4.2.3 Elevation Effects on Fire Behavior

High-elevation sites consistently exhibited lower flame lengths, reduced rates of spread, and lower fuel loads. Environmental constraints—including cooler temperatures, higher moisture availability, and shorter growing seasons—likely limit both biomass accumulation and flammability. Lower-elevation sites, by contrast, showed greater variability and higher modeled fire behavior, particularly within 2–3 years following fire.

Patterns observed across elevation gradients are consistent with broader studies showing strong climatic controls on post-fire recovery and vegetation development. Lower-elevation sites generally supported more flammable fuel complexes and slower conifer recovery, whereas higher-elevation sites maintained lower modeled fire behavior and greater persistence of mesic vegetation. Vegetation composition further reflected strong environmental filtering, with disturbance-adapted species associated with warmer, drier, and higher-severity environments, while mesic forest species remained associated with cooler and wetter conditions.

Our findings also contribute to growing recognition that post-fire fuel development and modeled fire behavior are highly variable and sensitive to assumptions regarding fuel succession. Kennedy et al. (2021) demonstrated that modeled fire behavior and woody fuel trajectories can vary substantially depending on assumptions regarding post-fire fuel accumulation, highlighting the importance of empirical field measurements for constraining simulation outputs. In this context, the field-based fuel observations presented here provide evidence that reburned landscapes may maintain or rapidly redevelop flammable fuel conditions despite assumptions that recently burned areas necessarily represent reduced fire hazard.

These findings also contrast with assumptions used in recent FSim modeling of future wildfire regimes in Pacific Northwest forests, which prescribed lower flammability in recently burned areas due to reduced fuel loads (Dye et al. 2024). Instead, our results suggest that repeated high-severity fire may reinforce positive fire–vegetation feedbacks by slowing conifer recovery while maintaining elevated burn potential through rapidly developing surface and ladder fuels. While these patterns do not necessarily indicate permanent conversion to non-forest conditions, they do suggest that repeated burning can substantially alter successional trajectories and prolong periods of elevated fire hazard.

4.4 Significance

This study demonstrated that interactions among fire history, time since fire, and environmental gradients strongly influence post-fire vegetation structure, fuel development, and modeled fire behavior in Western Cascade Range forests. The identification of a 2-3 year period of elevated modeled flammability following fire suggests that recently burned landscapes may remain vulnerable to reburning sooner than is often assumed, particularly at lower elevations under dry and windy conditions. Reburned areas frequently supported dense fine fuels and shrub-dominated vegetation capable of sustaining modeled fire behavior comparable to, or exceeding, that of adjacent mature forests.

More broadly, this study highlights the importance of incorporating empirically observed post-fire fuel dynamics into fire behavior and vegetation modeling efforts. Because modeled fire behavior is highly sensitive to assumptions regarding fuel succession (Kennedy et al. 2021), field-based measurements such as those presented here are critical for improving predictions of future wildfire behavior and ecosystem recovery under increasingly frequent and severe fire regimes.

This is particularly important given that early -seral vegetation dynamics in the western Cascades are often generalized in models, despite evidence that post-fire fuel development and flammability can vary widely across space and environmental gradients (Friesen and Swanson)

4.5 Limitations

This study is limited to early post-fire stages and uses a chronosequence approach, which infers temporal patterns from spatial variation rather than directly tracking change through time. As a

result, differences among sites may reflect not only time since fire, but also underlying variation in climate, soils, fire severity, and pre-fire stand structure. While the chronosequence design allowed sampling across a broad range of post-fire conditions, long-term monitoring of individual sites would provide stronger inference regarding successional trajectories and fuel development through time.

Sample sizes were also uneven across environmental gradients and fire histories. High-elevation sites and areas that experienced three fires were relatively uncommon within the study area, reducing statistical power and limiting the ability to detect subtle effects of repeated burning. Additional sampling across a larger number of reburned sites would improve the ability to isolate interacting controls on post-fire recovery, such as the combined effects of elevation, burn severity, and fire frequency.

