

Fire Resistance in Planted Western Larch Stands
under Tribal Stewardship on the Colville Reservation

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Abstract

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Wildfire severity in the interior Pacific Northwest has increased over recent decades due to interacting climatic, ecological, and management drivers that have contributed to longer fire seasons, warmer temperatures, and altered fuel structures. Understanding how forest composition, stand structure, and fuel bed characteristics influence fire behavior and post-fire resilience is critical for managing semi-arid conifer forests under a changing climate. In this thesis, we examine these dynamics through two complementary studies of planted western larch (*Larix occidentalis*) stands on the Colville Reservation, where Tribally led forest management and long-term investments in western larch restoration provide a unique opportunity to evaluate wildfire resilience across multiple ecological scales.

Chapter 1 establishes the ecological, historical, and epistemological foundations of this research. We review historical fire regimes in the inland Pacific Northwest, the role of Indigenous fire stewardship in shaping landscape heterogeneity before colonial disruption, and the consequences of fire exclusion and climate change for contemporary forest and fire dynamics. We also introduce the ecology of western larch, including its fire-adaptive traits and its potential functional roles as both a fire resister and a fire impeder. Finally, we situate this research within a co-produced framework developed under Tribal authority and leadership, where research questions, analytical priorities, and interpretations were developed in partnership with the Confederated Tribes of the Colville Reservation.

In Chapter 2, we evaluate fire outcomes in planted western larch stands across approximately 137

restoration units spanning three wildfire footprints: the 2015 North Star Fire, the 2021 Summit Trail Fire, and the 2024 Swawilla Basin Fire. We quantified burn severity within planted western larch stands and adjacent unplanted forests using satellite-derived spectral indices and a validated Random Forest model implemented in Google Earth Engine (Parks et al., 2019). To assess structural factors associated with observed fire effects, we measured understory structure and surface fuel loads in 10 burned plots within planted western larch stands, 9 unburned plots within planted western larch stands, and 6 untreated mixed-conifer plots within the Summit Trail Fire footprint, and compared these measurements with six unburned high-elevation mixed-conifer forest plots. Our results show that planted western larch stands exhibited distinct fire effects relative to surrounding forests across the three wildfire footprints. Landscape-scale analyses indicated that planted western larch stands generally experienced lower modeled burn severity (Composite Burn Index [CBI]) than adjacent unplanted forests, with significantly lower severity observed in two of the three fires examined. Field measurements showed that adjacent mixed-conifer forests contained significantly greater dead woody fuel loads, whereas planted western larch stands supported greater live shrub cover. These differences suggest that variation in stand structure and fuel composition may contribute to observed burn severity patterns. However, we detected no significant difference in burn severity within the Swawilla Basin Fire, indicating that the influence of planted stand conditions on wildfire outcomes varies with species composition, fuel characteristics, stand structure, and fire context.

In Chapter 3, we investigate the fuel bed properties of western larch and co-occurring pine species through controlled laboratory assessments of moisture retention dynamics and flammability.

While Chapter 2 evaluates fire effects at the stand and landscape scales, Chapter 3 isolates the surface-fuel component of these systems to examine how species composition influences fuel moisture dynamics and combustion behavior. We reconstructed fuel beds from field-collected needle litter across nine compositional gradients spanning pure western larch, pure lodgepole pine, pure ponderosa pine, and mixed larch–pine combinations. We evaluated each fuel bed under both oven-dry and equilibrium moisture content (EMC) treatments.

Our results demonstrate that western larch fuel beds retained significantly more moisture than pine fuel beds, reaching more than five times the saturation moisture content of ponderosa pine litter. Western larch fuel beds also exhibited lower flammability across all five measured combustion metrics: flame height, fuel consumption, flaming duration, smoldering duration, and total burn duration. Mixed fuel beds containing western larch showed intermediate but consistently reduced combustion relative to pure pine fuel beds, with fire-moderating effects becoming most pronounced when western larch represented approximately 50% or more of fuel bed mass. These findings provide a mechanistic basis for interpreting the stand- and landscape-scale burn severity patterns observed in Chapter 2 and suggest that western larch restoration may influence surface fuel characteristics across mixed-conifer forests of the Colville Reservation.

In Chapter 4, we synthesize findings from Chapters 2 and 3 within the broader ecological and management context established in Chapter 1. We integrate landscape-scale burn severity patterns with laboratory-scale flammability mechanisms to develop a multi-scale interpretation of western larch fire performance. We identify the structural and compositional conditions under which western larch may most strongly moderate fire effects and discuss the implications of these findings for Tribal forest restoration planning on the Colville Reservation. We also address key limitations of the current evidence base and identify priority directions for future co-produced research.

Together, these chapters demonstrate that fire outcomes in planted western larch stands emerge from interactions among species traits, stand structure, and surface fuel composition, even before the full development of mature fire-resistance characteristics. This work provides mechanistic insight into how planted western larch may contribute to fire-adapted forest restoration and climate adaptation strategies in semi-arid landscapes. More broadly, this research supports ongoing Tribal-led restoration efforts by evaluating the ecological outcomes of long-term western larch restoration investments on the Colville Reservation.

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I am grateful not only to the people who supported this research, but also to the forests themselves. Spending time in these landscapes changed the way I understand disturbance, recovery, adaptation, and survival. The forests I worked in had endured fire, drought, management legacies, and ongoing change, yet they continued to regenerate, persist, and teach. They reminded me that resilience is

not the absence of hardship, but the capacity to keep living through transformation. Those lessons shaped this research, but they also shaped the person I became while completing it.

I would like to express my deepest gratitude to my mother, an English teacher and the primary provider for our family, whose sacrifices made this journey possible long before I fully understood what it would demand. She carried the weight of our family with extraordinary strength and dignity, often putting her own needs aside so that I could have opportunities she never had herself. From an early age, she taught me that education was something no one could take away. She instilled in me the discipline, resilience, and determination that carried me through every stage of this work. In the moments when I doubted myself, felt exhausted, or wanted to give up, her belief in me never wavered. This thesis is as much a reflection of her labor, sacrifice, and love as it is of my own work. I would not be here without her.

I am also deeply grateful to my Brazilian family, friends, and community for sustaining me emotionally throughout this journey. Living and studying far from home often came with a profound sense of distance and loneliness, but they continually reminded me of who I am, where I come from, and why perseverance matters. Through late-night phone calls, messages of encouragement, humor, affection, and unwavering belief in me, they carried me through some of the hardest moments of graduate school. Their warmth, resilience, and love grounded me in ways that academia never could. No matter how far away I was, they made sure I never felt alone.

Finally, I would like to acknowledge my spirit guides and ancestors, whose presence and protection I felt throughout this journey in ways that are difficult to fully express in academic language. This master's degree taught me not only about ecology, fire, and research, but also about faith, intuition, resilience, and the unseen forms of strength that carried me through moments of uncertainty. There were many times when I felt guided, protected, and reminded that I was not walking this path alone. I carry deep gratitude for that spiritual grounding, and for all those who came before me and made my path possible.

Mojubá. Axé!

Researcher Positionality and Theoretical Orientation

Who I Am, Where I Speak From, How and Why I Approached This Work

I approach this research as a Brazilian scholar from a working-class background in the interior of São Paulo, shaped by movement across distinct social, cultural, linguistic, and institutional contexts. I was born in the United States but raised in Brazil after my family returned following post–September 11 immigration reforms. Growing up between countries, languages, and expectations shaped my attentiveness to belonging, displacement, and the institutional forces that determine whose knowledge, labor, and relationships are recognized. These experiences inform how I enter research relationships, especially in contexts where academic and governmental institutions have historically caused harm.

My family background reflects layered colonial histories. On my mother’s side, my grandparents carried mixed European and Indigenous ancestry, but they were assimilated and unaffiliated with any Tribal nation. I do not claim formal Indigenous affiliation. Rather, I carry a syncretic Afro-Indigenous spiritual inheritance rooted in Brazil’s histories of colonization, resistance, and cultural survival. I do not mobilize this inheritance to claim Indigenous identity. Instead, I situate myself as a researcher of mixed descent working on Indigenous lands as a guest, collaborator, and learner.

The asymmetries of global knowledge production have also shaped my academic formation. I have been trained within institutions that often extract local knowledge from the Global South while failing to reciprocate credit, resources, or accountability. My own experiences of displacement have sharpened my ability to recognize extractive research logics and strengthened my commitment to refusing them. As a result, I approach this work with sustained attention to how colonial power operates through research institutions, methods, and claims to objectivity (Tuhiwai Smith, 1999; Wilson, 2008).

I am not a member of the Confederated Tribes of the Colville Reservation, and I enter this research as an outsider. For that reason, I approach this work with humility, accountability, and an understanding that the authority to define the meaning, relevance, and use of this research rests with the Tribes. Navigating both Global South and predominantly white North American academic contexts

has made me attentive to how academic institutions legitimize some knowledge systems while marginalizing others. That experience has shaped my commitment to treating Western science as one knowledge system among many, rather than as a universal standard against which other ways of knowing must be measured. In this project, I center Tribal authority, governance, and epistemologies by recognizing Indigenous nations as sovereigns who guide the framing, execution, interpretation, and use of research conducted on their lands.

I situate this thesis within critical Indigenous and decolonial scholarship that cautions against reducing decolonization to metaphor (Tuck & Yang, 2012). Following Tuhiwai Smith (1999), Whyte (2018), and Coulthard (2014), I understand decolonization as requiring structural shifts in authority over research questions, data, methods, analysis, interpretation, and benefit. In this project, Tribal leadership shaped the research questions, Tribal governance guided the analytical framework, and Tribal forest managers contributed to the interpretation of findings.

Within this context, I treat Western methodological rigor not as fixed or universal, but as something researchers must continually interrogate and rework (Wilson, 2008). Rather than forcing Indigenous priorities into established academic conventions, I adapted methods, timelines, and analytical frameworks to remain accountable to Tribal governance and community-defined meanings of relevance and success. This approach does not abandon rigor. It redefines rigor by rejecting the assumption that credible research requires detachment, extraction, or epistemic hierarchy.

Ongoing reflexivity remains central to this work. I recognize that scientific institutions continue to enact epistemic violence when they marginalize Indigenous knowledge systems or treat them as secondary to Western science (Deloria, 1969; TallBear, 2014). My own experiences navigating academia as a Latina woman of color have heightened my awareness of how institutions distribute legitimacy and authority unevenly. While these experiences remain distinct from Indigenous experiences of dispossession, they deepen my attentiveness to power and strengthen my commitment to research practices grounded in accountability rather than extraction.

My research orientation also draws from Tuck's (2009) critique of damage-centered research. Rather than framing Indigenous communities through vulnerability, loss, or deficit, this thesis

adopts a desire-based framework that centers sovereignty, leadership, capacity, resilience, and self-determined futures. The central research question—*how planted western larch stands perform under fire and climate stress*—emerged from Tribal leadership and reflects ongoing stewardship priorities rather than externally imposed narratives of vulnerability.

This project developed through collaboration with the Confederated Tribes of the Colville Reservation following fieldwork conducted in 2022. From its inception, Tribal priorities guided the research, and principles of reciprocity, accountability, and respect for sovereignty shaped its design. Tribal leadership co-developed the project, and Tribal collaborators reviewed its framing as part of that ongoing partnership.

Ultimately, this work reflects a sustained partnership with Tribal forest managers, technicians, and leaders whose expertise and lifelong dedication are foundational to this thesis. Centering their knowledge is not only an ethical responsibility; it is also necessary for producing research that is relevant, accountable, and ecologically meaningful.

My hope is that this thesis contributes to fire-resilient forest restoration and climate adaptation while supporting research practices grounded in care, reciprocity, and respect for Indigenous sovereignty.

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Figure 27. Modeled percent difference in fuel loads between planted western larch and mixed-conifer forest. Points show estimated percent change in planted stands relative to mixed-conifer

controls from linear mixed-effects models fit separately for each fuel class ($\log_{1+1}$ -transformed loads $\sim$ plot type + (1|subplot)); error bars show 95% confidence intervals. Woody fuel classes (blue) show significant reductions in planted stands across all size classes, with the largest effect in the 1000-hr class. Live fuel classes (green; herbs and shrubs) show modest but significant increases in planted stands. The dashed vertical line at zero indicates no difference.

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orange). Compact letter display (CLD) indicates results of Tukey HSD post-hoc comparisons; compositions sharing a letter are not significantly different (one-way ANOVA: $F_{8,36} = 3.59$, $p = 0.004$). Pure larch had the longest mean τ (15.3 ± 1.8 hours), while 70% ponderosa / 30% larch, 100% ponderosa, and 100% lodgepole pine had the shortest (7.0–7.2 hours).

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composition means ± 1 SE. PC1 scores declined strongly and near-monotonically with increasing larch proportion, indicating systematic dampening of fire intensity across the larch composition gradient.

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Chapter 1: Western Larch Restoration and Fire-Adapted Ecosystems Across Scales

1.1 Introduction: Fire as an Ecological Process

1.1.1 Fire as an ecological process in the Americas

Fire has shaped terrestrial ecosystems across the Americas for millennia, influencing vegetation patterns, species composition, and ecosystem processes (Agee, 1993; Pausas & Keeley, 2009; Perry et al., 2011; Pivello, 2011). Rather than functioning solely as a destructive force, recurring fire has contributed to the development and maintenance of diverse fire-adapted plant communities. Fire regimes, defined by variation in frequency, intensity, severity, seasonality, and spatial extent, create different ecological conditions and selective pressures across landscapes (Agee, 1993; Pausas et al., 2017).

Across the Americas, fire regimes and vegetation patterns have also been shaped by long-term interactions between people and ecosystems. Archaeological, paleoecological, and historical evidence increasingly demonstrates that Indigenous societies influenced landscape structure through intentional burning, cultivation, species movement, and resource management practices over centuries to millennia (Balée, 2006; Boyd, 1999; Denevan, 1992; Heckenberger et al., 2007; Levis et al., 2024; Neves & Petersen, 2006). Rather than isolated populations occupying untouched landscapes, Indigenous societies maintained extensive routes of travel, trade, and communication that connected ecosystems across broad geographic regions. In Amazonia, archaeological evidence demonstrates that river corridors functioned as major pathways connecting communities and facilitating the movement of people, crops, technologies, and ecological knowledge across large landscapes (Heckenberger et al., 2007; Neves & Petersen, 2006). These interconnected social–ecological systems contributed to the distribution of culturally important species, the creation of anthropogenic landscapes, and the maintenance of heterogeneous vegetation patterns across the Americas (Balée, 2006; Levis et al., 2024). Recognition of these long-term human influences challenges interpretations of pre-colonial ecosystems as unmanaged wilderness and highlights the importance of considering Indigenous stewardship as a component of historical disturbance

regimes (Denevan, 1992; Fletcher et al., 2021; Jessen et al., 2022).

Plant species in fire-adapted ecosystems have evolved a range of strategies that promote persistence under recurring disturbance. These include traits that increase resistance to fire injury, such as thick insulating bark, elevated crown base heights, and protection of living tissues, as well as traits that support post-fire recovery, including serotinous cones, resprouting capacity, and rapid establishment following disturbance (Agee, 1993; Keeley et al., 2011; Pausas et al., 2017). Over ecological and evolutionary timescales, interactions among fire, climate, vegetation, and topography have contributed to spatial and temporal heterogeneity in forest structure, species composition, and successional stages (Hessburg et al., 2019, 2021; Perry et al., 2011).

In fire-adapted forests, disturbance regimes emerge from complex interactions among climate, topography, vegetation structure, and ignition patterns, producing characteristic fire return intervals, severity patterns, and patch size distributions. In the mixed-conifer forests of the inland Pacific Northwest, historical fire regimes included frequent low- to moderate-severity surface fires interspersed with less frequent high-severity events, creating shifting mosaics of forest age classes, densities, and structures (Agee, 1993; Hessburg et al., 2005; Heyerdahl et al., 2001; Perry et al., 2011). These mixed-severity regimes maintained heterogeneous forest conditions, moderated ladder fuel development, and favored species with traits that increase survival under recurring fire, including western larch (*Larix occidentalis*), ponderosa pine (*Pinus ponderosa*), and Douglas-fir (*Pseudotsuga menziesii*) (Agee, 1993; Arno & Fischer, 1995; Barrett et al., 1991; Schmidt et al., 1976).

The ecological role of fire extends beyond vegetation mortality to influence nutrient cycling, seedbed conditions, competitive interactions, and plant regeneration processes. At the individual plant scale, fire acts as a selective pressure influencing traits related to survival and recovery, including protective morphology, resource allocation strategies, and post-fire regeneration mechanisms (Keeley et al., 2011; Pausas et al., 2017). Variation in fire effects across space and time contributes to structural complexity, from individual tree survival patterns to landscape-level mosaics of burn severity that support diverse habitat conditions and ecological processes (Hessburg

et al., 2019, 2021; Perry et al., 2011).

Understanding fire as an ecological process requires recognizing that fire regimes are dynamic and respond to changes in climate, vegetation, and human land use. Contemporary departures from historical fire regimes can therefore alter ecosystem structure, composition, and resilience by changing the disturbance processes under which these forests developed (Hagmann et al., 2021; Hessburg et al., 2021).

1.1.2 Climate, Vegetation, and Fuel Traits Across Fire-Prone Landscapes

Fire behavior and fire regime characteristics are shaped by interactions among climate, vegetation structure, and fuel properties across fire-prone landscapes. Climate influences fire activity through multiple pathways, including temperature, precipitation patterns, atmospheric moisture deficits, and wind regimes that collectively influence fuel moisture, fire weather conditions, and fire season length (Wasserman & Muller, 2023). Vegetation structure and composition further mediate fire behavior through fuel arrangement, continuity, and flammability traits. Fuel characteristics such as particle size, bulk density, moisture retention capacity, and chemical composition influence ignitability, rates of spread, combustion efficiency, and fire intensity (Pausas et al., 2017; Varner et al., 2015).

Plant functional traits related to fire response and flammability vary widely across species and functional groups, reflecting different ecological strategies shaped by historical fire regimes. Stevens et al. (2020) developed a trait-based framework for western U.S. conifer forests that evaluated species using an integrated fire resistance index combining bark thickness, maximum tree height, self-pruning capacity, and litter flammability characteristics. This analysis demonstrated that species associated with frequent-fire environments often exhibit traits that increase individual survival during fire, such as thick bark and elevated crowns, while also producing fuels that vary widely in their influence on surface fire behavior (Stevens et al., 2020; Varner et al., 2015).

The distinction between fire resisters and fire impellers separates species that tolerate fire through morphological resistance traits from species whose litter properties reduce surface fuel flammabil-

ity (Varner et al., 2015). Fire-resistant conifers such as ponderosa pine often combine thick bark and high crown base heights with relatively flammable litter that promotes rapid surface fire spread and shorter combustion residence times. This combination can facilitate low-severity surface fire regimes where mature trees survive repeated burning (Pausas et al., 2017; Schwilk, 2015).

In contrast, species with low-flammability litter reduce fire spread through fuel characteristics that limit ignition, combustion efficiency, or flame propagation, functioning as fire impeters rather than fire facilitators (Varner et al., 2015). Litter particle size, leaf area, moisture absorption capacity, and packing density are important determinants of fuel bed flammability. Shorter and thinner litter particles often create more compact fuel beds with reduced airflow, limiting oxygen availability and suppressing combustion under certain fuel moisture conditions (Burton et al., 2021; Campbell-Lochrie et al., 2021; Cornwell et al., 2015).

1.1.3 Indigenous Fire Stewardship and Landscape Management

First Nations across the Americas have maintained relationships with fire for millennia through governance systems, cultural responsibilities, and place-based stewardship practices. Intentional burning has supported food systems, culturally important species, wildlife habitat, resource abundance, and reciprocal relationships between people and landscapes (Kimmerer & Lake, 2001; Lake et al., 2017). Rather than representing a single management approach, Indigenous fire stewardship reflects diverse knowledge systems in which the timing, frequency, intensity, and location of burning are guided by ecosystem conditions, seasonal indicators, cultural responsibilities, and community-defined objectives.

Fire functions as a stewardship tool by managing resource availability, vegetation structure, and ecological processes. Through the removal of accumulated biomass, increased light availability, changes in nutrient cycling, and stimulation of resprouting, fire can promote conditions that support culturally desired plant communities, wildlife habitat, and natural resources essential to human survival (Keeley et al., 2011; Kimmerer & Lake, 2001). The application and ecological effects of fire vary across ecosystems depending on climate, productivity, vegetation structure, and fuel

dynamics. In more water-limited or lower-productivity ecosystems, frequent burning can maintain open vegetation structure, limit woody encroachment, and sustain herbaceous communities. In productive forests and mixed-severity systems, intentional burning can create openings, promote understory productivity, enhance food and medicinal plants, and generate habitat diversity for wildlife species (Kimmerer & Lake, 2001; Lake et al., 2017).

Across the Pacific Northwest, Indigenous fire stewardship has supported diverse objectives, including maintaining prairie and forest openings, improving habitat conditions for game species, increasing productivity of berry-producing shrubs, supporting culturally important plant materials, and sustaining self-sufficient livelihoods (Kimmerer & Lake, 2001; Lake et al., 2017). These practices reflect broader patterns documented across the Americas, where First Nation societies shaped vegetation composition, disturbance regimes, and landscape structure over centuries to millennia through diverse forms of land management and extensive networks of movement and exchange (Denevan, 1992; Heckenberger et al., 2007; Levis et al., 2024; Neves & Petersen, 2006). Archaeological, paleoecological, dendrochronological, and Indigenous Knowledge sources demonstrate that Indigenous fire stewardship influenced fire regimes and vegetation patterns across diverse ecosystems, contributing to landscape heterogeneity before widespread colonial disruption (Copes-Gerbitz et al., 2023; Roos et al., 2025).

However, many Euro-American descriptions of western North American landscapes were recorded only after Indigenous communities had already endured catastrophic population losses from introduced diseases, displacement, and restrictions on land access and governance (Boyd, 1999). As a result, settlers often encountered landscapes that had already been profoundly altered by the disruption of Indigenous stewardship, even as they interpreted those same landscapes as “natural,” “wild,” or untouched (Boyd, 1999). In many regions of the Americas, extensive Indigenous trade routes, river corridors, and social networks facilitated the movement of people, materials, crops, and information, which likely contributed to the spread of introduced diseases beyond areas of direct European contact (Crosby, 1972; Neves & Petersen, 2006). These disruptions reduced the continuity and spatial extent of Indigenous stewardship practices, including cultural

burning, meaning that early colonial descriptions reflected landscapes had already undergone much ecological and social transformation rather than conditions representative of long-term Indigenous management systems.

Research conducted through collaboration with Indigenous Knowledge systems and fire history methods has documented the extent and complexity of cultural burning practices across multiple regions. In the Karuk Aboriginal Territory in northern California, Greenler et al. (2024) estimated approximately 6,972 annual cultural ignitions, averaging 6.5 ignitions per steward. These fire patterns differed from contemporary ignition regimes and were guided by governance systems, intergenerational knowledge, seasonal conditions, fuel receptivity, and relationships with culturally important resources (Greenler et al., 2024).

Tree-ring reconstructions from Western Apache (Ndee) territory similarly indicate frequent, small, and asynchronous fires between 1600 and 1870 CE, with fire occurrence concentrated during seasonal subsistence activities and exhibiting patterns distinct from those driven solely by climate (Roos et al., 2025). These findings demonstrate that historical fire regimes cannot be understood solely as ecological processes separated from Indigenous governance systems, stewardship practices, and reciprocal relationships with place.

Indigenous fire stewardship contributed to landscape heterogeneity through spatially and temporally variable burning practices that influenced vegetation structure, successional patterns, habitat conditions, and culturally important resources. In British Columbia, Copes-Gerbitz et al. (2023) reconstructed a mixed-severity fire regime in Douglas-fir-dominated forests characterized by median fire intervals of 18 years at the plot scale and 4 years at the site scale. Their findings demonstrate that Indigenous stewardship contributed to frequent, low-severity fires in areas of sustained human use, reinforcing the role of cultural burning within historical fire regimes.



Figure 1. Prescribed burn conducted by the Confederated Tribes of the Colville Reservation, November 2024, with western larch in autumn foliage visible in the foreground. Photograph by Priscilla Sperandio.

1.1.4 Colonial Disruption, Tribal Self-Determination, and Contemporary Fire Governance

The historical fire regimes described above were not altered by climate, fuels, or forest succession alone. Colonial land policies disrupted Indigenous fire stewardship through forced displacement, the criminalization of Indigenous burning practices, institutional fire suppression, and changes in land governance. These disruptions, together with timber extraction and federal fire exclusion policies, altered disturbance processes and contributed to shifts in forest density, species composition, fuel structure, and fire behavior across many western North American forests (Copes-Gerbitz et al., 2023; Hagmann et al., 2021). At the same time, Indigenous fire stewardship was not eliminated. Many Indigenous Nations continued to maintain, adapt, and revitalize fire practices despite legal, political, and institutional constraints.

The expansion of Tribal self-determination policies created an important pathway for rebuilding Tribal authority over forest and natural resource management. The Indian Self-Determination and Education Assistance Act of 1975 (Public Law 93-638) supported greater Tribal administration of programs previously managed by federal agencies, including forestry and natural resource programs. Across Indian forests, this policy shift contributed to a gradual transition from externally administered management toward Tribal-led governance, allowing Tribal Nations to expand natural resource departments, employ Tribal staff and contractors, and develop management approaches grounded in community priorities and long-term stewardship objectives (Indian Forest Management Assessment Team, 1993, 2003, 2013).

On the Colville Reservation, this transition included a shift away from forest management historically administered primarily through the Bureau of Indian Affairs and toward increasing Tribal leadership, staffing, and decision-making authority. The development of Tribal forestry capacity enabled the Confederated Tribes of the Colville Reservation to expand local expertise and guide forest management according to Tribal priorities (Rellergert-Taylor & O'Dea, 1988). This institutional transition is part of a broader national pattern documented by the Indian Forest Management Assessment Team reports, which emphasize the role of Tribal forestry programs in integrating ecological restoration, cultural resources, wildlife habitat, economic self-determination, and responsibilities to future generations (Indian Forest Management Assessment Team, 1993, 2003, 2013).

Contemporary forest governance on the Colville Reservation reflects this history of disruption, persistence, and self-determination. The Confederated Tribes of the Colville Reservation's Integrated Resource Management Plan, Forest Management Plan, and Wildland Fire Management Plan establish priorities that integrate forest resilience, sustainable resource use, wildlife habitat, cultural values, and the continued availability of resources for current and future generations (Confederated Tribes of the Colville Reservation, 2018, 2023, n.d.). These governance frameworks support active stewardship approaches aimed at improving forest health, restoring fire-adapted forest conditions, and strengthening landscape resilience under changing climate and wildfire regimes.

Contemporary restoration initiatives, including precision forestry approaches, emerge from this governance context. Rather than treating fire resilience as a purely technical objective, Tribal-led forest management on the Colville Reservation links restoration, wildfire adaptation, cultural values, and community-defined priorities. This framing is central to understanding western larch restoration not only as a silvicultural or fire management strategy, but also as part of a broader Tribal-led effort to sustain resilient forest landscapes across generations.

1.1.5 Changing Fire Regimes in Western North America

1.1.5.1 Fire Exclusion and Structural Homogenization

Fire exclusion policies implemented across western North American forests beginning in the late nineteenth and early twentieth centuries have fundamentally altered forest structure, species composition, and fuel conditions, particularly in ecosystems historically shaped by frequent fire. The reduction of recurring surface fires, combined with historical timber harvest and changing land-use practices, has contributed to increased tree density, greater canopy continuity, altered species composition, and fuel accumulation across many dry and mixed-conifer forests (Agee, 1993; Hagmann et al., 2021; Hessburg et al., 2005, 2021). These structural changes interact with climate warming, increasing atmospheric aridity, and more extreme fire weather conditions, contributing to contemporary shifts in wildfire behavior and fire effects across western North America (Abatzoglou & Williams, 2016; Halofsky et al., 2020; Jolly et al., 2015).

Fire exclusion has contributed to widespread increases in stand density, canopy closure, and fuel continuity, particularly in forests historically characterized by frequent, low- to moderate-severity fire regimes. In many dry forests, reduced fire frequency has favored the establishment of shade-tolerant and fire-sensitive species, increased the abundance of small-diameter trees, and promoted the development of dense understory and midstory vegetation that can increase vertical fuel continuity (Hagmann et al., 2021; Hessburg et al., 2005; Keane et al., 2002). These changes have altered forest conditions that historically limited fire spread and severity, increasing the likelihood that fires occurring under hot, dry, and windy conditions may transition from surface

fires to higher-severity crown fires (Fischer et al., 2016; Hessburg et al., 2019, 2021).

The structural consequences of fire exclusion include increased canopy layering, multistoried forest structure, and greater surface and ladder fuel connectivity. Increased vertical fuel continuity can facilitate crown fire initiation and spread by connecting surface fuels with forest canopies, altering fire intensity and severity patterns (Keane et al., 2002; Vose et al., 2021). These structural departures have reduced resilience in many historically fire-prone forests by increasing vulnerability to drought stress, insect disturbance, and severe wildfire events (Hagmann et al., 2021; Hessburg et al., 2019, 2021).

Across the Pacific Northwest, the reduction of frequent fires has produced substantial departures from historical disturbance regimes. Haugo et al. (2019) described this pattern as a persistent “missing fire” deficit, estimating that forests across the region experienced substantially less fire between 1984 and 2015 than expected under historical fire regimes. This reduction has been particularly pronounced in dry forests adapted to frequent, low-severity fire, where altered disturbance processes have contributed to shifts in forest structure, composition, and landscape pattern (Hagmann et al., 2021; Haugo et al., 2019).

Fire exclusion has also contributed to landscape homogenization by reducing the spatial variability in stand ages, densities, structures, and species composition historically maintained by heterogeneous disturbance regimes. Historically, interactions among fire, topography, climate, and vegetation created shifting mosaics of forest conditions that supported landscape resilience (Hessburg et al., 2015, 2019; Perry et al., 2011). The reduction in these processes has contributed to more continuous forest structures and reduced landscape diversity, potentially limiting ecosystems' ability to buffer future disturbances under changing climate conditions (Cassell et al., 2019; Hessburg et al., 2021).

The interaction between fire exclusion and climate change represents a major driver of contemporary fire regime change. Warmer temperatures, increased vapor pressure deficits, earlier snowmelt, and longer fire seasons have intensified climatic constraints on forest resilience, interacting with accumulated fuels and altered forest structure (Abatzoglou & Williams, 2016; Halofsky et al.,

2020; Jolly et al., 2015). However, the relative importance of fuels and climate varies across ecosystems, with some landscapes primarily limited by fuel availability and others increasingly influenced by climate-driven fire weather. These interacting drivers highlight the importance of spatially explicit restoration and fuel management strategies that consider both historical departures and future climate conditions (Coop et al., 2020; Hanan et al., 2021; Parks et al., 2014).

1.1.5.2 Climate Change and Shifting Fire Regimes in Western North America

Climate change is altering fire regimes across western North America by changing the environmental conditions that regulate fuel moisture, fire weather, and vegetation dynamics. Rising temperatures, earlier snowmelt, longer dry seasons, and increasing atmospheric moisture demand have contributed to greater climatic water deficit, vapor pressure deficit, and evapotranspiration, reducing fuel moisture and increasing the frequency of conditions that support fire spread when fuels and ignitions are available (Abatzoglou & Williams, 2016; Jolly et al., 2015; Wasserman et al., 2023).

Multiple lines of evidence link climate warming to increased wildfire activity across western U.S. forests. Warmer and drier fire seasons have contributed to increases in area burned and area burned at high severity, with the strongest effects occurring where fuels remain abundant and fire-season aridity continues to increase (Parks & Abatzoglou, 2020; Parks et al., 2025). However, future fire effects will not be determined by climate alone, but by interactions among vegetation structure, fuel availability, topography, disturbance legacies, and restoration actions that influence how fire moves through landscapes.

Climate change influences fire regimes through both direct effects on fire weather and indirect effects on vegetation composition, fuel dynamics, and disturbance interactions. Increasing climatic water deficit, vapor pressure deficit, and evaporative demand interact with existing forest conditions to influence fire severity, patch size, and post-fire recovery trajectories (Halofsky et al., 2020; Wasserman et al., 2023). In some ecosystems, larger high-severity patches and more frequent fire events may reduce regeneration potential and increase the likelihood of vegetation

transitions where post-fire environments exceed the physiological tolerance or dispersal capacity of dominant tree species (Coop et al., 2020; Wasserman et al., 2023). Regional simulations for the Pacific Northwest project that continued warming and intensified summer drought conditions may increase both area burned and fire severity by the end of the twenty-first century (Halofsky et al., 2020; Rogers et al., 2011).

The 2020 Labor Day fires in the Pacific Northwest illustrate how extreme fire weather can overcome historical constraints on fire activity, including in ecosystems where large fires were historically less frequent. During this event, approximately 340,000 hectares burned west of the Cascade Range crest within two weeks, approaching the total area burned in the region during the previous five decades (Reilly et al., 2022). These fires demonstrate the influence of interacting climate drivers, including drought, low fuel moisture, and extreme wind events, on fire behavior and landscape-scale fire effects (Evers et al., 2022; Reilly et al., 2022).

The effects of changing fire regimes extend beyond vegetation structure and ecosystem processes, influencing relationships between people and landscapes. Changes in disturbance patterns can alter the availability, distribution, and timing of culturally important plants, wildlife habitat, and subsistence resources. For First Nations whose stewardship systems are rooted in long-term relationships with specific landscapes, climate-driven ecological change poses challenges to maintaining food systems, cultural practices, and resource sovereignty, while reinforcing the importance of Indigenous-led adaptation and restoration strategies (Lake et al., 2017; Whyte, 2018).

Across western North America, these interacting changes highlight the need for restoration approaches that account for altered climate conditions, historical land management legacies, and future disturbance dynamics. In fire-adapted forests of the interior Pacific Northwest, increasing resilience requires more than reducing fuels alone; it requires restoring ecological processes, supporting adaptive capacity, and promoting forest structures and species compositions that can persist under changing climate and fire regimes (Halofsky et al., 2020; Hessburg et al., 2021).

1.1.5.3 Increasing Burn Severity in Interior Pacific Northwest Forests

Fire regimes of the interior Pacific Northwest have historically included a wide range of fire effects, from frequent low-severity surface fires to mixed-severity events that produced complex mosaics of forest structure, species composition, and successional stages (Agee, 1993; Hessburg et al., 2005; Perry et al., 2011). Contemporary fire effects reflect the interaction of this historical variability with altered forest structure, changing climate conditions, and increasingly extreme fire weather. Although burn severity has not increased uniformly across all forests, shifts in the size, distribution, and ecological effects of high-severity fire have been documented across portions of western North America (Hagmann et al., 2021; Parks & Abatzoglou, 2020; Reilly et al., 2017).

In forests historically shaped by low- and mixed-severity fire, large high-severity patches raise concern when they exceed the spatial and ecological conditions under which dominant tree species established and persisted. Across Pacific Northwest vegetation zones associated with historically low- and mixed-severity fire regimes, Reilly et al. (2017) found that high-severity fire accounted for approximately 23–26% burned area, with nearly half occurring in patches (≥ 100) ha. These patterns can influence post-fire recovery by increasing distances to surviving seed sources, altering microclimatic conditions, and shaping regeneration trajectories (Coop et al., 2020; Reilly et al., 2017).

Burn severity patterns emerge from interactions among climate, fuels, vegetation structure, topography, and fire weather. In the northern Cascade Range of Washington, Cansler and McKenzie (2014) found that climate, fire size, fuel continuity, and topographic complexity influenced both the proportion and spatial aggregation of high-severity fire. Warmer and drier conditions can increase fire size and the likelihood of larger high-severity patches, while ecological outcomes depend on how climate drivers interact with pre-existing landscape conditions, fuel structure, and vegetation patterns (Cansler & McKenzie, 2014; Parks & Abatzoglou, 2020; Parks et al., 2025). Concerns over changing fire regimes are closely linked to questions of forest resilience and post-fire recovery. Larger high-severity patches and repeated short-interval fires may reduce conifer regeneration by limiting seed availability, increasing seedling exposure to drought stress, and

creating conditions that favor transitions toward alternative vegetation states (Busby et al., 2020; Coop et al., 2020). At the same time, post-fire trajectories vary across ecosystems and species, reflecting differences in fire adaptations, regeneration strategies, seed dispersal capacity, and tolerance to changing environmental conditions.

The spatial patterns of burn severity highlight the importance of restoring and maintaining landscape heterogeneity. Historically, variation in fire effects produced complex patterns of forest structure, species composition, and successional stages across the interior Pacific Northwest. Contemporary changes associated with climate, altered disturbance regimes, and past management practices underscore the need for restoration strategies that account for spatial variability, historical fire regimes, and future climate conditions (Hagmann et al., 2021; Hessburg et al., 2021; Perry et al., 2011).

In this context, restoration approaches that promote fire-adapted species composition and structural diversity may increase forest resilience under changing fire regimes. In the interior Pacific Northwest, understanding how fire-adapted species influence burn severity and post-fire outcomes is central to developing management strategies that support ecological function, adaptive capacity, and long-term forest persistence (Hessburg et al., 2021; Prichard et al., 2021; Stevens et al., 2020).

1.1.5.4 Ecological and Social Consequences of High-Severity Fire

High-severity fire is an important component of many fire-adapted ecosystems, contributing to landscape heterogeneity, wildlife habitat, nutrient cycling, and successional processes (Agee, 1993; Perry et al., 2011). However, changes in the frequency, size, and spatial arrangement of high-severity fire can alter forest recovery trajectories when disturbance patterns exceed the adaptive capacity of existing species and ecosystems. These outcomes are shaped by interactions among fire severity, climate conditions, seed availability, species traits, and subsequent disturbances (Coop et al., 2020; Turner & Seidl, 2023).

One concern associated with changing fire regimes is the potential for fire-catalyzed vegetation transitions. Large high-severity patches can reduce post-fire tree regeneration by increasing

distances from surviving seed sources and altering post-fire microclimates. Under warmer and drier conditions, regeneration may be further limited when post-fire environments exceed the establishment requirements of historically dominant tree species, increasing the likelihood of transitions toward alternative forest structures or non-forest vegetation types (Busby et al., 2020; Coop et al., 2020; Davis et al., 2023). These transitions can alter dominant species, ecosystem processes, and landscape functions, with implications for carbon storage, hydrology, wildlife habitat, and resource availability (Coop et al., 2020; Turner & Seidl, 2023).

The consequences of changing fire regimes extend beyond ecological structure and function, influencing relationships between communities and landscapes. Shifts in forest composition, wildlife habitat, and plant communities can affect the availability and distribution of culturally important species, subsistence resources, and ecosystem services. For First Nations, these changes intersect with ongoing efforts to maintain resource sovereignty, cultural practices, and stewardship responsibilities under rapidly changing environmental conditions (Copes-Gerbitz et al., 2022; Kimmerer & Lake, 2001; Lake et al., 2017; Whyte, 2018).

Communities living in fire-prone landscapes are also increasingly affected by interactions among wildfire, climate change, and development patterns. Longer fire seasons and larger fire events can increase smoke exposure, affect public health, threaten infrastructure, and create growing challenges for fire response and adaptation. At the same time, expanding development in these landscapes can reinforce management approaches that prioritize short-term risk reduction over long-term adaptation to living with fire (Fischer et al., 2016; Reid et al., 2016; Schoennagel et al., 2017).

Addressing changing fire regimes requires approaches that recognize fire as an inevitable ecological process while supporting adaptation across ecosystems and communities. Suppression-focused strategies alone are unlikely to maintain resilient landscapes under continued warming. Adaptive approaches increasingly emphasize restoring fire-adapted forest structures, reintroducing beneficial fire where appropriate, supporting species compositions suited to future conditions, and integrating ecological restoration with community-defined priorities (Halofsky et al., 2020; Hessburg et al.,

2021; Schoennagel et al., 2017).

Within the interior Pacific Northwest, these challenges have renewed interest in restoration strategies that increase resilience to changing disturbance regimes. Understanding how fire-adapted species influence forest structure, fuel characteristics, and post-fire outcomes is central to developing approaches that maintain ecological function and support long-term relationships between people and fire-adapted landscapes (Hessburg et al., 2021; Prichard et al., 2021; Stevens et al., 2020).

1.1.6 Western Larch Ecology and Restoration

1.1.6.1 Ecology and Distribution of Western Larch

Western larch is a deciduous conifer native to northwestern North America, occurring across the northern Rocky Mountains, eastern Cascade Range, interior British Columbia, and adjacent inland portions of the Pacific Northwest (Figure 2) (Keane, 2008; McCaughey & Schmidt, 1990; Schmidt et al., 1976). Across its range, western larch occurs in mixed-conifer forests with Douglas-fir, grand fir, western white pine, lodgepole pine, Engelmann spruce, and ponderosa pine. The species spans a broad elevational gradient, commonly occurring from approximately 460 to 1,700 m in the northern portion of its range and extending above 2,100 m in the southern portion. Western larch is often associated with cool, moist sites, relatively deep soils, and environments where sufficient moisture supports establishment and growth (Keane, 2008; McCaughey & Schmidt, 1990; Schmidt et al., 1976).

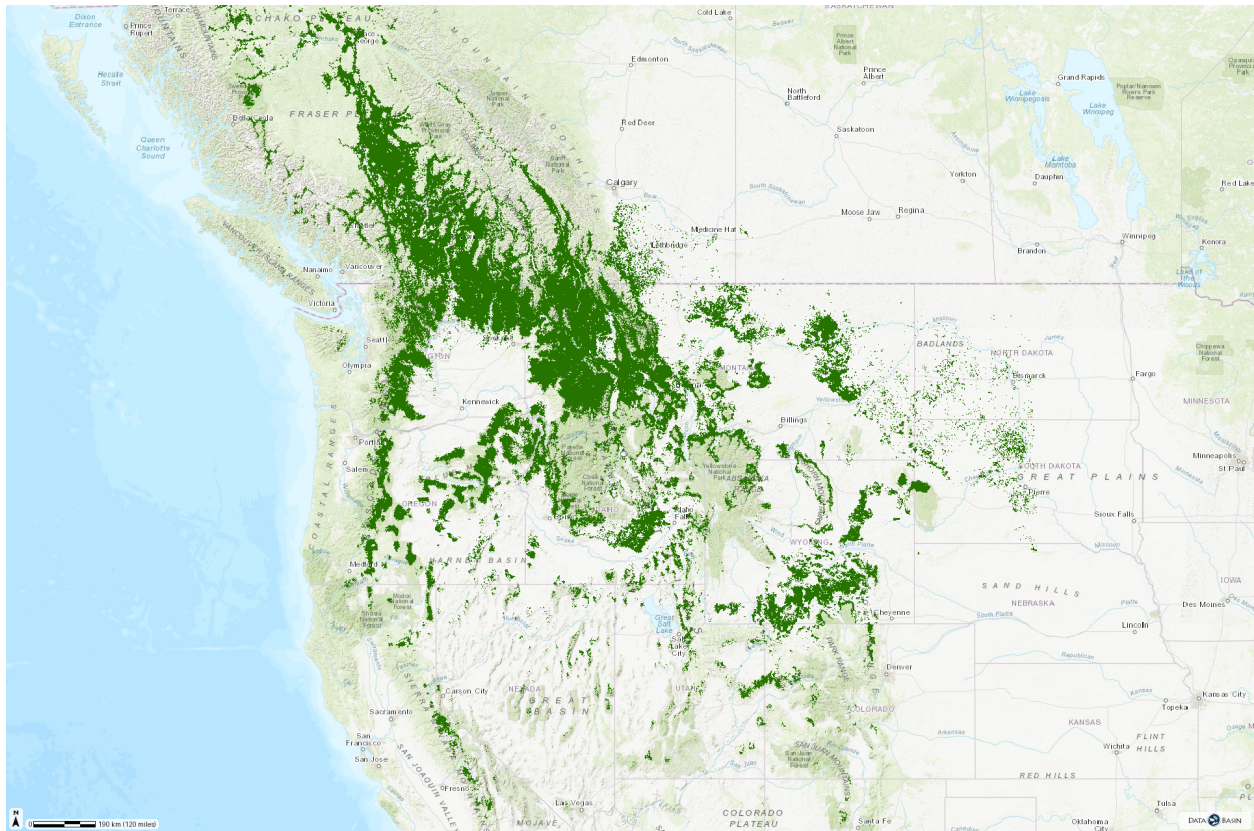


Figure 2. Modeled contemporary range of western larch in western North America based on species distribution models using climate conditions averaged from 1950 to 1975 at 1 km spatial resolution. Map retrieved from Mathys et al. (2014) via Data Basin.

Western larch occupies a distinctive ecological niche as a long-lived, shade-intolerant, early-seral species adapted to disturbance-driven forest dynamics. Following canopy-opening disturbances, including wildfire, western larch establishment is favored by increased light availability, exposed mineral soil, and reduced competition from shade-tolerant species (Arno & Fischer, 1995; Graham et al., 1995; Keane, 2008; Schmidt et al., 1976). Rapid early height growth allows seedlings and saplings to occupy growing space quickly and maintain access to light during early stand development. Other traits, including deciduous foliage (Figure 3), indeterminate growth, and flexible biomass allocation, further support the species' ability to respond to variable environmental conditions (Dumroese et al., 2020; Williams et al., 2018).



Figure 3. Alpine larch (*Larix lyallii*) in autumn foliage in the North Cascades, October 2024. Although distinct from western larch, alpine larch shares the deciduous habit characteristic of the genus *Larix*. Photograph by Priscilla Sperandio.

Unlike many associated conifers, western larch combines early-seral regeneration strategies with traits that allow mature individuals to persist through repeated disturbance events. Mature trees can live for several centuries and continue contributing seed for long periods once they reach reproductive maturity (Schmidt & Shearer, 1990). This longevity, combined with high fire resistance in mature trees, allows large western larch to persist as biological legacies following some disturbance events (Arno & Fischer, 1995; Schmidt & Shearer, 1990; Stevens et al., 2020) (Figure 4). Large living trees, snags, and decay-resistant wood contribute to forest structural complexity, provide important habitat features, and support post-disturbance recovery (Bisbing et al., 2010; Kilgore, 1981; Schmidt & Shearer, 1990; Williams et al., 2018).

The contemporary distribution and abundance of western larch reflect interactions among climate, disturbance history, and forest management. Historically, recurring fires helped maintain the open,

high-light, and exposed mineral soil conditions favorable for western larch establishment while limiting competition from more shade-tolerant species (Agee, 1993; Arno & Fischer, 1995; Barrett et al., 1991; Schmidt et al., 1976; Schmidt & Shearer, 1990). However, fire exclusion and selective harvesting during the late nineteenth and twentieth centuries reduced the abundance of mature western larch in portions of its range, altered old-growth stand structure, and shifted many forests toward younger cohorts and more shade-tolerant species compositions (Arno et al., 1997; Bisbing et al., 2010; Hessburg et al., 2005, 2021; Hopkins et al., 2014).

Climate change is expected to further influence western larch distribution and competitive dynamics across the inland Northwest. Species distribution modeling suggests that changing temperature and moisture regimes may shift suitable habitat over time, with responses varying across elevation, aspect, and local site conditions (Rehfeldt & Jaquish, 2010). Although western larch has traits associated with drought tolerance and fire adaptation relative to some co-occurring species, future persistence will depend on interactions among climate stress, disturbance regimes, regeneration opportunities, and restoration strategies (Crotteau et al., 2019; Halofsky et al., 2020; Steed & Goeking, 2020; Stevens et al., 2020).



Figure 4. Western larch on the Colville Reservation with visible bole char from a previous fire, July 2024. Photograph by Priscilla Sperandio.

1.1.6.2 Fire Adaptations and Regeneration Dynamics

Western larch is among the most fire-resistant conifers of the inland Pacific Northwest, possessing morphological and life-history traits that support persistence in fire-prone landscapes. Across western North American conifer forests, species associated with frequent-fire environments commonly exhibit traits that reduce fire-induced mortality, including thick bark, tall growth forms, and elevated crown structures (Stevens et al., 2020). Western larch expresses many of

these characteristics, combining resistance traits that allow mature individuals to survive surface fires with regeneration strategies favored by post-disturbance environments (Agee, 1993; Arno & Fischer, 1995; Barrett et al., 1991; Moris et al., 2022; Schmidt & Shearer, 1990; Stevens et al., 2020).



Figure 5. Standing snags mark the recent fire perimeter, beyond which golden-needled western larch crowns in autumn senescence are visible against surviving mixed-conifer canopy. Photograph by Priscilla Sperandio, 2024.

A primary mechanism underlying western larch fire resistance is its exceptionally thick bark, which insulates the cambium during fire events. Mature western larch develops among the thickest bark of inland conifers, reducing the likelihood of stem injury and mortality during low- and moderate-severity surface fires (Arno & Fischer, 1995; Harrington, 2013; Schmidt & Shearer, 1990; Sparks et al., 2018; Stevens et al., 2020). Following prescribed burning in an old-growth western larch stand after approximately 150 years without fire, Harrington (2013) found that mature individuals experienced limited cambial injury and no mortality seven years after burning,

despite deep duff consumption and prolonged smoldering near tree bases. Earlier work examining duff reduction during broadcast burning in western larch–Douglas-fir forests similarly highlighted the importance of duff depth and consumption patterns in determining fire effects around mature trees (Artley, 1976).

Western larch crown architecture further contributes to fire resistance by reducing the likelihood of crown scorch and transition from surface to crown fire. Through natural self-pruning of lower branches and the development of elevated crown base heights, mature western larch reduces vertical fuel continuity between surface fuels and live canopy fuels (Arno & Fischer, 1995; Schmidt & Shearer, 1990; Williams et al., 2018). A recent analysis of conifer canopy architecture found that species-specific crown structure can limit live crown fuel consumption in Intermountain West conifers, including western larch, reinforcing the importance of canopy traits in shaping fire resistance (Conrad et al., 2024).

In addition to surviving fire as mature trees, western larch regeneration is favored by the conditions created following disturbance. As a highly shade-intolerant, early-seral species, western larch establishes most successfully where canopy openings increase light availability, expose mineral soil, and reduce competition from shade-tolerant vegetation (Keane, 2008; Schmidt & Shearer, 1990; Shearer et al., 1999). Its small, wind-dispersed seeds allow colonization of disturbed areas when seed sources remain available, enabling western larch to establish following mixed- and high-severity fire events (Steed & Goeking, 2020; Vieira et al., 2024).

Regeneration success, however, depends on interactions among disturbance severity, seed availability, site conditions, climate, and competing vegetation. Western larch recruitment is strongly influenced by canopy openness, stand structure, and microsite availability, with establishment often limited as competing vegetation develops during later stages of succession (Shearer et al., 1999; Steed & Goeking, 2020). Because western larch seed production varies substantially among years, successful regeneration also depends on the timing of disturbance relative to periods of adequate seed availability (Schmidt & Shearer, 1990; Stoehr, 2000). Recent analyses suggest that wildfire-related factors, site conditions, and indirect climate effects may be stronger predictors of

regeneration patterns than direct climate variables alone, highlighting the importance of disturbance processes and management actions in maintaining western larch populations under changing conditions (Steed & Goeking, 2020; Vieira et al., 2024).

The longevity of western larch provides evidence of its persistence within historically fire-prone landscapes. Fire history reconstructions using old western larch individuals have documented repeated fire events over multiple centuries, with individual trees surviving numerous surface fires throughout their lifetimes (Barrett et al., 1991; Hall, 2008). These patterns reflect the role of western larch as both an early-seral colonizer following disturbance and a long-lived structural component of mixed-conifer forests historically maintained by recurring fire (Agee, 1993; Arno et al., 1997; Bisbing et al., 2010; Hessburg et al., 2005).

1.1.6.3 Deciduous Needle Traits and Surface Fuel Characteristics

Western larch is distinctive among inland Pacific Northwest conifers in its deciduous needle habit, shedding its foliage annually and adding surface fuels that differ from those produced by co-occurring evergreen conifers. Western larch needles are short (2.5–4.5 cm), thin, and borne in dense clusters on short shoots, contrasting with the longer needles of ponderosa pine and the paired, twisted needles of lodgepole pine (Keane, 2008; Schmidt et al., 1976). These differences in needle morphology and annual litter input contribute to distinct fuel bed structures that may influence fuel packing, moisture dynamics, decomposition, and combustion processes (Cornwell et al., 2015; Magalhães & Schwilk, 2012; Varner et al., 2015).



Figure 6. Autumn foliage of alpine larch displaying the golden needle color characteristic of larches before annual needle shed, November 2024. Photograph by Priscilla Sperandio.

Plant flammability is controlled by multiple interacting traits that influence ignitability, combustibility, sustainability, and fuel consumption (Pausas et al., 2017; Schwilk, 2015; Varner et al., 2015). In conifer forests, litter morphology plays a central role in regulating surface fire behavior because particle size, shape, arrangement, and packing influence airflow, drying rates, and heat transfer within fuel beds (Cornwell et al., 2015; Ganteaume et al., 2009; Magalhães & Schwilk, 2012; Schwilk, 2015; Varner et al., 2015). Across gymnosperms, differences in litter particle size explain substantial variation in fuel bed flammability, with smaller particles often forming denser fuel beds that alter oxygen availability and combustion dynamics (Cornwell et al., 2015).