Modeled fire behavior represents another important limitation. Fire behavior outputs were generated using standardized fuel models and weather assumptions that may not fully capture the complexity of real-world fire conditions. Factors such as extreme weather events, spatial heterogeneity in fuel continuity, and live fuel moisture variability are difficult to fully represent in simulation models. Consequently, modeled flame lengths and rates of spread should be interpreted as relative indicators of potential fire behavior rather than direct predictions of actual wildfire behavior.

Finally, the study focuses primarily on surface fuels and early vegetation recovery and does not evaluate longer-term ecosystem processes such as delayed tree mortality, canopy redevelopment, or changing snag dynamics. These later successional processes may substantially alter fuel structure and future fire behavior beyond the temporal window captured here.

4.6 Recommendations for Future Research

Longer-term studies tracking individual sites would capture later successional stages and fuel development. Investigating drivers of alternative vegetation states—including seed availability, microsite conditions, and fire severity—would improve understanding of regeneration patterns. Integrating empirical fire observations with modeled outputs would strengthen conclusions about fire behavior and its applicability to management.

5. CONCLUSION

This study demonstrates that post-fire landscapes in the western Cascade Range are shaped by complex and interacting controls, where fire history, time since fire, and environmental gradients collectively influence vegetation recovery, fuel development, and potential fire behavior. However, the results suggest that post-fire dynamics are driven primarily by temporal patterns and environmental constraints, with repeated fires acting as secondary modifiers of ecosystem structure and fuels.

Repeated fires reduced live biomass, seedling recruitment, and fine fuels, while in some cases increasing coarse woody debris. These patterns indicate that reburns do not simply increase or decrease fuels, but instead restructure fuel composition, shifting systems from standing biomass toward downed woody material. This structural transition has important implications for fire behavior, as different fuel types influence fire spread and intensity in distinct ways. Importantly, modeled fire behavior did not increase consistently with the number of fires, providing limited support for the hypothesis that reburns inherently increase flammability. Instead, fire behavior was more strongly influenced by time since fire, fuel moisture, and wind conditions, suggesting that the effects of repeated fire are mediated by broader environmental and temporal controls.

Time-since-fire emerged as a key driver of early successional dynamics, with a consistent peak in both fuel availability and modeled fire behavior occurring approximately 2–3 years after fire. This period represents a critical window of elevated flammability, likely driven by the rapid accumulation of fine, continuous fuels such as herbaceous vegetation. Beyond this window, fuel dynamics became more variable, and modeled fire behavior stabilized or declined, indicating that the elevated flammability associated with early succession is likely transient rather than persistent.

Elevation strongly mediated these processes, with high-elevation sites exhibiting reduced vegetation recovery, limited conifer regeneration, and minimal fire behavior potential. In contrast, low-elevation sites showed greater biomass accumulation, stronger responses to fire history, and higher modeled fire behavior, suggesting increased vulnerability to short-interval reburns. Vegetation composition further reflected strong environmental controls, with clear gradients in species distribution and evidence of alternative successional pathways. The dominance of either shrub or herbaceous species at individual sites suggests that early post-fire conditions may establish trajectories that influence long-term ecosystem structure and function.

Overall, these findings emphasize the importance of temporal dynamics and environmental context in understanding and managing post-fire landscapes in the western Cascades. As fire frequency continues to increase under changing climatic conditions, management strategies will need to account for the dynamic nature of post-fire fuel development and the relatively short windows of elevated fire potential that occur during early succession. Future research extending beyond early post-fire stages will be essential for understanding how these ecosystems continue to develop through time and under repeated disturbance.

APPENDIX

Table S1. All species identified in this study, the frequency of plots where it was found (out of maximum 60 plots) and the mean percent cover within the plots where it was found.