The short, fine needles of western larch may therefore produce fuel beds with different physical properties than those formed by longer-needled evergreen conifers. Long pine needles often create loosely arranged litter layers with greater vertical structure and airflow, conditions that can facili-

tate flame spread under dry conditions. In contrast, shorter and less curved needles can form more compact fuel beds with greater bulk density and higher packing ratios, potentially slowing drying rates and reducing the oxygen availability needed to sustain combustion (Cornwell et al., 2015; Magalhães & Schwilk, 2012; Varner et al., 2015). However, the relationship between packing and flammability is context-dependent because fuel bed structure interacts with fuel moisture, particle size, and environmental conditions to determine combustion outcomes (Ganteaume, 2018; Schwilk, 2015; Varner et al., 2015).



Figure 7. Western larch litter bed within a planted western larch stand on the Colville Reservation, November 2024. Photograph by Priscilla Sperandio.

Beyond physical fuel bed structure, western larch's deciduous habit may influence surface fuel dynamics through differences in needle chemistry and decomposition processes. Leaf lifespan is associated with a broader spectrum of plant functional traits, in which short-lived deciduous foliage often reflects lower structural investment, higher nutrient concentrations, and faster resource

turnover than long-lived evergreen foliage (Aerts, 1995; Wright et al., 2004). As a deciduous conifer that replaces its needles annually, western larch may therefore produce litter with chemical and structural properties that differ from those of evergreen associates (Keane, 2008).

Litter decomposition rates are strongly influenced by traits such as nitrogen concentration, carbon-to-nitrogen ratio, lignin content, and tissue structure, which regulate microbial activity and organic matter turnover (Cornelissen et al., 1999; Cornwell et al., 2008). Nutrient-rich litter with lower structural investment generally supports faster microbial decomposition, whereas chemically defended and structurally resistant tissues often decompose more slowly and contribute to longer-term accumulation of surface organic material (Aerts, 1995; Cornwell et al., 2008). As a result, western larch litter may promote faster nutrient cycling and reduced persistence of surface fuel layers relative to some evergreen conifers, although these processes remain influenced by site conditions, climate, and microbial communities.

Differences between deciduous and evergreen conifer foliage may also influence fuel moisture dynamics. Evergreen conifers commonly possess structural and chemical traits associated with year-round foliage retention, including protective cuticular layers that reduce water loss. In contrast, deciduous larch needles may differ in surface chemistry, specific leaf area, and hygroscopic properties, potentially influencing rates of moisture absorption and drying. Studies of mixed-conifer litter show that species-specific litter traits can shape moisture absorption, drying rates, and flammability under moist and dry fuel conditions (Magalhães & Schwilk, 2021). Whether similar patterns occur in western larch forests of the inland Pacific Northwest remains poorly understood. Trait-based perspectives increasingly recognize that variation in conifer fire strategies emerges from suites of interacting traits related to survival, regeneration, and fuel characteristics (Pausas et al., 2017; Stevens et al., 2020; Varner et al., 2015). Western larch has historically been characterized primarily as a fire-resistant species because of its thick bark, elevated crown base heights, and ability to survive surface fire (Arno & Fischer, 1995; Schmidt & Shearer, 1990; Sparks et al., 2018; Stevens et al., 2020). However, its deciduous needle habit, litter morphology, and potential differences in decomposition and moisture dynamics suggest that western larch may also influence

fire behavior through its effects on surface fuel characteristics, functioning in ways consistent with fire-impeding strategies described for other low-flammability species (Kane et al., 2008; Varner et al., 2015).

Despite extensive research on western larch fire resistance and regeneration ecology, relatively little is known about the flammability of western larch litter or how larch needle inputs influence surface fuel dynamics when mixed with co-occurring species. Understanding these mechanisms is increasingly important as restoration efforts seek to promote forest compositions that support resilience, ecological function, and adaptation to changing climate and fire regimes (Crotteau et al., 2019; Halofsky et al., 2020; Hessburg et al., 2021).

1.1.6.4 Western Larch in Contemporary Restoration and Climate Adaptation

Western larch has become an important species in forest restoration and climate adaptation strategies across the inland Pacific Northwest due to its fire-resistance traits, rapid juvenile growth, ecological value, and capacity to establish following disturbance. The species' thick bark, elevated crown architecture, and early-seral regeneration strategy align with restoration objectives focused on increasing structural diversity, maintaining fire-adapted forest conditions, and supporting long-term ecosystem resilience (Crotteau et al., 2019; Hessburg et al., 2021; Moris et al., 2022; Stevens et al., 2020).

Restoration efforts involving western larch often focus on maintaining or increasing the abundance of a species that has declined across portions of its historical range due to interactions among fire exclusion, selective harvesting, and successional shifts toward more shade-tolerant species (Arno et al., 1997; Bisbing et al., 2010; Hessburg et al., 2005). Because western larch regeneration requires high-light environments and reduced competition, successful restoration often depends on creating or maintaining early-seral conditions through active management, including thinning, prescribed fire, and planting where natural regeneration is limited (Dumroese et al., 2020; Hopkins et al., 2014; Schmidt & Shearer, 1990; Steed & Goeking, 2020). Complicating natural regeneration further, western larch seed production is episodic, with cone crops varying substantially among

years and seed availability influencing recruitment opportunities following disturbance (Schmidt & Shearer, 1990; Stoehr, 2000). Future changes in the timing, frequency, or reliability of seed production remain uncertain, creating additional challenges for restoration planning and seed-resource management.

Climate change has increased interest in western larch as a component of adaptive forest management, although future responses will depend on interactions among climate conditions, genetic variation, disturbance, and regeneration opportunities (Crotteau et al., 2019; Halofsky et al., 2020; Rehfeldt & Jaquish, 2010). Species distribution and genetic modeling suggest that suitable climate space and appropriate seed sources for western larch may shift under future climates, highlighting the importance of considering seed sources, genetic variation, and site-specific conditions when designing restoration strategies (Rehfeldt & Jaquish, 2010). Climate-informed seed transfer, assisted gene flow, and assisted migration may help maintain western larch populations where future conditions differ from historical climates. However, uncertainties remain regarding local adaptation, drought tolerance, seedling survival, and long-term performance under changing environmental conditions (Davis et al., 2026; Roskilly & Aitken, 2024; Roskilly et al., 2025).



Figure 8. Female seed cones and male pollen cones of western larch at Pack Forest, Washington, May 2026. Photograph by Priscilla Sperandio.

Western larch restoration extends beyond increasing the abundance of individual trees because the species influences forest structure, successional trajectories, and disturbance responses. In fire-excluded western larch forests, restoration approaches that increase spatial heterogeneity, retain biological legacies, and create regeneration opportunities may better support the dynamic conditions under which western larch historically persisted (Arno et al., 1997; Hessburg et al.,

2021; Hopkins et al., 2014). Hopkins et al. (2014) found that wildfire-created conditions in western larch forests generated greater structural complexity, including variable regeneration patterns, coarse woody debris, and canopy openings, emphasizing the importance of restoring ecological processes rather than recreating static historical conditions.

The success of western larch restoration depends on matching management actions with site conditions, disturbance regimes, and long-term objectives. Regeneration is influenced by forest floor conditions, canopy openness, competing vegetation, seed source, and climatic conditions, reinforcing the importance of adaptive management approaches that account for both ecological variability and future environmental change (Davis et al., 2026; Dumroese et al., 2020; Steed & Goeking, 2020; Williams et al., 2018). Long-term evaluations of western larch-dominated forests indicate that disturbance history and site conditions can influence vegetation structure for decades, highlighting the importance of considering disturbance legacies when evaluating restoration outcomes (Williams et al., 2026).

On the Colville Reservation, western larch restoration occurs within broader Tribal forest management efforts focused on maintaining resilient forests, supporting wildlife habitat, sustaining resource availability, and adapting to changing climate and wildfire conditions (Figure 9) (Confederated Tribes of the Colville Reservation, 2018, 2023, n.d.; Indian Forest Management Assessment Team, 1993, 2003, 2013). Despite extensive understanding of western larch ecology, fire resistance, and regeneration dynamics, important uncertainties remain about how western larch influences fire outcomes at stand and landscape scales. Addressing these knowledge gaps is essential for evaluating the role of western larch restoration in supporting fire-adapted landscapes under changing disturbance regimes.



Figure 9. Planted western larch stand in autumn foliage along Summit Trail on the Colville Reservation, 2024. Photograph by Priscilla Sperandio.

1.7 Tribal Stewardship and Restoration on the Colville Reservation

1.7.1 Historical and Contemporary Forest Stewardship

The Confederated Tribes of the Colville Reservation have maintained long-standing relationships with the forests, wildlife, and resources of northeastern Washington through governance systems and stewardship practices developed over generations. These relationships reflect responsibilities to maintain ecosystem function, support culturally important species, sustain resource availability, and ensure that forest landscapes continue providing for present and future generations. Indigenous stewardship practices across the inland Pacific Northwest historically included intentional burning, harvesting practices, and other forms of active management that influenced vegetation structure, wildlife habitat, and resource abundance (Copes-Gerbitz et al., 2022; Kimmerer & Lake, 2001;

Lake et al., 2017; Morishima et al., 2017; Rellergert-Taylor & O'Dea, 1988).

The establishment of the Colville Reservation occurred within a broader history of colonial land dispossession, treaty negotiations, and federal policies that substantially altered Indigenous access to ancestral territories and transformed patterns of land stewardship. The reservation was created by Executive Order in 1872, but subsequent federal actions repeatedly altered reservation boundaries and displaced Tribal communities from their homelands. A later Executive Order relocated the reservation west of the Columbia River, and subsequent reductions removed the northern portion of the reservation, substantially decreasing the Tribal land base and access to ancestral landscapes (Confederated Tribes of the Colville Reservation, 2015, 2023, n.d.; Rellergert-Taylor & O'Dea, 1988).

The contemporary Confederated Tribes of the Colville Reservation comprise 12 distinct bands whose histories, homelands (Figure 10), and ecological relationships span what is now northeastern Washington and surrounding regions. These include: *ščə́lám̓xəxʷ* (deep water) or Chelan; *wałwáma* (Wallowa people) or Chief Joseph Band of Nez Perce; *s̓x̌w̓yʔiɫp* (sharp pointed trees) or Colville; *šnt̓iyátkʷəxʷ* (grass in the water) or Entiat; *sn̓áyckst* (speckled fish) or Lakes; *mətxʷu* (blunt hills around a valley) or Methow; *škwáxčənəxʷ* (people living on the bank) or Moses-Columbia; *nspilm* (prairie) or Nespelem; *uknaq̓in* (seeing over the top) or Okanogan; *palúšpam* (people from Palouse) or Palus; *sənp̓ɣ̌w̓ilx* (grey mist as far as one can see) or San Poil; and *šnp̓əšq̌w̓áwsəxʷ* (people in between) or Wenatchi (Confederated Tribes of the Colville Reservation, 2015, 2023, n.d.; Rellergert-Taylor & O'Dea, 1988).

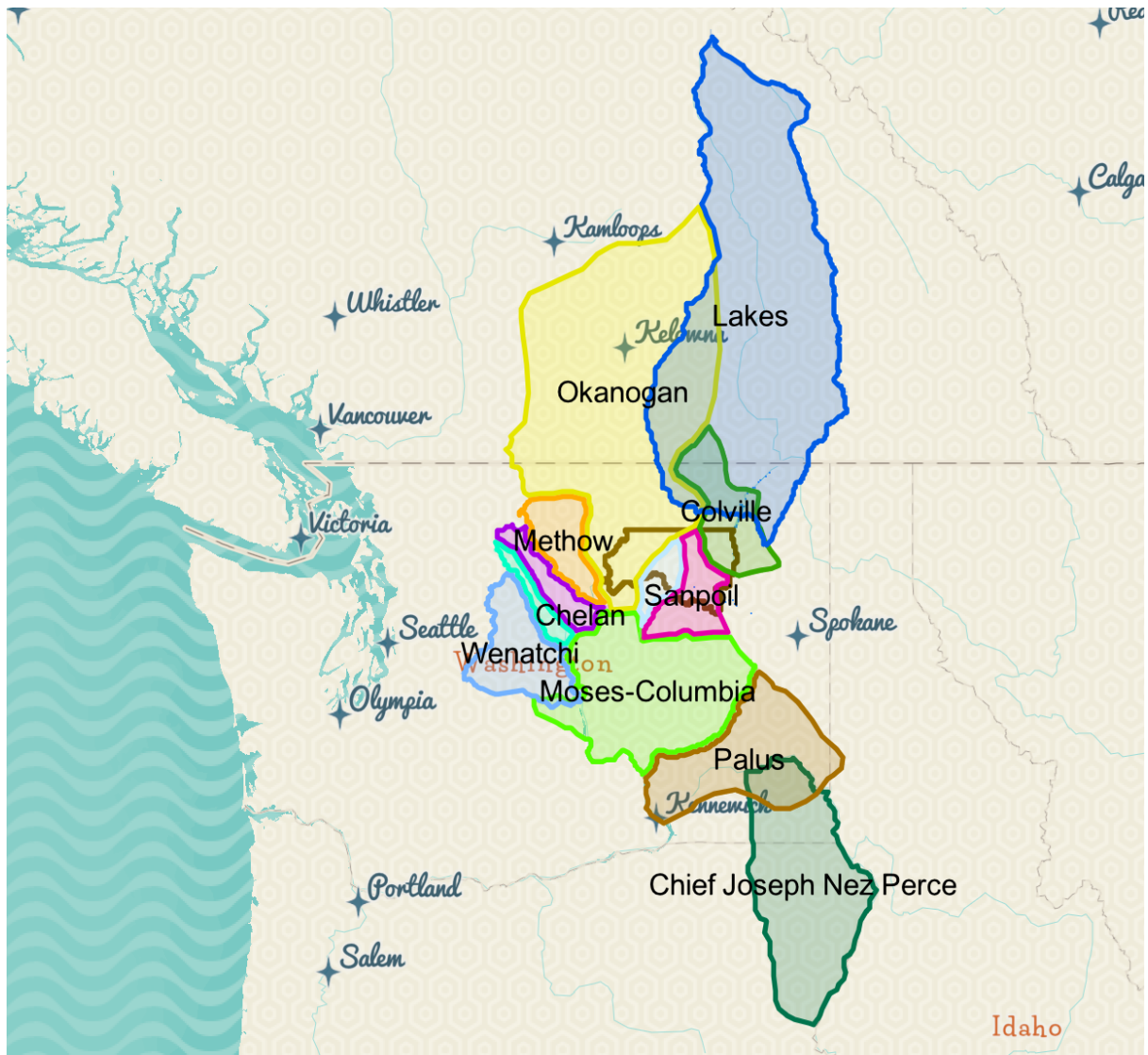


Figure 10. Traditional territories of the 12 constituent bands of the Confederated Tribes of the Colville Reservation. Territories are shown for the Lakes/*sn̓áyckst* (blue), Okanogan/*uknaqin* (yellow), Colville/*s̓x̓w̓y̓i̓lp* (orange), Methow/*mətx̓w̓u* (pink), Chelan/*ščə́l̓ám̓xəx̓w̓* (purple), San Poil/*sənp̓ɣ̓w̓ilx̓* (teal), Moses-Columbia/*škwáx̓čənəx̓w̓* (green), Palus/*palúšpam* (salmon), Chief Joseph Band of Nez Perce/*wałwáma* (dark green), Wenatchi/*šnp̓əšq̓áw̓səx̓w̓* (light blue), Nespelem/*nspilm* (gold), and Entiat/*šnt̓iyátk̓wəx̓w̓* (tan). Map retrieved from Johnson and Confederated Tribes of the Colville Reservation History/Archaeology Department (2024).

The forests of the Colville Reservation have been shaped by a complex history of federal forest administration, timber extraction, fire exclusion, and changing governance structures. During the late nineteenth and early twentieth centuries, federal policies substantially altered Tribal land ownership and management authority. Under the allotment era, communal reservation

lands across the United States were divided into individual parcels assigned to Tribal members, while remaining lands classified as “surplus” were opened to non-Indigenous settlement. On the Colville Reservation, allotment and subsequent land sales fragmented ownership patterns, reduced Tribal control over portions of the reservation landscape, and disrupted long-standing systems of collective resource management (Deloria, 1969; Indian Forest Management Assessment Team, 1993; Rellergert-Taylor & O'Dea, 1988).

For much of the twentieth century, forest management on many Tribal lands, including the Colville Reservation, was administered primarily through the Bureau of Indian Affairs under federal trust authority. During this period, decision-making was often directed by federal agencies and non-Tribal personnel, limiting Colville Tribal citizens' ability to exercise authority over forest management decisions affecting their own lands (Indian Forest Management Assessment Team, 1993, 2003). These governance changes occurred alongside broader federal policies that restricted Indigenous burning practices and promoted forestry approaches centered on timber production and fire suppression, contributing to shifts in forest structure, species composition, and fire regimes across many inland Northwest landscapes (Copes-Gerbitz et al., 2022; Hagmann et al., 2021; Lake et al., 2017).

Despite repeated displacement, land reduction, and externally imposed changes in governance, the Confederated Tribes of the Colville Reservation maintained cultural, ecological, and management relationships with these landscapes. The expansion of Tribal self-determination policies, including the Indian Self-Determination and Education Assistance Act of 1975, created new pathways for Tribal governments to assume greater authority over natural resource management. On the Colville Reservation, this transition supported the expansion of Tribal forestry programs, strengthening local expertise, employment opportunities, and Tribal decision-making capacity following earlier periods of externally administered management (Indian Forest Management Assessment Team, 1993, 2003, 2013; Rellergert-Taylor & O'Dea, 1988).

Today, forest stewardship on the Colville Reservation reflects Tribal-led approaches that integrate ecological restoration, cultural resources, wildlife habitat, economic self-determination, and long-

term landscape resilience (Indian Forest Management Assessment Team, 2013; Indian Forest Management Assessment Team, 2023). Management priorities are guided by planning frameworks including the Integrated Resource Management Plan, Forest Management Plan, and Wildland Fire Management Plan, which emphasize active management strategies designed to sustain forest health, support resource availability, maintain wildlife habitat, and respond to changing climate and wildfire conditions (Confederated Tribes of the Colville Reservation, 2015, 2023, n.d.).

Within this framework, restoration extends beyond reducing wildfire risk to sustaining landscapes that support ecological processes, community priorities, and relationships between people and forests. Western larch restoration represents one component of these broader efforts because the species contributes to fire-adapted forest structure, provides ecological and economic value, and supports objectives to promote resilient forest conditions under changing disturbance regimes (Crotteau et al., 2019; Hessburg et al., 2021).

1.7.2 Restoration Priorities and Reforestation Programs

Restoration priorities on the Colville Reservation reflect Tribal objectives to maintain resilient forests, sustain wildlife habitat, support resource availability, and adapt forest landscapes to changing climate and disturbance regimes. These priorities extend beyond individual treatments and are embedded within broader systems of forest governance that emphasize long-term stewardship, ecological function, and responsibilities to future generations. Planning frameworks, including the Integrated Resource Management Plan, Forest Management Plan, and Wildland Fire Management Plan, identify active forest management, restoration of fire-adapted conditions, and protection of ecological and cultural resources as central components of contemporary forest stewardship (Confederated Tribes of the Colville Reservation, 2015, 2023, n.d.; Indian Forest Management Assessment Team, 2013, 2023).

Across western North America, Tribal-led forest management and restoration approaches often emphasize restoring disturbance processes, increasing landscape heterogeneity, and supporting resources tied to community priorities, including wildlife habitat, timber production, foods,

medicines, and culturally significant plant species (Copes-Gerbitz et al., 2022; Lake et al., 2017; Long et al., 2018; Wynecoop et al., 2019). These approaches are guided by place-based knowledge, contemporary ecological information, and Tribal decision-making frameworks that recognize forests as interconnected social and ecological systems.

On the Colville Reservation, reforestation has been a central component of forest restoration following both historical timber harvesting and recent wildfires. Western larch has been incorporated into these efforts because of its ecological role as a long-lived, fire-adapted species that can contribute to resilient mixed-conifer forest conditions. Its rapid juvenile growth, mature-tree fire resistance, and decline across some portions of its historical range following fire exclusion and selective harvesting have made western larch restoration an important strategy for maintaining fire-adapted forest composition under changing environmental conditions (Arno & Fischer, 1995; Croteau et al., 2019; Hessburg et al., 2021; Stevens et al., 2020).

Recent restoration efforts on the Colville Reservation reflect extensive Tribal forestry capacity developed through long-term, adaptive forest management. The Confederated Tribes of the Colville Reservation Department of Natural Resources maintains reforestation programs that include local seed collection, preservation of site-adapted seed sources, greenhouse seedling production, and coordinated planting strategies designed to restore resilient forest conditions following harvest, wildfire, and other disturbances. These efforts are supported by forest inventory programs, GIS-based mapping, remote sensing technologies, LiDAR-derived forest structure assessments, spatial planning tools, and monitoring systems that guide restoration decisions across diverse forest types and environmental gradients (Confederated Tribes of the Colville Reservation, 2023).

In addition to established forestry practices, the Colville Tribes have explored emerging technologies, including drone-assisted reforestation, as complementary tools for addressing restoration challenges following large wildfire events. Together, these approaches demonstrate Tribal leadership in forest restoration through technical capacity, landscape-scale planning, and self-determined management systems that support forest resilience under changing climate and disturbance regimes

(Confederated Tribes of the Colville Reservation, 2023; Indian Forest Management Assessment Team, 2013, 2023).

Western larch restoration on the Colville Reservation therefore represents more than the reestablishment of a single tree species. It is part of a broader effort to restore forest structures and processes that support fire resilience, wildlife habitat, sustainable resource availability, and long-term relationships between people and forest landscapes (Hagmann et al., 2021; Hessburg et al., 2021). Evaluating the performance of restored western larch stands under contemporary wildfire conditions provides an opportunity to assess how these restoration strategies contribute to forest resilience in a changing climate.

1.7.3 Western Larch as a Restoration Species

Western larch has been actively incorporated into restoration and reforestation programs on the Colville Reservation for decades because of its ecological role within fire-adapted mixed-conifer forests, rapid juvenile growth, longevity, and resistance to multiple disturbance agents (Arno & Fischer, 1995; Schmidt & Shearer, 1990; Stevens et al., 2020). Early restoration efforts emphasized western larch as a strategy for addressing shifts in forest composition associated with fire exclusion and past management, including the increased dominance of shade-tolerant Douglas-fir and grand fir in areas where early-seral species were historically more abundant. Increasing western larch composition was also identified as a forest health strategy because the species can contribute to greater compositional diversity and may reduce vulnerability to root diseases, insect outbreaks, and other disturbance agents associated with dense, homogeneous forest conditions (Confederated Tribes of the Colville Reservation, 2023; Hessburg et al., 2005).

On the Colville Reservation, western larch restoration has been implemented across broad environmental gradients that reflect the diversity of forest conditions in which establish western larch at approximately 300 seedlings per acre (~ 740 seedlings ha^{-1}), with many restoration units located on north- and east-facing slopes where moisture availability supports early establishment. These plantings occur across elevations ranging from approximately 760 to 1,675 m (2,500–5,500 ft) and

precipitation gradients of roughly 400–760 mm annually (16–30 inches), spanning multiple forest types across the Reservation.

Rather than being limited to historically mesic western larch habitats, restoration plantings occur across a range of mixed-conifer environments, including lower-elevation dry forests dominated by ponderosa pine and Douglas-fir, as well as higher-elevation mixed-moist forests where species such as subalpine fir and Engelmann spruce become more abundant (Figure 11). This broad application reflects management objectives focused on increasing fire-adapted species composition, improving forest health, and promoting resilience across diverse landscape conditions (Confederated Tribes of the Colville Reservation, 2023; Crotteau et al., 2019; Halofsky et al., 2020).

Across the inland Northwest, western larch abundance declined as interactions among selective harvesting, fire exclusion, and succession favored more shade-tolerant species, reducing regeneration opportunities for this highly shade-intolerant conifer. Restoring western larch within mixed-conifer forests therefore represents an effort to reestablish an important early-seral component of these landscapes while increasing structural and compositional diversity (Arno et al., 1997; Bisbing et al., 2010; Hopkins et al., 2014; Moris et al., 2022; Steed & Goeking, 2020).



Figure 11. Thinned mixed-conifer stands along Summit Trail on the Colville Reservation, November 2024. This silvicultural treatment was designed to reduce competing conifer species and promote western larch restoration. Photograph by Priscilla Sperandio.

On the Colville Reservation, decades of western larch planting have created a unique opportunity to evaluate restoration outcomes under contemporary wildfire conditions. Recent fires, including the North Star Fire (2015), Summit Trail Fire (2021), and Swawilla Basin Fire (2024), have burned through areas containing restored western larch stands, providing an opportunity to assess how these stands are associated with burn severity patterns and forest resilience.

Although western larch is widely recognized for individual-level fire-resistance traits, including thick bark, elevated crown architecture, and survival during surface fires, less is known about how restored western larch stands influence fire effects at broader spatial scales (Harrington, 2013; Stevens et al., 2020). In addition, limited research has examined whether western larch's distinctive litter characteristics influence surface fuel dynamics compared with co-occurring conifer species (Cornwell et al., 2015; Varner et al., 2015).

Understanding these mechanisms is important for evaluating the role of western larch restoration within adaptive forest management strategies. By examining both landscape-scale wildfire outcomes and species-level fuel characteristics, this research assesses how restored western larch forests may contribute to fire-adapted landscapes and support ongoing Tribal-led restoration efforts on the Colville Reservation (Confederated Tribes of the Colville Reservation, 2023; Indian Forest Management Assessment Team, 2013, 2023).

1.7.4 Co-Produced Research and Applied Management Context

Addressing contemporary forest challenges requires research approaches that recognize forests as interconnected ecological, social, and governance systems. For Indigenous Nations, forest management decisions are shaped not only by ecological conditions, but also by responsibilities to sustain relationships with landscapes, maintain resource availability, support community priorities, and exercise sovereignty over natural resource management (Whyte, 2018). Collaborative research approaches increasingly emphasize Indigenous leadership and co-production models in which research questions, methods, interpretation, and applications are developed with the Nations, communities, and managers who use the resulting knowledge (David-Chavez & Gavin, 2018; Lake, 2021; Long et al., 2018).

Co-produced research differs from conventional research models by shifting Indigenous Nations, communities, and resource managers from being consulted after research decisions are made to serving as collaborators, decision-makers, and leaders in the research process. In forestry and fire science, these approaches recognize that Indigenous Nations maintain long-standing systems of environmental knowledge, governance, and stewardship while also applying contemporary scientific tools, monitoring approaches, and management practices to address changing ecological conditions (Lake, 2021; Wynecoop et al., 2019).

Within fire and forest restoration contexts, collaborative approaches demonstrate the importance of aligning research with locally defined management objectives. Studies developed with Tribal partners have highlighted priorities such as restoring fire processes, maintaining culturally impor-

tant species, supporting wildlife habitat, strengthening climate adaptation strategies, and sustaining relationships between people and landscapes (Kimmerer & Lake, 2001; Lake et al., 2017; Long et al., 2018; Wynecoop et al., 2019). These approaches emphasize that effective restoration is not only a technical challenge, but also a matter of governance, values, and decisions about desired future landscape conditions.

This thesis was developed within the context of Tribal-led forest restoration on the Colville Reservation and ongoing efforts to evaluate the outcomes of long-term management decisions. The research questions originated from priorities identified by the Confederated Tribes of the Colville Reservation Department of Natural Resources regarding the performance of restored western larch stands under contemporary wildfire conditions. Decades of western larch planting across diverse forest types and environmental gradients created an opportunity to evaluate how these restoration investments are associated with fire-resilience outcomes under recent wildfire events (Confederated Tribes of the Colville Reservation, 2023).

This research combines remote sensing, field-based measurements, and laboratory fire experiments to address applied management questions about western larch restoration. Rather than treating research findings as separate from management, this approach aims to produce information directly relevant to ongoing decision-making, including species selection, restoration planning, and adaptation strategies under changing climate and disturbance regimes (Indian Forest Management Assessment Team, 2013, 2023).

In this context, evaluating western larch is not only a question of species ecology. It is also part of a broader effort to support Tribal-led restoration, adaptive forest management, and long-term stewardship on the Colville Reservation.

1.8 Research Gaps and Multi-Scale Framework

1.8.1 Linking Stand Structure, Fuel Composition, and Fire Behavior

Understanding how species traits, forest structure, and fuel characteristics interact to influence wildfire outcomes remains a central challenge in fire ecology and adaptive forest management. Fire

behavior and fire effects emerge from interactions among climate, topography, vegetation composition, and fuels, yet these processes operate across spatial scales that are often studied separately. Individual tree traits influence survival during fire, stand structure affects fuel continuity and fire behavior, and landscape conditions shape broader patterns of burn severity and post-fire recovery (Graham et al., 2004; Perry et al., 2011; Stevens et al., 2020).

Restoration and fuel management strategies often focus on modifying forest conditions that influence fire behavior, including reducing surface and ladder fuels, increasing canopy base height, reducing canopy bulk density, and promoting fire-resistant species composition (Graham et al., 2004; Hessburg et al., 2021; Hood et al., 2022). These approaches are supported by well-established relationships between forest structure and fire effects. However, predicting how restored stands perform during wildfire remains challenging because outcomes depend on interactions among treatment history, species composition, fuel characteristics, fire weather, topography, and broader landscape context (Hood et al., 2022; Prichard & Kennedy, 2014; Sanna et al., 2025).

A persistent knowledge gap lies in connecting species-level fire adaptations with stand- and landscape-scale wildfire outcomes. Many fire-adapted tree species are classified based on traits that influence individual survival, including bark thickness, crown architecture, and regeneration strategies. However, species also shape the fire environment through litter production, fuel arrangement, decomposition processes, and moisture dynamics, all of which can influence surface fuel conditions and combustion behavior (Cornwell et al., 2015; Schwilk, 2015; Stevens et al., 2020; Varner et al., 2015). Understanding how these mechanisms scale from individual traits to stand-level fire effects remains an important challenge.

This gap has become increasingly important as restoring conifer forests under contemporary climate and disturbance regimes has become more uncertain. Larger high-severity patches, increasing fire frequency, warmer post-fire environments, and changing moisture conditions can limit conifer regeneration by reducing seed availability, increasing seedling stress, and altering competitive dynamics during post-fire recovery (Coop et al., 2020; Davis et al., 2019; Stewart et al., 2021). These challenges have increased interest in identifying restoration strategies and species compositions

capable of supporting forest persistence under future climate and fire conditions (Crotteau et al., 2019; Halofsky et al., 2020).

Western larch provides an important system for evaluating these questions because it combines multiple fire-adapted strategies across life stages. Many traits traditionally associated with western larch fire resistance, including thick bark, elevated crown base height, and self-pruning architecture, become more developed as trees mature (Harrington, 2013; Schmidt & Shearer, 1990; Stevens et al., 2020; Williams et al., 2018). As a result, uncertainty remains about how younger restored western larch stands respond to wildfire before these mature fire-resistance traits are fully expressed.

Despite this uncertainty, forest managers with the Confederated Tribes of the Colville Reservation have observed that some young planted western larch stands have persisted through recent wildfire events, including in areas where surrounding forest types experienced greater fire effects. These observations raised applied management questions about whether restored western larch stands experience different burn-severity outcomes and which ecological mechanisms may contribute to these patterns.

Addressing these questions requires approaches that connect multiple scales of ecological organization. Remote sensing enables evaluation of wildfire effects across landscapes and assessment of restoration outcomes during observed fire events, while field measurements and laboratory experiments provide mechanistic insight into the stand characteristics and fuel traits that may contribute to those patterns (Hood et al., 2022; Parks et al., 2019). Integrating these approaches can improve understanding of how restoration strategies are associated with forest resilience under changing climate and disturbance regimes.

Within this framework, western larch restoration on the Colville Reservation provides an opportunity to examine how species-level traits relate to stand- and landscape-scale outcomes. By linking remotely sensed burn severity patterns with experimental evaluation of fuel characteristics, this research addresses an important gap in understanding how restored fire-adapted species may contribute to forest resilience in a rapidly changing fire environment.

1.8.2 Limitations of Existing Fire Severity and Fuelbed Dynamics Research

Advances in remote sensing, field ecology, and experimental fire science have substantially improved understanding of wildfire effects across forest landscapes. However, an important challenge remains: linking broad-scale patterns of burn severity to the ecological mechanisms that influence fire behavior at stand and fuel bed scales. Fire effects emerge from interactions among climate, topography, vegetation structure, species composition, and fuel characteristics, yet these drivers operate across scales that are often evaluated independently (Graham et al., 2004; Hessburg et al., 2021; Perry et al., 2011).

Remote sensing has transformed the ability to quantify wildfire effects across large spatial extents, enabling comparisons across fires, forest types, and management histories. Satellite-derived burn severity metrics and machine-learning approaches provide valuable information about spatial patterns of vegetation change and fire effects following wildfire (Gallagher et al., 2021; Gómez et al., 2016; Parks et al., 2019). However, remotely sensed fire severity reflects the outcome of many interacting processes and cannot independently identify the mechanisms underlying observed differences among forest conditions. Connecting landscape-scale fire effects with stand structure, species composition, and local fuel conditions remains a key challenge for understanding forest resilience.

Experimental flammability research provides an important complementary approach by identifying mechanisms through which plant traits and fuel characteristics influence combustion processes. Plant flammability is multidimensional, encompassing ignitability, combustibility, sustainability, and consumability, with each component influenced by fuel morphology, chemistry, arrangement, and moisture dynamics (Ganteaume et al., 2009; Schwilk, 2015; Varner et al., 2015). However, translating controlled laboratory measurements to wildfire outcomes remains challenging because fire behavior depends on interactions among fuels, weather, topography, and spatial context.

Species composition represents an important but understudied link between these scales. Tree species influence fire outcomes not only through traits that determine individual survival, but also through their effects on fuel environments, including litter production, decomposition, fuel

bed structure, and moisture dynamics (Cornwell et al., 2015; Stevens et al., 2020; Varner et al., 2015). Mixed-species fuel beds introduce additional complexity because litter interactions may produce non-additive effects, where observed combustion behavior differs from predictions based on individual species alone (Magalhães & Schwilk, 2012). Differences in particle size, packing structure, and fuel arrangement among conifers can strongly influence airflow, drying rates, and combustion dynamics (Campbell-Lochrie et al., 2021; Cornwell et al., 2015; Zhao et al., 2016). These uncertainties are highly relevant for evaluating restored western larch forests. Although western larch is recognized as one of the most fire-resistant conifers of the inland Pacific Northwest, most research has focused on mature-tree survival traits and regeneration ecology (Arno & Fischer, 1995; Harrington, 2013; Schmidt & Shearer, 1990). Less is known about whether restored western larch stands are associated with different burn severity patterns during actual wildfires or whether species-specific fuel traits contribute to observed fire effects in younger planted stands where mature resistance traits may not yet be fully expressed (Crotteau et al., 2019; Hopkins et al., 2014).

Addressing this gap requires connecting landscape-scale observations with mechanistic understanding of fire processes. By combining remotely sensed burn-severity assessments from multiple wildfires with field measurements and experimental evaluations of litter flammability, this research evaluates both the outcomes and potential mechanisms associated with western larch restoration. This multi-scale framework provides insight into how restored fire-adapted species may contribute to resilient forest landscapes under changing climate and disturbance regimes.

Wildfire has long been a defining ecological process in the inland Pacific Northwest. For millennia, fire moved through forests of western larch, ponderosa pine, and Douglas-fir under regimes shaped by climate, topography, lightning ignitions, and Indigenous stewardship practices (Barrett et al., 1991; Hessburg et al., 2005; Kimmerer & Lake, 2001; Lake, 2013). Across northeastern Washington and surrounding regions, Indigenous fire stewardship influenced vegetation structure, habitat conditions, resource availability, and landscape heterogeneity through practices guided by cultural objectives, ecological knowledge, and relationships with place (Confederated Tribes of the

Colville Reservation, 2015; Lake et al., 2017; Rellergert-Taylor & O'Dea, 1988; Wynecoop et al., 2019).

These long-standing relationships with fire were substantially altered during the late nineteenth and twentieth centuries through the combined effects of colonial land-use changes, restrictions on Indigenous burning practices, timber extraction, and institutional fire-suppression policies (Fletcher et al., 2021; Hagmann et al., 2021; Hessburg et al., 2005). In the absence of recurring fire, many historically frequent-fire forests shifted toward denser conditions characterized by increased abundance of shade-tolerant conifers, greater continuity of surface and ladder fuels, and reduced structural heterogeneity (Hessburg et al., 2021). These changes, interacting with climate warming and increasing fire-season aridity, have contributed to contemporary challenges including larger high-severity patches, altered regeneration dynamics, and uncertainty in future forest trajectories (Coop et al., 2020; Stevens-Rumann et al., 2022).

The 2015 North Star Fire, 2021 Summit Trail Fire, and 2024 Swawilla Fire, all of which burned across the Colville Reservation and surrounding landscapes, reflect these broader challenges and provide an opportunity to evaluate the outcomes of long-term restoration investments. This thesis was developed in response to these changing forest and fire conditions and addresses a management question with implications extending beyond any individual stand or fire event: do planted western larch stands experience different wildfire severity outcomes, and what ecological mechanisms may contribute to those patterns?

This question developed through collaboration with the Confederated Tribes of the Colville Reservation, whose forestry and restoration programs have invested for decades in restoring western larch to landscapes where the species has declined due to selective harvesting, altered disturbance regimes, and reduced regeneration opportunities. More directly, Tribal forest managers and technicians sought to understand whether these restoration efforts are shaping not only future forest composition and stand development, but also how contemporary wildfire interacts with restored forest landscapes.

1.9 Thesis Structure, Research Objectives, and Questions

This thesis is organized into two empirical chapters that together examine whether and how restored western larch stands are associated with wildfire effects on the Colville Reservation. By integrating landscape-scale burn severity assessment, field-based forest structure measurements, and controlled fuel experiments, this research evaluates western larch restoration across multiple ecological scales and considers its implications for adaptive forest management.

The overarching objective of this thesis is to evaluate how planted western larch is associated with wildfire effects across multiple ecological scales, from landscape-level patterns of burn severity to species-specific fuel characteristics and mechanisms of fire behavior. This research was conducted within the context of ongoing forest restoration led by the Confederated Tribes of the Colville Reservation, where western larch restoration represents decades of management investment aimed at sustaining resilient forest conditions amid changing disturbance regimes. This work therefore seeks not only to advance understanding of western larch fire ecology, but also to provide information relevant to ongoing Tribal forest management decisions related to restoration, reforestation, and adaptation strategies.

Chapter 2 examines whether planted western larch stands exhibit different wildfire severity patterns than surrounding mixed-conifer forests and evaluates potential structural mechanisms that may contribute to these differences. Using a validated Random Forest burn severity model implemented in Google Earth Engine (Parks et al., 2019), this chapter compares modeled Composite Burn Index (CBI) values within planted western larch stands and adjacent surrounding forests across three wildfire footprints on the Colville Reservation: the North Star Fire (2015), Summit Trail Fire (2021), and Swawilla Fire (2024). To link remotely sensed burn severity patterns with stand-level mechanisms, field measurements collected within the Summit Trail Fire footprint quantify differences in surface fuel loads, litter and duff depth, ladder fuel continuity, and forest structure between burned planted western larch stands and adjacent mixed-conifer forests (Keane & Dickinson, 2007; Lyons-Tinsley & Peterson, 2012).

Specifically, Chapter 2 addresses the following research questions:

1. Do planted western larch stands exhibit different burn severity patterns relative to surrounding forest types across the North Star (2015), Summit Trail (2021), and Swawilla (2024) fire footprints?
2. How do surface fuel characteristics and forest structure differ between burned planted western larch stands and adjacent mixed-conifer forests within the Summit Trail Fire footprint?

Chapter 3 investigates species-level fuel mechanisms that may contribute to observed landscape-scale fire patterns by evaluating moisture dynamics and flammability characteristics of western larch litter compared with those of co-occurring conifer species. Controlled drying and combustion experiments compare pure- and mixed-species fuel beds representative of western larch restoration stands on the Colville Reservation, assessing differences in moisture retention, drying rates, ignition, flame characteristics, fuel consumption, and smoldering behavior. These experiments evaluate whether western larch's deciduous needle habit and litter properties influence surface fuel dynamics relative to ponderosa pine and lodgepole pine and provide a mechanistic basis for interpreting landscape patterns observed in Chapter 2 (Kreye et al., 2013; Magalhães & Schwilk, 2021; Varner et al., 2015).

Specifically, Chapter 3 addresses the following research questions:

1. How do western larch litter characteristics influence moisture dynamics and flammability relative to co-occurring conifer species?
2. Do mixed-species fuel beds containing western larch alter combustion behavior compared with single-species pine fuel beds?

Together, these chapters integrate satellite-derived burn severity modeling, field-based fuel measurements, and controlled laboratory experiments to provide a multi-scale assessment of western larch restoration and its potential association with wildfire outcomes. By linking landscape-scale fire effects to underlying fuel mechanisms, this thesis contributes to a broader understanding of how species selection and restoration strategies may support fire-adapted forest management amid changing wildfire regimes.

1.9.2 Study Area

The study focused on planted western larch stands within the study area. The study included three wildfire footprints on the Colville Reservation: the 2015 North Star Fire (~88,200 ha), the 2021 Summit Trail Fire (~20,050 ha), and the 2024 Swawilla Basin Fire (~21,630 ha), all of which burned on the Colville Reservation and surrounding lands (Figure 12). The Colville Reservation is located in northeastern Washington State, west of the Columbia River and east of the Cascade Mountains. Established in 1872, the reservation spans approximately 566,560 ha and features a diverse landscape, including forests, arid plains, and rivers.

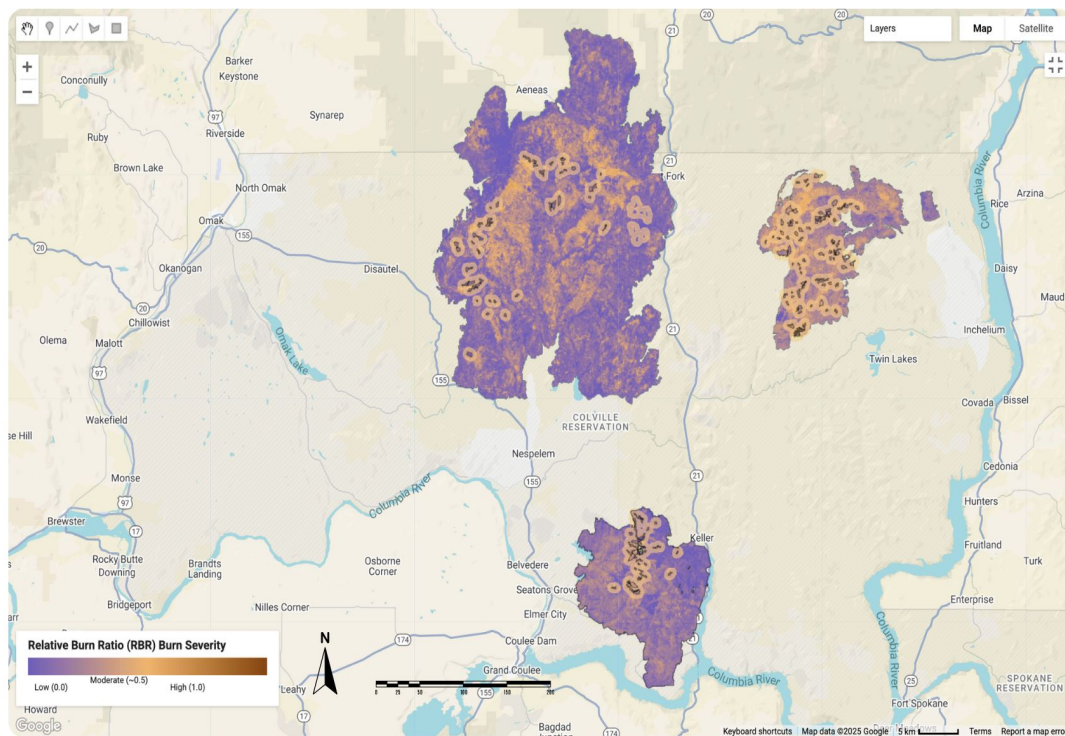


Figure 12. Colville Reservation, study area fires, planted larch stands outlined in black, and respective relative burn severity (RBR). 2015 North Star fire (upper left), 2021 Summit Trail fire (upper right), and the 2024 Swawilla fire (bottom left).

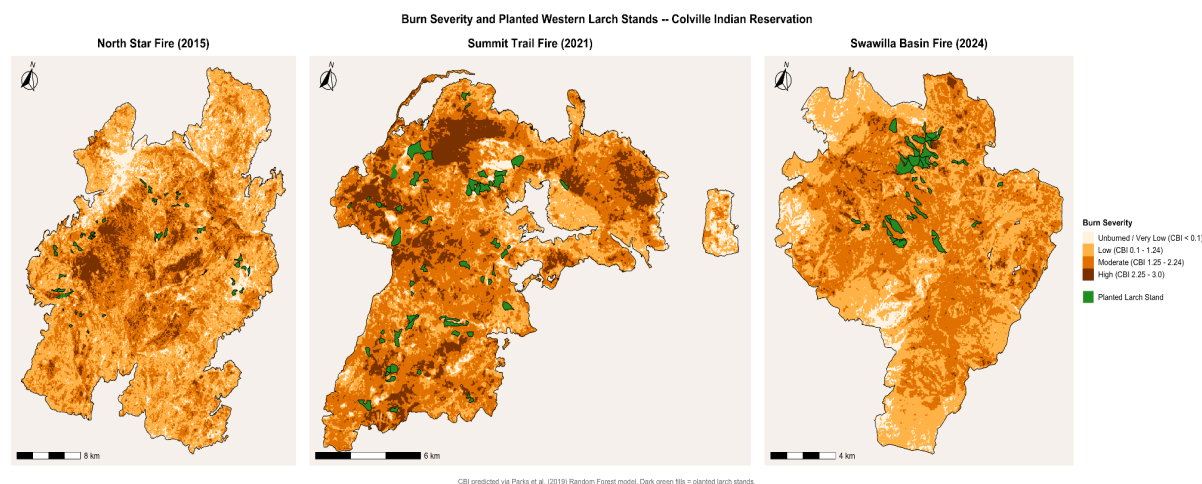


Figure 13. Modeled burn severity and planted western larch stand locations across the North Star (2015), Summit Trail (2021), and Swawilla Basin (2024) fire perimeters on the Colville Reservation. Green polygons denote planted western larch stands. Burn severity classes (unburned/very low, low, moderate, and high) represent estimated Composite Burn Index (CBI) values generated using the Parks et al. (2019) Random Forest model.

The 2015 North Star Fire (~88,244 ha), the 2021 Summit Trail Fire (~20,055 ha), and the 2024 Swawilla Fire (~21,630 ha) each burned across distinct forest types on and adjacent to the Colville Reservation, collectively spanning the ecotonal gradients that characterize eastern Washington’s fire-adapted landscapes. All three events share a common climatic signature: fire behavior was strongly shaped by seasonal drought, elevated temperatures, low fuel moisture, and episodic wind events typical of recent fire seasons in the inland Northwest (Halofsky et al. 2020; Hessburg et al. 2021; Clark-Wolf et al. 2023; Dye et al. 2024; Walsh 2023; Reilley et al. 2024; Kruger 2003; Walsh 2018). Together, they offer an opportunity to compare fire effects in planted western larch stands with adjacent forests across multiple fire events and variable fire conditions (Figure 13).

1.9.2.1 North Star Fire (2015): Mosaic of Dry and Moist Forests

The 2015 North Star Fire burned a large, structurally heterogeneous landscape encompassing ponderosa pine-dominated dry forests with grass and shrub understories, interspersed with mixed-conifer stands where Douglas-fir, lodgepole pine, and western larch co-occur (Figure 14). Despite this landscape-scale heterogeneity, post-fire reports describe extensive, dense fire-excluded forests

that fueled high-severity fire behavior, reflecting a departure from the open, low-density stand structures that frequent fire historically maintained across forest types (Hessburg et al. 2007; Mutch et al. 1993). Transitions from xeric ponderosa pine sites to more mesic mixed stands on northerly aspects and in valley bottoms create a patchwork of fuel structures across the North Star footprint, providing valuable context for comparing planted western larch stands with the surrounding vegetation matrix.

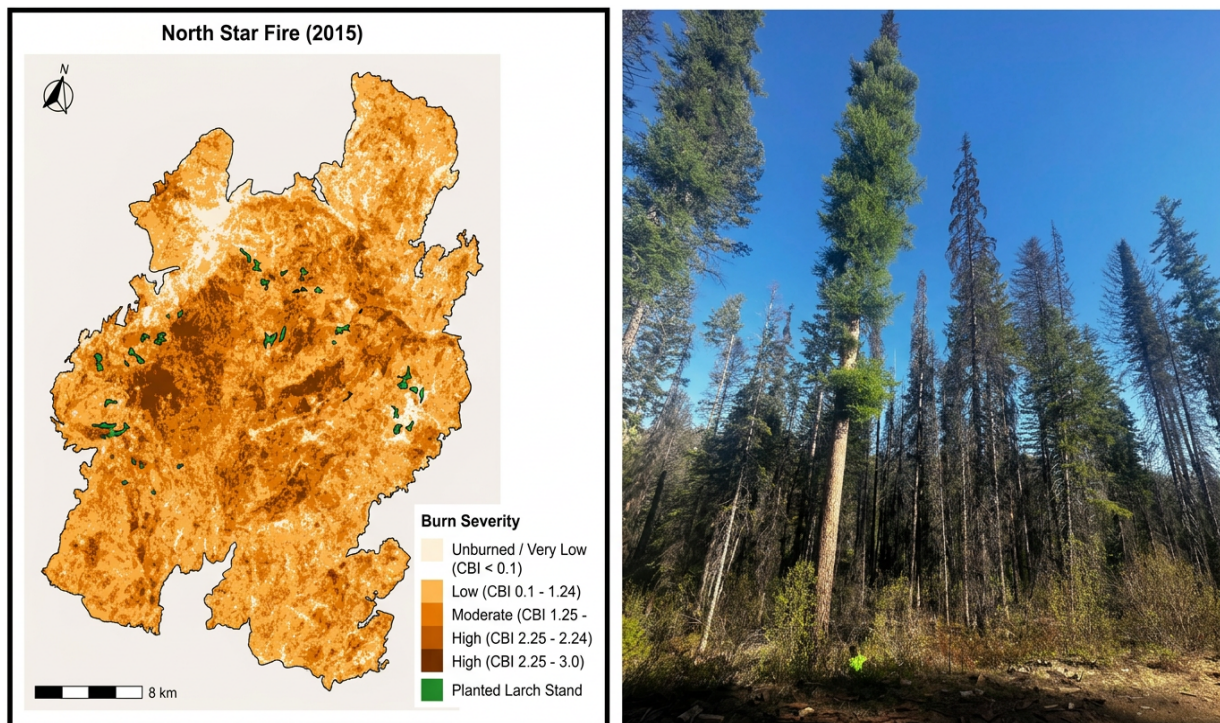


Figure 14. Dense secondary growth typical of post-clearcut regeneration under fire exclusion, North Star Fire (2015), Colville Reservation, Washington. High stem densities, continuous ladder fuels, and prominent dwarf mistletoe (*Arceuthobium spp.*) infections reflect the compounding effects of overcrowding and the absence of recurrent low-severity fire. The large-diameter western larch, identifiable by its spire crown and reddish-furrowed bark, provides a reference for the mature structural conditions that pre-exclusion fire regimes maintained and that Tribal restoration programs aim to reestablish (Schmidt et al. 1976; Scher 2002). This stand represents the fire resistance of planted western larch stands we evaluated against. Photograph by Priscilla Sperandio, 2024.

The North Star fire ignited on August 13, 2015, during one of the most severe wildfire seasons on record in Washington State, ultimately burning approximately 88,207 ha. The summer of 2015 was characterized by prolonged drought, record-breaking temperatures, and exceptionally

low fuel moisture across the Pacific Northwest (Halofsky et al. 2020). Strong winds gusting to approximately $64\text{--}80\text{ km h}^{-1}$) drove fire runs of up to 19 km through mixed-conifer forests in a single day, accompanied by widespread group torching, long-range spotting, and sustained high-intensity burning across complex terrain. Cooler temperatures and snowfall in early September eventually moderated fire behavior, though active burning persisted well into late summer (Figure 15).

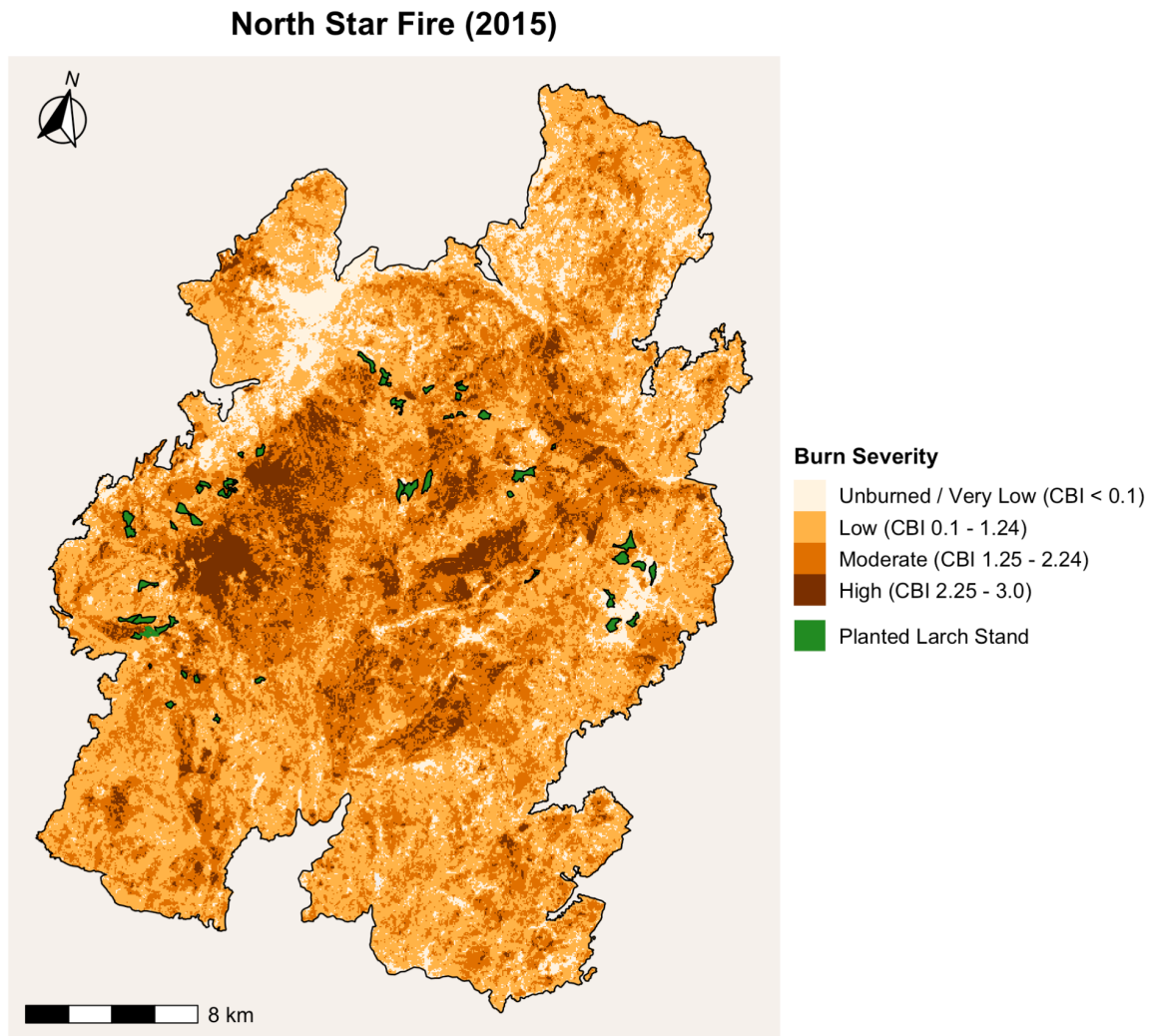


Figure 15. Modeled burn severity and planted western larch stand locations within the North Star Fire (2015), Colville Reservation. Green polygons denote planted larch stands; burn severity classes are derived from the Parks et al. (2019) Random Forest CBI model using Landsat 8 imagery.

1.9.2.2 Summit Trail Fire (2021): Higher-Elevation Mixed-Moist Forest

The 2021 Summit Trail Fire offers a contrasting window into higher-elevation mixed-moist conifer ecosystems. Burning primarily above approximately 1,494 m the Summit Trail footprint historically supported stands dominated by western larch, Douglas-fir, lodgepole pine, alpine-fir and Engelmann spruce, forests shaped by higher precipitation and cooler temperatures than lower-elevation dry forests, with deeper snowpacks, greater structural complexity, and a different fuel regime than the more xeric landscapes burned by the North Star and Swawilla fires (Stine et al. 2013; Perry et al. 2011). This elevational and compositional contrast makes Summit Trail the primary site for stand-scale fuel and structure sampling in this study.

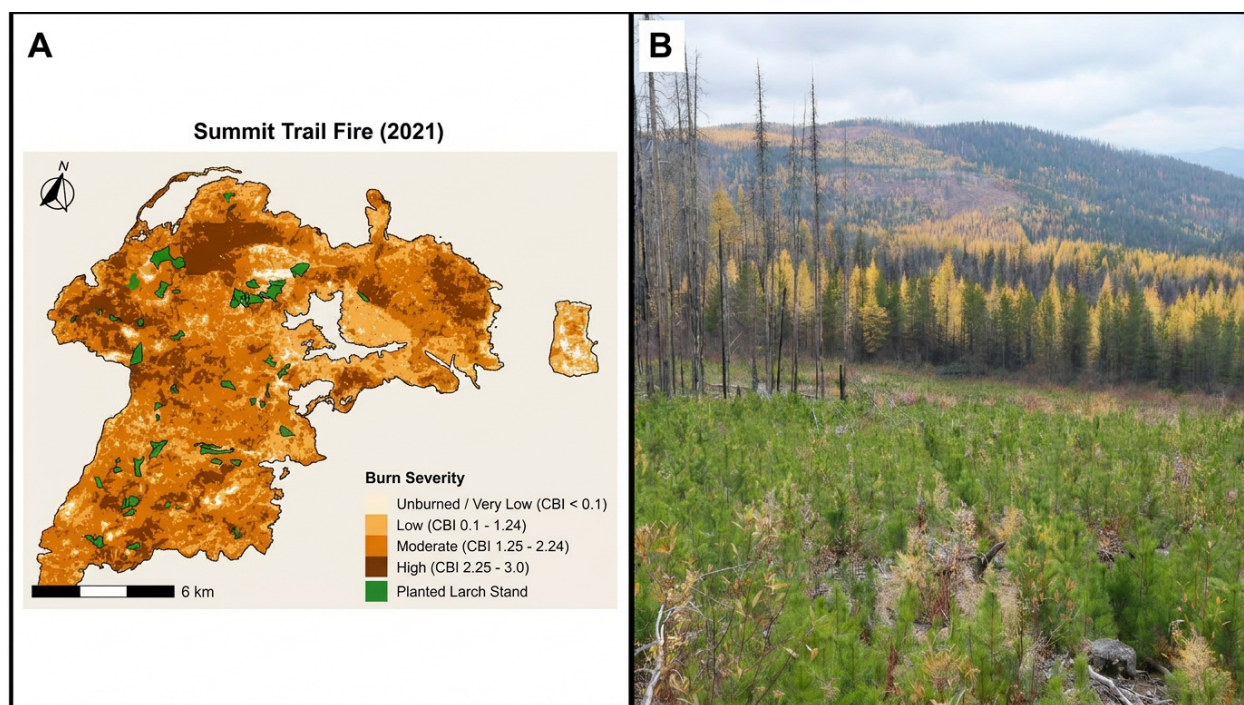


Figure 16. (A) Modeled burn severity and planted western larch stand locations within the Summit Trail Fire (2021), Colville Reservation. Green polygons denote planted larch stands; burn severity classes are derived from the Parks et al. (2019) Random Forest CBI model using Sentinel-2 imagery. (B) Dense lodgepole pine seedling regeneration in early post-fire succession at higher elevations within the Summit Trail footprint. Standing snags demarcate the recent fire perimeter, beyond which golden-needled western larch crowns in autumn senescence are visible against surviving mixed-conifer canopy. Lodgepole's serotinous seed ecology drives rapid, even-aged post-fire dominance that excludes more diverse regeneration, including western larch, and produces structurally homogeneous stands highly susceptible to future high-severity fire; redirecting this successional trajectory is a primary objective of the Colville Tribes' larch planting program.

Photograph by Priscilla Sperandio, 2024.

A distinctive feature of this forest type is the important role of lodgepole pine in post-disturbance succession (Figure 16). Lodgepole pine can begin producing viable seed at a young age, and serotinous cones, where present, can remain closed in the canopy for extended periods, releasing stored seed when heat breaks the resin bond between cone scales (Lotan, 1976). This combination of early seed production, canopy seed storage, and fire-triggered seed release can promote rapid post-fire establishment and the development of dense, even-aged lodgepole cohorts. Long-term studies of post-fire lodgepole pine forests indicate that early regeneration patterns can continue to shape stand structure and function for decades (Turner et al., 2016).

In landscapes shaped by historical clearcutting, fire exclusion, and repeated disturbance, this successional pathway may be reinforced where competing seed sources are reduced or absent. Under these conditions, dense lodgepole regeneration can limit establishment opportunities for western larch and other conifers, contributing to structurally homogeneous patches with reduced compositional diversity. Redirecting this successional trajectory toward greater structural complexity and species diversity is a central objective of the Colville Tribes' western larch planting program (Figure 17).

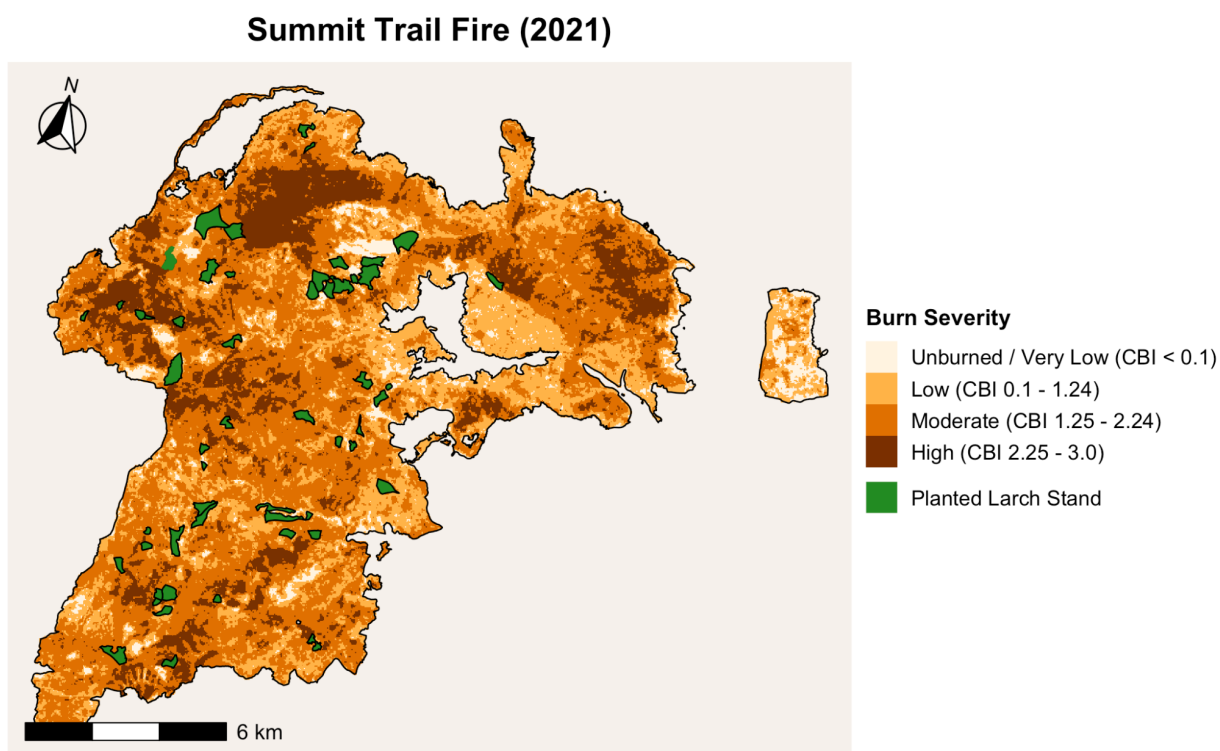


Figure 17. Modeled burn severity and planted western larch stand locations within the Summit Trail Fire (2021), Colville Reservation. Green polygons denote planted larch stands; burn severity classes are derived from the Parks et al. (2019) Random Forest CBI model using Sentinel-2 imagery.

The fire ignited on July 12, 2021, as a result of lightning during an already active fire season in eastern Washington. Abnormally dry conditions supported elevated fire danger across the inland Northwest, and fire growth accelerated during late July and August as dry weather, gusty winds, and atmospheric instability aligned with receptive fuels. Active spread was particularly pronounced along the north and east flanks, where rugged terrain complicated suppression efforts. Overall, the Summit Trail Fire exhibited moderate to high fire behavior characteristic of late-

summer fire seasons in high-elevation mixed-moist forests (Halofsky et al. 2020).

1.9.2.3 Swawilla Fire (2024): Dry Forest and Fuel Mosaic

The 2024 Swawilla Fire represents dry forest dynamics at lower elevations (approximately 3,000–4,000 ft) where semi-arid conditions support a fuel mosaic of grass, shrub, and timber understory dominated by ponderosa pine and Douglas-fir. These dry forests historically experienced frequent low-severity fire; however, accumulated surface and ladder fuels have increased their susceptibility to more variable fire behavior (Hessburg et al. 2007; Vashista 2022). Notably, relatively light surface fuels were observed in some planted and harvested units within the footprint, reflecting the moderating influence of past treatments and providing an early indication of the stand-level patterns this chapter aims to quantify (Figure 18).

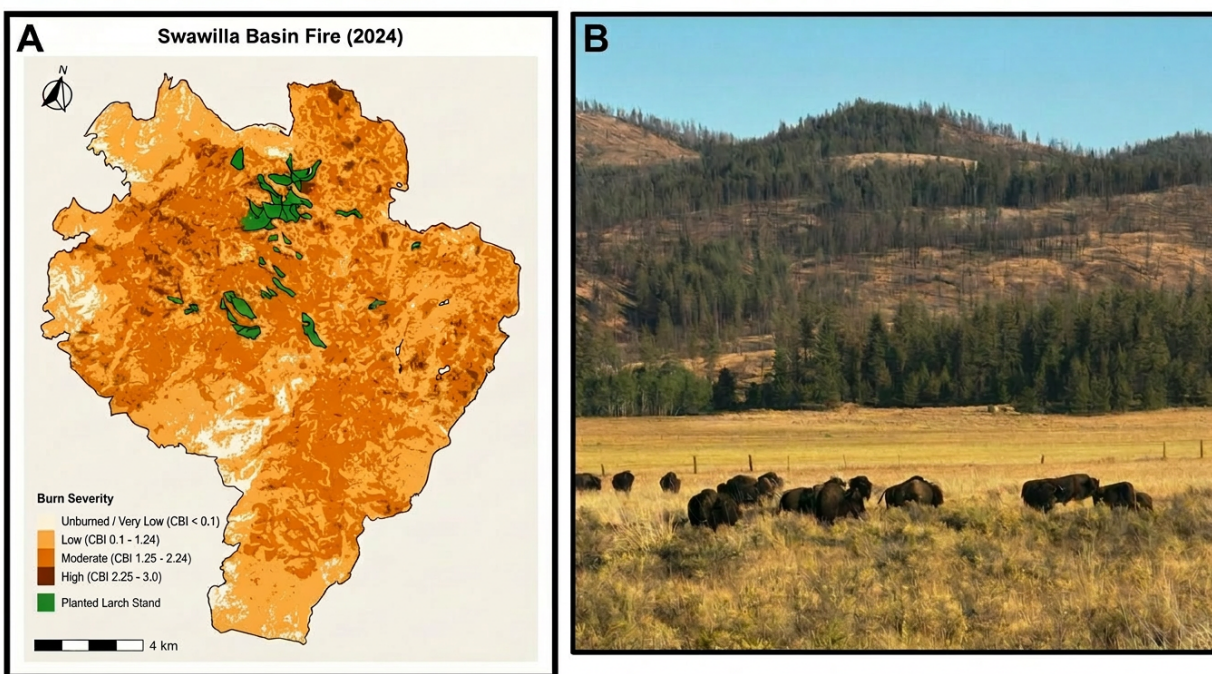


Figure 18. Modeled burn severity and planted western larch stand locations within the Swawilla fire (2024), Colville Reservation. Green polygons denote planted larch stands; burn severity classes are derived from the Parks et al. (2019) Random Forest CBI model using Sentinel-2 imagery (A). American bison (*Bison bison*), reintroduced to the Colville Reservation in 2023 as part of a Tribal ecological and cultural restoration initiative, grazing across a cheatgrass (*Bromus tectorum*)-invaded grassland along Nespelem Creek Road, 2024 (B). Cheatgrass creates a continuous, highly flammable fine fuel bed that compresses fire return intervals, suppresses native perennial vegetation, and drives a grass-fire cycle that inhibits conifer regeneration (D'Antonio and

Vitousek 1992; Balch et al. 2013). The dry ponderosa pine forest and recent fire scar visible on the hillside reflect the interacting disturbance drivers, invasive fine fuels, altered fire regimes, and fire exclusion that define the ecological context in which western larch restoration is being carried out.

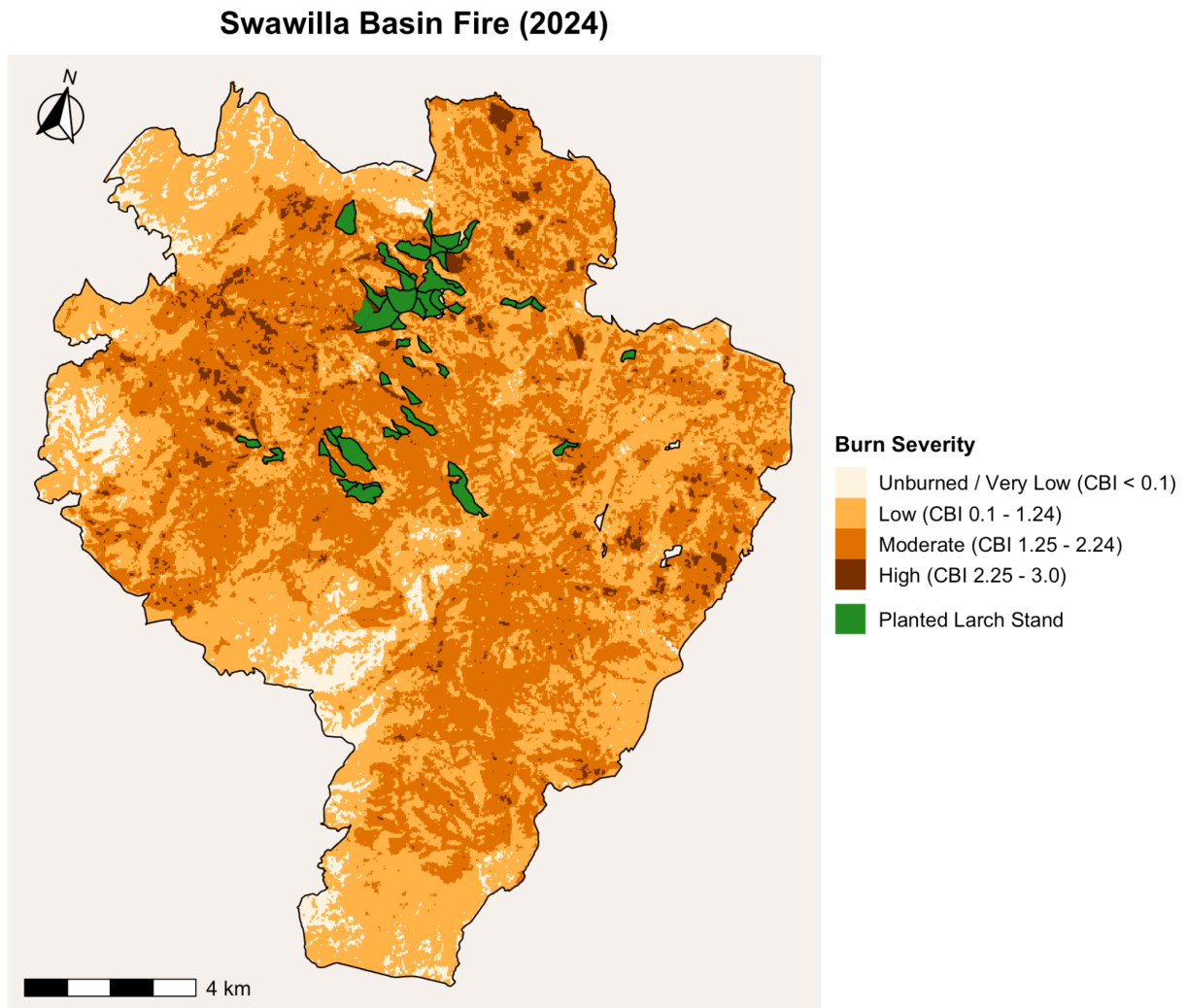


Figure 19. Modeled burn severity and planted western larch stand locations within the Swawilla Basin Fire (2024), Colville Reservation. Green polygons denote planted larch stands; burn severity classes are derived from the Parks et al. (2019) Random Forest CBI model using Sentinel-2 imagery.

The fire ignited on July 17, 2024, following a lightning event, and burned approximately 21,630 ha before reaching approximately 98% containment by August 9, 2024. Fire behavior was predominantly characterized by surface and backing fires through fine fuels and the forest understory, with

warm, dry conditions, low relative humidity, and occasional erratic outflow winds that supported continued activity and localized torching. Compared to the North Star and Summit Trail fires, the Swawilla Fire exhibited less widespread crown fire behavior, likely reflecting both the moderating influence of past treatments in portions of the footprint and the effectiveness of suppression later in the event (Figure 19).

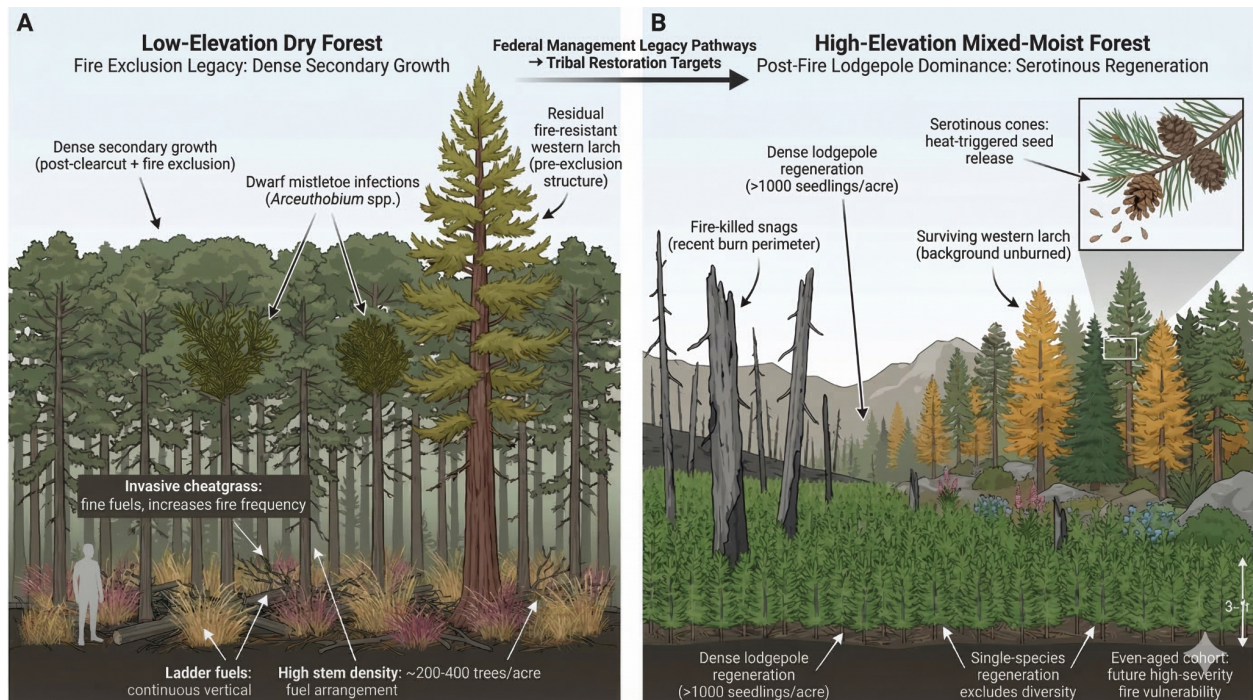


Figure 20. Contrasting forest conditions shaped by federal management legacies across two elevation zones in the inland Pacific Northwest highlight Tribal restoration targets. (A) A low-elevation dry forest altered by post-clearcut regrowth and decades of fire exclusion, characterized by high stem density (~494–988 trees/ha), continuous ladder fuels, dwarf mistletoe (*Arceuthobium* spp.) infections, and invasive cheatgrass that amplifies fine fuel loads and fire frequency, with only isolated residual fire-resistant western larch persisting from pre-exclusion forest structure. (B) A high-elevation mixed-moist forest following high-severity fire, now dominated by dense lodgepole pine regeneration (>2,471 seedlings/ha) driven by serotinous cone release. Fire-killed snags mark the perimeter of the recent burn, while surviving western larch stands persist in adjacent unburned areas. The resulting even-aged, single-species lodgepole cohort suppresses structural and biological diversity, increasing vulnerability to future high-severity fire. Image generated by FigureLabs.

Together, the North Star, Summit Trail, and Swawilla fires span the principal forest types and elevation zones of the Colville Reservation — from low-elevation ponderosa pine and grass-

shrub mosaics vulnerable to cheatgrass-driven fire spread, through mid-elevation mixed-conifer transitions, to high-elevation mixed-moist forests where lodgepole pine succession and deep fuel accumulation under fire exclusion have reshaped post-fire recovery trajectories (Figure 20). This gradient captures not only differences in species composition and fuel structure, but also meaningful variation in fire weather, fire behavior, and the disturbance legacies that shaped pre-fire stand conditions across each footprint. Critically, planted western larch stands are distributed across all three elevation zones and forest types, having been established under varied management histories and planting designs that reflect the Colville Tribes' spatially explicit restoration approach. This distribution provides a rare opportunity to evaluate planted larch performance not as a single treatment type under a single set of conditions, but as a landscape-scale restoration strategy tested simultaneously across a range of ecological contexts and fire events — from the extreme wind-driven crown fire of the 2015 North Star to the backing surface fire dynamics of the 2024 Swawilla. The consistency or variability of severity patterns across these contrasting contexts is central to interpreting whether planted larch stands represent a broadly effective tool for moderating fire behavior or whether their influence is conditional on the forest type, fire weather, or management history in which they are embedded.

2.0 Chapter 2: Landscape-Scale Patterns of Fire Severity and Forest Structure in Planted Western Larch Stands, Colville Reservation

Increasing wildfire activity across western North America has raised important questions about how restoration strategies may affect forest vulnerability and resilience under changing disturbance regimes. In the inland Pacific Northwest, climate change, historical fire exclusion, selective harvesting, and altered disturbance processes have interacted to reshape forest structure and composition, increasing stand density, vertical fuel continuity, and the abundance of shade-tolerant species in many historically fire-adapted forests (Hagmann et al., 2021; Hessburg et al., 2005; Parks & Abatzoglou, 2020; Perry et al., 2011). These changes have altered wildfire behavior and raised concerns about forest persistence under future climate and disturbance conditions (Coop et al., 2020; Hessburg et al., 2021; Parks & Abatzoglou, 2020).

On the Colville Reservation, managers have documented similar structural changes across portions of mixed-conifer forests, including increased forest density and shifts toward more shade-tolerant species compositions that influence forest health and disturbance dynamics (Confederated Tribes of the Colville Reservation, 2015, 2023; Rellergert-Taylor & O'Dea, 1988). In response, Tribal forest management programs have implemented restoration strategies focused on restoring fire-adapted species composition, increasing structural heterogeneity, and supporting long-term ecosystem resilience (Churchill et al., 2013; Graham et al., 2004; Hessburg et al., 2021).

Western larch restoration provides an opportunity to evaluate how species selection and stand development are associated with wildfire outcomes. Unlike conventional fuel treatments that modify existing vegetation structure, reforestation and planting decisions shape future forest composition, fuel arrangement, and disturbance response over decades (Crotteau et al., 2019; Hopkins et al., 2014). On the Colville Reservation, Tribal forest managers have planted western larch across broad environmental gradients as part of long-term efforts to restore early-seral, fire-adapted forest species, improve forest health, and increase resilience to disturbance (Figure 21) (Confederated Tribes of the Colville Reservation, 2023).

Western larch possesses several traits associated with fire resistance, including thick bark, elevated

crown architecture, and self-pruning characteristics that reduce ladder fuel continuity as trees mature (Arno & Fischer, 1995; Moris et al., 2022; Schmidt & Shearer, 1990; Stevens et al., 2020). However, many planted stands currently experiencing wildfire are relatively young and may not yet have fully developed the mature structural characteristics traditionally associated with fire resistance. This creates an important knowledge gap regarding whether young restored western larch stands experience different fire effects before these traits are fully expressed.

Understanding wildfire outcomes in restored forests requires connecting landscape-scale patterns with stand-level mechanisms. Climate, weather, topography, species composition, and forest structure interact to shape fire severity by influencing surface fuel accumulation, canopy arrangement, and vertical fuel continuity (Agee & Skinner, 2005; Cansler & McKenzie, 2014; Prichard et al., 2017). Recent studies using remote sensing and field-based approaches demonstrate that pre-fire forest structure, vegetation condition, topography, and management history can influence patterns of fire severity and tree mortality across heterogeneous landscapes (Cova et al., 2023; Cova, 2024; Sanna et al., 2025). Through differences in stand density, species composition, and fuel arrangement, planted western larch stands may contribute to variation in these structural conditions, yet few studies have evaluated their performance during actual wildfire events.

Evaluating these patterns requires approaches that can measure wildfire effects across large, heterogeneous landscapes. Researchers have widely used satellite-based burn severity metrics to assess fire outcomes across multiple fires, forest types, and management histories by quantifying spectral changes associated with vegetation loss and post-fire ecosystem effects (Key & Benson, 2006; Miller & Thode, 2007). Metrics such as the differenced Normalized Burn Ratio (dNBR), relative differenced Normalized Burn Ratio (RdNBR), Relativized Burn Ratio (RBR), and related spectral approaches allow researchers to characterize spatial patterns of burn severity and examine relationships among fire effects, climate, vegetation, and landscape characteristics (Cansler & McKenzie, 2014; Miller & Thode, 2007; Parks et al., 2014).

More recently, researchers have expanded ecological burn severity assessments by using machine-learning approaches that integrate satellite-derived spectral indices with field-based measurements

of fire effects. Random Forest models calibrated with Composite Burn Index (CBI) observations provide continuous estimates of burn severity that capture gradients of ecological change across heterogeneous landscapes (Breiman, 2001; Parks et al., 2019). These approaches improve comparisons of fire effects across regions by incorporating spectral, climatic, and biophysical predictors rather than relying on individual spectral indices alone (Amroussia et al., 2023; Parks et al., 2019). In this chapter, we integrate landscape-scale satellite-derived burn-severity modeling with stand-scale measurements of forest structure and fuels to evaluate wildfire outcomes in planted western larch stands on the Colville Reservation. Specifically, we examine whether planted western larch stands experienced different modeled burn severity patterns than surrounding forests across three recent wildfire events: the North Star Fire (2015), Summit Trail Fire (2021), and Swawilla Fire (2024). We further evaluate differences in surface fuels, ladder fuels, and stand structure within the Summit Trail Fire footprint to identify potential mechanisms associated with observed burn severity patterns.

Together, these analyses provide a multi-scale assessment of how planted western larch stands are associated with contemporary wildfire effects and whether restoration strategies centered on fire-adapted species may contribute to resilient forest conditions under changing climate and disturbance regimes (Crotteau et al., 2019; Halofsky et al., 2020; Hessburg et al., 2021).

2.1 Study System and Research Opportunity

The Colville Reservation provides a well-suited setting for this research. Over the past decade, the 2015 North Star, 2021 Summit Trail, and 2024 Swawilla fires burned across mosaics of planted and unplanted forests, creating opportunities to evaluate differences in burn severity across forest types exposed to the same wildfire events. The actively managed landscape, encompassing varied stand ages, species compositions, thinning histories, and planting designs, reflects real-world stewardship conditions and provides an opportunity to examine how species composition and stand structure are associated with fire effects across heterogeneous forest conditions (Confederated Tribes of the Colville Reservation, 2023). Understanding how planted western larch performs

within this mosaic is directly relevant to Tribal decision-making, post-fire restoration planning, and broader efforts to restore fire-resilient landscapes (Kimmerer & Artelle, 2024; Lake, 2021; Long et al., 2021).

2.2 Study Design and Analytical Framework

To evaluate whether planted western larch stands experienced different wildfire effects relative to adjacent forests, we combined landscape-scale satellite-derived burn severity assessments with targeted field sampling across three wildfire footprints. We used Relative Burn Ratio (RBR) maps derived from satellite imagery to identify planted western larch polygons located within areas of moderate- to high-severity fire effects and to stratify field sampling across the range of burn severity conditions observed within planted stand boundaries (Miller & Thode, 2007; Parks et al., 2014). This approach allowed us to select sites where surrounding fire effects were sufficient to evaluate differences between planted western larch stands and adjacent mixed-conifer forests.

We measured forest structure, surface fuels, and post-fire conditions within planted western larch stands and paired mixed-conifer plots three years after the Summit Trail Fire during the 2024 field season. These measurements allowed us to evaluate stand-level characteristics associated with the landscape-scale burn severity patterns identified through satellite-derived models and to examine potential structural mechanisms contributing to observed differences in fire effects (Cova et al., 2023; Cova, 2024).

We quantified surface fuel loads using the photoload sampling technique developed by Keane and Dickinson (2007), which estimates fuel loading through visual comparison of field conditions with calibrated photographic fuel references. We used a nested macroplot and microplot sampling design, establishing one 10-m-radius macroplot at each site. We divided each macroplot into four quadrants and measured ten 1-m² microplots per quadrant, for a total of 40 microplots per macroplot.

Within planted western larch, mixed-conifer, and unburned reference plots, we measured forest structure, fire effects, and fuel characteristics, including tree density, Composite Burn Index

(CBI), and photoload-based surface fuel estimates. To refine fuel load estimates, we collected additional measurements of duff and litter depth, understory vegetation height, and woody debris diameter, including ten randomly distributed duff and litter depth measurements within each quadrant. Together, these measurements allowed us to quantify differences in fuel abundance, vertical structure, and fine-scale fuel heterogeneity within and across forest types.

2.3 Study Objectives and Hypotheses

This chapter addresses two primary objectives. First, we quantify burn severity within planted western larch stands relative to adjacent unplanted forests across three wildfire footprints using a satellite-derived Random Forest model of Composite Burn Index (CBI) implemented in Google Earth Engine (Parks et al., 2019). This landscape-scale approach allows us to evaluate whether restored western larch stands experienced different fire effects compared with surrounding forest conditions exposed to the same wildfire events.

Second, we characterize surface fuels, ladder fuels, litter and duff depths, and stand structural attributes within the Summit Trail Fire footprint to identify stand-level conditions associated with observed burn severity patterns. By comparing burned planted western larch stands, unburned planted western larch stands, and mixed-conifer reference forests, we evaluate how differences in fuel composition and forest structure may contribute to variation in fire effects across forest types (Graham et al., 2004; Hopkins et al., 2014; Jain et al., 2021).

We evaluate two primary hypotheses:

Hypothesis 1 — Burn severity: We hypothesize that planted western larch stands will exhibit lower modeled burn severity than adjacent unplanted forests within the same wildfire footprints. Specifically, we expect the distribution of modeled CBI values within planted stand boundaries to shift toward lower severity values relative to surrounding forest buffers, with planted stands containing a smaller proportion of area classified as high severity (Parks et al., 2019; Prichard & Kennedy, 2014). These patterns would suggest that restored western larch stands are associated with different fire effects than neighboring forest conditions.

Hypothesis 2 — Forest structure and fuel characteristics: We hypothesize that planted western larch stands will exhibit differences in surface fuel accumulation, ladder fuel abundance, and stand structure compared with mixed-conifer forests. Specifically, we expect planted western larch stands to have lower dead woody fuel loads, reduced ladder fuel continuity, and structural conditions associated with lower potential fire severity, reflecting differences in species composition, stand development, and management history (Graham et al., 2004; Stephens et al., 2009; Jain et al., 2021). We evaluate these patterns while accounting for variation in site context, including elevation, slope, and aspect.

2.4 Methods

2.4.1 Sampling site selection - Fuel Load Assessment

We selected sampling sites within our study areas using vegetation polygons provided in the Tribes' spatial treatment database. The database labels and classifies polygons according to established guidelines in *The Forester's Guidebook* (Arney 2015), ensuring consistency in forest inventory and analysis. The database categorizes polygons by dominant tree species, with this study focusing on western larch (WL), and further classifies stands by diameter at breast height (DBH) size classes: Class 1 (0–5 inches), Class 2 (6–11 inches), Class 3 (12–21 inches), and Class 4 (22+ inches). The database also assigns stocking IDs based on the proportion of western larch present: Stocking ID 1 (10–39%), Stocking ID 2 (40–69%), and Stocking ID 3 (>70%).

Stand placement reflects restoration priorities rather than experimental randomization. Planted stands occur disproportionately on accessible, previously disturbed sites that may differ systematically from adjacent unplanted forest in pre-fire fuel structure, disturbance history, management history, and site productivity. This non-random placement represents a recognized limitation in observational comparisons of managed and unmanaged stands and requires careful interpretation of burn severity and fuel structure differences (Prichard and Kennedy 2014; Prichard et al. 2020; Sanna et al. 2025).

2.4.2 Remote Sensing of Fire Severity

We quantified burn severity within planted western larch (WL) stands and adjacent forests using satellite-derived imagery and a field-calibrated Random Forest model of Composite Burn Index (CBI) implemented in Google Earth Engine (GEE; Gorelick et al., 2017; Parks et al., 2019). Burn severity mapping across large, heterogeneous wildfire footprints presents important methodological challenges because spectral responses vary with vegetation type, pre-fire structure, climate, and post-fire ecological change. Spectral indices such as the differenced Normalized Burn Ratio (dNBR), relativized differenced Normalized Burn Ratio (RdNBR), and Relative Burn Ratio (RBR) are widely used to map burn severity, but researchers must interpret these metrics carefully because relationships between spectral change and ecological fire effects can vary across bioclimatic gradients and vegetation conditions (Key and Benson, 2006; Miller and Thode, 2007; Parks et al., 2014).

These limitations are particularly relevant when comparing young planted stands with surrounding mature forests because differences in pre-fire canopy cover, vegetation structure, and background reflectance can influence spectral responses independently of ecological fire effects. Recently managed or structurally open stands may follow different spectral trajectories than closed-canopy forests, which can complicate direct comparisons based solely on individual spectral indices (Parks et al., 2014; Harvey et al., 2019; Fernández-Guisuraga et al., 2023).

To improve ecological interpretation of burn severity patterns, we used modeled CBI values generated from the Random Forest framework developed by Parks et al. (2019). This approach integrates multiple satellite-derived spectral predictors, including Relative Burn Ratio (RBR), delta Mid-Infrared Burn Index (dMIRBI), and delta Normalized Difference Vegetation Index (dNDVI), together with climatic water deficit and latitude to account for geographic variability in relationships between spectral change and field-observed fire effects (Parks et al., 2019). By incorporating both spectral and bioclimatic predictors, this model provides continuous estimates of ecological burn severity across broad environmental gradients rather than relying on individual spectral thresholds alone (Parks et al., 2019; Sanna et al., 2025).

This modeling framework was well suited for evaluating fire effects on the Colville Reservation because the study fires occurred across complex elevational gradients, diverse forest compositions, and variable moisture conditions characteristic of the inland Pacific Northwest (Reilly et al., 2017). Accounting for bioclimatic context is particularly important because similar spectral changes may represent different ecological effects depending on local climate, productivity, and vegetation structure (Parks et al., 2019).

We acknowledge several limitations associated with applying remotely sensed burn severity models across multiple wildfire events. First, Parks et al. (2019) developed the model using fires through 2017; therefore, applying it to the Summit Trail (2021) and Swawilla (2024) fires extends the model beyond its original training period. Second, imagery sources differed among fires: we used Landsat 8 imagery for the North Star Fire and Sentinel-2 imagery for the Summit Trail and Swawilla fires, which may introduce residual differences associated with sensor characteristics (Cohen et al., 2017). Finally, modeled CBI values estimate field-based severity conditions and do not replace direct field measurements of CBI. The reported model uncertainty ($RMSE = 0.47$) should therefore be considered when interpreting fine-scale differences among stands (Parks et al., 2019).

Because this study uses a retrospective observational wildfire design, we interpret observed differences in modeled burn severity as associations between planted western larch stands and fire effects rather than as direct evidence of planting effects alone. Pre-existing differences in site conditions, stand history, management activities, and suppression actions may also contribute to observed patterns (Prichard and Kennedy, 2014; Sanna et al., 2025). However, by pairing planted stands with adjacent forest buffers, we evaluated whether restored western larch stands experienced different fire effects than nearby forest conditions exposed to the same wildfire event.

2.4.3 Quantifying Burn Severity

We adopted the Composite Burn Index (CBI; Key and Benson, 2006) as our primary burn severity metric and used the spatially explicit Random Forest modeling framework developed by Parks

et al. (2019), implemented in Google Earth Engine (GEE; Gorelick et al., 2017). CBI provides a field-based assessment of post-fire ecological change by integrating fire effects across multiple vertical strata, including substrates, understory vegetation, intermediate vegetation layers, and overstory canopy conditions (Key and Benson, 2006). Unlike individual spectral indices, modeled CBI provides a continuous estimate of ecological burn severity calibrated against field observations of fire effects.

Parks et al. (2019) developed the model using 8,075 field-based CBI plots from 263 fires that occurred between 1994 and 2017 across broad geographic and climatic gradients in the United States and Canada. The model estimates CBI using multiple satellite-derived spectral predictors, including Relative Burn Ratio (RBR), delta Mid-Infrared Burn Index (dMIRBI), delta Normalized Difference Vegetation Index (dNDVI), and post-fire MIRBI, together with climatic water deficit and latitude (Parks et al., 2019). By incorporating both spectral and bioclimatic predictors, the model accounts for geographic variability in relationships between remotely sensed vegetation change and field-observed fire effects, improving interpretation across diverse forest types and climate conditions (Harvey et al., 2019; Parks et al., 2019).

This approach is particularly appropriate for evaluating wildfire effects on the Colville Reservation because the study area occurs within the Northwestern Forested Mountains ecoregion, where Parks et al. (2019) reported strong model performance. The training dataset included extensive representation from inland western forests, including Northern Rocky Mountain and Pacific Northwest mixed-conifer systems containing species assemblages similar to those present in our study area, such as western larch, ponderosa pine, lodgepole pine, and Douglas-fir (Parks et al., 2019). The model achieved strong cross-validated performance across all training plots ($R^2 = 0.72$, RMSE = 0.47, MAE = 0.37) and performed similarly well within the Northwestern Forested Mountains ecoregion ($R^2 = 0.74$; Parks et al., 2019).

The inclusion of climatic water deficit further supports model application across the heterogeneous environmental gradients of the Colville Reservation, where forests span dry ponderosa pine systems, mixed-conifer forests, and higher-elevation mesic forest types. Because similar

spectral changes can correspond to different ecological effects depending on climate, vegetation composition, and productivity, incorporating biophysical variables improves comparisons among fires occurring across diverse landscapes (Parks et al., 2019).

For analysis and visualization, we treated modeled CBI as both a continuous variable and a categorical burn severity metric. Continuous modeled CBI values allowed us to compare severity distributions between planted western larch stands and adjacent forest conditions. We also classified modeled CBI values into four severity categories following Parks et al. (2019): unburned/very low severity (CBI = 0), low severity (CBI > 0–1.25), moderate severity (CBI > 1.25–2.25), and high severity (CBI > 2.25).

Although the Random Forest model improves ecological interpretation of satellite-derived fire effects relative to individual spectral indices alone, modeled CBI values remain estimates rather than direct field measurements. We therefore interpret modeled severity differences as relative patterns of fire effects between planted western larch stands and surrounding forests rather than exact measurements of individual-tree mortality, fuel consumption, or stand-level damage (Key and Benson, 2006; Parks et al., 2019).

Because this study uses a retrospective observational wildfire design, we interpret observed differences in modeled burn severity as associations between planted western larch stands and wildfire outcomes rather than as direct evidence of planting effects alone. Pre-existing differences in site characteristics, stand development, treatment history, species composition, suppression activities, and fire behavior may also contribute to observed patterns. However, paired comparisons between planted stand boundaries and adjacent forest conditions allow us to evaluate whether restored western larch stands experienced different fire effects during the same wildfire events, while acknowledging the inherent limitations of observational wildfire studies (Prichard and Kennedy, 2014; Sanna et al., 2025).

2.4.4 Stand Selection and Spatial Comparison

We identified planted western larch stands using the forest inventory geospatial database maintained by the Confederated Tribes of the Colville Reservation Department of Natural Resources. Stand polygons and classification attributes were provided through the co-produced research partnership guiding this study. The stand-based inventory database contains forest management polygons across the Reservation, including planted western larch units classified by dominant species, size class, and stocking characteristics following the Forester's Guidebook classification system (Arney, 2015).

We restricted our analysis to planted western larch stands classified as WL12, WL13, WL22, and WL23, representing established planted stands across the range of size and stocking classes present within the study landscape. We selected these classes to focus our analyses on stands with sufficient establishment and structural development to enable meaningful comparison with adjacent forest conditions.

After applying stand selection criteria and the 500 m fire perimeter exclusion described below, our final dataset included 137 planted western larch stands across the three wildfire footprints: 49 stands within the North Star Fire (2015), 52 within the Summit Trail Fire (2021), and 36 within the Swawilla Basin Fire (2024).

To reduce potential edge effects associated with suppression activities, including hand lines, dozer lines, and aerial retardant applications, which are commonly concentrated near fire boundaries, we excluded planted stands located within 500 m of mapped fire perimeters (Kolden et al., 2015). This criterion reduced potential suppression-related influences; however, we acknowledge that it does not eliminate all suppression effects, as complete operational records were unavailable for all three fires, and some suppression activities may occur within fire interiors.

For each retained planted stand, we created a paired comparison area representing the immediately adjacent unplanted forest matrix. We generated ring buffers surrounding each planted stand and removed the planted stand area from the buffer polygon, ensuring no spatial overlap between comparison areas. Buffer areas were scaled to match the area of each corresponding planted stand,

creating equal-area planted stand–buffer pairs.

To evaluate the sensitivity of the results to buffer size, we compared multiple buffer configurations ranging from one-ninth of the planted stand area (~11%) to the planted stand area (100%), including intermediate buffer sizes of 50% and 75%. Differences in modeled burn severity between planted stands and surrounding forests increased with buffer size across all three fire footprints, with the most consistent separation observed using equal-area buffers. Therefore, we selected equal-area planted stand–buffer pairs as the primary analytical configuration.

Equal-area buffers enabled spatially paired comparisons between planted western larch stands and adjacent forests that were exposed to the same wildfire event; however, these comparisons should not be interpreted as randomized experimental controls. Adjacent forests may differ from planted stands due to pre-existing variation in site characteristics, historical management, stand development, or fuel conditions. This type of observational comparison is common in retrospective wildfire analyses but requires caution when interpreting the mechanisms driving observed differences in severity (Coppoletta et al., 2016; Prichard & Kennedy, 2014; Prichard et al., 2020; Sanna et al., 2025).

We extracted modeled CBI values separately for each planted western larch stand and paired buffer. Using the *landscapemetrics* package in R (Hesselbarth et al., 2019), we calculated total burned area and proportional area within each severity class for planted stands and adjacent forest buffers.

Because stands located within the same fire perimeter may exhibit spatial autocorrelation due to shared fire weather, topography, and landscape context, individual stand observations may not be fully independent. We addressed this limitation by using paired statistical comparisons that evaluated differences between each planted stand and its corresponding adjacent buffer rather than comparing pooled severity distributions. However, residual spatial autocorrelation may remain and should be considered when interpreting statistical significance (Harvey et al., 2019; Sanna et al., 2025).

2.4.5 Field-Based Fuel Load Sampling (Photoload Method)

To characterize fine-scale fuel structure, we used the Photoload sampling method (Keane & Dickinson, 2007) within field plots established in the Summit Trail Fire (2021) footprint. We selected the Summit Trail Fire for ground-based sampling because it provided recent wildfire exposure within mixed-conifer forests containing established western larch restoration stands and adjacent comparison areas. These forests occur within mixed-mesic environments where historical fire exclusion, past timber harvest, and subsequent stand development have contributed to increased stand density, a multi-layered canopy structure, and greater continuity of surface and ladder fuels.

We did not conduct field sampling within the Swawilla or North Star fire footprints due to differences in site conditions and time since fire. The Swawilla Fire primarily burned across drier forest types, where vegetation structure, productivity, and fuel accumulation patterns differ from those of the mixed-mesic forests targeted for field sampling. The North Star Fire was excluded because the longer time since fire (~10 years) increased the likelihood that post-fire succession, tree mortality processes, regeneration, salvage activities, or other management actions had altered fuel and stand conditions relative to the initial fire effects. We acknowledge that post-fire vegetation change and management activities cannot be fully controlled in retrospective wildfire studies, including within the Summit Trail Fire footprint.

We selected field plots within planted western larch stands using criteria designed to minimize confounding effects and align field measurements with the landscape-scale burn severity analysis. Sampled stands were required to: (1) occur within a continuous forest matrix surrounded by adjacent mixed-conifer forests rather than roads, openings, or stand edges (Figure 22); (2) have no documented salvage logging or post-fire fuel treatments between the wildfire event and field sampling; and (3) classified as WL13 and WL23, representing two size classes with $\geq 70\%$ western larch composition of stand composition based on CTCR forest inventory classifications.

The final field dataset included 10 plots in burned planted western larch stands, 11 in unburned planted western larch stands, and 6 in adjacent mixed-conifer forests. Although this sampling

design provided detailed stand- and fuel-level measurements to complement the landscape-scale remote sensing analysis, the sample size and focus on the Summit Trail Fire limit inference to similar forest types and stand conditions. Field sampling was further constrained by post-fire access limitations, including road closures, safety considerations, and operational restrictions, which may introduce access-related sampling bias toward more accessible areas. Similar logistical constraints are common in post-fire field studies conducted within actively managed landscapes (Keane, 2013; Coppoletta et al., 2016).

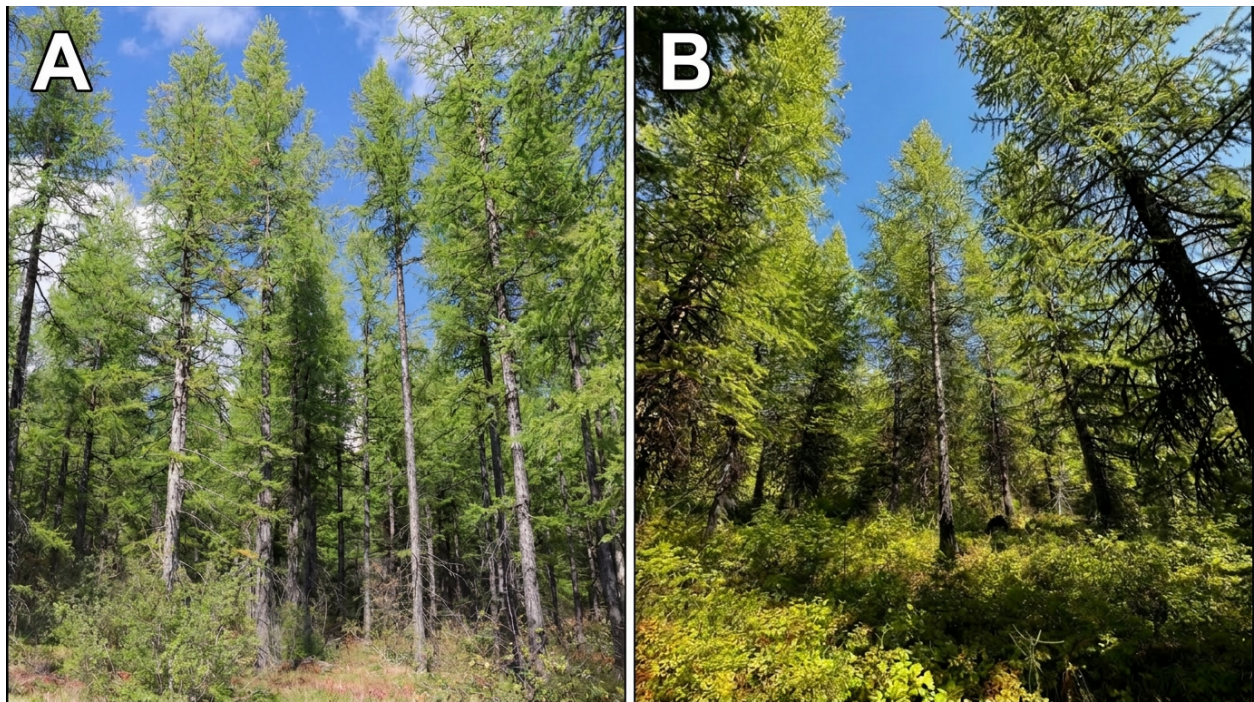


Figure 21. Planted western larch stand (WL13: sapling, $\geq 70\%$ larch) within the Summit Trail Fire (2021), Colville Reservation, Washington. (A) Burned portion of the stand following the fire, showing low to moderate burn severity with high canopy survival; green foliage on surviving larch demonstrates the fire-resistance capacity of high-stocking planted larch under extreme fire weather. (B) Adjacent unburned portion of the same stand (CBI = 0), where the open, self-pruned canopy, compact low-flammability larch needle litter, and dense huckleberry (*Vaccinium spp.*) and thimbleberry (*Rubus parviflorus*) understory contributed to fire exclusion while maintaining habitat for culturally significant plant species. Together, the two panels illustrate the range of fire outcomes observed within a single planted larch stand and the structural and fuel characteristics associated with reduced burn severity. Photographs by Priscilla Sperandio, 2024.