Code	Species/cover type	Common name	Freq	Mean cover		
BG	Bare ground –	60	31.8			
LT	Litter –	60	15.8			
CHAN9	*Chamerion angustifolium*	fireweed	52	8.4		
RUUR	*Rubus ursinus*	trailing blackberry	45	10.7		
MANE2	*Mahonia nervosa*	Cascade barberry	42	4.9		
TRBOL	*Trientalis borealis*	broadleaf starflower	33	2.2		
GR	Graminoids –	30	1.7			
PTAQ	*Pteridium aquilinum*	western brackenfern	30	10.9		
WHMO	*Whipplea modesta*	common whipplea	28	6.9		
MAGL2	*Madia glomerata*	mountain tarweed	26	1.3		
CEVE	*Ceanothus velutinus*	snowbrush ceanothus	25	7.0		
GASH	*Gaultheria shallon*	salal	25	3.2		
PSME	*Pseudotsuga menziessi*	Douglas-fir	24	1.1		
EPCI	*Epilobium ciliatum*	fringed willowherb	22	0.2		
HYRA3	*Hypochaeris radicata*	common cat's ear	21	0.8		
GAAP2	*Galium aparine*	cleavers	20	0.9		
MO	Mosses –	18	4.9			
CETH	*Ceanothus thyrsiflorus*	blueblossom	16	11.6		
RUPA	*Rubus parviflorus*	thimbleberry	15	4.3		
VIGL	*Viola glabella*	pioneer violet	15	0.4		
SEVU	*Senecio vulgaris*	old-man-in-the-spring	14	0.5		
VIAM	*Vicia americana*	American vetch	14	1.2		
LAPO3	*Lathyruphylluss poly*	leafy pea	11	1.9		
POMU	*Polystichum munitum*	western swordfern	11	3.3		
ANMA	*Anaphalis margaritacea*	western pearly everlasting	10	3.3		
HOFU	*Horkelia fusca*	pinewoods horkelia	10	0.5		
PREM	*Prunus emarginata*	bitter cherry	9	2.9		
PSCAT	*Pseudognaphalium thermale*	Wright's cudweed	9	1.6		
RONUH	*Rosa nutkana*	bristly nootka rose	9	2.7		
SA	*Salix* spp.	willow	9	3.0		
ACMA3	*Acer macrophyllum*	bigleaf maple	8	6.0		
OXOR	*Oxalis oregana*	redwood sorrel	8	1.6		
SYAL	*Symphoricarpos albus*	common snowberry	8	1.2		
XETE	*Xerophyllum tenax*	bear grass	8	3.4		
ARCO3	*Arctostaphylos columbiana*	hairy manzanita	7	2.9		
HIAL2	*Hieracium albiflorum*	white hawkweed	7	0.4		
MYMU	*Mycelis muralis*	wall lettuce	7	0.2		
RULE	*Rubus leucodermis*	whitebark raspberry	7	2.7		

VAME	*Vaccinium membranaceum*	thinleaf huckleberry	7	1.0		
VAPL	*Vancouveria planipetala*	redwood inside out flower	7	0.3		
VISE3	*Viola sempervirens*	evergreen violet	7	1.0		
COCO6	*Corylus cornuta*	beaked hazelnut	6	0.7		
DIFO	*Dicentra formosa*	Pacific bleeding heart	6	0.5		
EUSP5	*Euchiton sphaericus*	globe cottonleaf	6	0.7		
RULA	*Rubus lasiococcus*	dwarf bramble	6	0.7		
ACCI	*Acer circinatum*	vine maple	5	3.2		
ADBI	*Adenocaulon bicolor*	American trailplant	5	0.6		
CHCH	*Chrysolepis chrysophylla*	golden chinkapin	5	1.4		
CIAR4	*Cirsium arvense*	Canada thistle	5	2.2		
PRHO2	*Prosartes hookeri*	drops-of-gold	5	0.8		
RHMA3	*Rhododendron macrophyllum*	Pacific rhodadendron	5	6.5		
VISA	*Vicia sativa*	common vetch	5	2.2		
CEINM	*Ceanothus integerrimus*	deerbrush	4	0.3		
FRVE	*Fragaria vesca*	woodland strawberry	4	0.5		
LEAU2	*Scorzoneroides autumnalis*	fall dandelion	4	2.6		
PAMY	*Paxistima myrsinites*	Oregon boxleaf	4	1.2		
RISA	*Ribes sanguineum*	red flowering currant	4	3.5		
SOAS	*Sonchus asper*	prickly snowthistle	4	0.7		
SYMO	*Symphoricarpos mollis*	creeping snowberry	4	1.5		
VAPA	*Vaccinium parvifolium*	huckleberry	4	0.6		
ACTR	*Achlys triphylla*	vanilla leaf	3	2.3		
ARME	*Arbutus menziesii*	Pacific madrone	3	5.3		
CIVU	*Cirsium vulgare*	bull thistle	3	0.4		
HODI	*Holodiscus discolor*	ocean spray	3	0.4		
LASE	*Lactuca serriola*	prickly lettuce	3	0.2		
LIBO3	*Linnaea borealis*	twinflower	3	1.6		
MADI	*Maianthemum dilatatum*	false lily of the valley	3	0.4		
PICO	*Pinus contorta*	lodgepole pine	3	0.2		
ROCA2	*Rosa californica*	California wildrose	3	0.3		
SANIC5	*Sambucus nigra*	blue elderberry	3	1.9		
STRI	*Stachys rigida*	rough hedgenettle	3	0.2		
TOAR	*Torilis arvensis*	spreading hedgeparsley	3	0.5		
TODI	*Toxicodendron diversilobum*	poison oak	3	1.1		
VASC	*Vaccinium scoparium*	grouse whortleberry	3	0.5		
APAN2	*Apocynum androsaemifolium*	spreading dogbane	2	1.2		
CAHI3	*Cardamine hirsuta*	hairy bittercress	2	1.3		
CHUM	*Chimaphila umbellata*	pipsissewa	2	0.1		
CLPE	*Claytonia perfoliata*	miner's lettuce	2	0.5		
CLSI2	*Claytonia sibirica*	candyflower	2	2.4		
CONU4	*Cornus nuttallii*	Pacific dogwood	2	0.4		
FRPU7	*Frangula purshiana*	cascara	2	1.1		
GERO	*Geranium robertianum*	Robert geranium	2	2.8		
IRTE	*Iris tenax*	toughleaf iris	2	0.2		
LOUNU	*Lotus unifoliolatus*	American bird's-foot trefoil	2	4.0		

LULA4	*Lupinus latifolius*	broadleaf lupine	2	0.4			
RUAR9	*Rubus armeniacus*	Himalayan blackberry	2	0.6			
SESY	*Senecio sylvaticus*	woodland ragwort	2	4.7			
STBU	*Stachys bullata*	California hedgenettle	2	2.5			
ACRU2	*Actaea rubra*	red baneberry	1	0.4			
AGGR	*Agoseris grandiflora*	bigflower agoseris	1	0.1			
ALRU2	*Alnus rubra*	red alder	1	4.7			
ANOR	Anemone oregana	blue windflower	1	0.4			
ARCA2	*Aralia californica*	California spikenard	1	7.8			
ARHI	*Arabis hirsuta*	hairy rockcress	1	1.9			
ARNE	*Arctostaphylos nevadensis*	pinemat manzanita	1	0.4			
ARPA6	*Arctostaphylos patula*	greenleaf manzanita	1	0.4			
ASCA2	*Asarum caudatum*	western wild ginger	1	1.9			
ASFA	*Asclepias fascicularis*	mexican whorled milkweed	1	0.3			
ATFI	*Athyrium filix-femina*	common ladyfern	1	0.1			
BLSP	*Struthiopteris spicant*	deer fern	1	4.7			
CASEI3	*Calystegia sepium*	hedge false bindweed	1	0.4			
CECO	*Ceanothus cordulatus*	whitethorn ceanothus	1	4.8			
CLUN2	*Clintonia uniflora*	bride’s bonnet	1	0.5			
COCAC3	*Conyza canadensis*	Canadian fleabane	1	12.5			
CRCA3	*Crepis capillaris*	smooth hawksbeard	1	0.1			
CRST2	*Cryptogramma stelleri*	fragile rockbrake	1	0.1			
CYSC4	*Cytisus scoparius*	scotch broom	1	0.1			
EQTE	Equisetum telmateia	giant Horsetail	1	21.8			
GACI2	*Galium circaezans*	licoriche bedstraw	1	0.4			
GEOR2	*Geranium oreganum*	Oregon geranium	1	2.1			
GOOB2	*Goodyera oblongifolia*	western rattlesnake plantain	1	0.4			
HOLOD	*Holodiscus discolor*	oceanspray	1	0.4			
HYPE	*Hypericum perforatum*	common St. Johnswort	1	0.1			
LETA	*Leontodon taraxacoides*	lesser hawkbit	1	0.1			
LEVU	*Leucanthemum vulgare*	oxeye daisy	1	0.1			
LYAM3	*Lysichiton americanus*	American skunkcabbage	1	4.7			
NEME	*Nemophila menziesii*	baby blue eyes	1	0.1			
OSOC	*Osmorhiza occidentalis*	western sweetroot	1	0.1			
PEDA2	*Penstemon davidsonii*	Davidson's penstemon	1	0.4			
PEFR5	*Petasites frigidus*	coltsfoot	1	1.9			
PHCA11	*Physocarpus capitatus*	Pacific ninebark	1	0.4			
PHMU2	*Phacelia mutabilis*	changeable phacelia	1	3.8			
PHNE2	*Phacelia nemoralis*	shade phacelia	1	0.1			
POTE	*Polycarpon tetraphyllum*	fourleaf manyseed	1	0.1			
PRVU	*Prunella vulgaris*	common selfheal	1	0.4			
PYPI2	P*yrola picta*	whiteveined wintergreen	1	0.1			
RIME	*Ribes menziesii*	canyon gooseberry	1	0.4			
ROGY	*Rosa gymnocarpa*	baldhip rose	1	0.1			
RUPH3	*Rupertia physodes*	forest scurfpea	1	6.9			
SIDO	*Silene douglasii*	Douglas's catchfly	1	0.1			