Figure 22. Dense, fire-excluded mixed-conifer forest outside the Summit Trail Fire boundary (2021), Colville Reservation, Washington. Heavy accumulations of coarse woody debris, thick duff layers, dense regeneration, and closed canopy characterize mixed-conifer forests in the study area. Fire exclusion has created continuous vertical fuel continuity from surface fuels through

ladder fuels to canopy, facilitating crown fire spread. The dense canopy limits light penetration, resulting in sparse, low-diversity understory vegetation and the absence of culturally important berry-producing shrubs. High fuel loading and lack of structural diversity contrast sharply with the open, self-maintained structure of planted western larch stands, contributing to higher fire severity in these forest types.

A total of 27 macroplots (20 m × 20 m) were established across burned and unburned planted western larch stands and adjacent mixed-conifer forests within the Summit Trail Fire perimeter. Each macroplot was divided into four quadrants, with 10 microplots (1 m²) sampled within each quadrant for a total of 40 microplots per macroplot. Surface fuel loads were estimated using the Photoload sampling method (Keane & Dickinson, 2007), which uses calibrated visual reference images to estimate fuel loading across standardized fuel classes (Figure 23). Measured fuel components included 1-hour, 10-hour, 100-hour, and 1,000-hour woody fuels, litter, and duff. Additional field measurements were collected to characterize stand structure and fuel conditions, including litter and duff depth, woody debris diameter, vegetation height, tree density, canopy base height, and canopy structure metrics. Canopy structure measurements were included because vertical fuel continuity strongly influences transitions from surface to crown fire and is particularly relevant for evaluating restored western larch stands. Mature western larch commonly develops elevated crown base heights through natural self-pruning; however, this trait may be less developed in younger, densely stocked stands where competition and limited growing space can delay crown recession and maintain lower live branches (Schmidt et al., 1976; Sparks et al., 2018; Conrad et al., 2024).

Unburned planted western larch and mixed-conifer comparison plots were sampled outside the active fire footprint to characterize reference fuel and structural conditions in the absence of recent fire effects. Because these plots represent contemporary unburned conditions rather than true pre-fire conditions, comparisons are interpreted as differences among current stand types rather than direct measurements of pre-fire fuel structure.

The Photoload method provides efficient estimates of surface fuel conditions across large field campaigns but carries known sources of uncertainty, particularly for larger woody fuel classes

where spatial heterogeneity, particle overlap, and fuel arrangement can influence visual estimates (Keane & Dickinson, 2007; Keane, 2013). Therefore, we interpret Photoload-derived estimates primarily as relative comparisons among planted western larch and mixed-conifer forest conditions rather than exact measurements of absolute fuel mass.

Because this study uses a retrospective wildfire design, field measurements are used to identify potential stand- and fuel-level mechanisms associated with observed burn severity patterns rather than to isolate the causal effects of western larch planting alone. Differences among planted western larch stands and adjacent mixed-conifer forests may reflect interactions among species composition, stand history, site conditions, prior management, and fire behavior during the wildfire event. Therefore, we interpret relationships between forest structure, fuel characteristics, and modeled burn severity as evidence of associated mechanisms that influence fire outcomes rather than direct causal attribution (Prichard & Kennedy, 2014; Sanna et al., 2025).

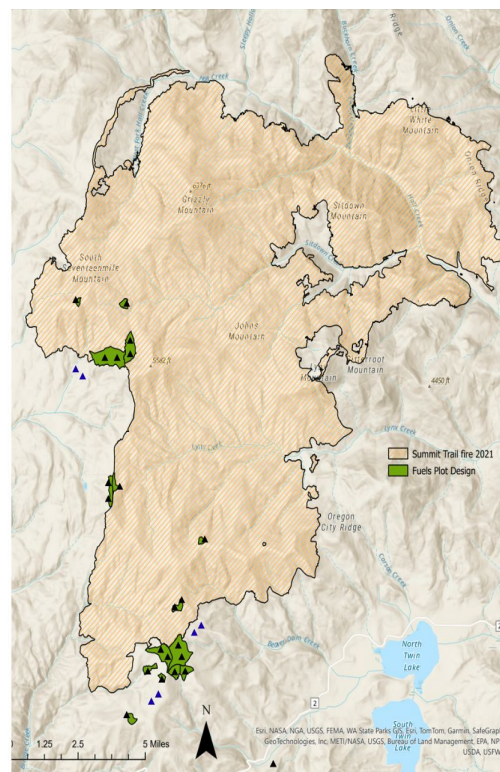


Figure 23. Summit Trail Fire (2021) perimeter (tan hatch) with planted western larch stands (light green) and the subset selected for fuel-load sampling (dark green; fuels plot design). Hydrography (blue) and hillshade provide topographic context. Scale bar and north arrow shown. Black triangles represent 10-m-radius macroplots within planted stands. Blue triangles represent control

macroplots.

Several constraints should be considered when interpreting the field sampling and spatial comparison results. Because western larch planting occurred as part of long-term restoration efforts rather than as part of an experimental design, stand locations were not randomly assigned across the landscape. Planted western larch stands may therefore differ from adjacent forests in pre-fire conditions, including historical management, disturbance history, site characteristics, stand structure, and fuel composition. These limitations are common in retrospective wildfire studies, where observed fire effects reflect interactions among vegetation, fuels, topography, weather, and prior management history rather than a single isolated driver (Prichard & Kennedy, 2014; Prichard et al., 2020; Sanna et al., 2025).

The equal-area buffer approach provided spatially paired comparisons between planted western larch stands and immediately adjacent forests exposed to the same wildfire event; however, these paired areas do not constitute randomized experimental controls. As a result, unmeasured differences between planted stands and surrounding forests before fire cannot be fully excluded (Coppoletta et al., 2016; Sanna et al., 2025). Similarly, excluding stands within 500 m of mapped fire perimeters reduced the likelihood of including areas influenced by suppression activities. Still, potential effects from internal suppression actions, including aerial retardant application or ground operations, could not be fully evaluated because complete operational records were unavailable. Spatial dependence among stands within the same wildfire footprint is an additional limitation, as nearby areas may experience similar fire weather, topography, and landscape conditions. Our paired analytical design reduced this concern by evaluating within-stand differences between planted western larch areas and adjacent comparison forests rather than treating all pixels or stands as fully independent observations. However, some residual spatial autocorrelation may remain without explicit spatial modeling and should be considered when interpreting statistical results (Harvey et al., 2019).

Field-based measurements of forest structure and fuels were limited to the Summit Trail Fire footprint and therefore represent a subset of the broader landscape-scale analysis. Plot selection

was constrained by post-fire access limitations, road closures, safety considerations, and operational conditions, potentially introducing bias toward more accessible locations. Additionally, the relatively small and uneven number of plots among forest types limits the extent to which field results can be generalized beyond similar stand conditions. Such logistical constraints are common in post-fire studies conducted across active management landscapes (Keane, 2013; Coppoletta et al., 2016).

Finally, Photoload estimates provide an efficient characterization of relative differences in surface fuel conditions but carry inherent uncertainty, particularly for larger woody fuel classes, where particle overlap, spatial variability, and fuel arrangement influence the accuracy of visual estimates (Keane & Dickinson, 2007; Keane, 2013). Therefore, we interpret field measurements as evidence of potential structural and fuel-related mechanisms associated with observed modeled burn severity patterns rather than direct causal evidence that western larch planting alone produced differences in wildfire outcomes.

2.5 Results

2.5.1 Surface Fuel Structure in Planted Western Larch vs. Mixed-Conifer Forests

2.5.2.1 Dead Woody Fuel Loads

Dead woody fuel loads differed between planted western larch and mixed-conifer forest plots across all time-lag size classes (Figure 24). Planted larch stands had lower mean loads across all dead fuel classes relative to mixed-conifer controls, with the magnitude of the reduction increasing with fuel size. Mean 1-hr fuel loads were $0.89 \pm 0.75 \text{ kg m}^{-2}$ in planted larch compared to $2.26 \pm 0.77 \text{ kg m}^{-2}$ in mixed-conifer forest; mean 10-hr loads were 0.32 ± 0.38 vs. $1.40 \pm 1.42 \text{ kg m}^{-2}$; mean 100-hr loads were 0.30 ± 1.20 vs. $6.25 \pm 14.9 \text{ kg m}^{-2}$; and mean 1000-hr loads were 0.12 ± 0.82 vs. $20.6 \pm 23.4 \text{ kg m}^{-2}$, respectively.

Linear mixed-effects models confirmed that these differences were statistically significant across all dead fuel classes (Figure 27). Several models returned singular fits, indicating negligible subplot-level variance in the random-effects structure; the results are therefore interpreted as

fixed-effects estimates. Planted larch stands showed estimated reductions of 43.9% (95% CI: -46.6 to -41.1%) in 1-hr fuels, 39.1% (95% CI: -42.0 to -36.1%) in 10-hr fuels, 55.2% (95% CI: -59.4 to -50.6%) in 100-hr fuels, and 92.3% (95% CI: -92.9 to -91.7%) in 1000-hr fuels relative to mixed-conifer controls, with confidence intervals entirely below zero for all size classes. The near-complete absence of 1000-hr coarse woody debris in planted larch stands represents the most ecologically consequential structural difference between forest types, as heavy fuels contribute disproportionately to sustained high-intensity combustion during wildfire events. These fuel sampling results are drawn entirely from the Summit Trail Fire footprint. They may not generalize to the drier, lower-elevation conditions of the North Star and Swawilla fires, where fuel accumulation dynamics, species composition, and management history differ.

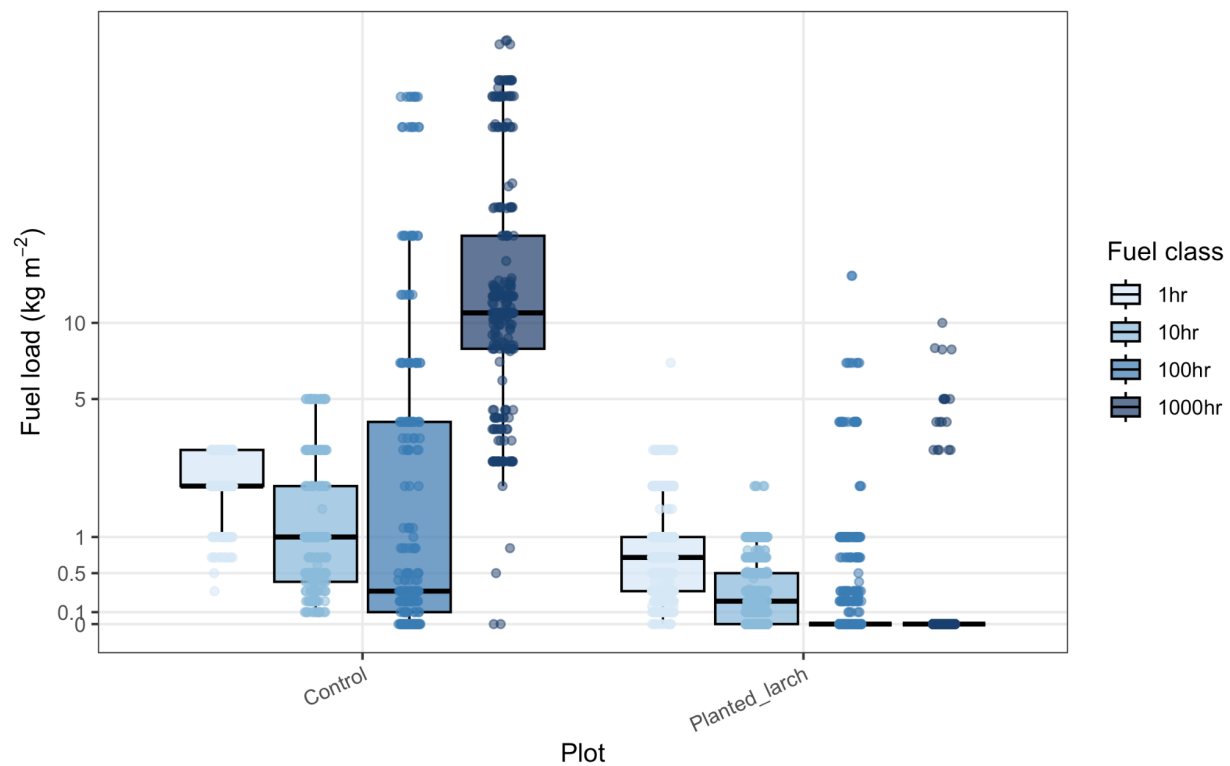


Figure 24. Dead woody fuel loads by plot type and size class. Boxplots show the distribution of surface fuel loads across 1-hr, 10-hr, 100-hr, and 1000-hr time-lag classes for planted western larch and mixed-conifer forest (Control) plots. The y-axis is $\log_{10}+1$ -scaled to accommodate the wide range of fuel loads across size classes. Points show individual microplot observations; boxes show the interquartile range with a median line.

5.5.2.2 Live Fuel Loads

In contrast to the reductions in dead woody fuels, planted western larch stands had greater live fuel loads than mixed-conifer controls in both herbaceous and shrub classes (Figure 25). Mean herbaceous fuel loads were $0.116 \pm 0.133 \text{ kg m}^{-2}$ in planted larch compared to $0.001 \pm 0.010 \text{ kg m}^{-2}$ in mixed-conifer forest, and mean shrub loads were 0.236 ± 0.093 vs. $0.059 \pm 0.049 \text{ kg m}^{-2}$, respectively. Mixed-effects models estimated increases of 10.7% (95% CI: 9.1 to 12.4%) in herbaceous fuels and 16.5% (95% CI: 15.3 to 17.6%) in shrub fuels in planted stands relative to controls, with confidence intervals entirely above zero for both classes. These percent-change estimates are back-transformed from the log scale and reflect modest absolute differences in fuel load between plot types, particularly for herbaceous fuels, where mean loads remain low across both forest types. The greater live fuel abundance in planted larch stands likely reflects greater light availability under the more open canopy structure of younger planted stands, which promotes understory vegetation development.

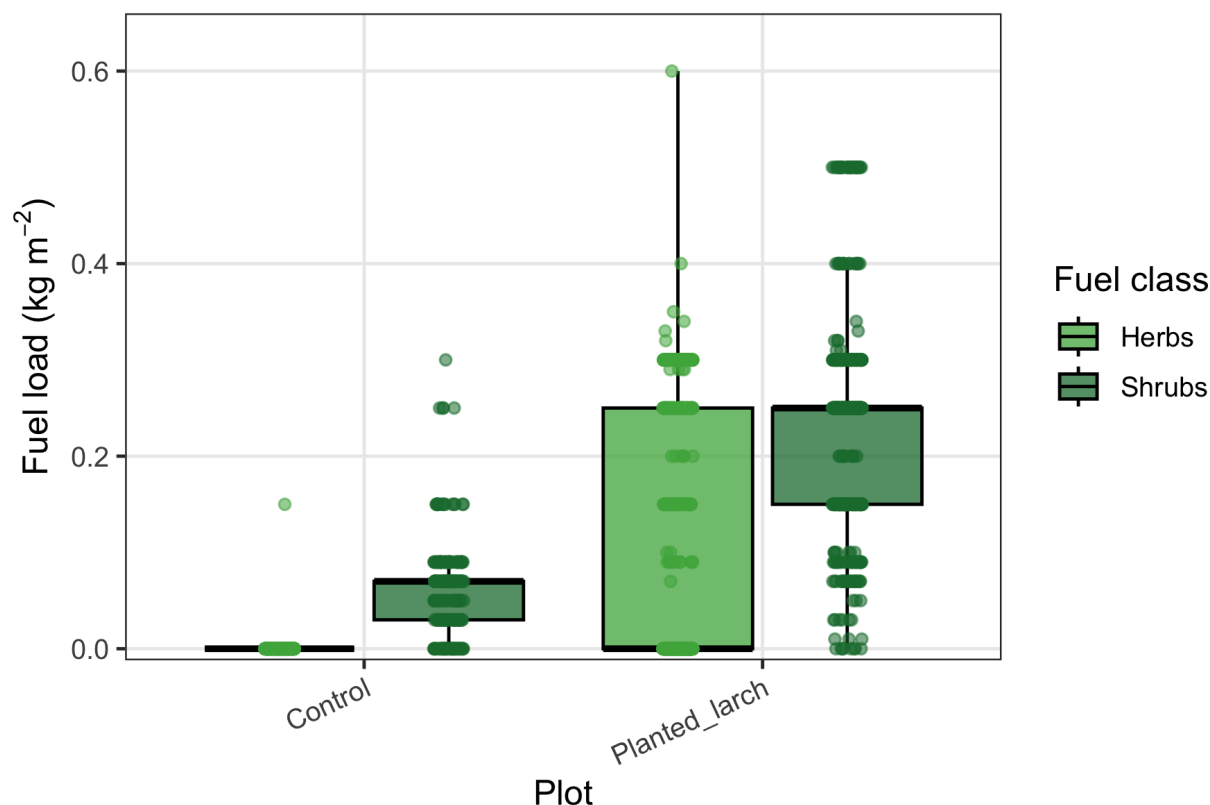


Figure 25. Live fuel loads by plot type. Boxplots show the distribution of herbaceous and shrub fuel loads for planted western larch and mixed-conifer forest (Control) plots on a linear scale. Points show individual microplot observations.

5.5.2.3 Litter and Duff Depths

Litter and duff depths differed between forest types, with patterns varying by treatment category (Figure 26). Mixed-conifer forest in the non-treated category had greater duff accumulation (mean ~5–8 cm) than all planted larch treatments. At the same time, litter depths were more similar across plot types, ranging from approximately 1.5 to 2.5 cm across most treatment categories. Planted larch plots across all treatment categories showed near-zero duff depths, consistent with shallower organic horizon accumulation expected in younger, managed stands with faster litter decomposition rates. The "Burned + Thinned" planted larch treatment showed reduced litter depths relative to unburned planted larch. At the same time, the mixed-conifer "Non-Treated" category had the highest and most variable duff depths among treatment-plot type combinations.

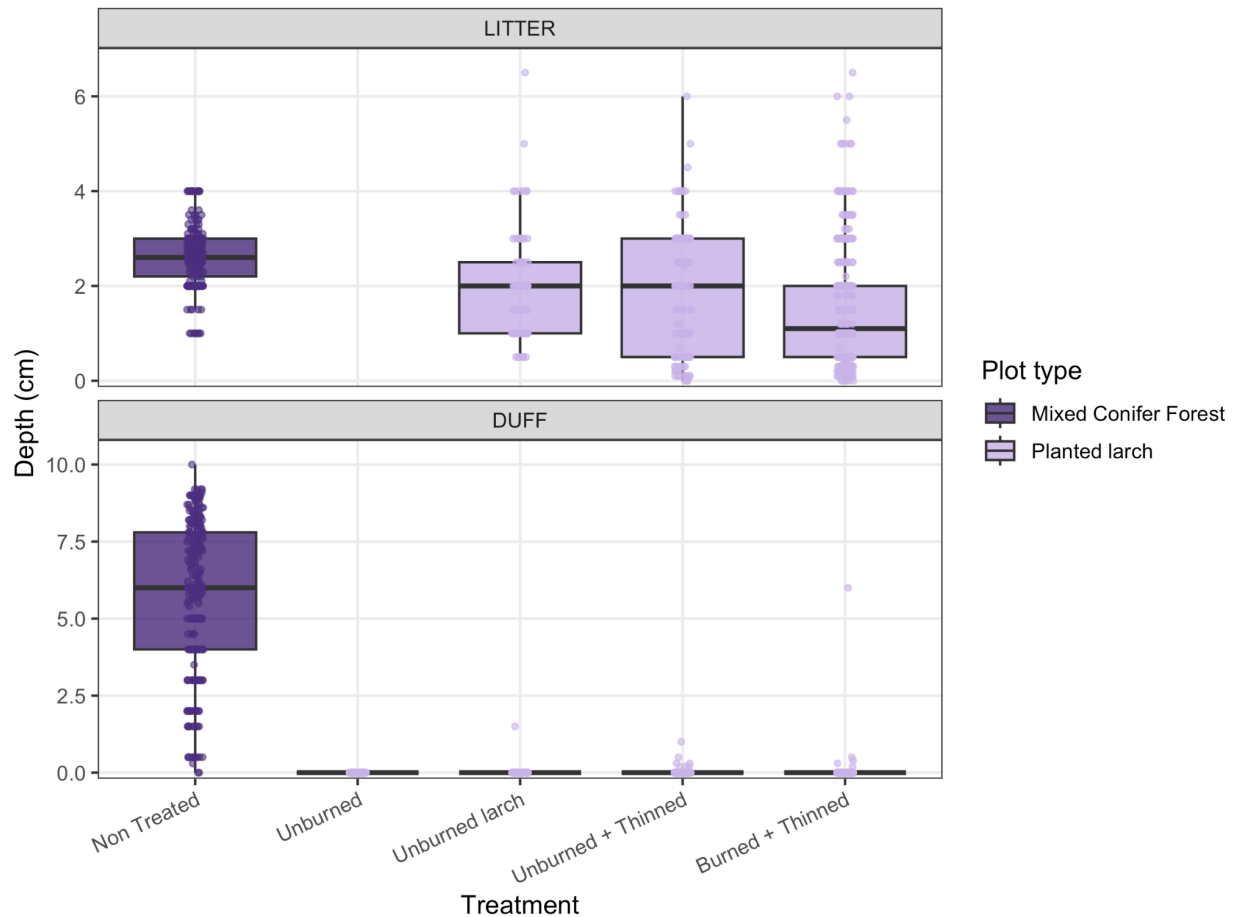


Figure 26. Litter and duff depths by treatment and plot type. Boxplots show the distribution of litter (top) and duff (bottom) depths across treatment categories for mixed-conifer forest (dark purple) and planted western larch (light purple) plots. Mixed-conifer forest in the non-treated category shows greater duff accumulation than all planted larch treatments, reflecting differences in stand age, management history, and litter decomposition dynamics. Points show individual sample observations.

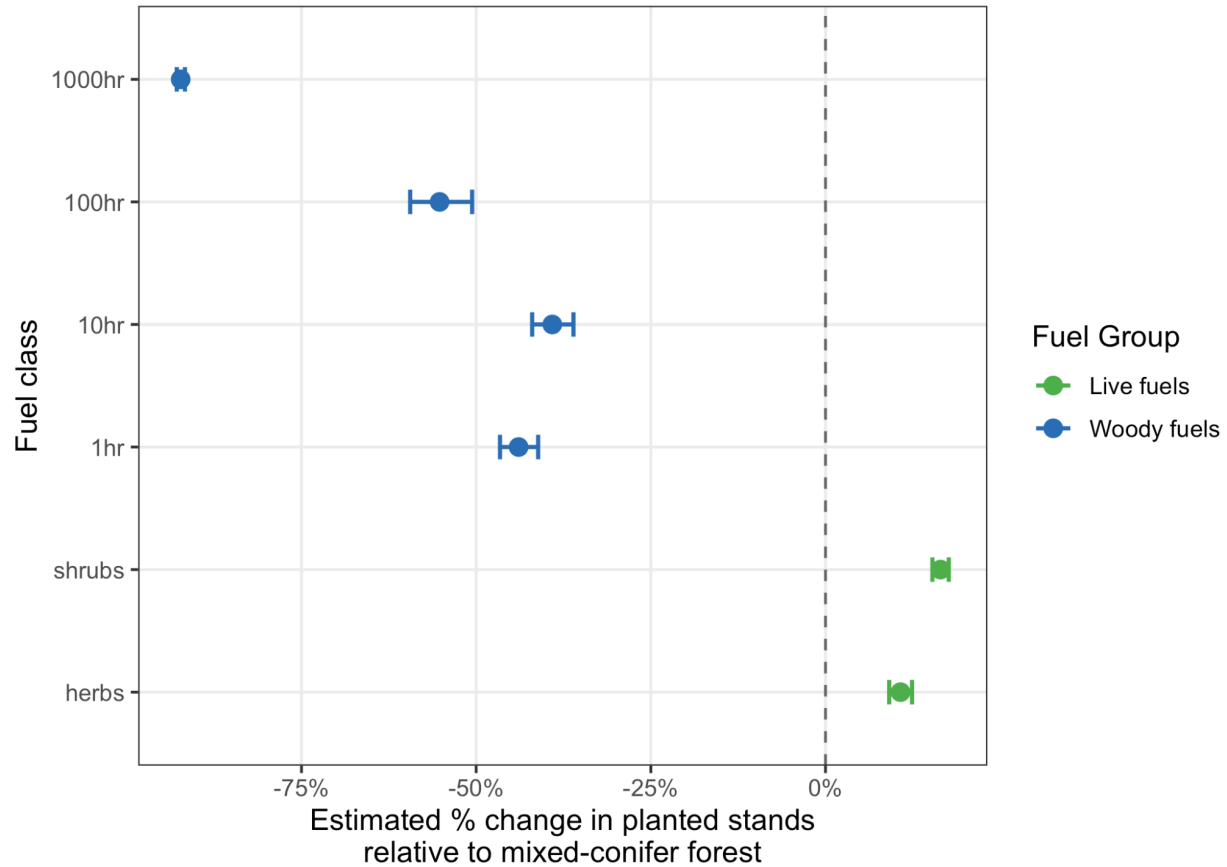


Figure 27. Modeled percent difference in fuel loads between planted western larch and mixed-conifer forest. Points show estimated percent change in planted stands relative to mixed-conifer controls from linear mixed-effects models fit separately for each fuel class ($\log(x + 1)$ -transformed loads $\sim$ plot type + (1 | subplot)); error bars show 95% confidence intervals. Woody fuel classes (blue) show significant reductions in planted stands across all size classes, with the largest effect in the 1000-hr class. Live fuel classes (green; herbs and shrubs) show modest but significant increases in planted stands. The dashed vertical line at zero indicates no difference.

2.5.2 Burn Severity in Planted Western Larch Stands vs. Surrounding Vegetation

2.5.2.1 Stand Inclusion and Spatial Comparison Design

Of the 149 planted western larch stands intersecting the three fire perimeters, 137 were retained for analysis (91.9% retention rate), encompassing a total planted area of approximately 1,794 ha. Retained stands ranged from 1.8 to 45.5 ha (mean = 13.1 ha). They spanned an elevational range of 679 to 1,635 m (mean = 1,249 m), representing habitat types from dry Douglas-fir associations at lower elevations to *Abies lasiocarpa/Vaccinium* communities at higher elevations.

Twelve stands (8.1%) were excluded from analysis because their surrounding forest comparison zones achieved less than 80% of the target equal-area. This threshold was applied to ensure that we compared each planted stand against a spatially adequate sample of adjacent unplanted forest. Exclusion occurred when planted stands were spatially clustered with neighboring planted stands, leaving insufficient unplanted forest area to construct a valid equal-area comparison zone; in the most extreme cases, two stands had effectively zero surrounding forest available after we subtracted all planted area. Ten of the 12 excluded stands were located within the Swawilla Basin footprint, where planted density was highest, and the remaining two were within the Summit Trail footprint. Among retained stands, the median surrounding forest zone achieved 326% of the target equal-area, and the minimum achievement ratio was 82.7%, confirming that all retained comparison zones provided ample unplanted forest area for severity extraction. Final per-fire sample sizes were 49 stands in the North Star Fire, 52 in the Summit Trail Fire, and 36 in the Swawilla Basin Fire.

Time since fire varied across the three events, approximately 10 years for the North Star Fire, 3 years for the Summit Trail Fire, and 1 year for the Swawilla Fire at the time of this analysis. Post-fire salvage logging, natural succession, and subsequent management activities cannot be fully controlled. These temporal differences introduce heterogeneity in the ecological context of each fire comparison that should be considered when interpreting cross-fire patterns.

Vegetation class effects on fire severity were examined separately for each of the three fires sampled in this study: the North Star Fire (2015), the Summit Trail Fire (2021), and the Swawilla Basin Fire (2024). For each fire, we characterized severity composition by vegetation class, compared high-severity occurrence within stands versus their paired equal-area buffer zones, examined the distribution of stand size across classes, and tested the relationship between stand size and high-severity area. Across all three fires, WL1x classes (WL12, WL13) tended to experience lower high-severity fire than WL2x classes (WL22, WL23), though the magnitude and direction of stand-versus-buffer differences varied by fire.

2.5.2.2 Landscape-Scale Burn Severity Patterns

Modeled burn severity maps across all three fire footprints show that planted western larch stands were distributed across heterogeneous severity mosaics and generally occupied areas of comparatively lower modeled CBI relative to the surrounding burned landscape (Figure 28). This visual pattern is supported by the severity distribution comparisons and paired statistical analyses below, though the strength and consistency of the effect varied across fire events. All stand-buffer comparisons reported below reflect associations between planting and burn severity outcomes. They document that planted stands burned differently than immediately adjacent unplanted forest exposed to the same fire event, but cannot isolate the causal contribution of planting itself from other factors, including pre-fire site characteristics, stand history, or residual differences in suppression activity (Prichard and Kennedy 2014; Sanna et al. 2025).

The North Star Fire burned a large, structurally heterogeneous landscape at predominantly moderate severity, consistent with the extreme fire weather conditions that characterized the 2015 fire season across eastern Washington. Within the fire footprint, planted larch stands were visually identifiable as lower-severity inclusions embedded within the broader burned matrix (Figure 28). The severity distribution within larch stands was dominated by moderate CBI (62.35%), with low severity at 21.74%, high severity at 14.94%, and unburned/very low at 0.97%. Surrounding forest zones showed a lower proportion of high-severity burning (4.97%) but a higher proportion of low severity (33.93%), with moderate severity similarly dominant (60.51%) and unburned/very low at 0.59% (Figure 29, Panel B).

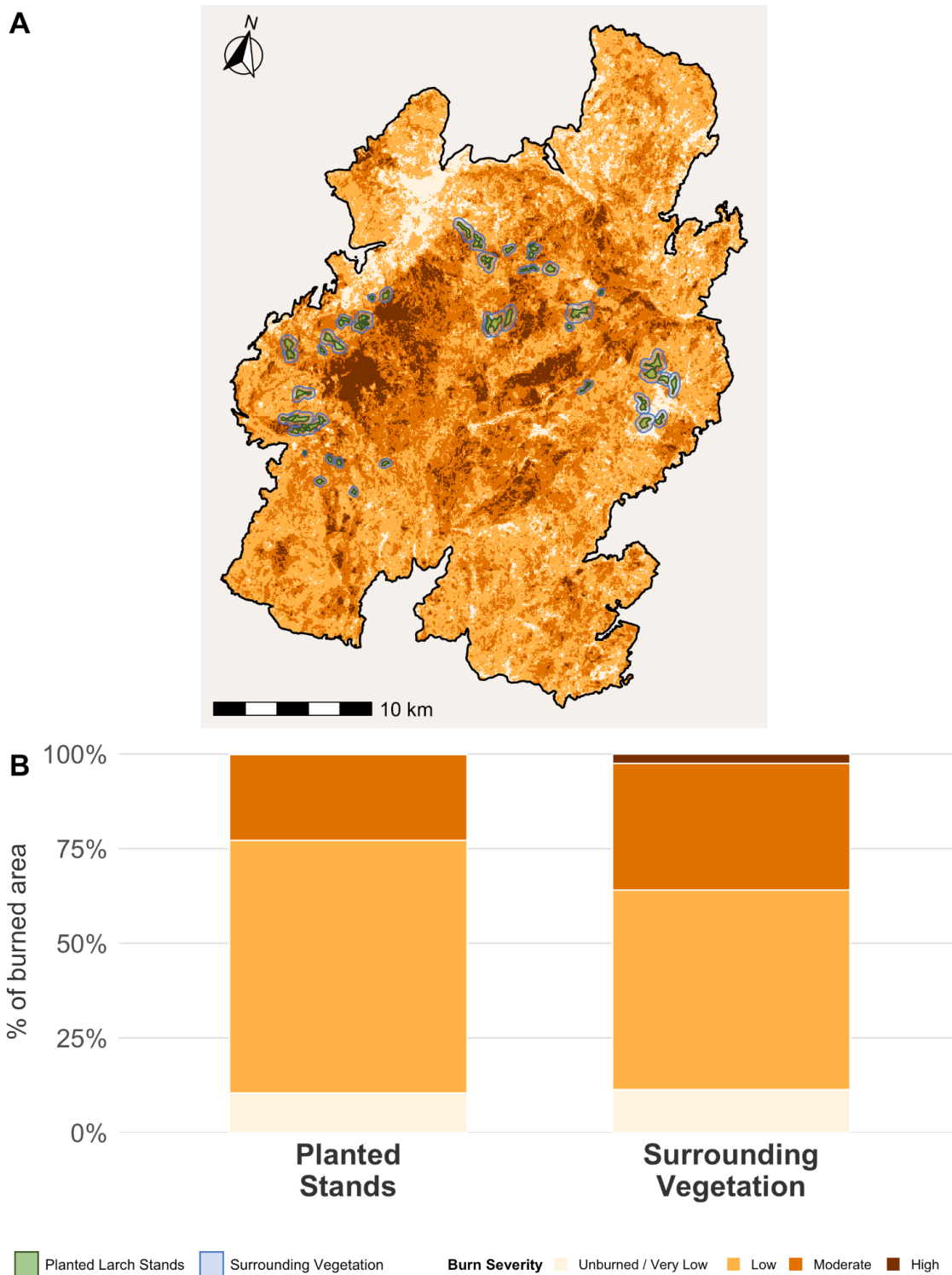


Figure 28. Modeled Composite Burn Index (CBI) and planted western larch stand locations within the North Star Fire (2015), Colville Reservation. (A) Burn severity map showing the spatial distribution of CBI classes (unburned/very low, low, moderate, and high) across the fire perimeter; green polygons denote planted western larch stands and blue polygons denote their

paired surrounding vegetation zones. (B) Proportional burn severity composition for planted stands versus surrounding vegetation. Burn severity classes are derived from the Parks et al. (2019) Random Forest CBI model using Landsat 8 imagery.

These severity distributions present an apparent complexity in interpretation: larch stands showed a higher raw percentage of high-severity area (14.94%) than the surrounding forest (4.97%), yet paired Wilcoxon signed-rank tests confirmed statistically significant reductions in both mean CBI and the proportion of high-severity area at the paired-stand level. Our primary inference rests on the paired analysis rather than the unpaired severity class distributions, because the paired design accounts for stand-specific differences in landscape position, fire weather exposure, and stand history that could otherwise confound comparisons. Mean CBI is the primary severity metric throughout; the paired test for the proportion of high-severity area provides a secondary, ecologically informative complement. The unpaired class distributions are presented for descriptive completeness and should not be interpreted as directly comparable, given the non-random placement of planted stands across the landscape.

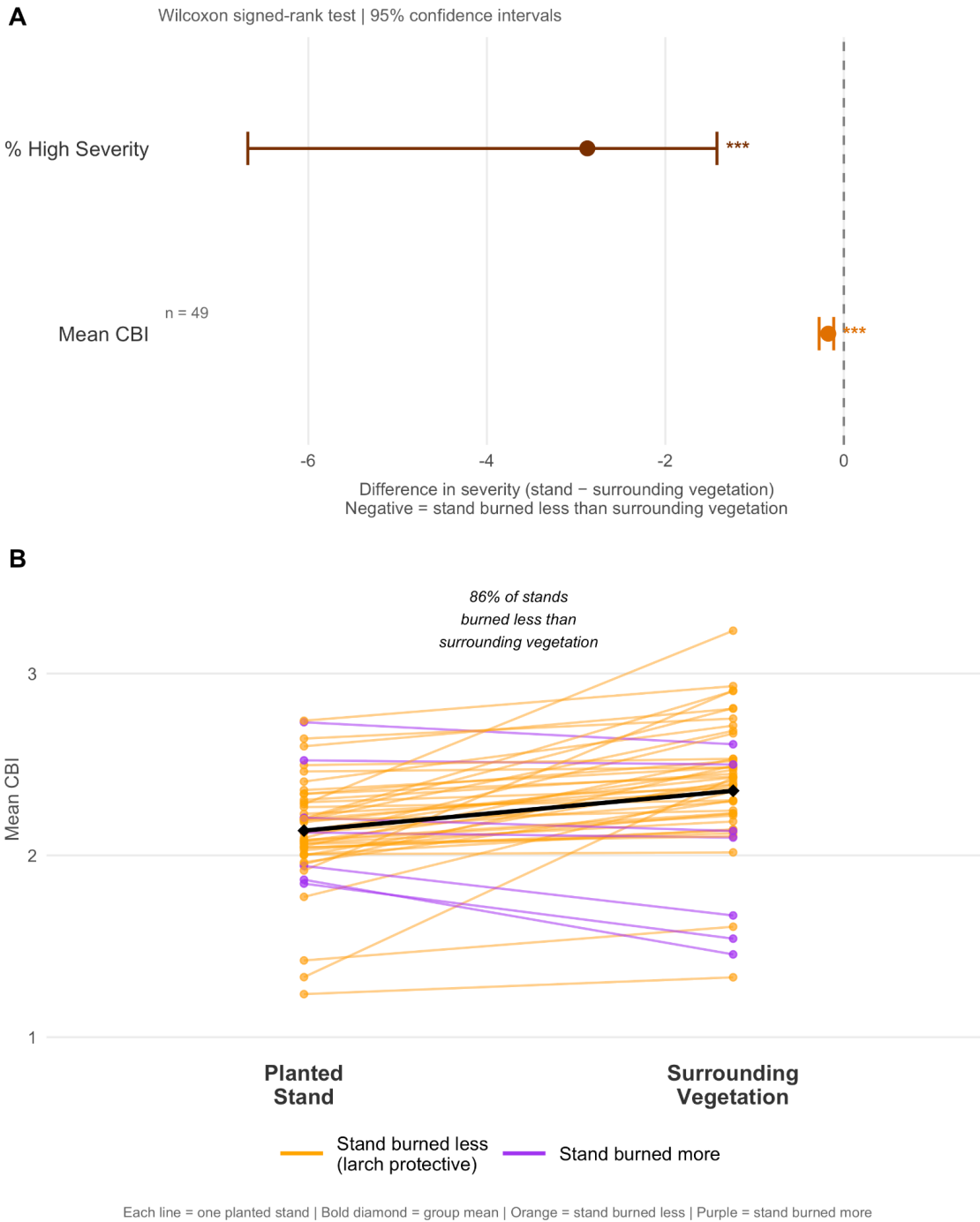


Figure 29. Effect size estimates and paired stand-level comparisons of burn severity between planted western larch stands and surrounding vegetation within the North Star Fire (2015), Colville Reservation. (A) Wilcoxon signed-rank test results for mean CBI and proportion of high-severity area (% High Severity); points show pseudomedian estimates with 95% confidence intervals; significance indicated by asterisks (***) $p < 0.001$. (B) Paired mean CBI for each planted stand (left) and its surrounding vegetation zone right); orange lines indicate stands that burned at lower severity than surrounding vegetation; purple lines indicate stands that burned at higher severity;

bold diamond indicates group means.

Paired Wilcoxon signed-rank tests confirmed statistically significant differences between planted stands and surrounding forest in both mean CBI (estimate = -0.175 , 95% CI: -0.278 to -0.114 , $p < 0.001$) and proportion of high-severity area (estimate = -2.874% , 95% CI: -6.678 to -1.422% , $p < 0.001$; $n = 49$ pairs; Figure 29, Panel A). These effect sizes are modest in absolute terms. A reduction of 0.175 CBI units corresponds to a shift within or between severity classes, depending on where the shift falls along the CBI continuum. At the landscape scale, however, consistent reductions of this magnitude across most stands are associated with lower rates of high-canopy scorch, soil heating, and post-fire conifer mortality (Key and Benson 2006; Davis et al. 2023). At the stand level, 86% of individual planted stands burned at a lower mean CBI than their paired surrounding forest.

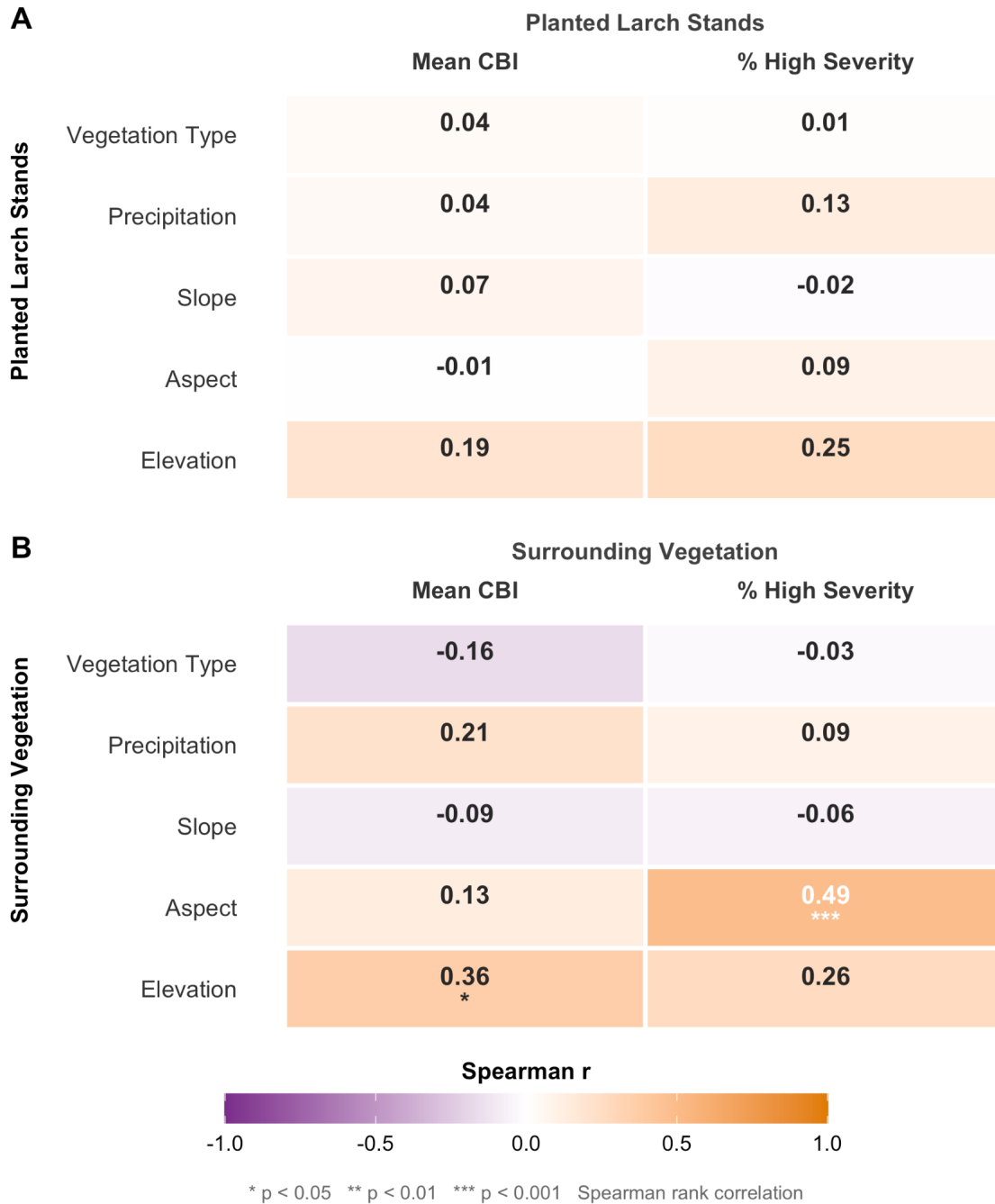


Figure 30. Spearman rank correlations between environmental predictors and burn severity metrics within the North Star Fire (2015) at the Colville Reservation. (A) Correlations within planted western larch stands. (B) Correlations within paired surrounding vegetation zones. Predictors include elevation, aspect, slope, precipitation, and vegetation type; severity responses are mean CBI and proportion of high-severity area (% High Severity). Cell color indicates correlation direction and strength (purple = negative, orange = positive); values in bold with asterisks indicate statistical significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Environmental predictors of burn severity within larch stands were weak and non-significant in the North Star Fire (Figure 30, Panel A). Spearman correlations between burn severity metrics and elevation, aspect, slope, precipitation, and vegetation type ranged from -0.01 to 0.25 with no predictor approaching significance. Elevation and aspect are proxies for fire weather and fuel moisture gradients rather than direct measurements of those processes; their weak performance within planted stands may reflect the moderating influence of stand structure, but may also reflect the spatial scale mismatch between plot-level severity and coarse-resolution climate covariates. In surrounding forest zones, elevation was a significant predictor of mean CBI ($r = 0.36$, $p < 0.05$; Figure 30, Panel B), suggesting that unplanted forest remained more responsive to topographic gradients in fire behavior than planted stands. This pattern is consistent with the interpretation that planted stand structure partially decouples within-stand fire behavior from broader environmental drivers. However, this interpretation should be tempered by the limitations of the available predictor set.

Summit Trail Fire (2021)

The Summit Trail Fire produced the strongest and most statistically robust evidence of an association between planted larch stands and reduced burn severity. The severity distribution within larch stands was dominated by low severity (66.75%), with unburned/very low severity at 10.45%, moderate at 22.64%, and high severity nearly absent at 0.16%. Surrounding forest zones showed a different distribution: low severity was less prevalent (52.73%), moderate severity was more prevalent (33.44%), high severity was present at 2.49%, and unburned/very low severity was at 11.34% (Figure 31, Panel B). The near-absence of high-severity burning within larch stands, compared to 2.49% in surrounding forest, represents one of the clearest quantitative contrasts observed across the three fires.

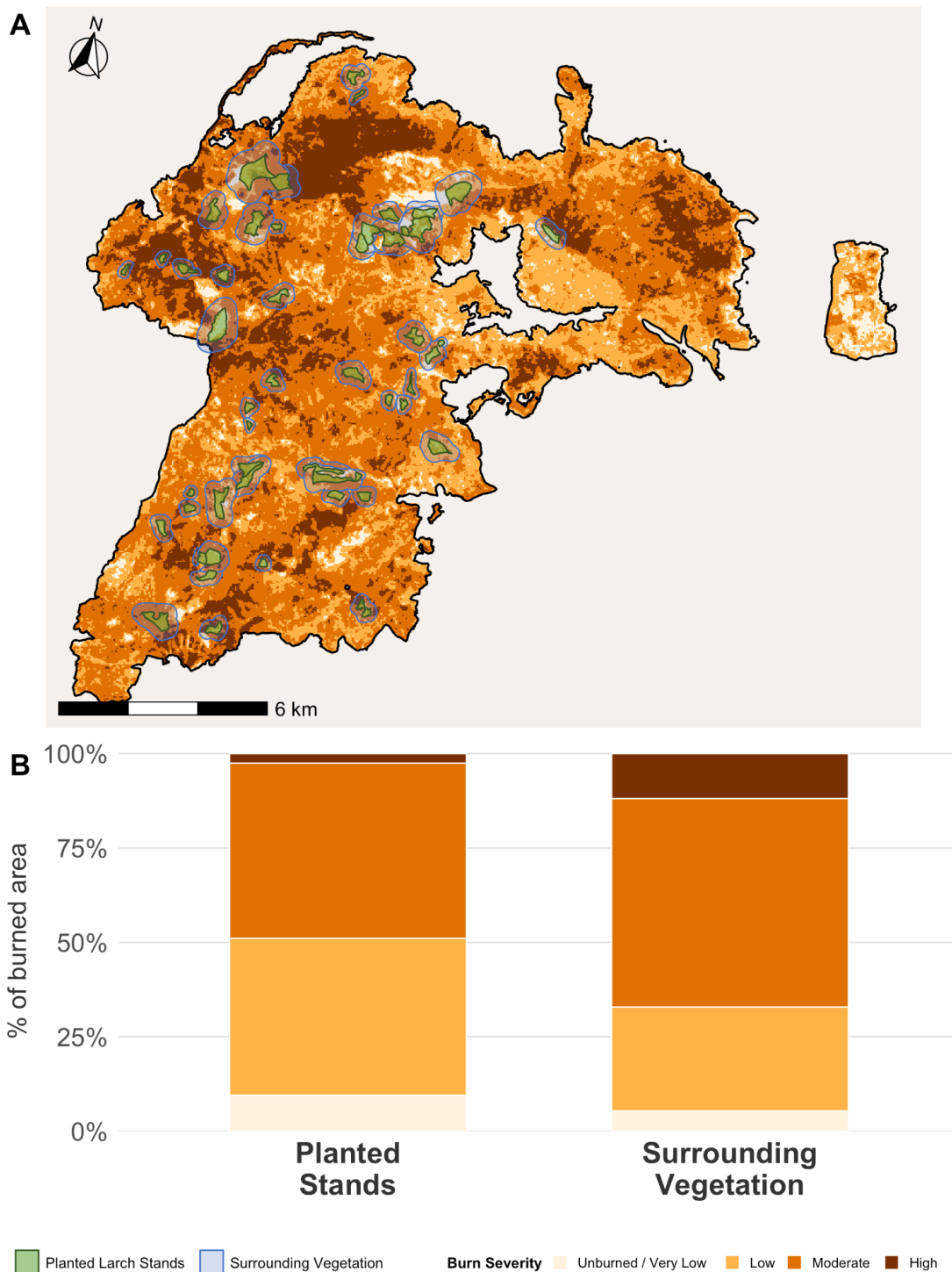


Figure 31. Modeled Composite Burn Index (CBI) and planted western larch stand locations within the Summit Trail Fire (2021), Colville Reservation. (A) Burn severity map showing the spatial distribution of CBI classes (unburned/very low, low, moderate, and high) across the fire perimeter; green polygons denote planted western larch stands and blue polygons denote their paired surrounding vegetation zones. (B) Proportional burn severity composition for planted

stands versus surrounding vegetation. Burn severity classes are derived from the Parks et al. (2019) Random Forest CBI model using Sentinel-2 imagery.

Paired Wilcoxon signed-rank tests confirmed statistically significant reductions in both mean CBI (estimate = -0.312 , 95% CI: -0.430 to -0.189 , $p < 0.001$) and proportion of high-severity area (estimate = -9.327% , 95% CI: -16.837 to -6.419% , $p < 0.001$; $n = 51$ pairs; Figure 32, Panel A). The effect size for both metrics was the largest of the three fires. A reduction of 0.312 CBI units is sufficient to shift many stands across the low-to-moderate severity threshold ($CBI = 1.25$), a transition that corresponds to differences in canopy survival, soil heating depth, and understory mortality (Key and Benson 2006). As in the North Star Fire, 86% of individual planted stands burned at a lower mean CBI than their matched surrounding forest.

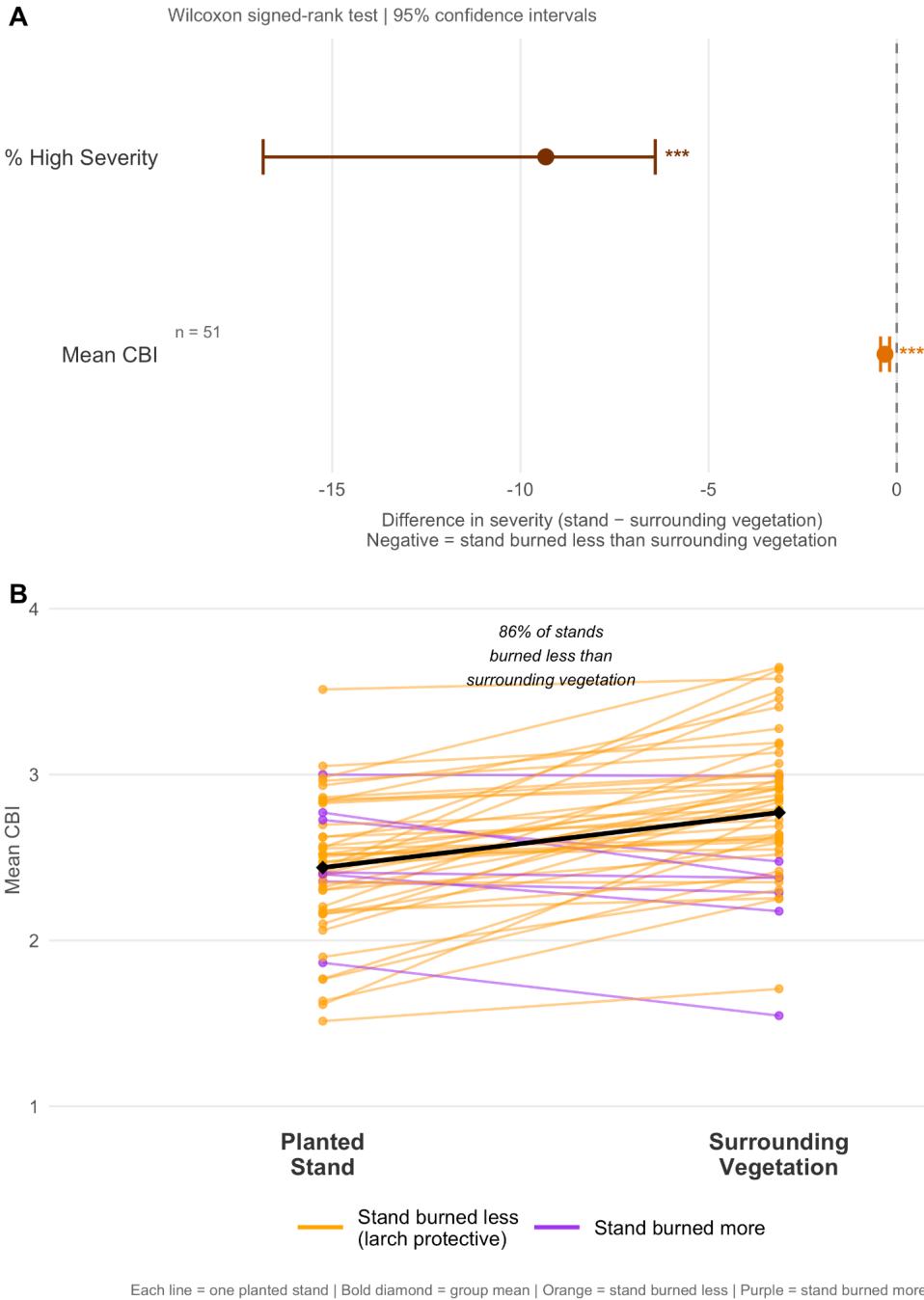


Figure 32. Effect size estimates and paired stand-level comparisons of burn severity between planted western larch stands and surrounding vegetation within the Summit Trail Fire (2021), Colville Reservation. (A) Wilcoxon signed-rank test results for mean CBI and proportion of high-severity area (% High Severity); points show pseudomedian estimates with 95% confidence intervals; significance indicated by asterisks (***) $p < 0.001$. (B) Paired mean CBI for each planted stand (left) and its surrounding vegetation zone (right); orange lines indicate stands that burned at lower severity than surrounding vegetation; purple lines indicate stands that burned at higher severity; bold diamond indicates group means.