THPL	*Thuja plicata*	western redcedar	1	0.1
TOME	*Tolmiea menziesii*	piggyback plant	1	1.9
TROV2	*Trillium ovatum*	Pacific trillium	1	0.8
VACE	*Vaccinium cespitosum*	dwarf bilberry	1	0.1
VAOV	*Vaccinium ovalifolium*	oval leaf huckleberry	1	1.9

REFERENCES CITED

Abatzoglou, John T., et al. “Compound Extremes Drive the Western Oregon Wildfires of September 2020.” *Geophysical Research Letters*, vol. 48, no. 8, 2021, p. e2021GL092520. https://doi.org/10.1029/2021GL092520.

Agee, J. K. *Fire Ecology of Pacific Northwest Forests*. 1st ed., Island Press, 1993.

Agee, J. K., and M. H. Huff. “Fuel Succession in a Western Hemlock/Douglas-Fir Forest.” *Canadian Journal of Forest Research*, vol. 17, 1987, pp. 697–704. https://doi.org/10.1139/x87-112.

Anderson, M. J. “A New Method for Non-Parametric Multivariate Analysis of Variance.” *Austral Ecology*, vol. 26, 2001, pp. 32–46.

Archibald, S., et al. “Biological and Geophysical Feedbacks with Fire in the Earth System.” *Environmental Research Letters*, vol. 13, no. 3, 2018, p. 033003. https://doi.org/10.1088/1748-9326/aa9ead.

Brown, James K. “Handbook for Inventorying Downed Woody Material.” Gen. Tech. Rep. INT-16. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, 1974.

Brown, Martin J., et al. *Natural Tree Regeneration and Coarse Woody Debris Dynamics after a Forest Fire in the Western Cascade Range*. PNW-RP-592, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 2013. https://doi.org/10.2737/PNW-RP-592.

Buma, B., et al. “Wildland Fire Reburning Trends across the US West Suggest Only Short-Term Negative Feedback and Differing Climatic Effects.” *Environmental Research Letters*, vol. 15, no. 3, 2020, p. 034026. https://doi.org/10.1088/1748-9326/ab6c70.

Burke, C. J. 1979. *Historic Fires in the Central Western Cascades, Oregon*. Corvallis, OR: Oregon State University.

Busby, Sebastian Upton. *Forest Structure, Composition, and Regeneration after High-Severity and Rapidly Repeated Wildfires in the Central Cascade Range*. 2019.

Busby, Sebastian U., and Arndt M. Holz. “Interactions between Fire Refugia and Climate-Environment Conditions Determine Mesic Subalpine Forest Recovery after Large and Severe Wildfires.” 2022.

Crockett, J., and M. D. Hurteau. “Climate Limits Vegetation Green-Up More than Slope, Soil Erodibility, and Immediate Precipitation Following High-Severity Wildfire.” *Communications Earth & Environment*, 2024, Article 41. https://doi.org/10.1038/s43247-023-00954-8.

Cruz, M. G., and M. E. Alexander. “Assessing Crown Fire Potential in Coniferous Forests of Western North America: A Critique of Current Approaches and Recent Simulation Studies.” *International Journal of Wildland Fire*, vol. 19, no. 4, 2010, pp. 377–398.

De Cáceres, Miquel, et al. “Improving Indicator Species Analysis by Combining Groups of Sites.” *Oikos*, vol. 119, no. 10, 2010, pp. 1674–1684. https://doi.org/10.1111/j.1600-0706.2010.18334.x.

Dobrowski, Solomon Z., et al. “How Much Influence Does Landscape-Scale Physiography Have on Air Temperature in a Mountain Environment?” *Agricultural and Forest Meteorology*, vol. 149, no. 10, 2009, pp. 1751–1758. https://doi.org/10.1016/j.agrformet.2009.06.006.

Dye, Alex W., et al. “Simulated Future Shifts in Wildfire Regimes in Moist Forests of Pacific Northwest, USA.” *Journal of Geophysical Research: Biogeosciences*, vol. 129, no. 2, 2024, p. e2023JG007722. https://doi.org/10.1029/2023JG007722.

Finney, M. A. *FARSITE: Fire Area Simulator—Model Development and Evaluation*. USDA Forest Service, 2004.

Franklin, Jerry F., and C. T. Dyrness. *Natural Vegetation of Oregon and Washington*. Oregon State University Press, 1988.

Friesen, C., and F. J. Swanson. *Early Seral Forest in the Pacific Northwest: A Literature Review and Synthesis of Current Science*.

Halofsky, Joshua S., et al. “The Nature of the Beast: Examining Climate Adaptation Options in Forests with Stand-Replacing Fire Regimes.” *Ecosphere*, vol. 9, no. 3, 2018, p. e02140. https://doi.org/10.1002/ecs2.2140.

Hoadley, R. “The Tillamook Burn: Separating Fact from Legend.” U.S. Forest Service, 2001.

Hoecker, T. J., et al. “Widespread Exposure to Altered Fire Regimes under 2 °C Warming Is Projected to Transform Conifer Forests of the Western United States.” *Communications Earth & Environment*, vol. 4, 2023, p. 295. https://doi.org/10.1038/s43247-023-00954-8.

Johnston, James D., et al. “Exceptional Variability in Historical Fire Regimes across a Western Cascades Landscape, Oregon, USA.” *Ecosphere*, vol. 14, no. 12, 2023, p. e4735. https://doi.org/10.1002/ecs2.4735.

Keane, Robert E., and Laura J. Dickinson. *The Photoload Sampling Technique: Estimating Surface Fuel Loadings from Downward-Looking Photographs of Synthetic Fuelbeds*. RMRS-GTR-190, USDA Forest Service, Rocky Mountain Research Station, 2007.

Keane, R. E., et al. “Ecological Effects of Large Fires on US Landscapes: Benefit or Catastrophe?” *International Journal of Wildland Fire*, vol. 17, no. 6, 2008, pp. 696–712.

Keeley, Jon E., and Paul H. Zedler. “Large, High-Intensity Fire Events in Southern California Shrublands: Debunking the Fine-Grain Age Patch Model.” *Ecological Applications*, vol. 19, no. 1, 2009, pp. 69–94. https://doi.org/10.1890/08-0281.1.

Kennedy, Maureen C., et al. “Model Predictions of Postwildfire Woody Fuel Succession and Fire Behavior Are Sensitive to Fuel Dynamics Parameters.” *Forest Science*, vol. 67, no. 1, 2021, pp. 30–42. https://doi.org/10.1093/forsci/fxaa036.