Within larch stands, elevation was the only significant environmental predictor, showing a moderate positive correlation with the proportion of high-severity area ($r = 0.61, p < 0.001$; Figure 33, Panel A), suggesting that higher-elevation stands experienced a greater proportion of high-severity burning. This may reflect greater pre-fire fuel accumulation or more severe fire weather at upper elevations within the footprint. Elevation and aspect serve as proxies for fuel moisture and fire weather gradients rather than direct measurements. The strength of the elevation signal in surrounding forest zones, where elevation significantly predicted both mean CBI ($r = 0.50, p < 0.001$) and proportion of high-severity area ($r = 0.64, p < 0.001$; Figure 33, Panel B), is consistent with the interpretation that planted stand structure moderated within-stand fire behavior relative to the broader topographic controls operating across the unplanted landscape, though direct fire weather measurements would be needed to confirm this interpretation.

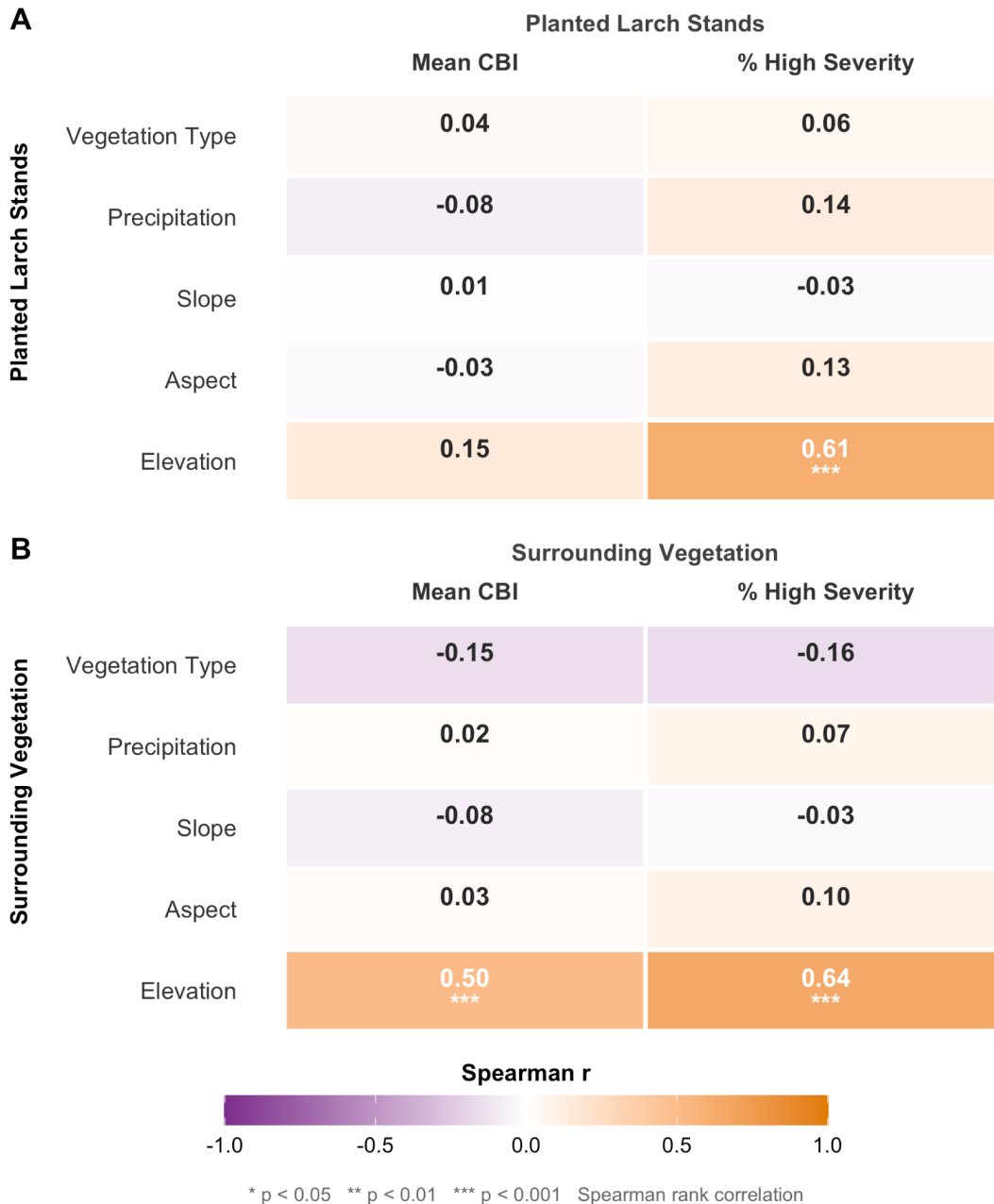


Figure 33. Spearman rank correlations between environmental predictors and burn-severity metrics for the Summit Trail Fire (2021) on the Colville Reservation. (A) Correlations within planted western larch stands. (B) Correlations within paired surrounding vegetation zones. Predictors include elevation, aspect, slope, precipitation, and vegetation type; severity responses are mean CBI and proportion of high-severity area (% High Severity). Cell color indicates correlation direction and strength (purple = negative, orange = positive); values in bold with asterisks indicate statistical significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Swawilla Basin Fire (2024)

The Swawilla Basin Fire diverged from the patterns observed in the North Star and Summit Trail fires. This null result is informative about the conditions under which planted larch stands do and do not moderate fire behavior. Within larch stands, moderate severity dominated (46.41%), followed by low severity (41.55%), with unburned/very low at 9.52% and high severity at 2.52%. Surrounding forest showed a different distribution: moderate severity was similarly dominant (55.19%), but high-severity burning was higher (11.89%), low severity lower (27.53%), and unburned/very low at 5.3% (Figure 34, Panel B).

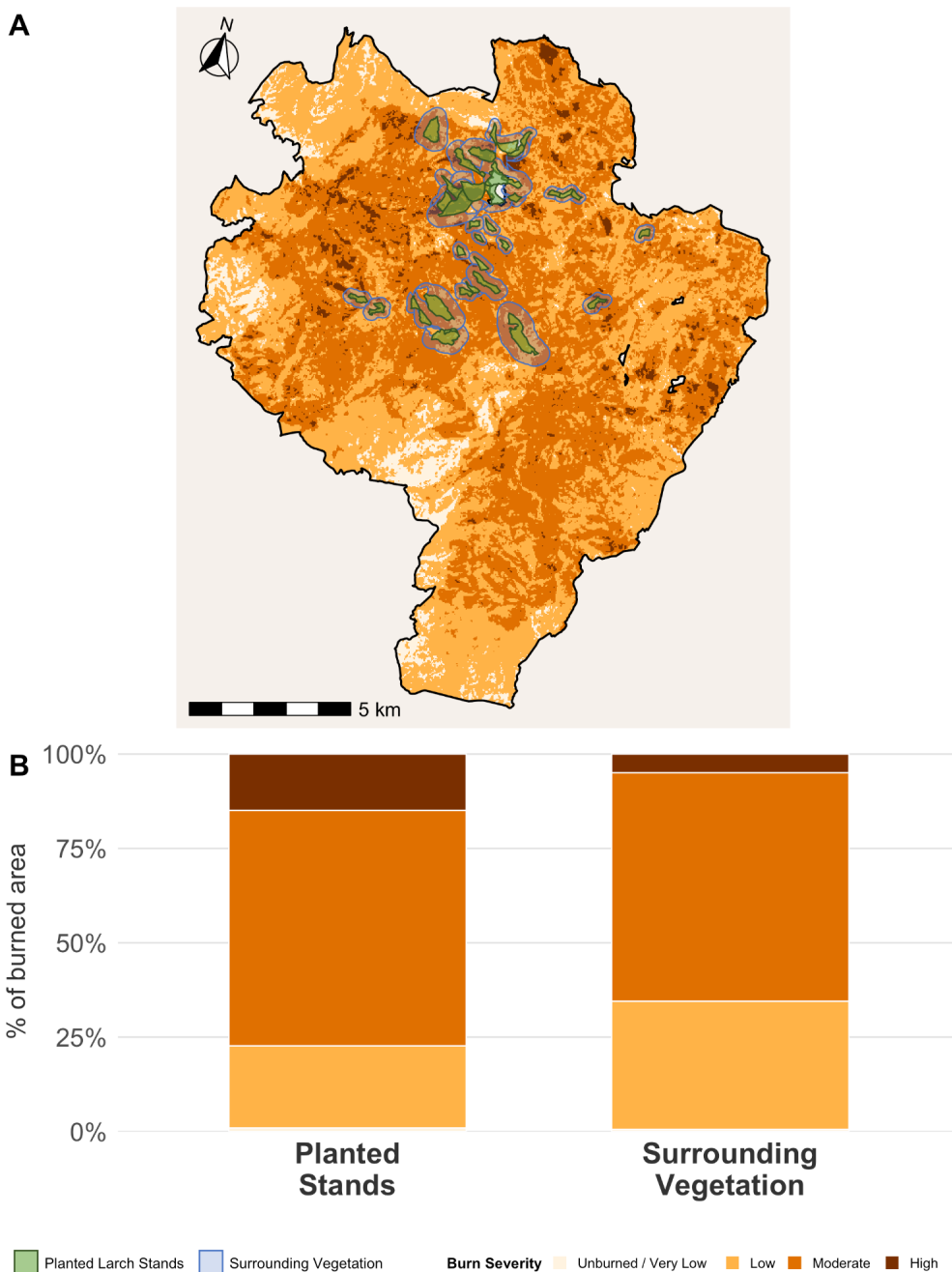


Figure 34. Modeled Composite Burn Index (CBI) and planted western larch stand locations within the Swawilla Basin Fire (2024), Colville Reservation. (A) Burn severity map showing the spatial distribution of CBI classes (unburned/very low, low, moderate, and high) across the fire perimeter; green polygons denote planted western larch stands and blue polygons denote their paired surrounding vegetation zones. (B) Proportional burn severity composition for planted stands versus surrounding vegetation. Burn severity classes are derived from the Parks et al. (2019) Random Forest CBI model using Sentinel-2 imagery.

Paired Wilcoxon signed-rank tests found no statistically significant difference in either mean CBI (estimate = 0.091, 95% CI: -0.082 to 0.227, $p = 0.298$) or proportion of high-severity area (estimate = 1.213%, 95% CI: -1.594 to 9.587%, $p = 0.381$) between larch stands and matched surrounding forest ($n = 35$ pairs; Figure 35, Panel A). The positive point estimates indicate that larch stands burned at slightly higher mean CBI and a greater proportion of high-severity area than the surrounding forest on average. However, wide confidence intervals reflect substantial uncertainty. At the stand level, only 37% of planted stands burned at a lower mean CBI than their paired surrounding forest.

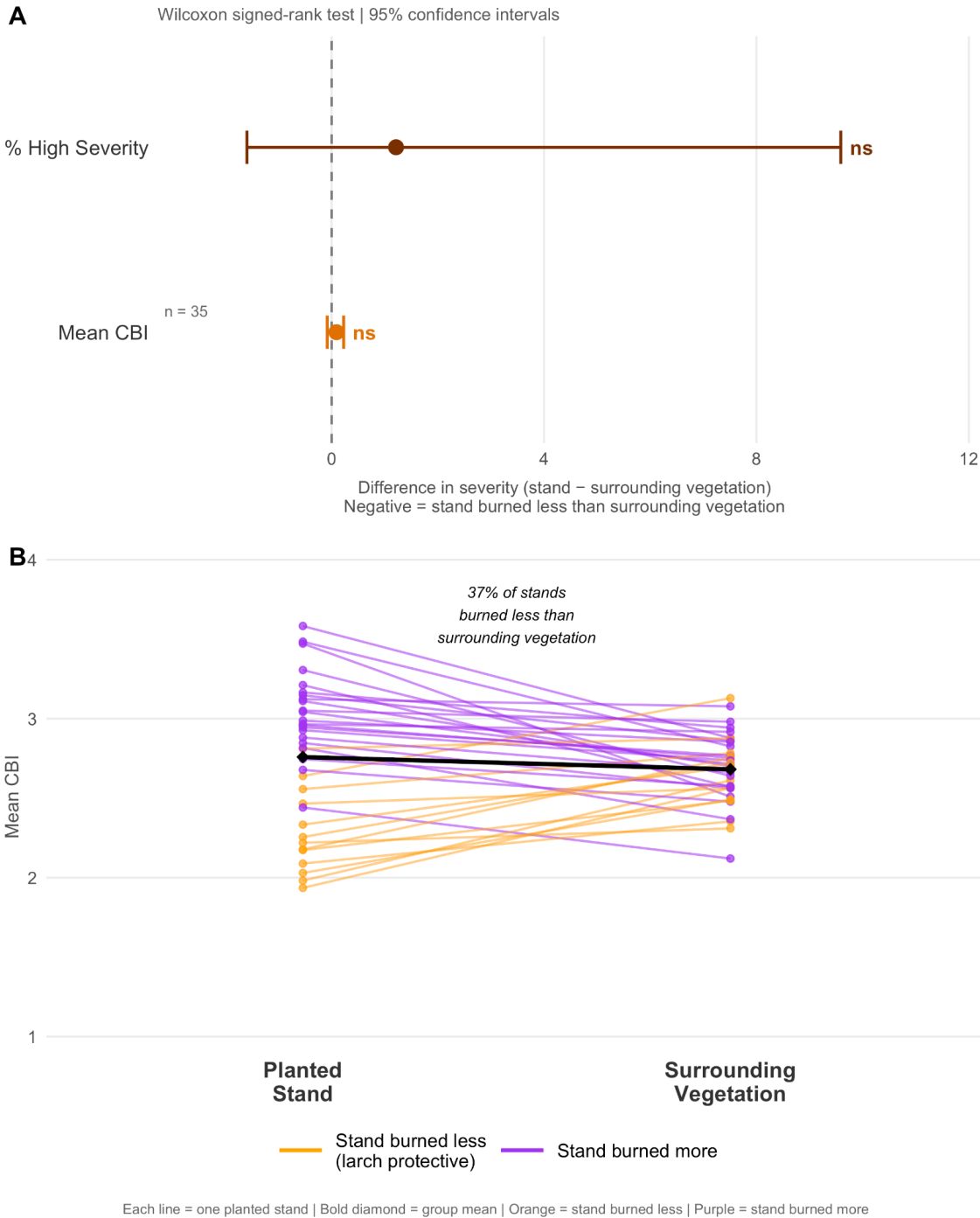


Figure 35. Effect size estimates and paired stand-level comparisons of burn severity between planted western larch stands and surrounding vegetation within the Swawilla Basin Fire (2024), Colville Reservation. (A) Wilcoxon signed-rank test results for mean CBI and proportion of high-severity area (% High Severity); points show pseudomedian estimates with 95% confidence intervals; ns = not significant. (B) Paired mean CBI for each planted stand (left) and its surrounding vegetation zone (right); orange lines indicate stands that burned at lower severity than surrounding vegetation; purple lines indicate stands that burned at higher severity; bold diamond

indicates group means.

Environmental predictor relationships in the Swawilla Fire were stronger than in the other two events. Within larch stands, vegetation type was significantly correlated with both mean CBI ($r = 0.52$, $p < 0.01$) and proportion of high-severity area ($r = 0.56$, $p < 0.001$), and aspect was significantly associated with both severity metrics ($r \approx 0.50$ – 0.60 , $p < 0.05$; Figure 36, Panel A), indicating that topographic exposure and forest type played a role in mediating fire behavior at this fire. As with the other fires, these predictors are proxies rather than direct measurements of fire weather or fuel moisture; the stronger explanatory power of environmental predictors in the Swawilla is consistent with fire behavior in this event being more strongly governed by landscape-level drivers, but direct attribution requires caution.

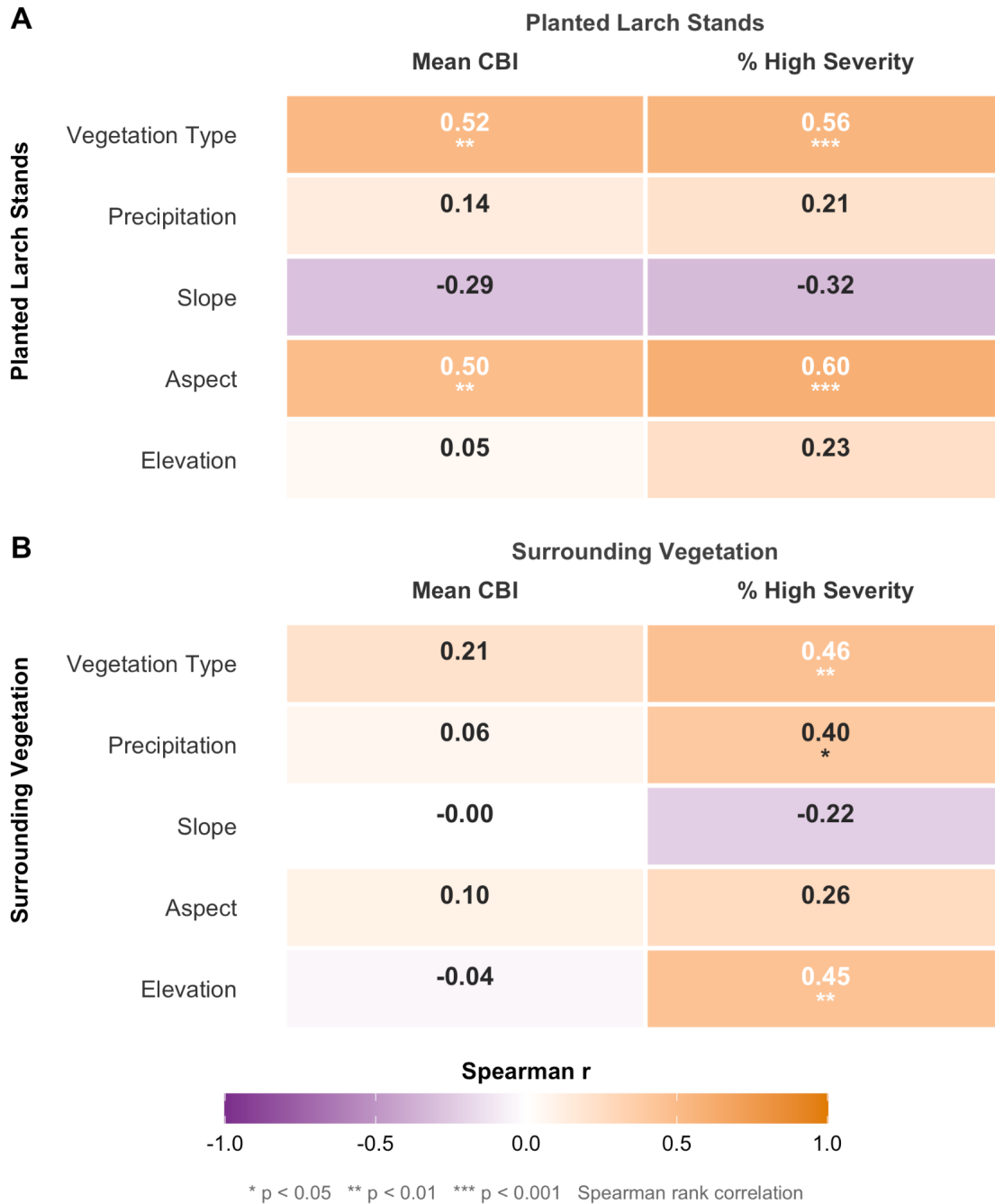


Figure 36. Spearman rank correlations between environmental predictors and burn severity metrics within the Swawilla Basin Fire (2024) on the Colville Reservation. (A) Correlations within planted western larch stands. (B) Correlations within paired surrounding vegetation zones. Predictors include elevation, aspect, slope, precipitation, and vegetation type; severity responses are mean CBI and proportion of high-severity area (% High Severity). Cell color indicates correlation direction and strength (purple = negative, orange = positive); values in bold with asterisks indicate statistical significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

2.5.2.3 Cross-Fire Synthesis

Across the three fires, a consistent pattern of reduced burn severity in planted western larch stands emerged in two of three events but proved conditional on fire context. In the North Star and Summit Trail fires, larch stands were associated with statistically lower mean CBI (estimates of -0.175 and -0.312 , respectively) and lower proportions of high-severity area (estimates of -2.874% and -9.327% , respectively) than matched surrounding forest, with 86% of stands burning at lower mean CBI than their comparison zones in both events. These CBI reductions are consistent with differences in canopy survival, soil heating depth, and post-fire recovery trajectory, and their directional consistency across two independent fire events strengthens confidence in the overall pattern (Key and Benson 2006; Davis et al. 2023). First, our results suggest that western larch must represent a substantial component of the surface fuel matrix before its litter traits measurably dampen fire behavior. In Chapter 3, mixed-species combustion experiments showed that fuel beds with low western larch proportions produced only limited reductions in flammability. In contrast, fuel beds with approximately 50% or more western larch showed stronger reductions in fuel consumption and combustion intensity.

This pattern supports a testable hypothesis: western larch alters combustion behavior most strongly once it becomes abundant enough to change fuel bed structure, packing density, and moisture dynamics. However, because controlled laboratory mixtures constructed by litter mass produced this result, managers should not interpret it as a direct stand-level planting threshold. Planting prescriptions that include western larch only as a minor component within pine-dominated stands may provide more limited surface-fuel moderation. Researchers should test this laboratory pattern in field settings across western larch proportions, site types, stand structures, and thinning histories before translating it into operational guidance.

In the Swawilla Basin Fire, this pattern was absent, and the null result is informative in its own right. Mean CBI and proportion of high-severity area did not differ significantly between larch stands and surrounding forest ($p = 0.298$ and $p = 0.381$, respectively); only 37% of stands burned at lower severity than their comparison zones, and environmental predictors, including vege-

tation type and aspect, explained more variance in within-stand severity than in the other fires. Landscape-level drivers most plausibly explain the absence of a detectable western larch effect in the Swawilla Fire. Dry forest conditions, fire weather, and cheatgrass-driven fine-fuel continuity may have promoted more homogeneous fire behavior across stand boundaries regardless of overstory composition, rather than indicating a failure of planted stand structure.

The use of a Random Forest CBI model calibrated on fires through 2017 and applied across two different sensors (Landsat 8 and Sentinel-2) introduces potential cross-sensor and temporal transferability uncertainties that could shift reported effect sizes in ways that are difficult to quantify. A sensitivity analysis using field-collected CBI plots within or adjacent to the study fires would be a valuable next step for validating the magnitude of reported differences and is recommended as a priority for future work in this system (Cohen et al. 2017; Radcliffe et al. 2024).

2.6 Discussion

This study evaluated whether planted western larch stands differed from adjacent mixed-conifer forests in surface fuel structure and whether those structural differences corresponded with burn severity outcomes across three large wildfires on the Colville Reservation. The results provide multi-scale evidence that planted western larch stands often experienced different fire effects than surrounding forest conditions. Within the Summit Trail Fire footprint, planted stands contained lower coarse woody fuel loads than adjacent mixed-conifer forests. Across the broader fire analysis, planted western larch stands also exhibited statistically significant reductions in both mean modeled CBI and the proportion of high-severity area relative to area-matched surrounding forest zones in two of the three fires examined.

These patterns suggest that planted western larch stands may contribute to lower-severity fire effects through differences in stand structure, species composition, and fuel characteristics. However, the observational design prevents us from fully isolating planting effects from other sources of stand-level variation, including pre-fire site conditions, stand history, management history, and

fire suppression activities. We therefore interpret the observed differences as associations between planted western larch stand conditions and fire effects rather than as direct evidence of planting effects alone.

These findings have implications for fire management, western larch restoration ecology, and Tribal-led forest stewardship under changing climate and disturbance regimes. By linking landscape-scale burn severity patterns with field-based fuel measurements, this chapter provides evidence that restored western larch stands can differ from surrounding mixed-conifer forests in ways that are relevant to fire resilience. At the same time, the variability among fires underscores that western larch restoration does not operate independently of ecological context. Fire outcomes reflect interactions among species composition, stand development, fuel structure, topography, fire weather, and continued management actions.

2.6.1 Fuel Structure Differences and Comparison to Existing Literature

Planted western larch stands differed from adjacent mixed-conifer forests in surface fuel structure within the Summit Trail Fire footprint. Across all measured dead woody fuel size classes, planted western larch stands contained lower fuel loads than adjacent mixed-conifer forests, including approximately 41% lower 1-hour fuels, 27% lower 10-hour fuels, 38% lower 100-hour fuels, and 92% lower 1000-hour fuels. Because we limited field-based fuel measurements to the Summit Trail Fire footprint, we interpret these patterns within the context of the mixed-conifer forests sampled in this fire area. These results may not fully represent fuel dynamics across the drier or lower-elevation conditions of the North Star and Swawilla fires, where differences in productivity, disturbance history, and fuel accumulation may shape fire effects differently (Hessburg et al., 2005; Reilly et al., 2017; Hagmann et al., 2021).

The large reduction in heavy woody fuels within planted western larch stands is broadly consistent with patterns documented in fuel treatment and restoration studies across western North American forests, although the mechanisms differ. Mechanical thinning and prescribed fire commonly alter fire behavior by reducing surface fuels, decreasing ladder fuel continuity, increasing canopy base

height, and restoring more heterogeneous stand structures (Agee and Skinner, 2005; Graham et al., 2004; Stephens et al., 2009; Churchill et al., 2013; Prichard et al., 2020). Treatment effectiveness varies with initial stand conditions, fire weather, treatment age, and landscape context (Cannon et al., 2020; Chamberlain et al., 2024). In contrast, the planted western larch stands examined here represent a different restoration pathway, where fuel structure reflects interactions among species composition, stand age, initial spacing, management history, and stand development rather than the removal of accumulated fuels from older forests.

This distinction has important implications for understanding restoration trajectories. Many fuel treatment studies evaluate forests where fire exclusion has already increased tree density, shade-tolerant species abundance, and surface and ladder fuel accumulation before managers apply treatments to restore fire-adapted structure (Graham et al., 2004; Hessburg et al., 2005; North et al., 2012; Hagmann et al., 2021). In comparison, planted western larch stands may develop along alternative structural pathways characterized by different species composition, reduced ladder fuel continuity, and altered surface fuel inputs. However, because this study does not include complete pre-fire stand histories, we cannot attribute fuel structure differences to planting alone. These differences likely reflect the combined effects of restoration history, site conditions, stand development, and subsequent management.

Species-specific traits of western larch may also contribute to fuel structure differences over time. Western larch has historically persisted within mixed-severity fire regimes because of traits including thick bark, longevity, elevated crown structure, and self-pruning architecture (Barrett et al., 1991; Arno et al., 1997; Harrington, 2013). Recent work shows that western larch canopy architecture produces relatively low available live crown fuel compared with many associated conifers, suggesting that branching patterns and foliar distribution may influence crown fire potential (Conrad et al., 2024). These structural characteristics support the persistence of mature western larch as biological legacies following disturbance and reinforce its role within fire-adapted mixed-conifer systems (Bisbing et al., 2010; Hopkins et al., 2014).

In addition to canopy traits, western larch may influence surface fuel environments through its

litter characteristics. Plant litter traits strongly regulate fuel bed structure and flammability because particle size, arrangement, packing, and chemistry influence airflow, moisture dynamics, and combustion processes (Cornwell et al., 2015; Belcher, 2016; Burton et al., 2021). The short, deciduous needles of western larch may create fuel beds with different packing structures and moisture dynamics than the longer needles of many evergreen conifers. Mixed-species litter beds can also produce non-additive effects, where combustion behavior differs from expectations based on individual species alone (Blauw et al., 2015; Magalhães and Schwilk, 2021). Western larch restoration may therefore influence fire behavior through both stand structure and surface fuel properties.

Planted western larch stands also supported greater live shrub and herbaceous vegetation than adjacent mixed-conifer forests. Restoration and thinning studies in mixed-conifer forests commonly document increased understory development following reductions in canopy cover, as greater light availability promotes shrub and herbaceous productivity (Lydersen et al., 2013; North et al., 2019). This shift represents an important ecological tradeoff. Understory vegetation contributes to biodiversity, wildlife habitat, nutrient cycling, and structural heterogeneity, but live and cured fine fuels can also influence surface fire behavior depending on seasonal moisture conditions.

The influence of live fuels depends strongly on moisture availability, species composition, and seasonal timing. When live vegetation maintains high foliar moisture content, it can reduce ignitability by increasing the energy required to heat and dry plant tissues before combustion occurs (Agee and Skinner, 2005; Stevens et al., 2020). Under drought conditions, however, declining live fuel moisture can increase fuel availability and contribute to surface fire spread (Rothermel, 1972; Finney, 2001). The influence of increased understory vegetation within planted western larch stands therefore likely depends on interactions among seasonal moisture conditions, drought severity, and fire weather.

The lower abundance of large dead woody fuels within planted western larch stands may be particularly relevant for fire effects because different fuel components influence different aspects of combustion. Fine fuels regulate ignition and rates of spread, whereas larger woody fuels contribute

disproportionately to combustion duration, heat release, soil heating, and residence time (Rothermel, 1972; Scott and Reinhardt, 2001; Ryan, 2002; Certini, 2005). Lower heavy woody fuel loads may therefore reduce prolonged heating associated with higher-severity fire effects, consistent with patterns observed following restoration and fuel reduction treatments across western forests (Prichard and Kennedy, 2014; Prichard et al., 2020; Radcliffe et al., 2024).

The burn severity patterns observed across the North Star and Summit Trail fires are consistent with these structural differences. Planted western larch stands exhibited reductions in mean modeled CBI of 0.175 and 0.312 units, respectively, along with lower proportions of high-severity area relative to adjacent forests. These patterns suggest that species composition, stand structure, and fuel characteristics may contribute to observed differences in fire effects. However, differences in pre-fire conditions and stand histories prevent direct causal attribution.

Future research that incorporates direct canopy structure measurements would improve understanding of the mechanisms linking planted western larch restoration to wildfire outcomes. LiDAR-derived estimates of canopy bulk density, canopy base height, and vertical fuel continuity could help evaluate how crown structure interacts with surface fuels to influence burn severity. Integrating these measurements with surface fuel assessments and remotely sensed burn severity models would strengthen our ability to evaluate how species traits, stand architecture, and fuel arrangements interact to influence fire effects across spatial scales (Parks et al., 2019; Cova et al., 2023; Cova et al., 2024; Radcliffe et al., 2024).

2.6.2 Western Larch Ecology and Fire Adaptation

The fuel and burn severity patterns observed in this study likely reflect interactions among management history, stand development, and the ecological traits of western larch as a fire-adapted species. Western larch possesses a suite of morphological and life-history characteristics associated with persistence in fire-prone landscapes, including thick bark, deep rooting systems, rapid juvenile growth, elevated crown structure, self-pruning capacity, and deciduous foliage (Schmidt et al., 1976; Arno and Fischer, 1995; Sparks et al., 2018; Stevens et al., 2020; Moris et al., 2022). These

traits contribute to individual-tree fire resistance while also influencing stand structure and fuel characteristics relative to many co-occurring evergreen conifers.

Canopy architecture represents one mechanism through which western larch may influence fire effects. Mature western larch commonly develops elevated crown base heights and reduced lower-branch density, which can decrease vertical fuel continuity between surface fuels and live canopy fuels (Schmidt et al., 1976; Harrington, 2013). Recent species-specific assessments of canopy traits indicate that western larch has lower available live crown fuel than predicted by generalized conifer fuel models, suggesting that branching architecture and foliar distribution may contribute to differences in crown fuel availability compared with other Intermountain West species (Conrad et al., 2024). However, stand age and density strongly influence these traits, and young planted stands may not yet express the crown characteristics observed in mature western larch forests.

In addition to canopy structure, western larch may influence surface fuel dynamics through its deciduous needle habit and litter characteristics. Plant litter traits, including particle size, arrangement, chemistry, and decomposition rate, strongly influence fuel bed structure, moisture dynamics, and combustion behavior (Cornwell et al., 2015; Varner et al., 2015; Burton et al., 2021). Compared with long-needled evergreen conifers, western larch produces short deciduous needles that may create different fuel bed structures and moisture environments, potentially influencing drying rates and surface fire behavior. Mixed-species litter studies further show that interactions among litter types can produce non-additive effects, where combustion characteristics differ from expectations based on individual species alone (Blauw et al., 2015; Magalhães and Schwilk, 2021). Historically, western larch formed an important component of fire-adapted forest mosaics across the inland Northwest, where recurring low- and mixed-severity fires maintained open stand structures, heterogeneous forest conditions, and regeneration opportunities (Barrett et al., 1991; Arno and Fischer, 1995; Hessburg et al., 2005). Indigenous fire stewardship by the Colville Tribes and other Indigenous peoples of the interior Pacific Northwest also contributed to landscape heterogeneity through intentional burning practices that supported culturally important resources, wildlife habitat, and diverse forest conditions (Boyd, 1999; Kimmerer and Lake, 2001; Lake et al.,

2017; Wynecoop et al., 2019; Copes-Gerbitz et al., 2023).

The reduction of frequent fire, restrictions on Indigenous burning practices, selective harvesting of large fire-resistant trees, and twentieth-century fire exclusion altered many of these disturbance relationships. Across portions of the inland Northwest, these changes increased stand density, favored shade-tolerant species, altered fuel structures, and reduced the representation of early-seral species such as western larch (Hessburg et al., 2005; Hagmann et al., 2021; Hessburg et al., 2021). Restoration efforts that increase western larch abundance may therefore support the recovery of some structural and compositional characteristics associated with historically fire-adapted forests. However, contemporary restoration occurs under climatic, ecological, and social conditions that differ from those that shaped historical forest mosaics.

The planted western larch stands evaluated in this study should therefore not be interpreted as direct analogs of historical larch-dominated forests. Mature western larch forests historically contained complex multi-aged structures, large-diameter trees with highly developed fire-resistant traits, spatially heterogeneous fuels, and disturbance legacies shaped by centuries of interacting ecological processes and Indigenous stewardship (Arno et al., 1997; Bisbing et al., 2010; Hopkins et al., 2014). Young planted stands have not yet developed many of these structural attributes. Instead, the lower burn severity and fuel differences observed here may represent an early stage in a longer restoration trajectory in which species composition, stand development, and future management interact to shape fire resilience over time.

2.6.3 Burn Severity Outcomes and Environmental Drivers

Planted western larch stands were associated with lower modeled burn severity than surrounding mixed-conifer forests in two of the three fires examined. Mean modeled CBI was 0.175 and 0.312 units lower in planted stands during the North Star and Summit Trail fires, respectively, and high-severity area was 2.8 to 9.3 percentage points lower relative to adjacent comparison forests. These effect sizes are consistent with findings from studies evaluating restoration and fuel treatments across western North American forests. Collins et al. (2011) and Lydersen et al. (2017)

documented lower burn severity within thinned and prescribed-burned stands relative to untreated forests in the Sierra Nevada, particularly where treatments reduced surface fuels and vertical fuel continuity. Similarly, Prichard et al. (2020) found that treated forests across the inland Northwest generally experienced lower CBI values and reduced high-severity fire effects. However, treatment effectiveness varied with treatment type, time since treatment, and fire weather conditions. Jain et al. (2021) likewise showed that fuel reduction treatments can moderate fire effects by altering stand structure and fuel availability.

Recent landscape-scale approaches using remotely sensed burn severity and machine-learning frameworks further demonstrate the importance of linking stand conditions to wildfire outcomes. Chamberlain et al. (2024) developed a scalable framework using Random Forest models and SHAP interpretation approaches to evaluate treatment effects on burn severity, showing that treatments incorporating prescribed fire were generally associated with the strongest reductions in fire severity. These findings emphasize that fire outcomes emerge from interactions among fuels, vegetation structure, weather, and landscape context rather than from any single treatment or species effect (Cansler et al., 2014; Prichard et al., 2017; Chamberlain et al., 2024).

The magnitude of the severity difference observed in the Summit Trail Fire (0.312 CBI units) is ecologically meaningful because CBI integrates fire effects across multiple forest strata, including surface fuels, understory vegetation, and overstory canopy change (Key and Benson, 2006; Parks et al., 2019). Differences of this magnitude may influence severity classification near threshold boundaries and correspond to changes in post-fire structure relevant to tree survival, regeneration environments, and ecosystem recovery. However, CBI classes represent gradients of ecological change rather than discrete ecological states, and relationships between modeled severity values and ecological outcomes vary across forest types and environmental conditions (Parks et al., 2019; Sanna et al., 2025). These considerations require careful interpretation of modeled CBI differences, especially when comparing planted stands with surrounding forests that may differ in pre-fire structure and productivity.

Within planted western larch stands, environmental predictors of modeled burn severity were

weak and non-significant in the North Star and Summit Trail fires, suggesting that the variables evaluated here did not explain substantial variation in severity within planted stand boundaries. This pattern may indicate that other factors, including stand structure, species composition, fuel arrangement, or management history, contributed to observed fire effects. However, because this study lacks complete pre-fire structural measurements, we cannot isolate these mechanisms. Elevation and aspect serve as indirect proxies for environmental gradients that influence fuel moisture and vegetation conditions rather than direct measures of fire behavior, and their influence may vary with scale, fire weather, and landscape context (Cansler et al., 2014; Reilly et al., 2017). In surrounding mixed-conifer forests, elevation significantly predicted severity in both fires, consistent with previous studies showing that topography interacts with climate, fuels, and vegetation structure to influence burn severity patterns across heterogeneous landscapes (Perry et al., 2011; Cansler et al., 2014; Reilly et al., 2017). The weaker relationship between these environmental gradients and severity within planted western larch stands may suggest that stand-level characteristics contributed additional variability, consistent with research showing that local forest structure can influence wildfire effects within broader topographic and climatic constraints (Koontz et al., 2020; Cova et al., 2023; Cova et al., 2024). Confirming these mechanisms would require direct pre-fire measurements of canopy structure, fuel continuity, and fire weather conditions.

Fuel treatment studies consistently demonstrate that fire weather strongly mediates the influence of vegetation and fuels on fire effects. Under moderate conditions, differences in fuel structure and stand composition can strongly influence fire behavior, whereas under extreme wind and drought conditions, atmospheric controls may override local fuel effects (Collins et al., 2011; Prichard and Kennedy, 2014; Prichard et al., 2020). The significant differences in severity observed during the North Star Fire, which occurred during the severe 2015 fire season, suggest that planted western larch stands maintained distinct fire outcomes even under challenging fire conditions. However, these patterns likely reflect interactions among stand structure, species composition, fuels, topography, and fire weather rather than structural conditions alone.

The absence of a significant severity difference within the Swawilla Fire highlights the importance

of local context and reinforces that western larch restoration outcomes are not uniform across landscapes. Stand age, species composition, fine fuel continuity, fire weather, suppression activities, and landscape position may all influence whether restored stands experience different fire effects than surrounding forests (Coppoletta et al., 2016; Prichard et al., 2020; Sanna et al., 2025). Understanding these interactions will require continued monitoring across additional fire events and integration of pre-fire structural data, remote sensing products, and field-based fuel measurements.

2.6.4 Moisture Regime, Species Composition, and the Limits of Structural Buffering

Planted western larch stands on the Colville Reservation occur across broad environmental gradients and vary substantially in species composition. These stands range from larch-dominated conditions to mixed forests containing ponderosa pine, lodgepole pine, Douglas-fir, and Engelmann spruce, depending on elevation, moisture availability, site conditions, and restoration objectives. This compositional variation is important because fire effects reflect not only stand structure, but also interactions among species traits, surface fuels, climate, and fire weather (Cansler et al., 2014; Stevens et al., 2020; Prichard et al., 2020).

Differences among the three fires examined in this study suggest that the influence of western larch restoration depends on the environmental and compositional context in which stands occur. We observed the largest differences between planted western larch stands and adjacent forests in the North Star and Summit Trail fires. In contrast, the Swawilla Fire showed no statistically significant difference in mean modeled CBI or proportion of high-severity area between planted stands and surrounding forest ($p = 0.298$ and $p = 0.381$, respectively). Only 37% of planted stands within the Swawilla Fire burned at lower severity than their comparison areas, compared with 86% in both the North Star and Summit Trail fires.

The weaker pattern observed in the Swawilla Fire may reflect differences in species composition, moisture regime, stand development, fine-fuel continuity, fire weather, and landscape context rather than the absence of a western larch influence alone. The Swawilla Fire burned primarily

through lower-elevation dry mixed-conifer forests where western larch commonly occurs with ponderosa pine and Douglas-fir. These forest types differ substantially from higher-moisture mixed-conifer settings in productivity, fuel accumulation, and fire behavior (Perry et al., 2011; Hessburg et al., 2021).

Species composition may be particularly important because co-occurring conifers differ strongly in litter traits that influence surface fuel structure and flammability. Long pine needles commonly create loosely packed fuel beds with greater vertical structure and airflow, conditions that can promote drying and facilitate flame spread under low-moisture conditions (Cornwell et al., 2015; Belcher, 2016; Burton et al., 2021). In contrast, shorter deciduous western larch needles may form more compact fuel beds with different packing properties, moisture dynamics, and combustion characteristics (Varner et al., 2015; Magalhães and Schwilk, 2021).

These differences suggest that western larch influence on surface fuels may depend on its relative contribution within mixed-species stands. Mixed fuel beds often produce non-additive combustion responses, meaning that fire behavior cannot always be predicted from individual species alone because interactions among litter types influence moisture retention, airflow, and heat transfer (Blauw et al., 2015; Magalhães and Schwilk, 2012). Results from the laboratory flammability experiments presented in Chapter 3 support this interpretation: mixtures containing lower proportions of western larch showed limited changes in combustion behavior, whereas stronger reductions in flammability metrics emerged when western larch accounted for approximately half or more of the litter mixture.

However, these experimental results should not be interpreted as fixed management thresholds. Laboratory fuel beds isolate species composition under controlled conditions and do not capture the complexity of wildfire environments, including live vegetation, wind, slope, fuel continuity, and canopy structure. Instead, these findings suggest a mechanism that requires field validation: western larch may contribute more strongly to fire moderation as its influence on stand composition and surface fuel characteristics increases.

The Swawilla Fire results highlight the limits of structural and species-based buffering under

variable environmental conditions. Fire severity emerges from interactions among fuels, vegetation, climate, and fire weather, and broader landscape drivers may override local stand characteristics when they dominate fire behavior (Cansler et al., 2014; Prichard and Kennedy, 2014; Prichard et al., 2020). Increasing drought stress, vapor pressure deficit, and fuel aridity under climate change further complicate these relationships by altering the moisture conditions that regulate fuel availability and combustion potential (Wasserman et al., 2023; Parks et al., 2025).

Together, these findings suggest that western larch restoration is most likely to influence wildfire outcomes where species composition, stand structure, and moisture conditions interact to reduce fuel availability and disrupt fire spread pathways. In drier forest settings or mixed stands where highly flammable fine fuels dominate surface fuel conditions, the structural and fuel-related advantages associated with western larch may be less detectable. Understanding these context-dependent responses will be essential for designing climate-adapted restoration strategies that align species composition and stand structure with future fire environments.

2.6.5 Developmental Thresholds in Young, Densely Stocked Planted Stands

Young, densely stocked planted western larch stands in the sapling-to-small-tree stage showed variable fire effects across the three study fires, suggesting that stand development may influence fire resilience trajectories. In the Summit Trail Fire, these stands experienced a higher proportion of high-severity burning than their matched surrounding forests (~16% vs. ~3%). In contrast, comparable stands in the North Star and Swawilla fires exhibited lower or similar severity relative to adjacent forests. This variability likely reflects the broad range of developmental conditions included within a single structural classification. A stand five years post-establishment differs substantially from a stand that has reached canopy closure at 15–20 years, even when both occupy the same size class.

Young planted stands in early canopy development often contain sparse to moderate canopy cover, limited ladder fuel accumulation, vigorous live understory vegetation maintained by high light availability, and relatively low litter accumulation. These structural conditions can reduce crown

fire potential by limiting vertical fuel continuity between surface fuels and canopy fuels (Scott and Reinhardt, 2001; Agee and Skinner, 2005). However, planted stands that reach canopy closure without thinning may enter a developmental window of elevated fire hazard. During this period, canopy closure can suppress live understory vegetation, self-thinning mortality can generate standing dead and down woody material, and accumulated fine and medium fuels can increase vertical and horizontal fuel continuity. Together, these conditions may increase the likelihood of crown fire initiation, especially under dry and windy conditions.

This developmental vulnerability aligns with previous work showing that dense young stands in interior Pacific Northwest forests can develop structural conditions associated with elevated fire hazard before thinning or natural differentiation reduces fuel continuity (North et al., 2012; Radcliffe et al., 2024). In this study, we did not collect canopy bulk density, canopy base height, or vertical fuel continuity measurements at the resolution needed to fully characterize this developmental window. Future work incorporating LiDAR-derived canopy metrics or field-based crown fuel sampling would improve our ability to identify young stands that may be most vulnerable to high-severity fire and to target thinning interventions more effectively.

This pattern parallels the “fire hazard hump” described in the stand development and fuel treatment literature (Graham et al., 2004). Very young stands may exhibit relatively low fire hazard because they lack continuous canopy and ladder fuels. As stands approach canopy closure, fire hazard may increase because stem density, ladder fuels, and fuel continuity increase. After thinning or structural differentiation, hazard may decline again as canopy base height increases and vertical fuel continuity decreases. The timing and duration of this vulnerable window depend on site productivity, planting density, species composition, and thinning schedule.

The variable outcomes observed across fires suggest that planted western larch stands should not be treated as a uniform restoration category. Instead, fire resilience likely changes through stand development as species composition, stand density, live fuels, dead fuels, and management history interact. Maintaining timely thinning entries may therefore be essential for sustaining the fire-moderating potential of planted western larch stands through vulnerable developmental stages.

This need is especially important in Tribal and federal forest contexts where economic and funding constraints can limit the pace and completeness of fuel management interventions (IFMAT, 2013; Dockry et al., 2022).

2.6.6 Tribal Stewardship, Restoration, and Implications for Future Management

The empirical evidence presented here provides an additional ecological perspective on the Confederated Tribes of the Colville Reservation's long-standing recognition of western larch as an important restoration species. The Tribes have valued western larch not only for timber productivity, but also for its ecological traits, cultural significance, and alignment with long-term stewardship objectives that prioritize resilient forest landscapes (Confederated Tribes of the Colville Reservation, 2015, 2023).

The results suggest several practical implications. First, the association between planted western larch stands and reduced wildfire severity appeared across multiple fire contexts, particularly within the North Star and Summit Trail fires. This pattern suggests that western larch restoration may contribute to lower-severity fire effects across some moist and mixed-conifer forest settings, rather than only within a narrow set of climatic or vegetation conditions. This finding aligns with the Tribes' spatially explicit approach to western larch planting across elevational and precipitation gradients (Mason et al., 2012; Long et al., 2017).

Second, the variability among stands, including the exceptions observed in the Swawilla Fire and among young, densely stocked stands within the Summit Trail Fire, highlights the importance of stand age, thinning history, species composition, and fuel continuity in determining whether western larch-associated benefits are expressed under fire. Stands that maintain high western larch composition and receive timely thinning entries appear more likely to be associated with reduced fire severity across a range of fire contexts. This reinforces the importance of maintaining thinning schedules and avoiding reliance on species selection alone to produce fire resilience (Agee and Skinner, 2005; Jain et al., 2021; Radcliffe et al., 2024).

Third, the results support integrating planted western larch stands into broader landscape strategies

that include prescribed fire and cultural burning where conditions and Tribal objectives support fire reintroduction. Planted stands with reduced heavy woody fuels, elevated crown structure, and live understory development may provide conditions compatible with low-intensity surface fire, particularly when managers maintain fuel discontinuity through thinning and other treatments. Under these conditions, western larch restoration may support understory heterogeneity and surface fire dynamics associated with historically fire-influenced larch forests (Wynecoop et al., 2019; Hessburg et al., 2021).

Where Tribal-led cultural burning can be reintroduced alongside planted western larch stands, these practices may help restore fire regimes characterized by frequent, low-intensity surface fire, open forest structure, and limited coarse fuel accumulation. These conditions are consistent with the fire regimes under which western larch persisted and with long-standing Indigenous stewardship practices that maintained landscape heterogeneity, culturally important resources, and fire-adapted forest structure (Barrett, 1982; Kimmerer and Lake, 2001; Lake, 2017).

Finally, these findings underscore the value of co-produced research grounded in Tribal governance priorities and conducted in partnership with Tribal natural resource staff. Tribal management needs shaped the questions motivating this study, and the study area represents an actively managed Tribal landscape with management complexity often absent from research conducted on federal or experimental forests. The findings therefore provide information that can support ongoing planting, thinning, restoration, and fire management decisions led by the Colville Tribes Department of Natural Resources.

Rather than validating Tribal management through external scientific authority, this research provides an additional empirical perspective on restoration priorities developed through long-term Tribal stewardship, field observation, and forest management experience. Tribal expertise shaped the questions, methods, and interpretive frameworks that give these findings meaning (Kimmerer and Artelle, 2024; Bamzai-Dodson et al., 2024; Carroll et al., 2020).

2.6.7 Limitations and Considerations

Planted western larch stands on the Colville Reservation represent an underexamined restoration context within the broader fuel treatment and fire effects literature. Most existing studies evaluate mechanical thinning, prescribed fire, and restoration treatments in mature or historically fire-excluded forests rather than younger planted stands established to shape future forest composition and disturbance response (Agee and Skinner, 2005; Graham et al., 2004; Stephens et al., 2009; Churchill et al., 2013). Previous research has shown that forest structure, species composition, and treatment history influence wildfire outcomes (Prichard and Kennedy, 2014; Coppoletta et al., 2016; Prichard et al., 2020; Chamberlain et al., 2024), but quantitative evidence linking restored western larch stands to landscape-scale burn severity patterns remains limited (Hopkins et al., 2014; Jain et al., 2021).

Several limitations should guide interpretation of these findings. We conducted field-based fuel sampling only within the Summit Trail Fire footprint, so the fuel results may not fully represent the drier or lower-elevation forest conditions associated with the North Star and Swawilla fires. We also lacked pre-fire field measurements, which limits our ability to attribute burn severity differences exclusively to stand structure or fuel characteristics. Pre-existing differences in site productivity, disturbance history, microclimate, access, or management history may have contributed to the observed patterns, a limitation common to retrospective wildfire studies conducted across operational landscapes (Prichard and Kennedy, 2014; Coppoletta et al., 2016; Sanna et al., 2025). The three fires also differed in weather conditions, vegetation composition, topography, and time since disturbance. This variability allowed us to evaluate western larch restoration across realistic landscape conditions, but it also limits direct comparison among individual fire events. Time since fire ranged from approximately ten years for the North Star Fire to three years for the Summit Trail Fire and one year for the Swawilla Fire. As a result, post-fire succession, delayed mortality, vegetation recovery, and post-fire management activities may have influenced the observed conditions (Coppoletta et al., 2016; Stevens-Rumann et al., 2022). In addition, planted stands varied in age, thinning history, stocking density, and species composition. This heterogeneity

reflects operational restoration conditions, but it complicates generalization about planted western larch as a single treatment category.

Remotely sensed burn severity modeling also introduces important limitations. Spectral indices such as dNBR, RdNBR, and RBR provide powerful tools for mapping wildfire effects across large landscapes, but pre-fire vegetation structure, productivity, and post-fire spectral response can influence these metrics (Miller and Thode, 2007; Parks et al., 2014; Cansler et al., 2014; Gómez et al., 2016). Because spectral change represents vegetation response rather than direct measurement of ecological processes, similar index values may correspond to different levels of ecological change across forest types and structural conditions (Harvey et al., 2019; Parks et al., 2019). These limitations are especially relevant when comparing younger planted stands with older mixed-conifer forests that differ in canopy cover, biomass, and pre-fire spectral characteristics.

The Random Forest CBI model developed by Parks et al. (2019) reduces many of these limitations by integrating multiple spectral predictors with climatic and geographic variables, improving transferability across broad environmental gradients. However, model outputs remain estimates rather than direct field measurements of fire effects and include uncertainty (Parks et al., 2019; Sanna et al., 2025). Two of the three fires examined, Summit Trail (2021) and Swawilla (2024), occurred after the model training period of 1994–2017. Applying the model to these fires may introduce uncertainty if recent changes in climate, fuel conditions, or fire behavior differ from the conditions represented in the calibration dataset. Even-aged planted western larch stands also represent a specific structural condition that may be underrepresented within broad-scale model training data.

The use of different satellite sensors across fires introduces another source of uncertainty. We derived North Star severity estimates from Landsat imagery, whereas the Summit Trail and Swawilla assessments incorporated Sentinel-2 imagery. Although researchers widely use both sensors for burn severity assessment, differences in spatial resolution, spectral bands, and image acquisition timing can influence severity estimates (Gallagher et al., 2021; Kurbanov et al., 2022; Fernández-Guisuraga et al., 2023). These uncertainties reinforce the need to interpret results as

relative comparisons between planted stands and adjacent forests rather than as absolute measures of fire behavior or ecological damage.

Future work would benefit from integrating field-based validation with additional structural remote sensing approaches. Comparing modeled CBI values with independently collected field CBI measurements would help evaluate model performance specifically in planted western larch forests. Incorporating LiDAR-derived measurements of canopy height, canopy bulk density, canopy base height, and vertical fuel arrangement would improve understanding of the mechanisms linking stand structure to wildfire outcomes (Clawges et al., 2007; Gallagher et al., 2021; Chamberlain et al., 2024). These approaches would help distinguish the relative contributions of surface fuel characteristics, canopy structure, and species composition to observed burn severity patterns.

Despite these limitations, the Parks et al. (2019) Random Forest CBI framework remains one of the strongest available approaches for assessing wildfire effects across North American forest landscapes. By combining satellite-derived burn severity modeling with field-based measurements of fuels and stand structure, this study provides complementary lines of evidence suggesting that western larch restoration may influence wildfire outcomes through interactions among species composition, fuel structure, and stand development. Continued monitoring and expanded field validation will be essential for understanding how these relationships change as planted stands mature under future climate and disturbance regimes (Halofsky et al., 2020; Hessburg et al., 2021).

2.6.8 Ethical Considerations

We conducted this research in close partnership with the Confederated Tribes of the Colville Reservation, following the ethical principles for co-produced research on Indigenous lands described in the Preface. Throughout this collaboration, we recognized Tribal sovereignty, governance authority, and rights over knowledge, information, and data generated from Indigenous lands, resources, and management systems (Kukutai and Taylor, 2016; Carroll et al., 2020; Adams et al., 2024).

This study used publicly available satellite imagery and geospatial datasets, including Landsat, Sentinel-2, and TerraClimate products, as open-access federal datasets. However, the forest

inventory polygons, planting records, and spatial datasets defining restored western larch stand boundaries are Tribal data. The Confederated Tribes of the Colville Reservation Department of Natural Resources shared these datasets through a collaborative research agreement, and we used them exclusively for the research purposes identified through that partnership.

This approach follows Indigenous data sovereignty frameworks, which affirm that Indigenous Nations maintain authority over the collection, ownership, governance, interpretation, and application of data derived from their lands, resources, and communities (Kukutai and Taylor, 2016; Carroll et al., 2020; Adams et al., 2024). Within this framework, data are not only technical products. They are also connected to relationships, responsibilities, decision-making authority, and the right of Indigenous Nations to determine how information about their lands and resources is used (Kukutai and Taylor, 2016; Carroll et al., 2020).

We developed the research questions, analytical approaches, and interpretation of results in collaboration with Tribal forest managers to address locally identified priorities and support ongoing restoration decisions. Co-produced research approaches emphasize that effective environmental science requires technical rigor as well as relevance, legitimacy, accountability, and alignment with the needs and governance systems of the communities applying that knowledge (Cash et al., 2003; Chambers et al., 2021; Bamzai-Dodson et al., 2024).

Within forestry and fire science, collaborative research must recognize Indigenous Nations as decision-makers and research partners who maintain long-standing environmental knowledge systems while also applying contemporary scientific tools, monitoring approaches, and management strategies to address changing ecological conditions (Bussey et al., 2016; Brondizio et al., 2021; Adams et al., 2024). We approached this research with the understanding that the Confederated Tribes of the Colville Reservation guide forest management through interconnected ecological, cultural, economic, and governance priorities rather than through single-resource objectives alone. Any future land management decisions informed by this research, including reforestation planning, fuel treatment prioritization, or wildfire response strategies, remain under the authority and governance of the Confederated Tribes of the Colville Reservation. This study provides scientific

information to support Tribal-led forest restoration and adaptive management; it does not prescribe or direct Tribal stewardship practices.

2.7 Conclusion

Across three wildfires spanning nearly a decade of fire activity on the Colville Reservation, planted western larch stands generally experienced lower modeled burn severity than surrounding mixed-conifer forests, with statistically significant reductions observed in two of the three fires examined. These patterns occurred across fires that differed in size, timing, forest composition, and landscape context, highlighting the importance of evaluating restoration outcomes under actual wildfire conditions. Together, the results provide empirical evidence that long-term western larch restoration efforts implemented by the Confederated Tribes of the Colville Reservation are associated with differences in species composition, stand structure, fuel characteristics, and fire effects in mixed-conifer forests.

Western larch has persisted within inland Northwest forests shaped by recurring fire, climatic variability, and long-standing Indigenous stewardship practices. Its functional traits, including thick bark, deciduous foliage, elevated crown architecture, self-pruning capacity, and relatively low available live crown fuel compared with many co-occurring conifers, contribute to both individual-tree fire resistance and stand-level fuel characteristics that may influence fire behavior (Schmidt et al., 1976; Stevens et al., 2020; Conrad et al., 2024). Historical changes associated with fire exclusion, selective harvesting, and restrictions on Indigenous burning practices altered forest composition, increased fuel continuity, and reduced opportunities for early-seral species such as western larch to regenerate across portions of their historical range. Within this context, the Confederated Tribes of the Colville Reservation have incorporated western larch restoration as one strategy for increasing fire-adapted forest composition and supporting resilient mixed-conifer landscapes.

The variability observed among fires and stand conditions demonstrates that western larch restoration alone does not determine fire outcomes. Instead, wildfire effects emerge from interactions

among species composition, stand age, fuel structure, topography, weather conditions, and continued management actions. Young planted stands may require ongoing treatments during vulnerable developmental periods when canopy closure, self-thinning, and fuel accumulation can temporarily increase fire hazard. Maintaining restoration outcomes therefore requires not only planting fire-adapted species, but also sustaining the management capacity and long-term stewardship needed to guide stands through changing environmental conditions.

Despite these complexities, the patterns observed across multiple fires, elevations, and forest types suggest that western larch restoration can contribute to fire-adapted landscape management on the Colville Reservation and across the inland Northwest. By linking landscape-scale fire effects with stand structure and species traits, this study shows how restoration outcomes can be evaluated across ecological scales. These findings provide information to support ongoing Tribal-led forest management decisions as climate change, fuel aridity, and altered disturbance regimes continue to reshape fire-adapted forests.

3.0 Chapter 3. Deciduous Needles, Dampened Flames: Western Larch as a Fire-Mitigating Species in Conifer-Dominated Landscapes

3.1 Abstract

Western larch (*Larix occidentalis*) is one of the most fire-resistant conifers in the inland Pacific Northwest, with traits such as thick bark, elevated crown architecture, and self-pruning that promote individual survival during surface fires. However, fire-adapted species influence fire behavior not only through survival traits but also through their effects on surface fuel characteristics, including litter morphology, fuel bed structure, moisture dynamics, and combustion processes (Schwilk 2015; Varner et al. 2015; Pausas et al. 2017). Despite extensive research on western larch fire resistance, little is known about whether its deciduous needle litter contributes to reduced surface fuel flammability relative to co-occurring evergreen conifers.

In this chapter, we evaluated whether western larch functions as a potential fire-impeding species by comparing moisture dynamics and flammability characteristics of western larch litter with two common associates: ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*Pinus contorta*). We reconstructed fuel beds from field-collected needle litter across nine compositional gradients representing pure larch, pure pine, and mixed larch-pine fuel beds. We quantified saturation moisture content, drying dynamics, and five combustion metrics: flame height, fuel consumption, flaming duration, smoldering duration, and total burn duration.

Western larch fuel beds retained substantially greater moisture than pine fuel beds, reaching more than five times the saturation moisture content of ponderosa pine litter. Larch fuel beds also exhibited reduced flammability, including lower flame heights, reduced fuel consumption, and slower combustion patterns compared with evergreen pine fuel beds. Mixed-species fuel beds showed intermediate responses, with stronger dampening effects emerging at approximately 50% western larch composition. These results support broader trait-based frameworks showing that litter morphology, particle arrangement, and species mixtures influence fuel bed flammability and combustion behavior (Cornwell et al. 2015; Magalhães and Schwilk 2012; Burton et al. 2021).

Our findings suggest that western larch influences fire dynamics through multiple pathways: mature trees resist fire through structural traits. At the same time, deciduous needle litter may modify surface fuel conditions by increasing moisture retention and reducing combustion intensity. These results provide a mechanistic explanation for landscape-scale patterns observed in planted western larch stands and suggest that incorporating western larch into restoration strategies may contribute to fire-adapted forest conditions across mixed-conifer landscapes of the inland Pacific Northwest.

3.2 Introduction

3.2.1 Fire Exclusion, Adaptive Traits, and the Case for Western Larch

Across the fire-adapted mixed-conifer forests of the inland Pacific Northwest, more than a century of fire exclusion, selective harvesting, and altered disturbance processes have changed species composition, forest structure, fuel accumulation, and fire behavior. Historically, frequent and mixed-severity fires maintained heterogeneous forest conditions, reduced fuel continuity, and favored tree species with traits that increased survival under recurrent disturbance, including thick bark, elevated crowns, self-pruning architecture, and deep rooting systems (Barrett et al., 1991; Agee, 1993; Hessburg et al., 2005; Perry et al., 2011). In many dry and mixed-conifer forests, reduced fire frequency promoted increased stand density, expansion of shade-tolerant species, and greater vertical fuel continuity, contributing to conditions associated with increased vulnerability to drought, insects, and high-severity fire (Hessburg et al., 2021; Hagsmann et al., 2021).

Within these changing landscapes, restoration strategies increasingly emphasize the restoration of fire-adapted forest structures and species compositions. Historically dominant early-seral species, including western larch (*Larix occidentalis*), are of particular interest because they possess traits associated with survival in fire-prone environments and contribute to structural heterogeneity within mixed-conifer forests (Schmidt et al., 1976; Agee, 1993; Arno & Fischer, 1995; Bisbing et al., 2010; Hopkins et al., 2014; Williams et al., 2026). On the Colville Reservation, where the Confederated Tribes of the Colville Reservation have actively restored western larch for decades,

these efforts provide an opportunity to evaluate how a fire-adapted species influences both stand structure and fuel characteristics under contemporary fire regimes.

Western larch is widely recognized as one of the most fire-resistant conifers of the inland Pacific Northwest. Mature individuals develop exceptionally thick bark that protects the cambium from heat injury, elevated crown structures that reduce crown scorch potential, and self-pruning architecture that limits vertical fuel continuity between surface fuels and canopy fuels (Schmidt et al., 1976; Arno & Fischer, 1995; Sparks et al., 2018; Stevens et al., 2020; Williams et al., 2018). This resistance is reflected in the longevity of individual trees: Hall (2008) documented a 416-year-old western larch in southeastern British Columbia that survived numerous fire events over its lifespan, illustrating the long-term persistence enabled by these traits. Following prescribed burning in old-growth western larch stands, Harrington (2013) found that mature trees exhibited high survival despite prolonged duff combustion, demonstrating the effectiveness of these resistance traits during surface fire events. More recently, Conrad et al. (2024) showed that western larch canopy architecture limits available live crown fuel relative to that of many co-occurring conifers, suggesting that species-specific crown traits may reduce the likelihood of crown fire development.

However, fire-adapted species influence fire regimes not only through traits that determine individual survival but also through traits that modify the surrounding fire environment. Trait-based frameworks increasingly recognize that plant species can influence fire behavior through feedbacks involving litter production, fuel arrangement, decomposition, moisture dynamics, and combustion properties (Schwilk, 2015; Pausas et al., 2017; Stevens et al., 2020). Varner et al. (2015) distinguish between species that primarily function as fire resisters, surviving fire through protective traits, and fire impeters, whose fuel characteristics reduce ignition probability, flame spread, or combustion intensity. Similar mechanisms have been documented in other low-flammability species, where litter traits modify surface fuel conditions and influence fire behavior at stand scales (Kane et al., 2008; Varner et al., 2015).

Whether western larch also functions as a fire-impeding species remains poorly understood. Unlike most fire-resistant conifers of western North America, western larch combines classic fire-survival

traits with a deciduous needle habit, annually shedding short, thin needles that differ substantially from the persistent evergreen litter of co-occurring pines and firs. These differences may alter fuel bed structure, packing density, moisture retention, and combustion processes — mechanisms increasingly recognized as important controls on litter flammability (Cornwell et al., 2015; Burton et al., 2021).

Despite extensive research on western larch fire resistance and regeneration ecology, few studies have directly evaluated whether western larch litter influences surface fuel flammability. We address this gap by testing whether western larch needle litter differs from co-occurring ponderosa pine and lodgepole pine in moisture dynamics and combustion behavior. Specifically, we examine whether western larch functions not only as a species adapted to survive fire but also as a species capable of modifying surface fuel conditions that influence fire behavior.

3.2.2 Western Larch: Ecology and Litter Characteristics

Western larch occupies approximately 3.6 million hectares across the inland Pacific Northwest, typically in mixed stands with Douglas-fir, grand fir, western white pine, lodgepole pine, Engelmann spruce, and ponderosa pine at lower elevations. It is broadly distributed across elevational gradients from approximately 600 to 2100 m, occupying mesic sites with relatively deep soils. Keane (2008) documented that larch-dominated stands in the northern Rocky Mountains produce distinctive surface fuel loads characterized by relatively shallow annual needle deposits, modest litterfall rates compared to co-occurring conifers, and rapid decomposition, traits that may limit duff accumulation and reduce the depth of the organic layer available for smoldering combustion (see also Belcher, 2016). A broadly analogous pattern has been documented in oak-conifer mixtures of the Sierra Nevada, where duff load was negatively associated with oak abundance, a pattern attributed to the more rapid decomposition of hardwood litter relative to conifer litter (Lydersen et al., 2015). While the mechanisms differ — oak's effect stems from faster litter decomposition, whereas larch's effect on duff likely reflects lower annual litter inputs and needle morphology — both examples illustrate how deciduous or rapidly decomposing litter inputs from a single species

can measurably reduce duff accumulation relative to co-occurring evergreen conifers. The historical distribution of western larch was more extensive before fire exclusion and high-grade logging in the late nineteenth and early twentieth centuries, which preferentially removed large larch trees (Hopkins et al., 2014; Harrington, 2013).



Figure 37. The 2024 Swawilla Basin Fire burning at low severity through a juvenile mixed western larch and ponderosa pine planted stand on the Colville Reservation, August 2024. Photograph by Priscilla Sperandio.

Larch's deciduous needle litter is the most ecologically distinctive trait in the context of this study (Figure 37). Unlike the evergreen pines and firs with which it co-occurs, larch sheds all of its needles each autumn in a concentrated pulse, producing short (2.5–4.5 cm), thin, cluster-arranged needles that differ substantially from the longer, resinous needles of ponderosa pine (12–25 cm) and the shorter but twisted needles of lodgepole pine (3–7 cm). It is worth noting that ponderosa pine, while classified as evergreen, is semi-deciduous in practice: it drops a substantial fraction of its older needles in autumn, often a quarter to nearly half of its needles, contributing a significant

annual pulse of needle litter to the forest floor alongside its continuous low-level needle shed (Dickinson et al., 2016) — a pattern broadly consistent with the greater litter loads associated with pine abundance observed in mixed-conifer stands elsewhere (Lydersen et al., 2015). This means the distinction between larch and pine litter dynamics is partly one of amount and timing rather than a categorical difference between annual and continuous shedding. Nonetheless, the seasonal concentration of larch needle fall, combined with its deciduous leaves, creates a fundamentally different litter input regime than that of co-occurring pines.

Beyond timing and quantity, the structural and chemical properties of larch needles differ from those of co-occurring pines in ways that may have meaningful consequences for fuel bed flammability. Larch needles are shorter and thinner than ponderosa pine needles and lack the heavy cuticular wax coatings that evergreen conifers invest in to minimize winter desiccation. Cornwell et al. (2015), in a phylogenetic analysis of flammability across gymnosperms, demonstrated that litter particle size is among the strongest predictors of fuel bed flammability across conifer families. Shorter, smaller particles tend to pack more densely than long needles, thereby increasing bulk density and reducing interparticle airflow, which can either suppress or promote ignition depending on fuel moisture conditions (Zhao et al., 2016; Belcher, 2016). Burton et al. (2021) extended this finding globally, showing that leaf traits, including leaf area, thickness, and particle geometry, predict litter bed structure and flammability across forest types more reliably than species composition. Larch needles, as short, thin, cluster-arranged particles without pronounced curvature, may form denser, more compactly packed litter beds than the longer, more randomly oriented needles of ponderosa or lodgepole pine — a structural difference that could increase bulk density, slow drying rates, and reduce the airflow necessary to sustain active combustion (Campbell-Lochrie et al., 2021; Wang et al., 2019; Zhao et al., 2016; Belcher, 2016).

The chemical composition of larch needles further distinguishes them from evergreen conifer litter in ways relevant to decomposition rate. Evergreen conifer needles are typically built for multi-year persistence, requiring greater investment in structural and protective compounds, including cuticular waxes, lignin, and other carbon-rich defensive tissues, which carries a tradeoff of lower

nitrogen content per unit mass (Aerts, 1995; Matyssek, 1986). In contrast, deciduous species such as larch invest comparatively less in long-lived structural tissue and maintain a higher nitrogen-to-carbon ratio in their foliage, consistent with a "live fast" leaf economic strategy oriented toward a single growing season rather than multi-year persistence (Wright et al., 2004; Matyssek, 1986). Because litter decomposition rates are strongly controlled by initial litter chemistry, particularly nitrogen content, lignin concentration, and the presence of recalcitrant structural compounds, these chemical differences predict that larch litter should decompose more rapidly than the litter of co-occurring evergreen pines (Cornwell et al., 2008; Aerts, 1995). Direct evidence from larch-dominated stands supports this expectation: larch needle litter is colonized and broken down by a diverse community of decomposer fungi (Osono et al., 2003), and studies of fire-affected larch forests have documented relatively rapid litter decomposition and nutrient turnover relative to co-occurring conifers (Bryanin et al., 2020). Combined with the lower wax content and reduced cuticular investment already noted for larch needles (Loskutov et al., 2013), this faster decomposition may compound the effects of larch's lower annual litter inputs (Keane, 2008) to limit further duff accumulation relative to evergreen pine and Douglas-fir litter.

The absence of persistent resinous coatings on larch needles may also influence moisture absorption capacity. Loskutov et al. (2013), studying hygroscopic properties of conifer and deciduous litter in central Siberia, found that larch (*Larix sibirica*) litter absorbed atmospheric moisture substantially more readily than co-occurring pine and spruce litter under comparable humidity conditions, a difference they attributed to the lower wax content and greater surface hydrophilicity of deciduous larch needles relative to evergreen conifers. Whether analogous differences apply to western larch under the drier summer conditions of the inland Northwest remains untested. Still, the mechanistic basis is plausible and motivates the moisture-dynamics comparisons in this study. Terpene-rich pine needles may additionally resist wetting more effectively than deciduous litter types through the hydrophobic properties of resinous surface coatings (Ormeño et al., 2009; see also Ganteaume et al., 2009; Magalhães & Schwilk, 2021), though direct comparative studies for western North American species are lacking.

3.2.2.1 Trait-Based Frameworks for Litter Flammability

Understanding how larch litter might dampen fire behavior requires a conceptual framework for litter flammability. Varner et al. (2015), in a synthesis of forest and woodland litter flammability, stated that flammability is best understood as a multidimensional property rather than a single axis, encompassing ignitability (how readily a fuel ignites), combustibility (heat release rate during burning), consumability (completeness of combustion), and sustainability (ability to sustain active burning over time). Pausas et al. (2017) similarly proposed three distinct flammability strategies in fire-prone ecosystems: fast-flammable litter (high ignitability and spread rate, low heat release per unit mass), hot-flammable litter (high heat release and complete combustion), and low-flammability litter (low ignitability, high moisture retention, incomplete combustion). Species with fast-flammable litter, including most fire-resistant pines such as ponderosa pine, produce needles that ignite easily and burn rapidly, promoting quick fire spread at relatively low temperatures, a strategy adaptive for adult survival because it limits heat penetration into bark and soil (Varner et al., 2015; Pausas et al., 2017). Species with low-flammability litter resist ignition, retain high moisture content, and burn slowly or incompletely when they do ignite, functioning as fire impeters rather than fire facilitators.

Schwilk (2015) emphasizes that the trait basis for each flammability strategy differs: ignitability is governed primarily by moisture content and volatile chemistry, spread rate by particle geometry and packing, and combustibility by elemental carbon content and ash mineral ratios (Magalhães & Schwilk, 2021; Zhao et al., 2016; Willis et al., 2024). This multi-trait framework is directly relevant to larch, which may express divergent flammability properties across different dimensions, potentially showing relatively low ignitability and spread rate due to high moisture retention and compact packing, while its carbon and energy content may be similar to co-occurring pines. In temperate eastern North American forests, Kane et al. (2021) demonstrated empirically that these dimensions are indeed partially decoupled across species, finding that drying rate and litter curling, rather than moisture absorption capacity alone, best explained flammability differences between oak and maple litter — suggesting that larch's distinctive needle morphology and hygroscopic

properties could produce a coherent low-flammability profile even in the absence of chemical differences from co-occurring conifers.

The van Wagtendonk et al. (1998) characterization of Sierra Nevada conifer fuel beds provides a useful point of comparison for the physical fuel-bed properties expected for the species examined here. Their measurements of bulk density, particle size, and packing ratio across conifer species demonstrated substantial interspecific variation in these properties, variation that translated directly into predicted differences in fire behavior under the Rothermel surface fire spread model (Rothermel, 1972). While western larch was not included in their study, the framework for understanding how needle morphology drives fuel bed architecture is directly applicable (see also Cruz & Fernandes, 2008; Lydersen et al., 2015; Zhao et al., 2016).

3.2.2.2 The Literature on Mixed-Litter Flammability

The behavior of litter in mixed-species assemblages is not predictable from the individual species alone. A growing body of research on the effects of litter composition demonstrates that when species with contrasting flammability properties are combined in a single fuel bed, the resulting fire behavior frequently deviates from what would be expected based on weighted averages of the component species' properties, a phenomenon termed non-additive or mixture effects (Magalhães & Schwilk, 2012; van Altena et al., 2012; Zhao et al., 2016; Magalhães & Schwilk, 2021; Willis et al., 2024). These non-additive effects can operate in either direction: highly flammable litter can amplify fire behavior beyond what the proportion of that species would predict, or low-flammability litter can suppress fire behavior more than its proportional contribution would suggest.

In a temperate mixed-conifer forest, Magalhães and Schwilk (2012) demonstrated that the addition of moisture-retaining oak litter to a pine-dominated fuel bed suppressed fire spread more than the oak fraction alone would predict — a dampening, non-additive effect they attributed to the hygroscopic properties of oak litter raising the effective moisture content of the entire mixture above the threshold needed to sustain active combustion. Kreye et al. (2018) similarly showed

that mesophytic litter inputs — from fire-excluded broadleaf species recruiting into historically pyrophytic oak-hickory woodlands — dampened overall stand flammability, with implications for the self-reinforcing dynamics of fire exclusion. Blauw et al. (2015) demonstrated that non-additive dampening effects are particularly pronounced at intermediate fuel moisture levels, where the moisture-buffering capacity of hygroscopic litter components most effectively bridges the threshold between ignition and non-ignition (Magalhães & Schwilk, 2021; Zhao et al., 2016). Multiple European studies have corroborated these findings in contrasting forest types. Della Rocca et al. (2018) demonstrated non-additive dampening effects in Mediterranean mixed-forest fuel beds. Van Altena et al. (2012) showed that the direction and magnitude of mixture effects were strongly related to the flammability contrast between component species — with the largest dampening effects occurring when high- and low-flammability species were combined in roughly equal proportions. Zhao et al. (2016), working across gymnosperm species, found that non-pine members of the Pinaceae family, a group that includes larches, produced a distinctive mixture effect when combined with pine litter, attributed to their smaller, less aerodynamically sorted needle particles, which create denser packing in mixed beds. Zhao et al. (2019) further showed that leaf and twig mixtures from different tree species produced non-additive effects not predictable from leaf mixtures alone, underscoring the importance of the full litter particle-size distribution in driving mixture flammability. Gormley et al. (2020) confirmed non-additive effects in Australian forest litter mixtures, demonstrating their generality across biomes. Taken together, this literature provides strong theoretical and empirical grounding for the hypothesis that larch litter, as a structurally distinctive and potentially hygroscopic component of mixed pine-larch fuel beds, could produce non-additive dampening effects on fuel bed flammability, particularly under moderate post-precipitation moisture conditions when the buffering capacity of hygroscopic particles most influences whether ignition is sustained.

3.2.3 Study Context and Knowledge Gaps

Although researchers have extensively documented western larch fire ecology and advanced our understanding of litter flammability, important gaps remain in our understanding of how western larch influences surface fuel properties and combustion processes. Previous studies have shown that leaf and litter traits strongly regulate fuel bed structure, moisture dynamics, decomposition, and flammability across plant communities (Schwilk 2015; Cornwell et al. 2015; Burton et al. 2021). Research on mixed-species fuel beds has also demonstrated that species interactions can produce non-additive combustion responses, in which observed flammability differs from predictions based on individual species due to interactions among fuel morphology, packing structure, moisture retention, and species composition (Magalhães and Schwilk 2012; Blauw et al. 2015; Magalhães and Schwilk 2021). However, few studies have examined these mechanisms in western larch or evaluated how western larch litter interacts with co-occurring inland Northwest conifer species.

Western larch presents a particularly important system for addressing this knowledge gap because it combines traits that researchers rarely evaluate together: the fire-resistance characteristics typical of long-lived conifers and the deciduous needle strategy associated with faster nutrient cycling and lower structural investment. Leaf economics theory predicts that deciduous species generally produce shorter-lived tissues with greater nutrient availability, lower construction costs, and faster decomposition rates than evergreen species (Matyssek 1986; Aerts 1995; Wright et al. 2004). Across ecosystems, plant functional traits strongly influence litter decomposition rates, nutrient cycling, and fuel accumulation patterns (Cornwell et al. 2008). Studies of larch forests further indicate that microbial decomposition processes and nutrient cycling differ from those in many evergreen conifer systems (Osono et al. 2003; Bryanin et al. 2020), yet researchers have rarely linked these traits to western larch fuel bed moisture retention and flammability.

Most existing studies examining larch combustion have focused on Eurasian larch species, including Siberian and Dahurian larch (*Larix sibirica*, *Larix gmelinii*), primarily within boreal fire regimes where forests commonly experience stand-replacing fires under extreme weather

conditions (Loskutov et al. 2013; Yang et al. 2021; Bryanin et al. 2020). These systems differ substantially from the mixed-severity fire regimes of the inland Pacific Northwest, where western larch historically persisted through frequent surface and mixed-severity fires alongside ponderosa pine, lodgepole pine, and Douglas-fir (Barrett et al. 1991; Arno and Fischer 1995). Previous western larch fire studies have primarily examined tree survival, duff consumption, and regeneration dynamics rather than litter-level combustion processes (Artley 1976; Harrington 2013; Hopkins et al. 2014). Consequently, we still lack information on whether western larch needle litter differs from co-occurring pine species in moisture dynamics, combustion behavior, and mixed-species fuel bed interactions.

This knowledge gap has direct implications for restoration planning on the Colville Reservation, where the Confederated Tribes of the Colville Reservation have incorporated western larch planting across broad elevational gradients, forest types, and post-fire restoration contexts. Species selection decisions influence not only future forest composition but also the development of surface fuels and potential fire behavior over decades. The Colville Reservation provides a unique setting for evaluating these questions because long-term restoration records, Tribal forest inventory data, and a co-produced research partnership with the Colville Tribes Department of Natural Resources allow us to interpret experimental fuel findings alongside the landscape-scale wildfire outcomes examined in Chapter 2.

In this chapter, we address this gap by evaluating the moisture dynamics and flammability of western larch litter relative to those of co-occurring ponderosa pine and lodgepole pine. Specifically, we test whether western larch functions only as a fire-resistant species capable of surviving fire or whether its litter traits also contribute to stand-level fuel conditions that may reduce combustion intensity and influence fire behavior.

3.3 Research Questions and Hypotheses

To evaluate moisture dynamics and flammability characteristics of western larch litter, we used two main approaches: controlled drying trials to quantify saturation moisture content and drying

kinetics, and standardized laboratory burn trials to characterize flammability across a range of fuel bed compositions and moisture conditions.

This chapter addresses three research questions. First, how do the moisture dynamics, including saturation moisture content and drying rates, of western larch litter compare to those of ponderosa pine and lodgepole pine? Second, how do the flammability characteristics of larch litter, including ignitability, heat release, fuel consumption, and flame behavior, compare to those of pines across a gradient of moisture conditions? Third, how does flammability change with increasing proportions of larch litter in mixed larch-pine fuel bed compositions?

We hypothesized that larch litter would exhibit higher moisture retention and slower drying rates than pine litter. Under standardized moisture conditions, we predict larch litter will exhibit lower flammability than pine litter across multiple metrics, and that the dampening effect of larch will be most pronounced under moderately moist conditions representing typical post-precipitation field conditions. Finally, drawing on the non-additive mixture effects literature (Magalhães and Schwilk 2012; van Altena et al. 2012; Blauw et al. 2015), we predict that mixed larch-pine fuel beds will show dampening non-additive effects on flammability, with meaningful suppression apparent even at moderate larch proportions (Figure 38).

Morphological and litter characteristics of three dominant conifer species in inland Pacific Northwest forests

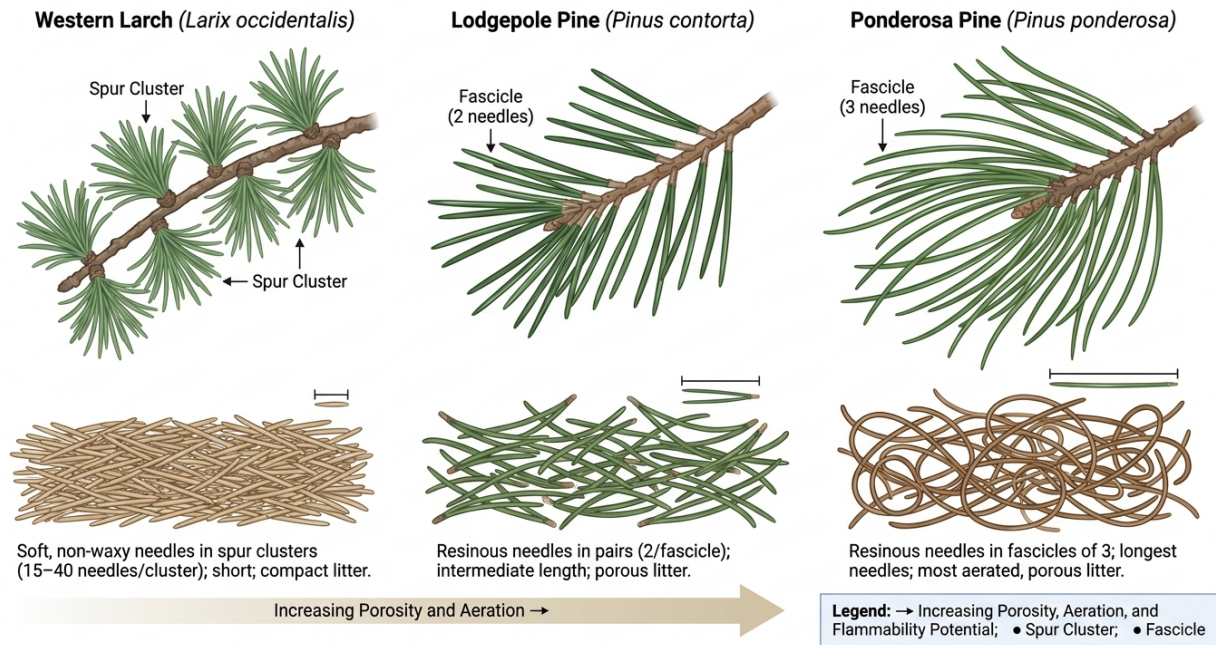


Figure 38. Morphological and litter characteristics of three dominant conifer species in inland Pacific Northwest forests: western larch, lodgepole pine, and ponderosa pine. The figure illustrates differences in needle arrangement, surface properties, and litter structure that influence the composition of the surface fuel bed. Western larch produces soft, non-waxy needles borne in spur clusters, resulting in compact, low-curl litter. In contrast, lodgepole and ponderosa pine exhibit resinous needles arranged in fascicles (two needles per fascicle in lodgepole pine; three to four in ponderosa pine), producing increasingly porous and aerated litterbeds with greater needle length and curvature. These structural differences contribute to variation in fuel packing, aeration, and potential flammability across species. Image generated by FigureLabs.

3.4 Materials and Methods

3.4.1 Study Area

We collected needle litter from mixed-conifer stands on the Confederated Tribes of the Colville Reservation in northeastern Washington State, where western larch has been actively planted as a restoration species since the early 1990s. The Reservation encompasses approximately 570,000 ha across a complex landscape of north-south trending ridges and valleys, with elevations ranging from roughly 400 to 2,400 m. The study area lies within the Interior Columbia Basin and experiences a semi-arid continental climate characterized by cold, snowy winters and warm, dry

summers.

Mixed-conifer forests across the Reservation historically supported western larch, ponderosa pine, lodgepole pine, Douglas-fir, Engelmann spruce, and subalpine fir in varying proportions across elevational and moisture gradients. The three focal species in this study—western larch, ponderosa pine, and lodgepole pine—represent dominant needle-litter contributors across two elevation zones where western larch restoration plantings occur. Lodgepole pine commonly co-occurs with western larch in higher-elevation mixed-moist forests at approximately 1,219–1,676 m, whereas ponderosa pine commonly co-occurs with western larch in lower-elevation dry forests at approximately 762–914 m. Together, these species represent the primary surface fuel types used to evaluate how western larch litter influences fuel moisture retention and flammability across contrasting forest settings.

3.4.2 Litter Collection

We collected recently senesced needle litter in June 2025, before the onset of peak fire season, which typically occurs from July through August across the Colville Reservation. We selected this collection timing to ensure that the sampled material represented sun-cured surface fuels most likely to contribute to fire spread during the wildfire season. We collected needle litter from mature stands of western larch, ponderosa pine, and lodgepole pine, gathering material from 20 individual trees distributed across at least three distinct stands per species to capture intraspecific variability. We collected intact, undecomposed needle litter directly from the forest floor beneath each tree, then air-dried and hand-sorted all samples to remove decayed material, foreign debris, and non-target organic matter. We collected at least 50 g of clean litter for each species and stored the samples in breathable paper bags before laboratory analysis.

3.4.3 Fuel Bed Compositions

To simulate the range of stand composition variability present across restored western larch landscapes on the Colville Reservation, we constructed nine distinct fuel bed compositions. These included pure fuel beds of each focal species and binary mixtures representing realistic stand

composition scenarios: 100% western larch, 100% ponderosa pine, 100% lodgepole pine, 70% western larch / 30% lodgepole pine, 50% western larch / 50% lodgepole pine, 70% lodgepole pine / 30% western larch, 70% western larch / 30% ponderosa pine, 50% western larch / 50% ponderosa pine, and 70% ponderosa pine / 30% western larch (Table 1).

We created all mixture proportions by dry mass. We prepared five replicate fuel beds for each composition and moisture treatment, yielding 45 replicates per treatment and 90 total burn trials across two moisture-conditioning treatments. We recognize that mass-based mixture proportions may not accurately reflect the volumetric deposition patterns that develop in field litterbeds, where needle length, aerodynamic sorting, and differential decomposition rates influence species stratification and interlocking within the fuel bed (Cornwell et al. 2015; Zhao et al. 2016). We therefore interpret these results as characterizing the flammability of compositionally defined fuel matrices rather than as direct simulations of natural field litter architecture.

Table 1. Experimental fuel bed compositions and burning treatment assignments. Each composition was replicated five times per treatment ($n = 5$). Percentages represent proportions by dry mass. Column shading indicates the moisture-conditioning pathway before burning: oven-dry and equilibrium chamber-dry.

Composition	Larch (%)	Pine (%)	Pine Species	Burning Treatment (n per composition)		
				Oven-dry (24 hr, 70°C)	Chamber- dry (to EMC)	Total (n)
100% western larch	100	0	0	5	5	10
100% lodgepole	0	100	<i>P. contorta</i>	5	5	10
100% ponderosa pine	0	100	<i>P. ponderosa</i>	5	5	10

Composition	Larch (%)	Pine (%)	Pine Species	Burning Treatment (n per composition)		
				Oven-dry (24 hr, 70°C)	Chamber- dry (to EMC)	Total (n)
70% Larch / 30% Lodgepole	70	30	<i>P. contorta</i>	5	5	10
50% Larch / 50% Lodgepole	50	50	<i>P. contorta</i>	5	5	10
70% Larch / 30% Ponderosa	70	30	<i>P. ponderosa</i>	5	5	10
50% Larch / 50% Ponderosa	50	50	<i>P. ponderosa</i>	5	5	10
70% Ponderosa / 30% Larch	30	70	<i>P. ponderosa</i>	5	5	10
70% Lodgepole / 30% Larch	30	70	<i>P. contorta</i>	5	5	10
Total replicates per treatment:				45	45	90

3.4.6 Drying Trials

We first oven-dried all 90 replicates at 70°C for a minimum of 24 hours to establish a consistent dry baseline mass. We then divided the samples into two moisture treatments to evaluate fuel flammability under contrasting moisture conditions and to distinguish differences driven by inherent litter characteristics from those influenced by moisture retention and drying dynamics. The oven-dry treatment evaluated combustion behavior under standardized low-moisture conditions, allowing us to compare fuel structure and composition independent of fuel moisture variation

(Figure 39). In this treatment, we burned samples immediately after oven drying, representing extremely low-moisture conditions analogous to late-season drought periods.

The equilibrium moisture content (EMC) treatment evaluated how species-specific differences in water retention and drying influenced flammability following moisture exposure. For this treatment, we fully submerged all 45 replicates in a water bath for 24 hours to achieve saturation, gently drained the samples, transferred them to pre-weighed perforated aluminum drying pans ($24 \times 24 \times 4$ cm; 36 holes of 5 mm diameter spaced 25 mm apart on the pan base), and placed them in the drying chamber. We elevated pans 1 cm above the table surface using wooden slats to permit free drainage.

We conducted drying trials in a 3×3 m climate-controlled chamber equipped with a dehumidifier (Frigidaire, Model FFAD7033R1) maintained at $24 \pm 0.1^\circ\text{C}$ and $54 \pm 0.6\%$ relative humidity throughout each trial. In the EMC treatment, we monitored samples for up to 120 hours using a progressive weighing schedule: every 2 hours for the first 12 hours, every 4 hours from 12–24 hours, every 8 hours from 24–48 hours, and every 12 hours from 48–120 hours. We considered samples to have reached equilibrium moisture content once mass stabilized across at least two consecutive measurements.

We calculated moisture content (MC) at each time point as the mass of water relative to the oven-dry mass of each sample. We acknowledge that the two moisture-conditioning treatments represent simplified endpoints that may not capture the full range of post-rain drying trajectories experienced in field settings, where ambient temperature, relative humidity, wind, and solar radiation vary continuously and interactively (Nelson & Hiers, 2008; Kreye et al., 2012). The fixed chamber conditions (24°C , 54% RH) represent one standardized drying environment; actual field drying rates likely vary substantially across seasons, aspects, and canopy positions. These constraints are inherent to controlled laboratory flammability research and are shared by comparable studies (Kreye et al., 2013; Magalhães & Schwilk, 2012; Blauw et al., 2015).

We calculated saturation moisture content (SMC) as:

$$\text{SMC (\%)} = \left[\frac{M_{\text{sat}} - M_{\text{dry}}}{M_{\text{dry}}} \right] \times 100$$

where M_{sat} represents the fully saturated sample mass, and M_{dry} represents the oven-dry sample mass. We calculated the normalized moisture content ratio $E(t)$ following Kreye et al. (2012):

$$E(t) = \frac{M_t - M_f}{M_{\text{sat}} - M_f}$$

where M_t represents sample mass at time t , M_f represents final equilibrium mass, and M_{sat} represents saturated mass. We determined response time, or time lag (τ), representing the time required to lose approximately 63% of initial moisture above equilibrium, using piecewise regression with the segmented package in R (Muggeo, 2008). Following Kreye et al. (2012), we estimated τ as:

$$\tau = \frac{\log(0.368)}{\text{slope}}$$

where slope represents the log-linear decay curve fitted to the initial drying trajectory. Faster response times (smaller τ) indicate more rapid moisture loss and greater potential flammability under ambient drying conditions.



Figure 39. Laboratory experimental setup for fuel bed flammability trials conducted at California State Polytechnic University, Humboldt, August 2025. Left: fuel bed samples drying in the drying chamber. Center: a 15 g ponderosa pine fuel bed arranged across the wire grid before burning, with xylene-soaked strings used for ignition. Right: fuel bed samples fully submerged in water during the saturation phase. Photographs by Priscilla Sperandio.

3.4.7 Burning Trials

We characterized combustion behavior across nine fuel bed compositions and two moisture treatments. For each trial, we placed a 15 g litter bed on a 35×35 cm lattice of xylene-soaked cotton strings mounted on a standardized burn platform positioned beneath a 2.75×2.75 m fume hood. This setup provided a consistent ignition source and maintained adequate ventilation while minimizing airflow variability that could influence flame behavior.

A single observer (E.M.B.) conducted all flammability trials to reduce observer variability. We excluded fuel beds that failed to sustain flaming combustion for more than 10 seconds from subsequent analyses. We recognize that this criterion may introduce bias in high-moisture comparisons by selectively removing the most fire-resistant fuel beds, potentially underestimating differences among compositions at elevated moisture conditions (Kreye et al. 2018; Blauw et al. 2015). We

conducted 90 total burn trials; final sample sizes varied because of failed ignitions in the EMC treatment, as described in Section 3.5.

For each trial, we measured litter bed depth before ignition as the mean of four corner measurements. During combustion, we recorded maximum flame height as the tallest flame observed during the flaming phase. We measured flame duration from ignition to the cessation of open-flame combustion. We measured smoldering duration from the end of flaming to the complete extinction of glowing combustion, recognizing smoldering as a distinct combustion phase characterized by exothermic oxidation without a visible flame, rather than as a continuation of flaming. We calculated mass consumed as the proportion of pre-burn mass lost during combustion by comparing conditioned pre-burn mass with residual post-burn mass after complete cooling (minimum 30 minutes). Together, these variables characterized fire behavior across species compositions and moisture conditions relevant to restoration planning on the Colville Reservation.

We recognize that standardized laboratory conditions, including 15 g fuel beds, fixed trays, controlled temperature and humidity, and xylene-based ignition, cannot replicate the complexity of field combustion environments, where wind, live fuel moisture, fuel layering, and spatial continuity interact to control fire spread and intensity (Rothermel 1972; Finney et al. 2015). Therefore, we interpret these laboratory experiments as measurements of intrinsic fuel properties under controlled conditions rather than direct predictions of wildfire behavior, consistent with comparable experimental flammability research (Varner et al. 2015; Kreye et al. 2013; Magalhães and Schwilk 2012). Additionally, mixed-species fuel beds may not perfectly replicate natural litter interlocking, and artificial tray boundaries may constrain lateral airflow in ways that influence burn completeness and smoldering duration, particularly in dense larch-dominated fuel beds where packing effects are most pronounced (Campbell-Lochrie et al. 2021; Zhao et al. 2016).

3.5 Statistical Analyses

Before analysis, we identified 17 individual weight measurements across multiple replicates and fuel bed compositions as non-monotonic, meaning that the recorded mass at a given time point

exceeded the previous measurement. We set these values to NA because this pattern was more consistent with balance disturbance, handling error, or localized air movement during weighing than with true moisture gain.

We conducted all statistical analyses in R version 4.3.1 (R Core Team, 2023) using the *vegan* (Oksanen et al., 2022), *car* (Fox and Weisberg, 2019), *emmeans* (Lenth, 2023), and *ggplot2* (Wickham, 2016) packages. Given the number of comparisons conducted across fuel metrics, moisture treatments, and fuel bed composition contrasts, we emphasized effect sizes alongside p-values rather than relying solely on significance thresholds. For paired tests, we reported Wilcoxon pseudomedian estimates with 95% confidence intervals. This approach follows recommendations for observational and experimental studies involving multiple comparisons, where both Type I and Type II error risks may increase (Nakagawa and Cuthill, 2007).

We did not apply a post-hoc correction for multiple comparisons because each response variable and fuel bed contrast addressed a distinct ecological question. However, we interpret individual p-values cautiously and place greater emphasis on the consistency, magnitude, and direction of effects across related flammability and moisture metrics.

3.5.1 Moisture Dynamics

Saturation moisture content and response time (τ) were each compared among the nine fuel bed compositions using one-way analysis of variance (ANOVA). Before analysis, assumptions of normality (Shapiro-Wilk test, $\alpha = 0.05$) and homogeneity of variance (Levene's test, $\alpha = 0.05$) were verified. Pairwise comparisons used Tukey's HSD to control the family-wise error rate. For all moisture analyses, $\alpha = 0.05$ for statistical significance.

3.5.2 Multivariate Flammability Analysis

To assess overall differences in flammability among fuel bed compositions, we used permutational multivariate analysis of variance (PERMANOVA; Anderson, 2001) with the *adonis2* function in the *vegan* package. The multivariate response matrix included five flammability metrics: maximum flame height, flame duration, smoldering duration, total burn duration, and consumption

percentage. We analyzed the oven-dry and equilibrium moisture content treatments separately to evaluate composition effects under each moisture condition.

Before analysis, we standardized all flammability variables to a mean of zero and a standard deviation of one so that metrics measured on different scales contributed comparably to the multivariate distance matrix. We used Euclidean distance as the dissimilarity metric and evaluated significance with 999 permutations. We tested homogeneity of multivariate dispersion using betadisper (Anderson, 2006) to determine whether significant PERMANOVA results reflected shifts in multivariate group centroids rather than differences in within-group dispersion.

3.5.3 Ordination and Composition Gradient Analysis

To visualize multivariate flammability patterns across the two moisture treatments, we conducted principal components analysis (PCA) on the standardized flammability matrix using the `rda` function in the `vegan` package. Because PCA is equivalent to redundancy analysis with no constraining variables, this approach allowed us to summarize dominant gradients in flammability among fuel bed compositions and moisture treatments.

We evaluated the proportion of variance explained by each PCA axis and used `envfit` with 999 permutations to assess correlations between individual flammability variables and the ordination axes. We also examined PC1 scores as a function of litter moisture content at the time of burning. To assess whether fire-dampening effects scaled with moisture availability across the composition gradient, we fit separate linear regressions for each western larch proportion group: 0%, 30%, 50%, 70%, and 100% western larch, following the general approach of Kreye et al. (2023).

3.5. Results

3.5.1 Moisture Dynamics

3.5.1.1 Saturation Moisture Content

Litter fuel bed compositions differed significantly in saturation moisture content (SMC; one-ANOVA: $F_{8,36} = 12.82$, $p < 0.001$). Levene's test supported homogeneity of variance across

groups ($F_{8,36} = 1.08$) $p = 0.399$), and all compositions satisfied Shapiro-Wilk tests of normality (all $p > 0.14$). Mean SMC ranged from $74.5 \pm 5.0\%$ in 100% ponderosa pine fuel beds to $412.5 \pm 38.4\%$ in 50% lodgepole pine / 50% western larch fuel beds, representing nearly a 5-fold difference in moisture content (SMC; one-ANOVA: 5-fold difference across the compositional gradient).

Tukey HSD post-hoc comparisons identified four partially overlapping statistical groups. The highest SMC values occurred in 50% lodgepole pine / 50% western larch fuel beds ($412.5 \pm 38.4\%$) and 100% western larch fuel beds ($401.7 \pm 39.7\%$). These two compositions did not differ from one another ($p > 0.99$), but both had significantly higher SMC than ponderosa-dominated and pure pine compositions. At the opposite end of the gradient, 100% ponderosa pine fuel beds had the lowest SMC ($74.5 \pm 5.0\%$) and differed significantly from all compositions except 100% lodgepole pine ($p = 0.411$) and 70% ponderosa pine / 30% western larch ($p = 0.278$).

Intermediate compositions occupied overlapping statistical groups, but the results showed a clear compositional pattern. Fuelbeds containing greater proportions of western larch generally had higher saturation moisture content, whereas increasing ponderosa pine dominance corresponded with lower moisture storage capacity (Figure 40). Lodgepole pine generally occupied an intermediate position, particularly when mixed with western larch. The high SMC observed in the 50% lodgepole pine / 50% western larch mixture suggests that litter mixing may enhance moisture retention under some compositional conditions, although this pattern should be interpreted cautiously because mixed fuel beds were constructed by dry mass and may not fully reproduce natural litterbed architecture.

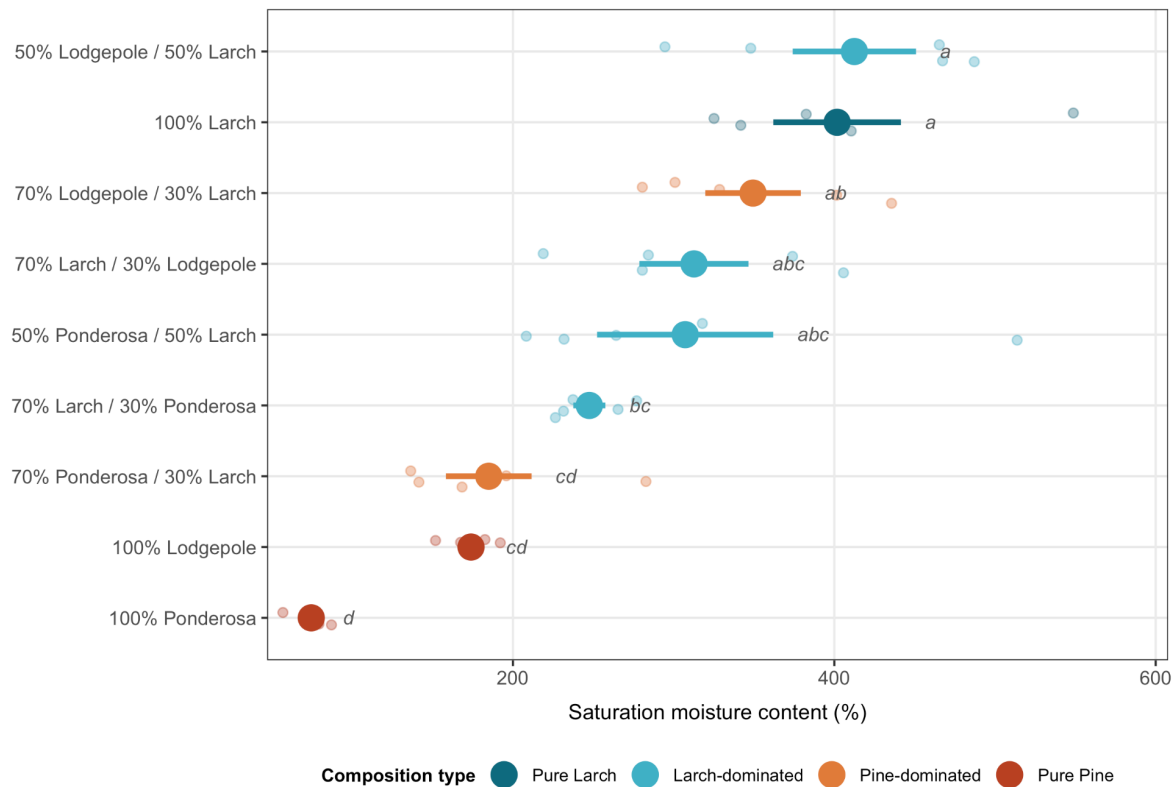


Figure 40. Mean saturation moisture content (SMC) across nine litter compositions. Points represent mean SMC per composition ($n = 5$), horizontal lines indicate ± 1 standard error, and small faded dots show individual replicate values. Colors denote composition type as above. CLD indicates Tukey HSD post-hoc comparisons (one-way ANOVA: $F_{8,36} = 12.82, p < 0.001$). Pure larch and 50% lodgepole / 50% larch had the highest SMC (mean $\sim 402\%$ and $\sim 412\%$, respectively), while 100% ponderosa had the lowest (mean $\sim 75\%$).