Kitzberger, T., et al. “Decreases in Fire Spread Probability with Forest Age Promotes Alternative Community States, Reduced Resilience to Climate Variability.” *Ecosystems*, vol. 15, 2012, pp. 97–112.

Landesmann, Jennifer Brenda, et al. “Increased Fire Severity Triggers Positive Feedbacks of Greater Vegetation Flammability and Favors Plant Community-Type Conversions.” *Journal of Vegetation Science*, vol. 32, no. 1, 2021, p. e12936. https://doi.org/10.1111/jvs.12936.

McDowell, Nate G., et al. “Pervasive Shifts in Forest Dynamics in a Changing World.” *Science*, vol. 368, no. 6494, 2020, p. eaaz9463. https://doi.org/10.1126/science.aaz9463.

McWethy, D. B., et al. “A Conceptual Framework for Predicting Temperate Ecosystem Sensitivity to Human Impacts on Fire Regimes.” *Global Ecology and Biogeography*, vol. 22, no. 8, 2013, pp. 900–912. https://doi.org/10.1111/geb.12038.

Moritz, Max A., et al. “Climate Change and Disruptions to Global Fire Activity.” *Ecosphere*, vol. 3, no. 6, 2012, p. art49. https://doi.org/10.1890/ES11-00345.1.

Morrison, P. H., and F. J. Swanson. *Fire History and Pattern in a Cascade Range Landscape*. Gen. Tech. Rep. PNW-GTR-254. USDA Forest Service, Pacific Northwest Research Station, 1990.

Pausas, Juli G., et al. “Flammability as an Ecological and Evolutionary Driver.” *Journal of Ecology*, vol. 105, no. 2, 2017, pp. 289–297. https://doi.org/10.1111/1365-2745.12691.

Reilly, Matthew J., et al. “Cascadia Burning: The Historic, but Not Historically Unprecedented, 2020 Wildfires in the Pacific Northwest, USA.” *Ecosphere*, vol. 13, no. 6, 2022, p. e4070. https://doi.org/10.1002/ecs2.4070.

Scott, Joe H., and Robert E. Burgan. *Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel’s Surface Fire Spread Model*. RMRS-GTR-153. USDA Forest Service, Rocky Mountain Research Station, 2005. https://doi.org/10.2737/RMRS-GTR-153.

Sheehan, T., Bachelet, D., & Ferschweiler, K. (2015). “Projected major fire and vegetation changes in the Pacific Northwest of the conterminous United States under selected CMIP5 climate futures.” *Ecological Modelling*, 317, 16–29.

Smith, Robert J., et al. “Peak Plant Diversity during Early Forest Development in the Western United States.” *Forest Ecology and Management*, vol. 475, 2020, p. 118410. https://doi.org/10.1016/j.foreco.2020.118410.

Spies, T. A., et al. (2018). *Synthesis of Science to Inform Land Management within the Northwest Forest Plan Area: Executive Summary*.

Swanson, M. E., et al. “The Forgotten Stage of Forest Succession: Early-Successional Ecosystems on Forest Sites.” *Frontiers in Ecology and the Environment*, vol. 9, 2011, pp. 117–125.

Teensma, Peter Dominic Adrian. *Fire History and Fire Regimes of the Central Western Cascades of Oregon*. University of Oregon, 1987.

Tepley, A. J., et al. “Vulnerability to Forest Loss through Altered Postfire Recovery Dynamics in a Warming Climate in the Klamath Mountains.” *Global Change Biology*, vol. 23, 2017, pp. 4117–4132.

Tepley, Alan J., et al. “Influences of Fire–Vegetation Feedbacks and Post-Fire Recovery Rates on Forest Landscape Vulnerability to Altered Fire Regimes.” *Journal of Ecology*, vol. 106, no. 5, 2018, pp. 1925–1940. https://doi.org/10.1111/1365-2745.12950.

Warton, D. I., Wright, T. W., and Wang, Y. “Distance-Based Multivariate Analyses Confound Location and Dispersion Effects.” *Methods in Ecology and Evolution*, vol. 3, 2012, pp. 89–101.