3.5.1.2 Drying Kinetics

Drying trajectories varied considerably across fuel bed compositions, with western larch-dominated fuel beds retaining moisture longer than pine-dominated fuel beds under identical chamber conditions (Figure 41). Pure western larch fuel beds showed the slowest and most gradual decline in normalized moisture ratio, E , over the drying period, and most replicates did not reach the time-lag threshold ($E = 0.368$) within the first 20 hours. In contrast, pure ponderosa pine and pure lodgepole pine fuel beds dried rapidly during the first 10 hours, with most replicates reaching the time-lag threshold well before 20 hours. Mixed compositions generally showed intermediate

drying rates that reflected the proportion of western larch in the mixture, although replicate-level variability was notable in several mixed compositions, particularly the 50% ponderosa pine / 50% western larch and 70% western larch / 30% ponderosa pine treatments.

Time-lag (τ) differed significantly among compositions (one-way ANOVA: $F_{8,36} = 3.59$, $p = 0.004$). Levene's test supported homogeneity of variance across groups ($F_{8,36} = 0.63$, $p = 0.745$). Shapiro-Wilk tests indicated normality for all compositions except 50% ponderosa pine / 50% western larch ($W = 0.771$, $p = 0.046$). Given the small sample size within each composition ($n = 5$) and the mild nature of this departure, we retained the ANOVA framework and interpreted pairwise comparisons alongside effect sizes and observed drying trajectories. Mean τ ranged from 7.0 ± 1.0 hours in the 70% ponderosa pine / 30% western larch mixture to 15.3 ± 1.8 hours in pure western larch, representing more than a two-fold difference across the compositional gradient (Figure 42). Tukey HSD post-hoc comparisons showed that pure western larch had a significantly longer τ than pure ponderosa pine ($p = 0.011$), pure lodgepole pine ($p = 0.012$), and the 70% ponderosa pine / 30% western larch mixture ($p = 0.009$). All other pairwise comparisons among compositions were non-significant. Larch-dominated mixtures showed intermediate τ values, ranging from 8.9 ± 2.3 hours in the 50% ponderosa pine / 50% western larch mixture to 12.5 ± 2.1 hours in the 70% western larch / 30% lodgepole pine mixture. These compositions did not differ significantly from either pure western larch or pure pine fuel beds, suggesting a gradual rather than threshold-like transition in drying response as the proportion of western larch decreased.

Within-composition variability in τ was highest in the 50% ponderosa pine / 50% western larch mixture ($SD = 5.2$ hours), consistent with the high replicate-level variability observed in the drying curves for that composition. This variability suggests that fuel bed arrangement, litter interlocking, or small differences in moisture distribution may influence drying behavior in mixed-species fuel beds, particularly where species differ strongly in needle morphology and packing structure.

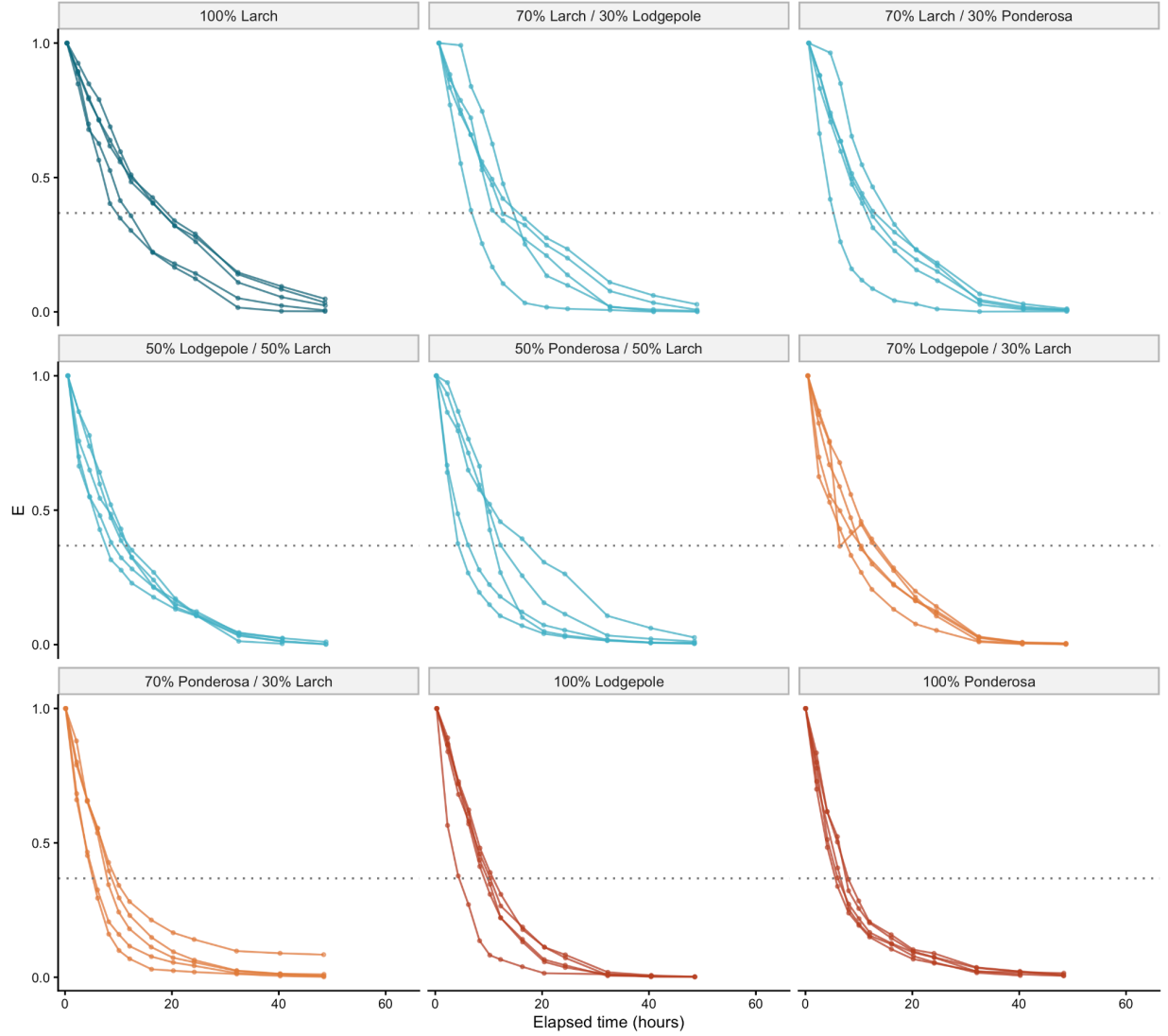


Figure 41. Drying dynamics of nine litter bed compositions ranging from pure western larch to pure pine, expressed as the normalized moisture ratio E over elapsed drying time (hours). $E = (M_t - M_f) / (M_{\text{sat}} - M_f)$ following Kreye et al. (2018), where $E = 1.0$ at saturation and $E = 0$ at equilibrium moisture content. Each line represents an individual replicate fuel bed ($n = 5$ per composition). The horizontal dotted line at $E = 0.368$ indicates the τ threshold, the point at which a fuel bed has completed 63% of its total drying. Colors denote composition type: pure larch (dark teal), larch-dominated mixtures (light teal), pine-dominated mixtures (orange), and pure pine (dark orange). Compositions are arranged from most larch-dominated (top left) to most pine-dominated (bottom right), reflecting the gradient in drying response observed across the study.

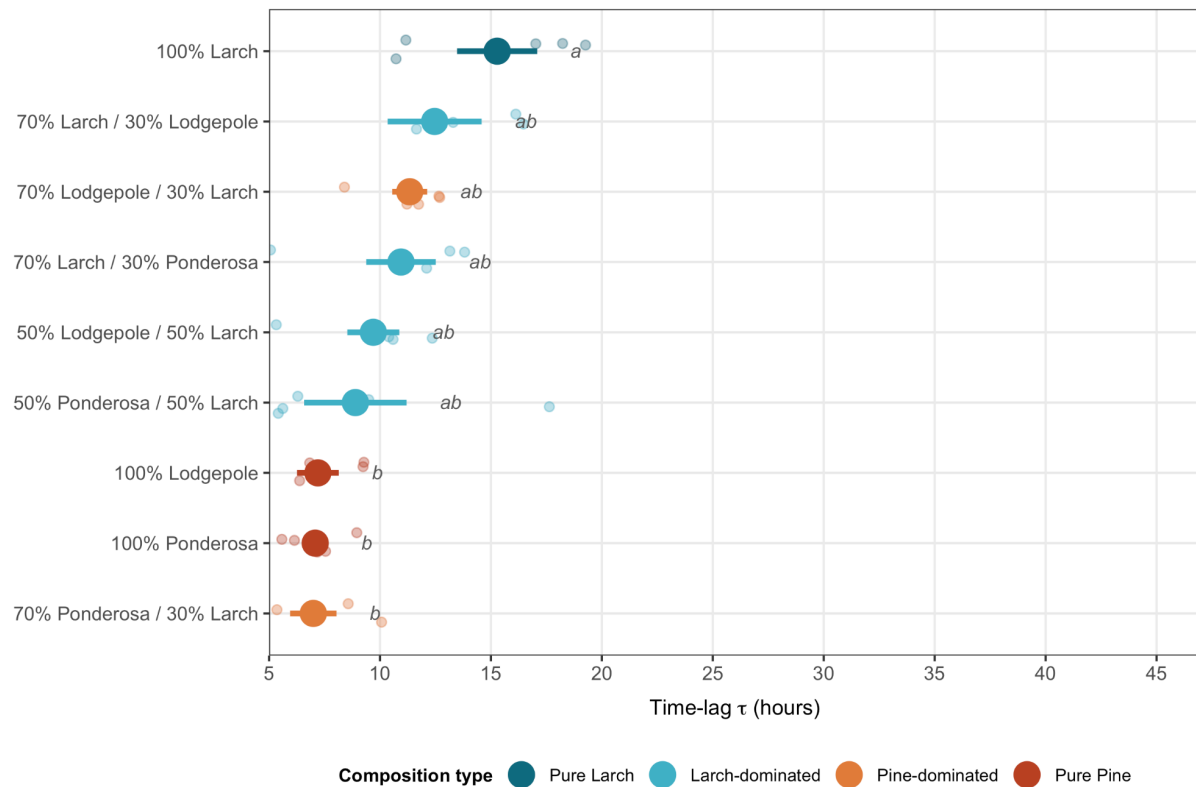


Figure 42. Mean time-lag (τ) of fuel bed moisture response across nine litter compositions ranging from pure western larch to pure pine, estimated using piecewise regression following Kreye et al. (2018). Points represent mean τ per composition ($n = 5$), horizontal lines indicate ± 1 standard error, and small faded dots show individual replicate values. Colors denote composition type: pure larch (dark teal), larch-dominated (light teal), pine-dominated (orange), and pure pine (dark orange). Compact letter display (CLD) indicates results of Tukey HSD post-hoc comparisons; compositions sharing a letter are not significantly different (one-way ANOVA: $F_{8,36} = 3.59$, $p = 0.004$). Pure larch had the longest mean τ (15.3 ± 1.8 hours), while 70% ponderosa / 30% larch, 100% ponderosa, and 100% lodgepole pine had the shortest (7.0–7.2 hours).

3.5.2 Flammability Characteristics

Table 2. Summary of statistical tests for moisture dynamics and flammability analyses. SMC = saturation moisture content; PERMANOVA = permutational multivariate analysis of variance. Effect directions are described qualitatively; full pairwise comparisons are reported in the text.

Analysis	Test	F-statistic	df	P-value	Effect
Moisture Dynamics					
SMC by composition	One-way ANOVA	$F_{8,36} = 12.82$	8, 36	$p < 0.001$	Larch and larch-lodgepole mixes are highest; ponderosa is lowest
Time-lag (τ) by composition	One-way ANOVA	$F_{8,36} = 3.59$	8, 36	$p = 0.004$	100% larch longest τ ; pure pine and 70% ponderosa / 30% larch shortest
Multivariate Flammability					
Multivariate flammability — oven-dry	PERMANOVA	$F_{8,36} = 15.04$	8, 36	$p = 0.001$	$R^2 = 0.77$; larch compositions distinct from pine
Multivariate flammability — EMC	PERMANOVA	$F_{8,34} = 6.59$	8, 34	$p = 0.001$	$R^2 = 0.61$; compositional differences maintained
Flame Height					
Flame height — oven-dry	One-way ANOVA	$F_{8,36} = 17.24$	8, 36	$p < 0.001$	100% larch < all pine compositions (CLD group e)
Flame height — EMC	One-way ANOVA	$F_{8,36} = 14.54$	8, 36	$p < 0.001$	100% larch < all pine compositions (CLD group e)
Fuel Consumption					
Fuel consumption — oven-dry	One-way ANOVA	$F_{8,36} = 36.85$	8, 36	$p < 0.001$	100% larch < all compositions (CLD group e)
Fuel consumption — EMC	One-way ANOVA	$F_{8,34} = 21.83$	8, 34	$p < 0.001$	100% larch < all compositions (CLD group e)
Flaming Duration					
Flaming duration — oven-dry	One-way ANOVA	$F_{8,36} = 21.74$	8, 36	$p < 0.001$	Complex pattern; 100% larch and 100% ponderosa shortest
Flaming duration — EMC	One-way ANOVA	$F_{8,36} = 3.38$	8, 36	$p = 0.005$	100% ponderosa shortest; effect weaker than oven-dry
Total Burn Duration					
Total burn duration — oven-dry	One-way ANOVA	$F_{8,36} = 10.37$	8, 36	$p < 0.001$	100% larch shortest (CLD group c)
Total burn duration — EMC	One-way ANOVA	$F_{8,36} = 4.13$	8, 36	$p = 0.001$	100% larch shortest (CLD group b)
Smoldering Duration					
Smoldering duration — oven-dry	One-way ANOVA	$F_{8,36} = 7.94$	8, 36	$p < 0.001$	100% larch shortest (CLD group d); pine compositions longest
Smoldering duration — EMC	One-way ANOVA	$F_{8,36} = 4.94$	8, 36	$p < 0.001$	100% larch and 70% larch / 30% lodgepole shortest (CLD group b)

CLD = Compact Letter Display (Tukey HSD, $\alpha = 0.05$); compositions sharing a letter are not significantly different. PERMANOVA was conducted with 999 permutations on z-score-standardized Euclidean distances.

3.5.2.1 Flammability Metrics by Litter Composition and Moisture Treatment

Litter composition had a significant effect on all five flammability metrics under both moisture treatments. Multivariate flammability differed significantly among compositions under oven-dry conditions (PERMANOVA: $F_{8,36} = 15.04$, $R^2 = 0.77$, $p = 0.001$) and EMC conditions ($F_{8,36} = 6.59$, $R^2 = 0.61$, $p = 0.001$), with no significant differences in multivariate dispersion among groups in either treatment (betadisper: oven-dry $p = 0.247$; EMC $p = 0.461$), confirming that PERMANOVA results reflect genuine location shifts in multivariate flammability space rather than differences in within-group variability (Table 2). A principal components analysis of the five flammability metrics yielded a first axis (PC1) explaining 62.6% of the total variance, representing a composite fire-intensity gradient from high flame height, high consumption, and long burn duration at positive scores to low values at negative scores. Higher larch proportions corresponded to lower PC1 scores under dry conditions and steeper moisture-driven declines in composite flammability with increasing EMC (Figure 43).

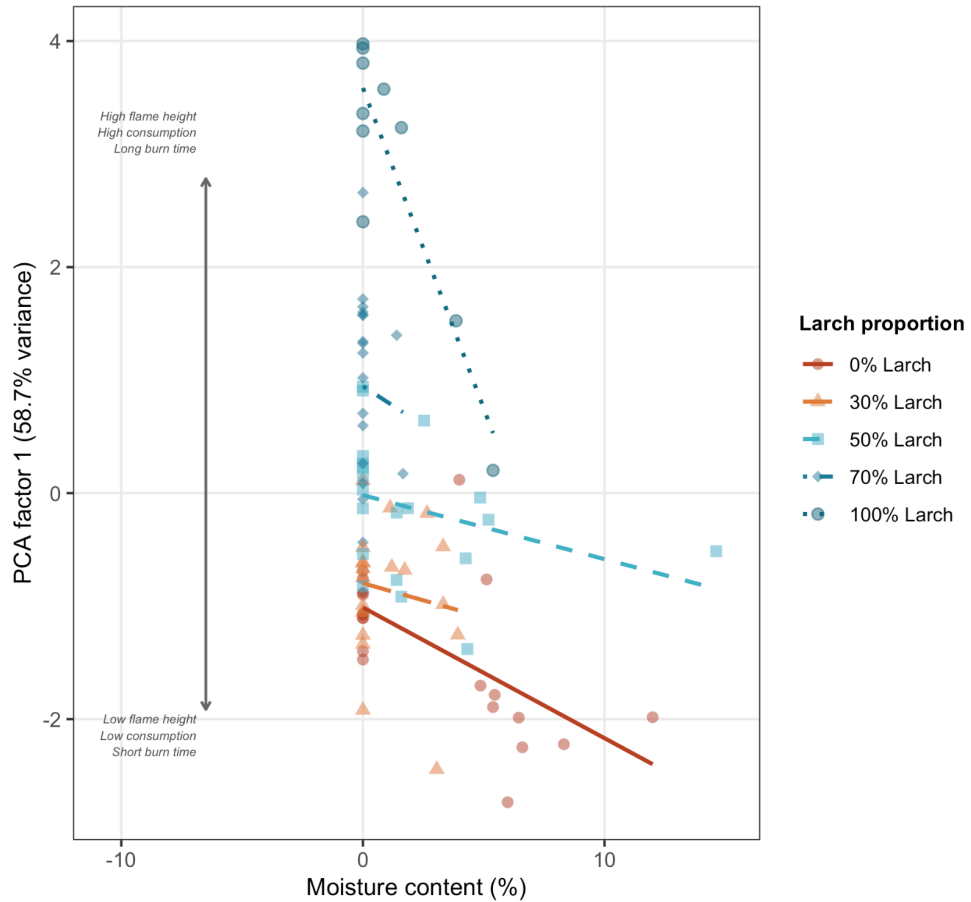


Figure 43. Flammability metrics of western larch and pine litter compositions combined through principal components analysis (PCA) as a function of litter moisture content at the time of burning. PCA factor 1 (62.6% of variance) represents a composite flammability gradient from high flame height, high fuel consumption, and long burn duration (positive scores) to low flame height, low consumption, and short burn duration (negative scores). Points represent individual burn trials under oven-dry (0% MC) and equilibrium moisture content (EMC, 2–15% MC) conditions. Lines show linear regressions fit separately for each larch proportion group (0%, 30%, 50%, 70%, and 100% larch by mass). Higher larch proportions corresponded to greater flammability under dry conditions and steeper moisture-driven dampening of flammability, consistent with the higher saturation moisture content and longer drying time-lag (τ) observed in larch-dominated fuel beds.

3.5.2.2 Flame Height

Maximum flame height differed significantly among compositions under both moisture treatments (oven-dry: $F_{8,36} = 17.24$, $p < 0.001$; EMC: $F_{8,36} = 14.54$, $p < 0.001$; Figure 44). Under oven-dry conditions, 100% ponderosa produced the tallest mean flames (59 ± 4 cm; CLD group a), followed

by 100% lodgepole (46 ± 4 cm) and pine-dominated mixed compositions ($41\text{--}51$ cm; ab–bcd). Larch-dominated mixtures produced intermediate flame heights ($29\text{--}33$ cm; cd–de), and 100% larch produced the shortest flames of any composition (15 ± 2 cm; CLD group e), significantly lower than all pine-dominated compositions. Under EMC conditions, the compositional gradient was maintained, with 100% lodgepole producing the tallest flames (53 ± 3 cm; CLD group a) and 100% larch again the lowest (16 ± 3 cm; CLD group e). Notably, 100% larch flame height was nearly unchanged between treatments (15 ± 2 cm oven-dry vs. 16 ± 3 cm EMC), indicating that larch litter achieves low flame heights regardless of moisture state.

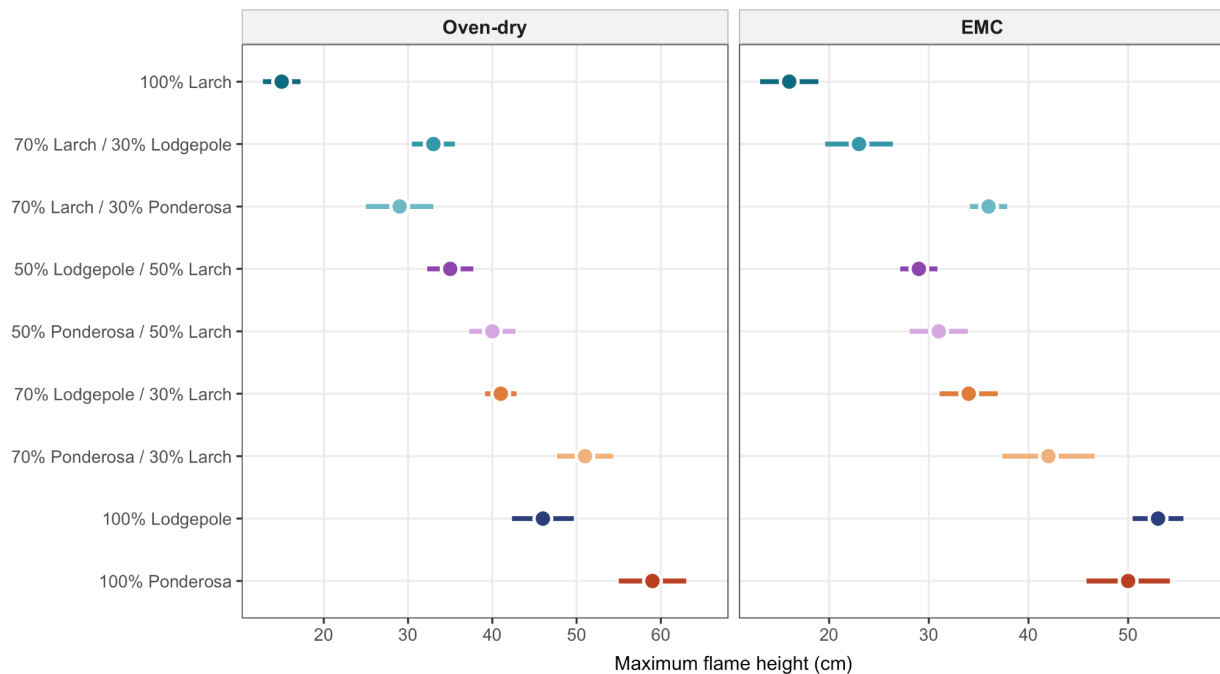


Figure 44. Maximum flame height (cm) of western larch and pine litter compositions under oven-dry (left) and equilibrium moisture content (EMC, right) conditions. Points show composition means ± 1 SE ($n = 5$ per composition). Compositions are ordered from highest to lowest larch proportion. Flame height declined progressively with increasing larch proportion under both moisture treatments, with 100% larch producing the lowest mean flame height regardless of moisture condition.

3.5.2.3 Fuel Consumption

Fuel consumption differed significantly among fuel bed compositions under both moisture treatments (oven-dry: $F_{8,36} = 36.85$, $p < 0.001$; EMC: $F_{\square, \square} = 21.83$, $p < 0.001$; Figure 45). Under oven-dry conditions, 100% ponderosa pine fuel beds consumed the greatest proportion of fuel mass ($82.6 \pm 2.4\%$; CLD group a), followed by 100% lodgepole pine fuel beds ($80.6 \pm 0.7\%$; CLD group b). In contrast, 100% western larch fuel beds had the lowest consumption ($29.0 \pm 4.7\%$; CLD group e), significantly lower than all other compositions.

Fuel consumption followed a pronounced compositional gradient. Pine-dominated mixtures maintained relatively high consumption, with 70% ponderosa pine / 30% western larch fuel beds consuming $81.8 \pm 2.2\%$ of fuel mass (CLD group a) and 70% lodgepole pine / 30% western larch fuel beds consuming $67.7 \pm 2.3\%$ (CLD group bc). In contrast, larch-dominated mixtures consumed substantially less fuel, with 70% western larch / 30% ponderosa pine fuel beds consuming $51.4 \pm 5.8\%$ (CLD group d) and 70% western larch / 30% lodgepole pine fuel beds consuming $49.1 \pm 2.1\%$ (CLD group d). These results suggest a strong compositional shift in fuel consumption as western larch becomes a dominant component of the fuel matrix, although this pattern should not be interpreted as a fixed field threshold.

Under EMC conditions, the same general pattern persisted. Pure lodgepole pine ($86.1 \pm 0.2\%$; CLD group a) and pure ponderosa pine ($82.5 \pm 1.1\%$; CLD group ab) remained the highest-consumption fuel beds, whereas 100% western larch ($33.1 \pm 5.8\%$; CLD group e) and 70% western larch / 30% lodgepole pine ($45.6 \pm 2.4\%$; CLD group de) remained among the lowest. Pine-dominated compositions showed little reduction in consumption between oven-dry and EMC treatments, indicating that moisture uptake under EMC conditions did not substantially reduce combustion efficiency in pine litter. In contrast, western larch-dominated fuel beds maintained consistently lower consumption across both moisture treatments, suggesting that litter composition and fuel bed structure strongly influenced the proportion of fuel consumed.

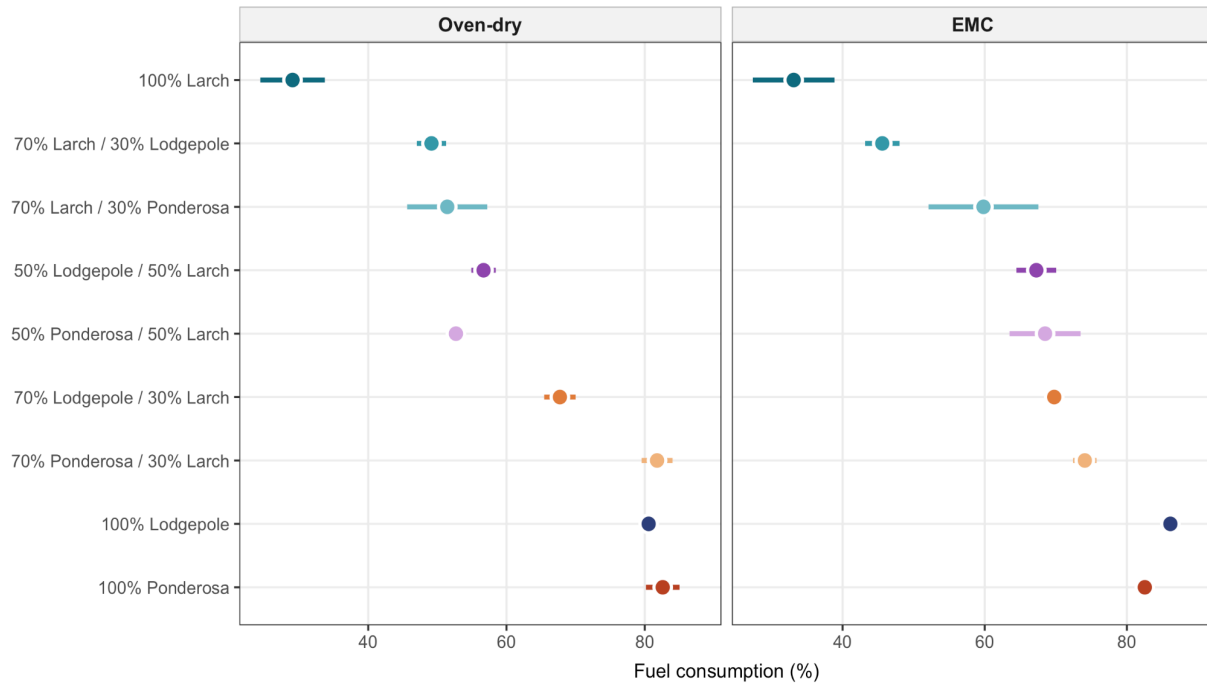


Figure 45. Fuel consumption (% of initial burn weight) of western larch and pine litter compositions under oven-dry (left) and equilibrium moisture content (EMC, right) conditions. Points show composition means ± 1 SE ($n = 5$ per composition). Compositions are ordered from highest to lowest larch proportion. Fuel consumption declined strongly with increasing larch proportion under oven-dry conditions. It remained low in larch-dominated compositions under EMC, while pine-dominated compositions maintained high consumption rates regardless of moisture treatment.

3.5.2.4 Flame Duration

Flaming duration differed significantly among compositions under both moisture treatments, though the pattern was less consistent than for flame height or consumption (oven-dry: $F_{8,36} = 21.74$, $p < 0.001$; EMC: $F_{8,36} = 3.38$, $p = 0.005$; Figure 46). Under oven-dry conditions, 100% Ponderosa and 100% larch shared the shortest mean flaming durations (76 ± 11 s and 77 ± 10 s, respectively; CLD group d), while mixed compositions dominated by lodgepole burned longest (70% larch / 30% lodgepole: 193 ± 13 s; 50% lodgepole / 50% larch: 187 ± 10 s; CLD group a). The similarly short flaming durations of 100% larch and 100% ponderosa reflect mechanistically different processes: rapid, efficient combustion in ponderosa versus low fuel availability and incomplete combustion in larch. Under EMC conditions, the compositional effect was weaker

($F_{8,36} = 3.38$, $p = 0.005$), with significant differences limited to comparisons between 100% ponderosa and several mixed or pine-dominated compositions (CLD group b vs. a). 100% larch showed the largest absolute increase in flaming duration between treatments (77 ± 10 s oven-dry to 140 ± 22 s EMC), consistent with moisture-limited, slower combustion.

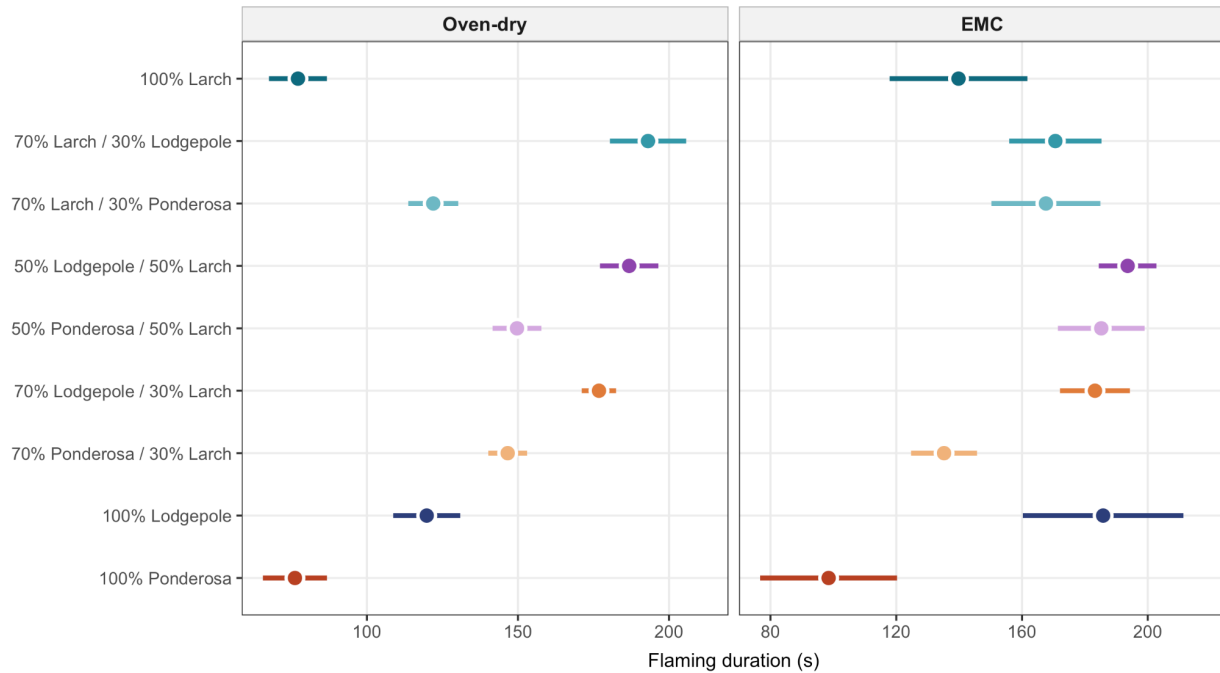


Figure 46. Flaming duration (s) of western larch and pine litter compositions under oven-dry (left) and equilibrium moisture content (EMC, right) conditions. Points show composition means ± 1 SE ($n = 5$ per composition). Compositions are ordered from highest to lowest larch proportion. Under oven-dry conditions, 100% larch and 100% ponderosa exhibited the shortest flaming durations despite differing combustion mechanisms; under EMC conditions, 100% larch showed the largest absolute increase in flaming duration, consistent with moisture-limited, incomplete combustion.

3.5.2.5 Smoldering Duration

Smoldering duration showed the strongest and most ecologically interpretable compositional gradient of all five metrics (oven-dry: $F_{8,36} = 7.94$, $p < 0.001$; EMC: $F_{8,36} = 4.94$, $p < 0.001$; Figure 47). Under oven-dry conditions, 100% larch smoldered for the shortest duration of any composition (57 ± 6 s; CLD group d), significantly shorter than 100% lodgepole (299 ± 17 s; a), 100% Ponderosa (286 ± 24 s; ab), and all pine-dominated mixed compositions (244–271 s; abc).

The gradient was nearly monotonic: larch-dominated mixtures smoldered for 142–166 s (cd), mixed 50/50 compositions for 206–237 s (abc), and pine-dominated mixtures for 244–271 s (abc). Under EMC conditions, the compositional gradient in smoldering duration was partially maintained but showed several notable shifts. Smoldering duration increased substantially in 100% western larch fuel beds, from 57 ± 6 s under oven-dry conditions to 122 ± 50 s under EMC conditions, and similar increases occurred in several larch-dominated compositions. These patterns are consistent with a transition from rapid, low-intensity combustion under dry conditions to more prolonged, moisture-limited smoldering under EMC conditions, as also reflected in the total burn duration results.

In contrast, the 70% western larch / 30% lodgepole pine mixture showed a decrease in smoldering duration under EMC conditions, from 166 ± 13 s to 118 ± 23 s. This pattern suggests that interactions between western larch moisture retention and lodgepole pine fuel bed structure may alter smoldering behavior under humid conditions, although this response should be interpreted cautiously given the controlled laboratory setting and replicate-level variability. Pine-dominated compositions showed variable and generally modest changes between treatments, with 100% ponderosa pine increasing from 286 ± 24 s to 345 ± 49 s and 100% lodgepole pine decreasing from 299 ± 17 s to 267 ± 35 s. These results suggest that smoldering duration in pine litter was less responsive to the moisture differences between oven-dry and EMC treatments than smoldering duration in western larch-dominated fuel beds.

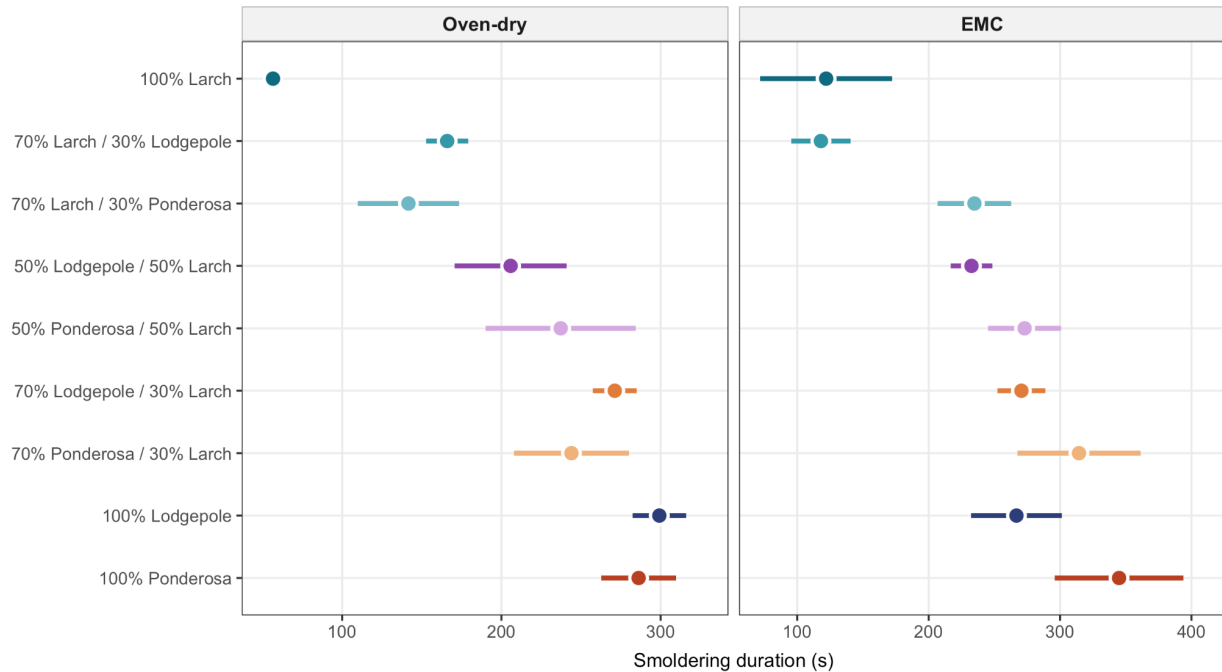


Figure 47. Smoldering duration (s) of western larch and pine litter compositions under oven-dry (left) and equilibrium moisture content (EMC, right) conditions. Smoldering duration was calculated as total burn duration minus flaming duration. Points show composition means ± 1 SE ($n = 5$ per composition). Compositions are ordered from highest to lowest larch proportion. Under oven-dry conditions, 100% larch exhibited the shortest smoldering duration of any composition, while pine-dominated compositions smoldered for substantially longer. Under EMC conditions, smoldering duration increased markedly for 100% larch, reflecting a shift toward prolonged, moisture-limited combustion, while pine-dominated compositions showed comparatively stable smoldering durations across moisture treatments.

3.5.2.6 Total Burn Time

Total burn duration was the metric that most strongly distinguished 100% larch from all other compositions (Figure 48). Under oven-dry conditions, 100% larch had by far the shortest mean total burn duration (134 s), approximately 2.5–3 times shorter than all other compositions, which ranged from 264 s (70% larch / 30% ponderosa) to 448 s (70% lodgepole / 30% larch). Under EMC conditions, 100% larch burn duration increased substantially (262 s), approaching values observed in larch-dominated mixed compositions under oven-dry conditions, indicating that moisture uptake shifts larch litter from a fast, low-intensity burn to a prolonged, smoldering combustion mode. Pine-dominated compositions showed comparatively small treatment differences, with total

burn durations remaining in the 390–460 s range across both moisture treatments.

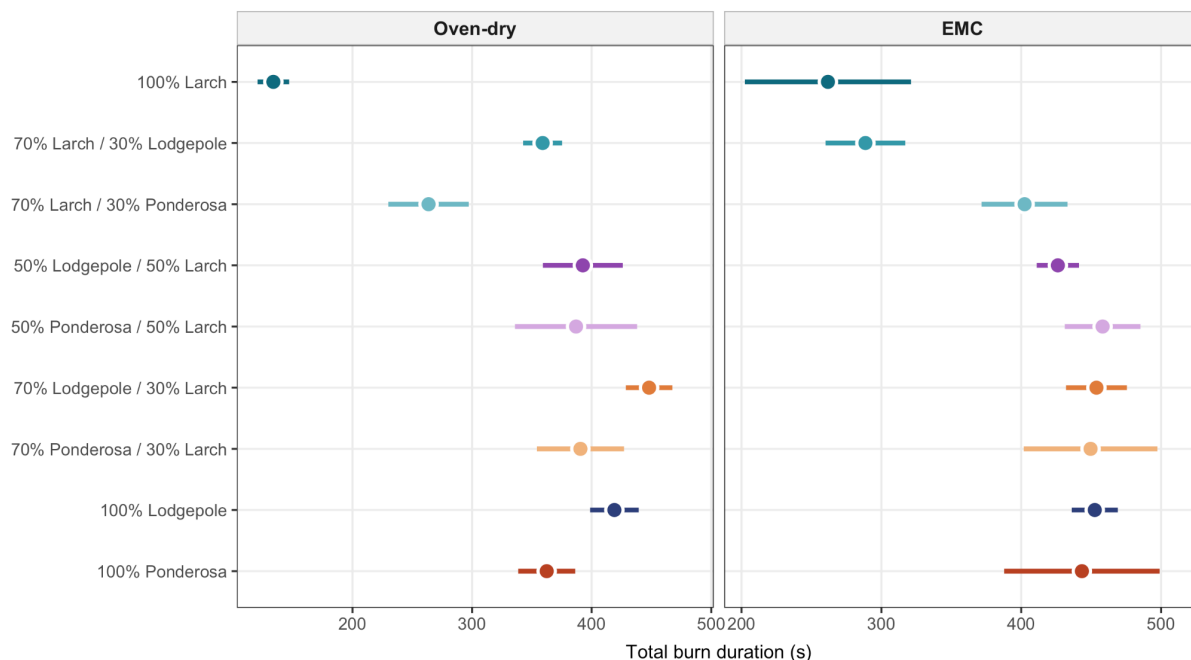


Figure 48. Total burn duration (s) of western larch and pine litter compositions under oven-dry (left) and equilibrium moisture content (EMC, right) conditions. Points show composition means ± 1 SE ($n = 5$ per composition). Compositions are ordered from highest to lowest larch proportion. Under oven-dry conditions, 100% larch produced the shortest total burn duration of any composition; under EMC conditions, burn duration increased markedly for larch-dominated compositions, reflecting a shift from rapid, low-intensity combustion to prolonged smoldering under higher moisture loads.

3.5.2.7 Compositional Gradients and Ordination

Across all five flammability metrics, increasing western larch proportion consistently reduced overall flammability under oven-dry conditions, with the strongest effects observed for fuel consumption and smoldering duration. PC1 from the oven-dry ordination explained 62.6% of the variance and declined strongly, nearly monotonically, with increasing western larch proportion (Figure 49). All five flammability metrics were significantly correlated with PC1 (envfit, all $r^2 \geq 0.83$, $p = 0.001$). Total burn duration ($r^2 = 0.95$), fuel consumption ($r^2 = 0.85$), smoldering duration ($r^2 = 0.83$), and flame height ($r^2 = 0.83$) showed particularly strong associations with this axis. PC2 explained an additional 24.3% of the variance and was driven primarily by flaming duration (r^2

= 0.89, $p = 0.001$). This axis separated mixed lodgepole pine–western larch compositions, which exhibited disproportionately long flaming duration relative to their overall flammability, from pure-species compositions (Figure 50).

The compositional transition at which dampening effects became most pronounced occurred between 30% and 50% western larch for fuel consumption and smoldering duration. The largest shift occurred between the 70% ponderosa pine / 30% western larch composition, which consumed $81.8 \pm 2.2\%$ of fuel mass and smoldered for 244 ± 36 s, and the 50% ponderosa pine / 50% western larch composition, which consumed $52.7 \pm 1.4\%$ of fuel mass and smoldered for 237 ± 47 s. This pattern suggests that western larch may begin to exert stronger control over fuel bed combustion once it becomes a substantial component of the fuel matrix, although this laboratory result should not be interpreted as a fixed field threshold.

Under EMC conditions, the higher moisture retention capacity of western larch litter, reflected in its greater saturation moisture content and longer drying time-lag (τ ; Section 5.1.1.3), further altered flammability patterns by slowing combustion and extending burn duration. The composite moisture-flammability relationship (Figure 43) showed that higher western larch proportions were associated with steeper moisture-driven declines in PC1 scores. These results suggest that western larch litter dampens flammability not only through lower fuel consumption under dry conditions, but also through moisture-mediated effects that become more pronounced under humid or post-precipitation fuel conditions.

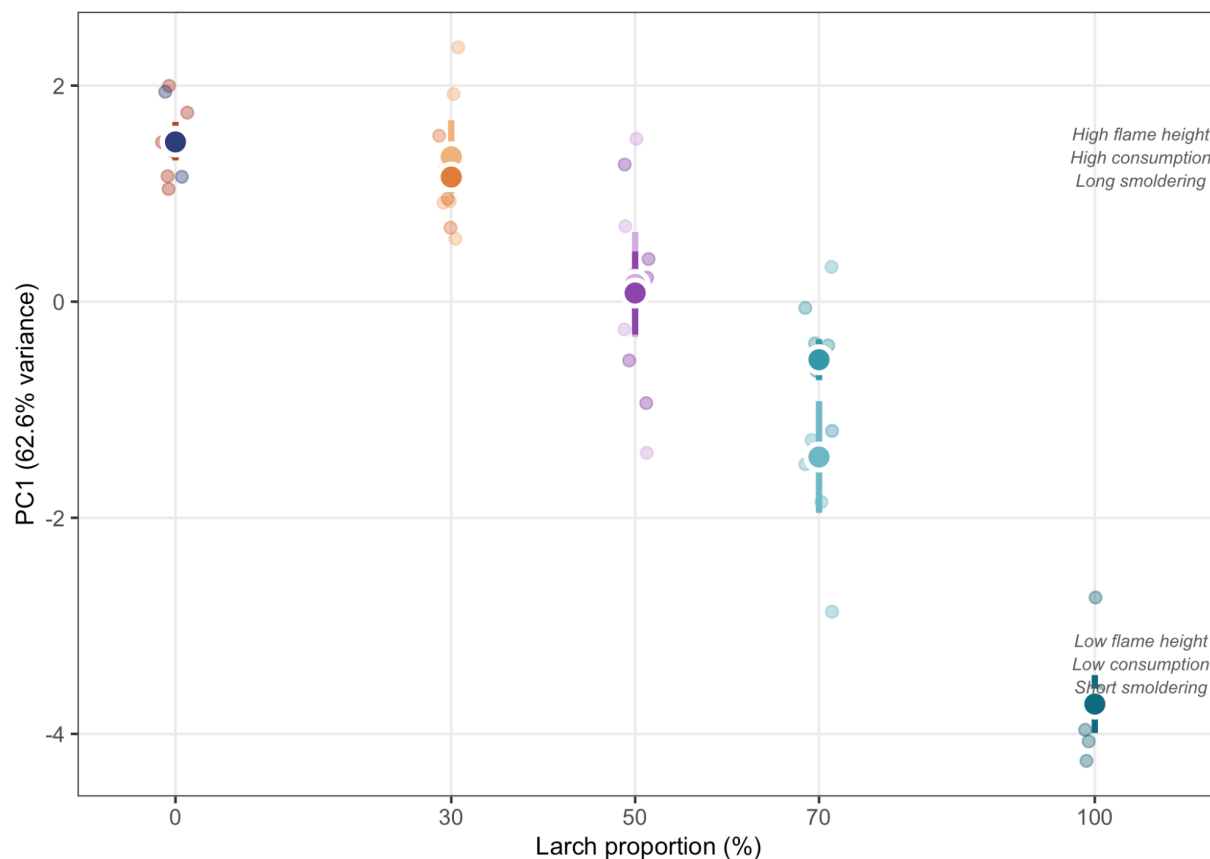


Figure 49. PC1 scores (62.6% of variance) from a principal components analysis of five oven-dry flammability metrics (maximum flame height, fuel consumption, flaming duration, total burn duration, smoldering duration) plotted against larch proportion in fuel bed composition. PC1 represents a composite fire intensity gradient; negative scores indicate low flame height, low consumption, and short smoldering duration, whereas positive scores indicate high values across all metrics. Points show individual replicates ($n = 5$ per composition); larger filled circles show composition means ± 1 SE. PC1 scores declined strongly and near-monotonically with increasing larch proportion, indicating systematic dampening of fire intensity across the larch composition gradient.

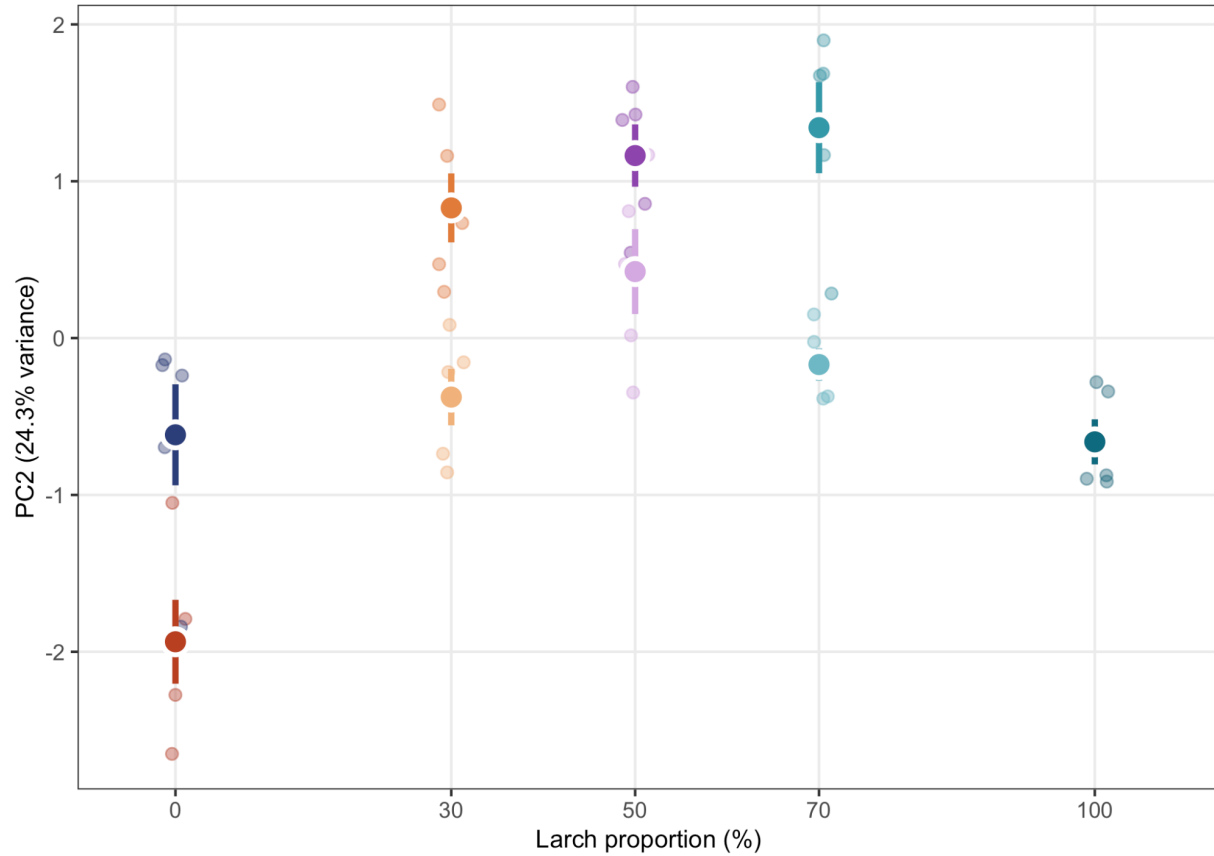


Figure 50. PC2 scores (24.3% of variance) from a principal components analysis of five oven-dry flammability metrics plotted against larch proportion in fuel bed composition. PC2 is driven primarily by flaming duration (envfit $r^2 = 0.89$, $p = 0.001$) and captures variation in combustion temporal patterns independent of overall fire intensity. Mixed lodgepole-larch compositions showed the highest PC2 scores, reflecting prolonged flaming duration relative to pure species compositions. Points show individual replicates ($n = 5$ per composition); larger filled circles show composition means ± 1 SE.

3.6 Discussion

3.6.1 Western Larch as a Fire Impeder

The substantial reduction in smoldering duration observed in larch-dominated fuel beds has important ecological implications. Smoldering combustion contributes strongly to duff consumption, prolonged soil heating, belowground tissue injury, and changes in post-fire seedbed conditions in forest ecosystems (Varner et al. 2015; Kreye et al. 2018), with important implications for post-fire regeneration in climate-stressed dry forests (Stevens-Rumann et al. 2022). We found that 100%

western larch fuel beds reduced smoldering duration nearly fivefold relative to pine-dominated compositions under oven-dry conditions, and larch-dominated mixtures maintained shorter smoldering durations across moisture treatments. These results suggest that western larch litter may reduce the duration of ground-level combustion processes that contribute to severe fire effects, providing a potential mechanistic explanation for the lower stand-level burn severity patterns observed in planted western larch stands in Chapter 2.

The reduced consumption of 100% western larch fuel beds ($29.0 \pm 4.7\%$) relative to pine-dominated fuel beds ($\geq 80\%$) under identical oven-dry conditions indicates that intrinsic litter characteristics influence combustion independently of fuel moisture. We attribute these differences primarily to western larch needle morphology and fuel bed structure, including shorter needle length, greater packing density, and reduced aeration compared with pine fuel beds. Previous studies have shown that litter particle size, packing arrangement, and fuel bed architecture strongly regulate airflow, heat transfer, and combustion efficiency (Cornwell et al. 2015; Zhao et al. 2016; Burton et al. 2021). In this context, densely packed larch litter may limit oxygen availability and reduce complete fuel consumption, even under extremely dry conditions.

Our results support the interpretation that western larch may function not only as a fire-resistant species but also as a fire-impeding species whose litter characteristics dampen components of fire behavior (Kane et al. 2008; Varner et al. 2015). Across multiple flammability dimensions measured under standardized laboratory conditions, western larch litter exhibited consistently lower flammability than litter from co-occurring ponderosa pine and lodgepole pine. These findings place western larch toward the lower-flammability end of the trait spectrum among western North American conifers, consistent with broader trait-based frameworks linking plant functional traits, fuel characteristics, and fire behavior (Schwilk 2015; Pausas et al. 2017; Stevens et al. 2020).

The PCA results further indicate that differences among species reflect an integrated flammability strategy rather than isolated variation in individual combustion traits. PC1, which explained 62.6% of the total variance under oven-dry conditions (Figure 49), loaded strongly on flame height, fuel

consumption, and smoldering duration. Pure western larch fuel beds had the lowest PC1 scores among all compositions, indicating consistently reduced combustion across multiple flammability components. This pattern aligns with previous work showing that flammability traits often covary across species as part of broader ecological strategies shaped by plant structure, chemistry, and resource allocation (Varner et al. 2015; Pausas et al. 2017; Kreye et al. 2023).

Importantly, these differences persisted under oven-dry conditions, indicating that the lower flammability of western larch litter cannot be explained by elevated fuel moisture alone. Instead, reduced flammability appears to reflect trait-mediated differences in needle morphology and fuel bed arrangement that persist even when moisture content is standardized. Litter chemistry may also contribute to these patterns, although chemical traits were not directly measured in this study.

This interpretation aligns with leaf economics theory, which predicts that deciduous species generally invest less carbon in long-lived structural tissues than evergreen species, producing differences in tissue chemistry, decomposition rates, and fuel accumulation dynamics (Matyssek, 1986; Aerts, 1995; Wright et al., 2004). Across ecosystems, plant functional traits strongly influence litter decomposition and fuel properties, and faster-decomposing litter may reduce long-term surface fuel accumulation relative to more persistent litter types (Cornwell et al., 2008).

When combined with field moisture dynamics, these differences may become more pronounced. Previous studies of larch systems indicate that larch litter can differ from evergreen conifers in moisture retention, decomposition pathways, and nutrient cycling dynamics (Osono et al. 2003; Loskutov et al. 2013; Bryanin et al. 2020). Our moisture results support this interpretation: 100% western larch fuel beds exhibited the highest saturation moisture content of any composition ($402 \pm 40\%$), more than five times that of ponderosa pine ($75 \pm 5\%$), and maintained the longest drying time lag ($\tau = 15.3$ h compared with approximately 7 h for the fastest-drying pine compositions).

Together, these structural and moisture-related traits suggest that larch-dominated litter layers may remain less available for combustion for longer periods following precipitation events, potentially narrowing the window during which surface fuels support ignition and sustained fire spread. This mechanism is consistent with broader evidence that fire danger and ignition probability vary

continuously with fuel moisture, atmospheric demand, and short-term weather conditions (Jolly et al. 2015).

3.6.2 Mechanisms of Flammability Reduction

Several interacting mechanisms likely explain the low-flammability profile observed in western larch fuel beds. The most structurally apparent mechanism involves fuel bed architecture and packing. Western larch sheds needles in compact clusters from deciduous spur shoots, producing litter beds with higher bulk density and reduced inter-particle spacing compared with the longer, loosely arranged needles of ponderosa pine and lodgepole pine (Cornwell et al. 2015; Burton et al. 2021). Our fuel bed depth measurements support this interpretation: western larch fuel beds constructed with the same 15 g dry mass were consistently shallower than pine fuel beds, indicating greater packing density.

Fuelbed structure strongly regulates combustion by controlling oxygen availability, heat transfer, and flame propagation. Brown (1981) identified bulk density as one of the most important fuel bed properties influencing surface fire behavior, while Van Wagtenonk et al. (1998) demonstrated that differences in litter packing ratio among conifer species translate into measurable differences in predicted fire behavior. More recent experimental work confirms that in-bed structure and bulk properties regulate airflow and flame spread in porous fuel beds, with compact packing reducing ventilation and altering combustion dynamics (Campbell-Lochrie et al. 2021). Similarly, increasing bulk density can delay ignition, constrain oxygen availability, and reduce combustion efficiency (Yang et al. 2024).

At broader phylogenetic scales, species with shorter needles, including non-pine members of the pine family such as western larch, generally form denser and less ventilated fuel beds than long-needled pines, which can reduce flammability by limiting airflow and flame propagation (Cornwell et al., 2015; Zhao et al., 2016). Our results align with this framework. Western larch fuel beds exhibited low fuel consumption ($29.0 \pm 4.7\%$) and shorter smoldering duration (57 ± 6 s) compared with pine fuel beds, which burned more completely (80–83% consumption) and sustained longer

smoldering periods (286–299 s). Although dense fuel beds can favor smoldering combustion under some conditions, western larch appeared to limit total smoldering duration because only a small fraction of the fuel bed was consumed. In contrast, pine litter supported sustained oxidation because greater fuel availability and ventilation allowed combustion to continue for longer periods. The packing artifact discussed in Section 3.5.1 does not alter the directional conclusions of the moisture dynamics or flammability analyses. Saturation moisture content results consistently identified ponderosa pine as the lowest-moisture composition, while flammability measurements placed ponderosa pine at the high-flammability end of the combustion gradient regardless of the observed drying time-lag anomaly.

Differences in fuel chemistry may provide an additional mechanism contributing to reduced western larch flammability, although we did not directly measure chemical composition in this study. Evergreen conifers such as ponderosa pine and lodgepole pine maintain relatively high concentrations of resins and terpenoid compounds, which influence ignition behavior, heat release, and flame intensity (Ormeño et al. 2009). Previous work has shown that chemical composition varies substantially among conifer fuels and influences thermal decomposition and combustion characteristics (Rogers et al. 1986). Resin duct anatomy also differs among western North American conifers, with western larch exhibiting defensive investment strategies distinct from co-occurring evergreen species (Arbellay et al. 2014).

Western larch's deciduous growth strategy may partly explain these differences. Unlike evergreen conifers that retain needles for multiple years, western larch replaces its foliage annually, reducing the need for long-term investment in chemically defended tissues. Leaf economics theory predicts that deciduous species generally have lower structural investment, faster tissue turnover, and different carbon allocation strategies than evergreen species (Matyssek 1986; Aerts 1995; Wright et al. 2004). These differences influence litter quality, decomposition rates, and ultimately fuel accumulation patterns (Cornwell et al. 2008). Although future chemical analyses are needed to quantify volatile compounds in western larch litter directly, our results are consistent with previous findings that deciduous gymnosperms and small-needled conifers often produce less flammable

litter than long-needled evergreen species (Cornwell et al. 2015; Zhao et al. 2016).

Moisture dynamics provide a third mechanism through which western larch may reduce surface fuel flammability under field conditions. Studies of other *Larix* species show that larch litter absorbs and retains moisture differently than co-occurring evergreen conifers, likely because of differences in surface chemistry, wax investment, and litter structure (Loskutov et al. 2013; Sun et al. 2015). Seasonal measurements of larch and pine litter further indicate that larch-dominated fuel beds can maintain higher moisture contents during drying periods, with litter age and environmental conditions influencing these dynamics across the fire season (Zhang 2014).

Our moisture-conditioning experiment supports this mechanism. In the EMC treatment, western larch fuel beds shifted from short-duration, low-consumption combustion under oven-dry conditions toward longer moisture-limited combustion (57 ± 6 s oven-dry compared with 122 ± 50 s EMC). In contrast, ponderosa pine maintained consistently long smoldering durations across treatments (286 ± 24 s oven-dry compared with 345 ± 49 s EMC). These results suggest that moisture retention amplifies existing structural differences among species rather than acting as the sole driver of reduced flammability.

Mixed-species interactions further support this interpretation. Previous studies have shown that litter mixtures can produce non-additive effects, where combustion behavior differs from predictions based on individual species alone because interactions among fuel structure, moisture dynamics, and chemistry alter flammability (Magalhães and Schwilk, 2012; Magalhães and Schwilk, 2021). The reduced consumption observed in larch-pine mixtures under moisture-conditioned treatments suggests that western larch litter may dampen combustion even when combined with more flammable pine fuels.

Together, these results indicate that the fire-impeding characteristics of western larch litter arise from multiple interacting mechanisms, including compact fuel bed structure, reduced ventilation, increased moisture retention, and potentially differences in litter chemistry. Because litter chemistry was not directly measured in this study, we interpret chemical contributions as a plausible mechanism requiring further investigation. Field moisture conditions may amplify the flamma-

bility differences observed under laboratory conditions by extending the period during which larch-dominated litter remains less available for sustained combustion. This mechanism aligns with broader evidence that fire activity responds dynamically to short-term variation in fuel moisture, atmospheric demand, and seasonal drying patterns (Jolly et al., 2015; Kreye et al., 2018).

3.6.3 Comparison with the Broader Flammability Literature

The flammability profile of western larch, characterized by reduced flame height, low fuel consumption, limited smoldering duration under dry conditions, and strong moisture sensitivity, parallels patterns documented for low-flammability deciduous species in other forest ecosystems. In eastern North American forests, deciduous hardwoods such as red maple (*Acer rubrum*), American beech (*Fagus grandifolia*), and American basswood (*Tilia americana*) produce litter with higher moisture retention and lower flammability relative to co-occurring oak and pine species (Kreye et al. 2013, 2018, 2023; Kane et al. 2021). Although western larch occurs in a fundamentally different ecological context, our findings suggest that deciduous leaf habit may produce convergent effects on litter traits that influence combustion processes across phylogenetically distinct tree groups.

Experimental studies across diverse forest systems support this interpretation. Leaf morphology, particle size, packing arrangement, and moisture absorption capacity strongly influence litterbed structure by controlling aeration, oxygen availability, and heat transfer during combustion (Cornwell et al. 2015; Zhao et al. 2016; Burton et al. 2021). Kreye et al. (2023) demonstrated that leaf thickness, particle size, and moisture dynamics independently regulate litter flammability, while mixed-species fuel experiments show that dominant litter components can produce non-additive effects by altering fuel bed packing and combustion behavior (Zhao et al. 2016, 2019; Magalhães and Schwilk 2021). Our results place western larch within this broader functional framework. Despite being a conifer, its deciduous needle habit creates fuel characteristics more similar to lower-flammability deciduous litter than to the long, aerated needle beds produced by many evergreen conifers.

However, western larch differs from mesophytic hardwood species in an important ecological respect: western larch evolved in fire-prone landscapes and possesses traits that promote persistence under recurrent fire. Mature western larch trees develop thick insulating bark, tall crowns, and strong self-pruning architecture, allowing individuals to survive low- and moderate-intensity surface fires (Schmidt et al. 1976; Sparks et al. 2018; Stevens et al. 2020). Therefore, the same species that produces relatively low-flammability surface fuels also maintains structural traits that allow persistence during fires.

This combination represents a distinct expression of the fire-imperder strategy described by Varner et al. (2015). Rather than simply surviving fire through resistance traits, western larch may influence the local fire environment by producing litter that moderates combustion intensity while remaining adapted to the fire regimes that historically maintained it (Kane et al. 2008; Stevens et al. 2020). This differs from the role of low-flammability mesophytic hardwood expansion in historically oak-dominated forests, where increasing dominance of shade-tolerant, low-flammability species can reinforce reduced fire frequency and facilitate transitions away from fire-maintained ecosystems (Nowacki and Abrams 2008; Kreye et al. 2018).

In contrast, western larch litter traits occur within forests historically structured by recurring fire. Rather than excluding fire from these systems, larch-associated fuel characteristics may contribute to spatial variation in fire behavior by creating localized areas of reduced combustion intensity embedded within broader fire-prone landscapes. These feedbacks are consistent with historical mixed-severity fire dynamics of the inland Northwest, where variation in species composition, fuel structure, topography, and fire history maintained heterogeneous forest mosaics across space and time (Barrett et al. 1991; Hessburg et al. 2005; Perry et al. 2011). In this context, western larch may contribute to fire resilience not by preventing fire, but by modifying fuel conditions in ways that support variable fire effects characteristic of fire-adapted landscapes.

3.6.4 Mixture Effects and Compositional Thresholds

The mixed-composition results indicate that western larch's fire-dampening influence on fuel bed flammability depends strongly on relative species composition, with the magnitude and direction of effects varying among flammability metrics and larch proportions. Fuel consumption showed the strongest and most consistent compositional gradient. Under oven-dry conditions, fuel beds containing 30% western larch showed limited reductions in consumption relative to pure pine compositions (70% ponderosa pine / 30% larch: $81.8 \pm 2.2\%$; 70% lodgepole pine / 30% larch: $67.7 \pm 2.3\%$), whereas mixtures containing equal or greater proportions of larch exhibited substantially lower consumption (50% ponderosa pine / 50% larch: $52.7 \pm 1.4\%$; 50% lodgepole pine / 50% larch: $56.7 \pm 1.8\%$; 70% larch / 30% ponderosa pine: $51.4 \pm 5.8\%$; 70% larch / 30% lodgepole pine: $49.1 \pm 2.1\%$).

Although our experimental design does not allow us to identify an exact ecological or management threshold, the largest reduction in fuel consumption occurred between the 30% and 50% western larch treatments. This pattern suggests a nonlinear transition in fuel bed behavior as western larch becomes a larger component of the litter matrix. Similar nonlinear responses have been documented in mixed-species litter experiments, where low-flammability species may need to reach sufficient abundance before their traits strongly influence fuel bed structure, moisture dynamics, and combustion behavior (Kreye et al., 2018; Magalhães and Schwilk, 2021).

A likely mechanism underlying this pattern is fuel bed matrix dominance. At lower larch proportions, longer pine needles continue to define fuel bed architecture, maintaining higher porosity, greater ventilation, and greater oxygen availability during combustion (Brown 1981; Campbell-Lochrie et al. 2021). As larch contribution increases, shorter and more densely packed larch needles increasingly influence fuel bed structure, reducing airflow and limiting combustion efficiency (van Wagtenonk et al. 1998; Cornwell et al. 2015; Zhao et al. 2016). Experimental mixture studies support this mechanism, showing that species can exert disproportionate effects on flammability through particle size, packing geometry, and fuel bed arrangement rather than through biomass contribution alone (Zhao et al. 2016, 2019).

Our moisture-conditioned results suggest that these compositional effects may become stronger under field-relevant moisture conditions. Previous work has shown that non-additive dampening effects in mixed fuel beds can become more pronounced when moisture dynamics interact with species-specific litter traits (Blauw et al. 2015; Magalhães and Schwilk 2021). Therefore, the larch proportions needed to influence combustion behavior under field conditions may differ from those observed under standardized oven-dry laboratory conditions.

Smoldering duration showed one of the clearest compositional gradients among the five flammability metrics and reinforced the fuel consumption patterns. Under oven-dry conditions, smoldering duration declined consistently as western larch contribution increased, from 299 ± 17 s in 100% lodgepole pine fuel beds and 286 ± 24 s in 100% ponderosa pine fuel beds to 57 ± 6 s in 100% western larch fuel beds, representing an approximately five-fold difference. Larch-dominated mixtures also smoldered for substantially shorter periods than pine-dominated mixtures. The 70% western larch / 30% ponderosa pine and 70% western larch / 30% lodgepole pine mixtures smoldered for 142 ± 32 s and 166 ± 13 s, respectively, whereas the 70% ponderosa pine / 30% western larch and 70% lodgepole pine / 30% western larch mixtures smoldered for 244 ± 36 s and 271 ± 14 s, respectively. These patterns indicate that majority-larch fuel beds altered the sustained oxidation phase of combustion and reduced the duration over which residual fuels continued to burn.

Under EMC conditions, smoldering duration increased for most larch-dominated compositions but remained lower than in pine-dominated fuel beds. Pure western larch increased from 57 ± 6 s under oven-dry conditions to 122 ± 50 s under EMC conditions, while pine compositions remained between 267 and 345 s. These results suggest that moisture retention shifted western larch fuel beds toward slower, moisture-limited combustion but did not eliminate the structural constraints on sustained burning imposed by western larch litter architecture. In contrast, pine fuel beds continued to support longer smoldering periods, likely because greater fuel consumption and higher ventilation allowed oxidation to persist after flaming ended.

Because smoldering combustion contributes strongly to prolonged soil heating, duff consumption,

belowground injury, and post-fire seedbed conditions (Varner et al., 2015; Kreye et al., 2018), reductions in smoldering duration may have important implications for post-fire recovery. In western North American dry forests, where regeneration failure is increasingly associated with larger high-severity patches and warmer post-fire conditions, shorter periods of ground-level heating may influence seed survival, resprouting capacity, and regeneration environments (Coop et al., 2020; Stevens-Rumann et al., 2022).

Flame duration showed a more complex response than fuel consumption or smoldering duration. Several mixed compositions, including 70% western larch / 30% lodgepole pine (193 ± 13 s) and 50% lodgepole pine / 50% western larch (187 ± 10 s), burned longer than either pure-species fuel bed. This pattern suggests a non-additive mixture effect for flaming duration, although the direction of the effect differed from the dampening response observed for consumption and smoldering. One possible explanation is that lodgepole pine needles provided sufficient aeration and ignition potential to sustain flaming. In contrast, adjacent western larch needles combusted more slowly and incompletely, extending flame duration without increasing flame height or total fuel consumption.

This result reinforces that flammability is multidimensional and that individual components do not necessarily respond in the same direction. Ignitability, combustibility, sustainability, and consumability can vary independently because they respond to different aspects of fuel structure, chemistry, and moisture dynamics (Schwilk 2015; Varner et al. 2015). Previous mixture experiments similarly demonstrate that species interactions can increase some flammability metrics while reducing others, depending on how fuel traits combine within the litter bed (Magalhães and Schwilk 2012; van Altena et al. 2012; Blauw et al. 2015; Della Rocca et al. 2018; Gormley et al. 2020).

Our results extend this framework to western larch–pine mixtures. Mixed fuel beds may sustain flaming for longer periods than either species alone while simultaneously producing lower flame heights, lower fuel consumption, and shorter smoldering duration. These contrasting responses emphasize that the implications of restoration depend on which component of fire behavior is most

relevant: rate of spread, intensity, fuel consumption, or ecological fire effects.

3.6.5 Landscape-Scale Implications and Management Strategies for the Colville Reservation

Translating laboratory flammability results to field-scale fire behavior requires caution, as wildfire outcomes arise from interactions among fuels, weather, topography, and vegetation structure at spatial scales beyond those captured in controlled experiments. Although our results identify differences in intrinsic fuel properties between western larch and co-occurring pine species, factors such as canopy structure, wind, fuel continuity, live fuel moisture, and landscape context ultimately regulate surface fire spread and intensity (Rothermel 1972; Agee and Skinner 2005; Finney et al. 2015). Therefore, we interpret these findings as mechanistic evidence of how western larch influences surface fuel properties rather than direct predictions of wildfire behavior.

Future work could incorporate the fuel bed properties quantified here into fire behavior modeling frameworks such as FARSITE and FlamMap to evaluate how species-driven differences in litter characteristics influence potential fire spread under realistic landscape conditions (Finney 1998). Scenario-based landscape modeling approaches provide useful decision-support frameworks for scaling stand-level mechanisms to watershed-level outcomes and evaluating alternative restoration strategies under changing fire regimes (Krofcheck et al. 2017; Povak et al. 2022). However, these applications require field validation of litter flammability parameters before they can confidently inform operational fire behavior predictions.

Within this framework, our results provide testable hypotheses about how western larch abundance and spatial arrangement may influence fire behavior in mixed-conifer forests across the Colville Reservation. The Colville Tribes Department of Natural Resources manages western larch restoration across broad elevational gradients and post-fire contexts where species composition, forest structure, cultural values, timber objectives, and climate adaptation goals intersect. Regional syntheses demonstrate that restoration effectiveness depends on matching treatments to historical landscape patterns, site conditions, and contemporary disturbance pressures rather than applying uniform prescriptions across heterogeneous landscapes (Hessburg et al. 2005; Churchill et al.

2013; Hessburg et al. 2021).

Our laboratory results suggest that increasing western larch representation within fuel beds may enhance surface fuel damping effects. Still, we emphasize that experimental litter proportions do not directly translate into stand-level planting targets. In our controlled trials, the largest reductions in fuel consumption and smoldering duration occurred in the 30%-50% larch mixtures, suggesting that larch effects may strengthen once larch begins to influence overall fuel bed architecture.

However, this pattern represents a laboratory-derived response based on litter mass and requires validation through prescribed-fire experiments and field monitoring before it can be applied as a management guideline.

The ecological influence of western larch likely depends not only on abundance but also on spatial arrangement. Concentrated patches of larch-dominated forest embedded within mixed-species landscapes may create localized areas of reduced surface fuel flammability and contribute to heterogeneous fire effects, even when larch represents a smaller proportion of the broader landscape. This interpretation aligns with landscape resilience frameworks that emphasize spatial heterogeneity, variable forest structure, and discontinuity in fuel arrangements as mechanisms that support fire-adapted ecosystems (Churchill et al. 2013; Hessburg et al. 2021). Moisture-related effects may also occur at different compositional levels because deciduous conifer litter can influence fuel availability through water absorption and drying dynamics (Loskutov et al. 2013; Sun et al. 2015).

High-composition (>70%) western larch plantings may provide the strongest opportunity to evaluate how larch modifies surface fuel characteristics at local scales. However, restoration objectives should consider historical species composition, site productivity, climate vulnerability, wildlife habitat, cultural resources, and forest management priorities, rather than uniformly maximizing larch abundance. Historical forest assessments described in the Integrated Resource Management Plan 2015: Final Programmatic Environmental Impact Statement indicate that western larch historically occurred within heterogeneous fire-adapted forest mosaics across the Colville Reservation, with species associations varying along environmental gradients (Confederated Tribes of

the Colville Reservation and Bureau of Indian Affairs 2018). Western larch occurred with ponderosa pine in warmer, drier forest types and within diverse mixed-conifer communities containing Douglas-fir, lodgepole pine, grand fir, and other conifers in cooler and moister environments.

Therefore, restoration strategies that increase western larch abundance may be most ecologically aligned with restoring site-appropriate mixtures and spatial mosaics of fire-adapted species rather than homogeneous single-species conditions. In areas where reducing potential fire intensity provides important ecological or community benefits, including portions of the wildland–urban interface surrounding Tribal communities and infrastructure, strategically increasing fire-resistant species such as western larch may complement existing mechanical treatments and prescribed fire programs (Graham et al. 2004; Thompson et al. 2011; Prichard et al. 2020).

Watersheds supporting culturally important plant communities, fisheries, and water resources may benefit in particular from restoration strategies that reduce the likelihood of extensive, high-severity fire. High-severity fires can increase erosion, sediment delivery, and degradation of aquatic habitats, particularly following severe soil heating and vegetation loss (Moody and Martin 2001; Sankey et al. 2017). Western larch restoration may help reduce these risks where species traits, stand structure, and site conditions collectively support lower-severity fire effects. These considerations are increasingly relevant as warming temperatures, longer fire seasons, and increasing atmospheric moisture demand alter fire regimes across western North America (Westerling 2016; Hessburg et al. 2021).

The companion chapter to this study documented consistent associations between planted western larch stands on the Colville Reservation and lower burn severity relative to surrounding mixed-conifer forests in two of three fires examined: the North Star (2015) and Summit Trail (2021) fires. Although the observational design prevents us from isolating the effects of species composition from differences in stand history, structure, and management, the consistency of these patterns across independent fire events suggests that planted western larch stands can contribute to fire-resilient landscape conditions under some contexts.

The present chapter provides a mechanistic explanation for one component of this pattern by

demonstrating that western larch litter differs substantially from co-occurring pine species in moisture retention, combustion efficiency, and fuel consumption. Together, these findings suggest that western larch restoration influences fire outcomes through interacting mechanisms operating across scales: individual fire-resistant traits, litter-level fuel properties, stand structure, and landscape composition.

Continued adaptive management will be essential for testing these mechanisms under field conditions. Future restoration projects incorporating western larch provide opportunities to monitor fuel moisture dynamics, prescribed fire behavior, stand development trajectories, and post-fire outcomes to determine whether laboratory-scale differences translate into measurable changes in wildfire behavior and ecological effects (Thompson et al. 2011; Prichard et al. 2020). Long-term monitoring would provide the field-scale evidence needed to refine restoration strategies while supporting ongoing Tribal-led forest management and climate adaptation efforts on the Colville Reservation.

3.6.6 Larch as a Functionally Distinctive Fire Impeder: Comparisons with Broadleaf Deciduous Species

Western larch occupies a distinctive functional position among tree species of eastern Washington's dry and mixed-mesic forests. Our results indicate that western larch combines the low-flammability litter characteristics often associated with deciduous species, including high moisture retention, dense fuel bed packing, and reduced combustion efficiency, with the structural traits of a fire-resistant conifer adapted to recurrent disturbance. This combination distinguishes larch from many other low-flammability species because it does not simply reduce fire behavior; it persists within and contributes to fire-adapted forest systems (Varner et al. 2015; Pausas et al. 2017).

The deciduous needle habit of western larch likely contributes to this functional strategy. Compared with evergreen conifers, deciduous species generally invest in shorter-lived foliage with lower structural investment, different carbon–nutrient relationships, and faster turnover rates (Aerts 1995; Matyssek 1986; Wright et al. 2004). These traits influence litter decomposition rates,

moisture dynamics, and fuel accumulation patterns (Cornwell et al. 2008; Osono et al. 2003). In western larch, annual needle turnover produces a fuel bed structurally and functionally different from the longer, more aerated needle litter produced by co-occurring pines, while the species maintains thick bark, elevated crown structure, and self-pruning traits that promote survival during surface fire (Schmidt and Shearer 1995; Sparks et al. 2018; Stevens et al. 2020).

Within restoration planning on the Colville Reservation, western larch occurs within a broader decision framework that integrates forest resilience, cultural resources, timber production, wildlife habitat, watershed protection, and climate adaptation. Western larch does not occupy all forest types across the Reservation, and increasing larch abundance is not appropriate at every site. Instead, our findings suggest that where site conditions support western larch establishment and reducing high-severity fire risk is a priority, increasing larch representation may provide an additional mechanism for modifying fuel conditions alongside existing thinning and prescribed fire programs (Agee and Skinner 2005; Thompson et al. 2011; Hessburg et al. 2021).

Native broadleaf deciduous species of eastern Washington may provide similar fire-dampening functions through different ecological pathways. Species such as quaking aspen (*Populus tremuloides*), Rocky Mountain maple (*Acer glabrum*), serviceberry (*Amelanchier alnifolia*), and black cottonwood (*Populus trichocarpa*) produce litter with traits associated with greater moisture retention, faster decomposition, and reduced combustion potential relative to many evergreen conifers (Cornwell et al. 2008; Kreye et al. 2013, 2018; Kane et al. 2021). However, their ecological role differs from the mesophication dynamics described in eastern North American oak systems. In the inland Northwest, many native broadleaf species occur naturally within fire-influenced mixed-conifer landscapes, where they contribute to structural complexity, wildlife habitat, and spatial heterogeneity rather than representing a directional shift away from historically fire-adapted conditions.

Where these species occur in mixed forests, their litter inputs may generate localized patches of reduced flammability that interact with surrounding conifer fuels, contributing to heterogeneous fire effects. Such fine-scale variability aligns with the concept of pyrodiversity, where variation

in fuels, vegetation structure, and fire effects supports broader landscape heterogeneity (Pausas and Keeley 2009; Hessburg et al. 2021). In these systems, fire-impeding traits may contribute to mixed-severity fire dynamics by moderating local fire intensity without eliminating fire as an ecological process.

The key distinction between western larch and many broadleaf deciduous species lies in their regeneration strategies and post-disturbance dynamics. Western larch regenerates primarily from seed and competes with other shade-intolerant conifers for establishment following disturbance (Schmidt and Shearer 1995). In contrast, many broadleaf species resprout from root systems or root crowns after top-kill, allowing rapid recovery following fire and providing an early competitive advantage over seed-dependent conifers (Welch et al. 2016). This strategy can promote resilience and rapid vegetation recovery but may also alter competitive dynamics where restoration objectives prioritize regeneration of fire-adapted conifer communities.

Aspen provides an important example of a broadleaf fire-impeding strategy operating at larger spatial scales. Aspen stands often maintain higher moisture conditions, lower surface fire intensity, and reduced fire spread compared with adjacent conifer-dominated stands (Shinneman et al. 2013). Landscape-scale studies demonstrate that increased aspen cover can reduce fire spread rates and influence fire boundaries, suggesting that deciduous species can alter fire behavior through the combined effects of stand structure, fuel moisture, and fuel composition (Harris et al. 2025).

Following disturbance, aspen's ability to regenerate through root suckering allows rapid recovery and can create stabilizing feedbacks that influence future fire behavior (Romme et al. 1995).

However, the fire-dampening effects of deciduous species depend strongly on ecological context. In some systems, expansion of low-flammability broadleaf species following fire exclusion can reinforce reduced fire activity and accelerate transitions away from historically fire-maintained communities (Nowacki and Abrams 2008; Kreye et al. 2018). In contrast, western larch represents a different functional pathway: a deciduous species whose low-flammability litter traits operate within a fire-adapted conifer framework rather than replacing it.

The practical implication is not that western larch should replace broadleaf species or that

broadleaf components should be reduced. Instead, our results suggest that restoration strategies can consider multiple forms of deciduous functional diversity. Western larch provides a pathway for incorporating low-flammability litter traits while maintaining fire-adapted conifer structure. In contrast, native broadleaf species contribute additional ecological functions, including habitat diversity, nutrient cycling, and fine-scale fuel heterogeneity. Maintaining these complementary strategies may better support resilient landscape mosaics that sustain ecological function under changing fire regimes (Hessburg et al. 2021; Coop et al. 2020).

3.7 Limitations and Future Research

This study provides a mechanistic foundation for understanding western larch litter flammability under controlled laboratory conditions. However, several knowledge gaps remain before these findings can be translated into operational fire management applications. Most importantly, future research should evaluate whether the flammability differences measured in small-scale experimental fuel beds produce measurable differences in fire behavior within field-scale fuel complexes, where vertical fuel structure, heterogeneous fuel moisture, variable fuel loading, slope, wind, and canopy fuels interact to shape combustion dynamics.

Laboratory flammability experiments provide controlled comparisons of intrinsic fuel properties but cannot fully reproduce the atmospheric coupling, convective processes, and spatial heterogeneity that regulate wildland fire behavior (Rothermel 1972; Rothermel and Deeming 1980; Nelson et al. 2012; Finney et al. 2015). These scaling challenges limit direct extrapolation from laboratory-derived combustion metrics to operational fire behavior, even when laboratory experiments identify important mechanistic differences among species.

Experimental prescribed burns comparing larch-dominated and pine-dominated stands on the Colville Reservation would provide the strongest test of whether the fuel bed mechanisms documented here influence fire behavior under field conditions. Future work could also incorporate species-specific fuel properties into fire behavior modeling frameworks such as FARSITE and FlamMap by modifying fuel model parameters and testing predicted differences in spread rate,

flame length, and fire intensity across realistic weather scenarios (Finney 1998). These approaches would allow researchers and managers to evaluate hypotheses generated from laboratory experiments before implementing larger field-scale studies.

Beyond surface fuels, western larch canopy traits likely contribute additional mechanisms of fire resistance. Traits such as elevated crown base height, reduced ladder-fuel continuity through self-pruning, and species-specific crown architecture may influence crown fire initiation and propagation independently of litter characteristics (Schmidt et al. 1976; Sparks et al. 2018; Conrad et al. 2024). However, because this study focused specifically on surface fuel properties, we could not quantify how litter and canopy traits interact to influence whole-stand fire behavior.

Future research should integrate surface fuel measurements with canopy structural metrics such as canopy bulk density, canopy base height, and vertical fuel continuity, which strongly influence crown fire initiation thresholds (Scott and Reinhardt 2001; Agee and Skinner 2005; Graham et al. 2004). Field-based crown measurements, terrestrial LiDAR, airborne LiDAR, and emerging remote sensing approaches could improve our ability to identify how western larch stand development influences fire behavior across different structural stages (Gallagher et al. 2021). These measurements would help distinguish the relative contributions of surface fuel modification, canopy architecture, and stand structure to the lower burn severity patterns observed in planted western larch stands in the companion chapter.

The spatial arrangement of western larch across landscapes represents another important research frontier. Litter-level dampening effects may produce different fire outcomes depending on whether western larch occurs as dispersed individuals, mixed stands, or aggregated patches with high local dominance. The planted western larch burn severity patterns documented in Chapter 2 represent one spatial configuration. Still, additional research is needed to determine how species arrangement influences fire spread, severity mosaics, and landscape-scale resilience. Future studies combining field observations, spatial fire modeling, and remote sensing could evaluate how different planting arrangements affect fire behavior under changing climate conditions (Hessburg et al. 2021; Povak et al. 2022).

Litter age and decomposition dynamics also warrant further investigation. We conducted this experiment using recently senesced litter that had accumulated on the forest floor for approximately eight months. Natural fuel beds contain litter from multiple years at varying stages of decomposition, and we do not yet know whether western larch's low-flammability characteristics persist through decomposition or change as microbial activity modifies needle structure and chemistry. Species traits strongly regulate decomposition rates and fuel accumulation patterns across ecosystems (Aerts 1995; Cornwell et al. 2008; Wright et al. 2004). Larch-specific studies suggest that larch litter undergoes relatively rapid decomposition and nutrient cycling compared with many evergreen conifers (Osono et al. 2003; Bryanin et al. 2020). These dynamics could either maintain low fuel accumulation through faster turnover or alter the structural characteristics responsible for the reduced flammability observed in fresh litter. Long-term decomposition and flammability experiments would clarify how persistent larch's fuel effects over multi-year accumulation periods. Finally, western larch occurs within diverse mixed-conifer communities, and this study evaluated only two common associates: ponderosa pine and lodgepole pine. Across its range, western larch also co-occurs with Douglas-fir, grand fir, Engelmann spruce, and western white pine (McCaughey and Schmidt 1990). Future experiments should evaluate whether the dampening effects observed here extend across broader species combinations and whether interactions among litter traits generate additive or non-additive effects in more diverse fuel mixtures (Magalhães and Schwilk 2021).

Addressing these questions will require coordinated field experiments, prescribed fire monitoring, remote sensing analyses, and long-term collaboration with Tribal forest managers. Integrating laboratory-derived fuel mechanisms with landscape-scale fire observations will improve our understanding of how western larch restoration influences fire resilience and will support adaptive management decisions across the Colville Reservation and other fire-adapted forests of the inland Northwest.

3.8 Conclusion

Western larch has long been recognized across the Colville Reservation as an important restoration species because of its ecological role, cultural significance, timber value, and ability to persist within the fire regimes that have shaped inland Northwest forests for millennia. In this chapter, we identify an additional mechanism that may contribute to that role: western larch litter exhibits substantially lower flammability than the litter of co-occurring ponderosa pine and lodgepole pine under controlled laboratory conditions.

These differences were not driven solely by fuel moisture at the time of burning. Even under oven-dry conditions, western larch fuel beds produced shorter flames, lower fuel consumption, and a distinct combustion pattern characterized by incomplete fuel consumption and reduced combustion efficiency relative to the rapid, near-complete combustion observed in pine litter. These findings indicate that intrinsic differences in litter morphology and fuel bed structure influence combustion behavior, consistent with broader evidence that plant traits regulate fuel arrangement, moisture dynamics, and flammability across forest ecosystems (Cornwell et al., 2015; Burton et al., 2021). These findings provide a mechanistic basis for interpreting the landscape-scale burn severity patterns documented in the companion chapter, but they should be viewed as a foundation for field validation rather than as direct predictions of operational wildfire behavior. Laboratory combustion experiments cannot reproduce the full complexity of wind, canopy structure, fuel continuity, fire weather, and atmospheric interactions that determine wildfire outcomes at stand and landscape scales (Rothermel, 1972; Finney et al., 2015; Schiks and Wotton, 2015; Kolaitis and Founti, 2023). Nevertheless, these results suggest that western larch may function not only as a fire-resistant species capable of surviving fire through traits such as thick bark and elevated crown architecture, but also as a species with litter characteristics that can modify surface fuel conditions and contribute to fine-scale variation in fire effects (Varner et al., 2015; Stevens et al., 2020). The implications of this finding are particularly relevant within the context of ongoing restoration efforts on the Colville Reservation. The Confederated Tribes of the Colville Reservation have invested decades in restoring western larch across post-fire and post-harvest landscapes as part of

broader efforts to maintain disturbance-adapted species, improve forest health, and support resilient forest conditions following the combined legacies of historical logging, altered fire regimes, and changing climate.

In the companion chapter, we found that planted western larch stands experienced lower burn severity relative to surrounding forests in two of the three fires examined. The absence of a detectable difference in the Swawilla Basin Fire demonstrates that larch-associated fire outcomes are context-dependent and shaped by interactions among species composition, stand structure, fuel continuity, and fire environment. The results presented here suggest that litter traits may be one mechanism contributing to these broader patterns by influencing surface fuel moisture, fuel bed structure, and combustion dynamics.

Western larch alone cannot address the complexity of wildfire risk across the Reservation, and planting fire-adapted species cannot replace the broader suite of management approaches implemented by the Colville Tribes Department of Natural Resources, including thinning, prescribed fire, and integrated fuel treatments (Agee and Skinner 2005; Hessburg et al. 2021). Restoration decisions must consider historical species distributions, site suitability, cultural resources, biodiversity objectives, economic considerations, and future climate conditions.

Our laboratory results suggest that larch influence on surface fuel behavior increases as larch becomes a larger component of the litter matrix, but translating these findings into restoration applications requires field validation. Relationships among litter composition, stand composition, spatial arrangement, and wildfire effects remain complex, and future work should evaluate how these mechanisms operate under prescribed fire and wildfire conditions (Magalhães and Schwilk 2021).

The relationship between these findings and existing Tribal restoration efforts underscores the importance of evaluating restoration strategies across multiple ecological scales. Western larch restoration on the Colville Reservation did not originate from laboratory measurements of litter flammability; it emerged from long-term forest management experience, ecological observation, and Tribal priorities centered on sustaining resilient forest landscapes. This research contributes

an additional mechanistic perspective by showing that western larch may influence fire adaptation not only through traits that support individual-tree survival, but also through the surface fuel characteristics its litter contributes to the forest floor.

Together, these findings suggest that western larch restoration represents a multi-scale pathway toward fire resilience, linking species traits, litter properties, stand structure, and landscape-level restoration objectives within fire-adapted forests of the inland Northwest.

4.0 Chapter 4: Thesis Synthesis: Western Larch Restoration, Fire Resilience, and the Future of Fire-Adapted Landscapes

4.1 Abstract

The two preceding chapters approached the central question of this thesis: do planted western larch forests behave differently under wildfire, and through what mechanisms? Chapter 2 examined landscape-scale patterns of burn severity across multiple wildfire events using remotely sensed burn severity metrics and field-based fuel characterization. Chapter 3 investigated the combustion dynamics and moisture relationships of western larch litter through controlled laboratory flammability experiments. Having examined each line of evidence separately, this chapter integrates the findings across scales, examines the ecological conditions under which the fire-moderating influence of western larch is expressed or constrained, considers the broader implications for restoration ecology and forest management, and identifies directions for future research. The multi-fire design spanning nearly a decade, the co-produced partnership with the Colville Tribes that shaped the research questions and field access, and the mechanistic link established between litter-level combustion properties and landscape-scale burn severity patterns are among the central strengths of this work.

4.2 Introduction

4.2.1 Integrating the Evidence: A Multi-Scale Interpretation of Larch Fire Performance

The consistency between Chapters 2 and 3 represents one of the central contributions of this thesis. We examined western larch fire performance using two independent yet complementary approaches: landscape-scale burn-severity analysis and laboratory-based fuel characterization. Although these chapters evaluated different ecological scales, both lines of evidence indicate that western larch is associated with forest conditions that can moderate fire effects relative to surrounding mixed-conifer systems.

At the landscape scale, we found that planted western larch stands experienced significantly lower burn severity than adjacent mixed-conifer forests during the 2015 North Star Fire and the 2021

Summit Trail Fire, estimated using the Composite Burn Index methodology (Key & Benson, 2006). Across these events, most planted stands exhibited lower modeled CBI values and smaller proportions of high-severity fire than surrounding comparison forests. These differences are ecologically meaningful because shifts from moderate- toward low-severity fire conditions are associated with greater canopy survival, reduced soil heating, and improved post-fire recovery potential — outcomes directly relevant to restoration objectives, fire resilience, and natural resource management on the Colville Reservation (Davis et al., 2023; Dumroese et al., 2020; Cansler et al., 2014; Reilly et al., 2017). However, because we derived burn severity estimates from a remotely sensed CBI model calibrated using fires through 2017 and applied this approach across fires occurring in 2015, 2021, and 2024, future local field calibration and sensitivity analyses would strengthen confidence in the magnitude of these observed differences, a concern consistent with broader challenges documented in linking field-measured and remotely sensed burn severity (Miller & Thode, 2007; Morgan et al., 2014; Parks et al., 2019).

In Chapter 3, we identified a potential mechanistic explanation for these landscape-scale patterns by demonstrating that western larch litter exhibited substantially lower flammability than co-occurring ponderosa pine and lodgepole pine litter under standardized laboratory conditions. Differences in fuel-bed structure, moisture retention capacity, and combustion dynamics contributed to reduced flame height, lower fuel consumption, and shorter smoldering duration in larch-dominated fuel beds relative to pine-dominated compositions (Varner et al., 2015; Pausas et al., 2017; Crawford et al., 2025). These patterns are consistent with the concept of fire-impeding litter traits, where species influence fire behavior not only through individual survival traits but also through the fuel environments they create (Varner et al., 2015; Kane et al., 2021). However, laboratory combustion experiments represent simplified fuel systems and should be interpreted as mechanistic evidence rather than direct predictions of wildfire behavior. Field validation through prescribed burning and monitoring of larch-dominated and pine-dominated stands will be necessary to determine how these litter-scale processes scale to operational fire behavior, given well-documented discrepancies between laboratory and field fire behavior predictions (Schiks &

Wotton, 2015; Kolaitis et al., 2023).

Independently, each line of evidence would remain incomplete. Landscape-scale differences in burn severity could reflect multiple interacting drivers, including topography, fire weather, pre-fire stand structure, treatment history, or suppression activities, rather than species composition alone. Similarly, laboratory-measured differences in litter flammability may not directly translate to wildfire behavior because wind, canopy structure, fuel continuity, and spatial variation in fuel moisture strongly influence fire spread and intensity. Together, however, these findings support a multi-scale interpretation in which the lower burn severity observed in many planted western larch stands is consistent with the distinct structural and fuel characteristics of this species.

Our laboratory results suggest that western larch litter may influence surface fire behavior through several interacting fuel properties. Larch fuel beds retained more moisture, dried more slowly, and combusted less completely than pine fuel beds under controlled conditions. In natural forests, particularly following precipitation events or during moderate fire weather, these properties may extend the period when surface fuels are less available for combustion and contribute to localized reductions in fire intensity. However, the relative importance of litter characteristics relative to canopy structure, stand density, fire weather, and management history cannot be fully disentangled within the observational framework of this study.

Overall, our findings suggest that western larch may influence wildfire outcomes through two interacting ecological pathways operating at different spatial scales. The first pathway is structural. Planted western larch stands generally contained lower ladder fuel continuity, reduced coarse woody fuel accumulation, and structural conditions that can limit the transition from surface fire to crown fire compared with denser mixed-conifer forests (Agee & Skinner, 2005; Peterson et al., 2005; Prichard & Kennedy, 2014; Radcliffe et al., 2024). As western larch matures, additional traits such as self-pruning, elevated crown base height, and reduced available crown fuel may further reinforce these structural differences (Schmidt et al., 1976; Sparks et al., 2018; Conrad et al., 2024).

The second pathway operates at the surface fuel scale. The physical properties of western larch lit-

ter, including dense fuel-bed packing, high moisture retention, and reduced combustion efficiency, appear to create fuel conditions that differ substantially from those produced by co-occurring pine species (Varner et al., 2022; Magalhães & Schwilk, 2021; Crawford et al., 2025). Because these pathways operate through different ecological mechanisms, they may interact across stand development: forests with high western larch abundance may combine reduced vertical fuel continuity with surface fuel characteristics that dampen combustion. Understanding how these mechanisms interact under field conditions represents an important next step for evaluating the role of western larch restoration in supporting fire-adapted landscapes.

4.2.2 Conditions and Ecological Constraints on Larch Fire Moderation

The fire-moderating influence of western larch did not appear consistently across all fire contexts, and this variation represents an important finding of this thesis. In contrast to the North Star and Summit Trail fires, we detected no statistically significant reduction in modeled burn severity within planted western larch stands relative to surrounding forests during the 2024 Swawilla Fire. This divergence helps define the ecological contexts in which western larch restoration may influence wildfire outcomes and the conditions under which other drivers, including fine fuel continuity, fire weather, species composition, and stand structure, may override or constrain species-level effects.

Several interacting factors may have contributed to the absence of a detectable western larch effect within the Swawilla Fire footprint. First, the Swawilla Fire burned primarily through lower-elevation dry forests and grass–shrub systems, where invasive annual grasses such as cheatgrass can create continuous, rapidly curing fine-fuel layers that carry fire across stand boundaries. Under these conditions, herbaceous fuel continuity and wind-driven surface fire spread may exert stronger control over fire behavior than overstory composition or planted stand structure (Balch et al., 2013; D'Antonio & Vitousek, 1992). This interpretation suggests that western larch restoration may exert a less detectable fire-moderating influence in settings where fine fuels dominate fire-spread pathways.

Second, many planted western larch stands within the Swawilla landscape were mixed stands with substantial ponderosa pine components. Ponderosa pine produces long needles that create porous, well-aerated fuel beds that support rapid ignition and combustion. When pine litter dominates the surface fuel matrix, it may offset or dilute the dampening effects associated with western larch litter, especially where larch represents only a moderate proportion of total fine fuel inputs. Results from Chapter 3 support this interpretation: mixtures containing approximately 30% western larch produced relatively limited reductions in flammability, whereas stronger dampening effects emerged when western larch represented approximately half or more of the litter mixture. We interpret this pattern as a laboratory-derived hypothesis rather than a field-validated management threshold. Prescribed fire experiments across stands with varying western larch composition would be necessary to test whether similar compositional responses occur under operational fire conditions.

At lower larch proportions, pine needles continued to dominate fuel bed architecture by maintaining high porosity, greater oxygen availability, and conditions conducive to rapid combustion. As larch abundance increased, denser needle packing increasingly constrained airflow and reduced combustion efficiency, consistent with the well-established principle that fuel bed bulk density and packing structure govern oxygen availability and flame spread in porous fuel beds (Brown, 1981; Campbell-Lochrie et al., 2021), and with documented interspecific variation in conifer fuel-bed packing properties (van Wagtendonk et al., 1998). This compositional threshold pattern is consistent with the fuel consumption and smoldering duration results presented in Chapter 3 (Section 6.4).

4.3 Thesis Contribution to Restoration Science

Research on fuel treatment effectiveness has consistently shown that mechanical thinning and prescribed fire can reduce burn severity in mature forests, particularly in dry and mixed-conifer systems where fire exclusion, past harvest, and stand densification have increased fuel continuity (Agee & Skinner, 2005; Stephens et al., 2009; Prichard et al., 2020; Radcliffe et al., 2024). Much

of this work evaluates treatments applied after hazardous fuel conditions have already developed. In contrast, the planted western larch stands examined in this thesis represent a different restoration pathway: one in which species composition, stand establishment patterns, and early stand development may influence fuel structure from the outset, rather than only reducing fuels after they accumulate.

This distinction is ecologically important because it suggests that planted western larch stands may develop along fuel trajectories that differ from pine-dominated or more densely structured mixed-conifer stands. Mechanical thinning and prescribed fire often require repeated entries to limit fuel re-accumulation. In contrast, western larch may influence fuel conditions through traits expressed continuously across stand development, including crown architecture, self-pruning, elevated canopy base height, and low-flammability litter inputs (Schmidt et al., 1976; Keane, 2008). In this sense, species composition functions not only as an outcome of restoration or succession but also as a potential long-term regulator of surface fuel properties, vertical fuel continuity, and fire behavior potential.

However, the persistence of these fuel effects remains an important uncertainty. Litter decomposition rates, multi-year accumulation patterns, and particle aging may alter the physical and chemical traits responsible for species-driven differences in flammability over time. Changes in litter structure, moisture dynamics, and thermal decomposition behavior could either maintain or diminish the fire-moderating properties observed in recently senesced western larch litter (Keane, 2008; Bryanin et al., 2020). Future decomposition and field-flammability studies will be necessary to determine whether western larch's low-flammability litter characteristics persist across longer fuel accumulation periods.

Chapter 3 further suggests that western larch occupies a functionally distinctive position among inland Northwest conifers because it combines traits associated with individual fire resistance and surface fuel modification. Previous research has identified several western larch traits that promote survival during surface fire, including thick bark, elevated crowns, and strong self-pruning capacity (Stevens et al., 2020). This thesis adds a litter-level mechanism to that understanding by showing

that western larch litter exhibits lower flammability and reduced combustion efficiency relative to co-occurring ponderosa pine and lodgepole pine litter under controlled laboratory conditions. These findings provide mechanistic support for a link between species composition, surface fuel properties, and the lower burn severity patterns observed in many planted western larch stands. Field validation through prescribed burning and post-fire monitoring remains a critical next step. The multi-fire, multi-year design of Chapter 2 also addresses a persistent limitation in research on fuel treatment effectiveness: many studies evaluate treatment performance during a single fire event or within a narrow range of fire weather and ecological conditions. By examining planted western larch stands across three fires spanning nearly a decade, multiple forest types, and contrasting fire contexts, this thesis evaluates western larch fire performance across a broader range of conditions. This design allowed us to identify both contexts in which planted western larch stands were associated with reduced burn severity and contexts in which that association was not detectable.

The North Star Fire provides particularly important evidence because it burned during severe drought and wind conditions, circumstances that often reduce the effectiveness of fuel treatments (Prichard & Kennedy, 2014). The lower modeled burn severity observed in planted western larch stands during this event suggests that structural and fuel-level characteristics associated with western larch restoration may continue to influence fire effects under some severe fire weather conditions. However, the absence of a detectable difference in the Swawilla Fire cautions against treating this influence as universal. Instead, the results indicate that western larch restoration may contribute to fire resilience under specific combinations of species composition, stand structure, fuel continuity, and fire environment.

4.4 Implications for Western Larch Restoration on the Colville Reservation

The findings of this thesis have several implications for ongoing western larch restoration efforts on the Colville Reservation, particularly in landscapes where reducing high-severity fire risk is one management objective among broader priorities related to timber production, watershed protection,

wildlife habitat, cultural resources, and natural resource stewardship.

First, our results suggest that western larch may need to represent a substantial component of the surface fuel matrix before its litter traits produce measurable fire-dampening effects. In Chapter 3, mixed-species combustion experiments showed that litter fuel beds containing low proportions of western larch produced relatively limited reductions in flammability. In contrast, stronger reductions in fuel consumption and combustion intensity emerged when western larch represented approximately half or more of the litter mixture. This pattern supports a testable hypothesis: western larch may need to become sufficiently abundant within the litter matrix before it substantially alters fuel bed structure, packing density, moisture dynamics, and combustion behavior. However, because this result comes from controlled laboratory mixtures constructed by litter mass, we should not interpret it as a direct stand-level planting threshold. Planting prescriptions that include western larch only as a minor component within pine-dominated stands may provide more limited surface-fuel moderation, but researchers need additional field studies before translating this laboratory pattern into operational guidance. Future work should evaluate how larch proportion interacts with site type, stand structure, litter deposition, canopy fuels, and management objectives to determine where and when western larch meaningfully alters surface fuel behavior in the field.

Second, the results reinforce the importance of stand development and thinning history in shaping fire behavior within planted western larch stands. Species composition alone did not ensure lower burn severity across all fire contexts. Young planted stands approaching canopy closure without thinning may develop elevated structural vulnerability through dense stem packing, ladder fuel development, and increased vertical and horizontal fuel continuity. These conditions are consistent with the transitional period of elevated fire hazard often observed during mid-successional canopy closure in dry and mixed-conifer forests (Graham et al., 2004; Agee & Skinner, 2005; Chiono et al., 2012). Maintaining appropriate thinning schedules and reducing ladder fuel continuity will likely be important for sustaining the fire-moderating potential of western larch restoration over time.

Finally, the findings suggest that western larch restoration may complement low-intensity prescribed fire and Tribal-led fire-based management where site conditions, fuels, and management

objectives support the reintroduction of frequent surface fire. Mature western larch stands with elevated crown base heights, reduced ladder fuel continuity, and compact lower-flammability litter layers may provide fuel conditions more compatible with low-severity surface fire than dense pine- or fir-dominated stands with continuous surface and ladder fuels. These conditions could support understory heterogeneity, reduce canopy fire potential, and contribute to the restoration of fire-adapted forest structure (Lake et al., 2017; Wynecoop et al., 2019; Hessburg et al., 2021; Dumroese et al., 2020).

In this context, managers should not treat western larch restoration as a substitute for prescribed fire, mechanical thinning, or other fuel treatments. Instead, western larch restoration can function as one component of a broader landscape strategy that restores species composition, stand structure, and fuel conditions more compatible with frequent low- to moderate-severity fire. Its value lies not in excluding fire from these landscapes, but in helping managers create forest conditions in which fire can burn with greater heterogeneity, lower fuel continuity, and more ecologically desirable effects.

4.5 Limitations and Directions for Future Research

Several limitations constrain the interpretation of these findings and identify important directions for future research. In Chapter 2, we limited field-based fuel sampling to the Summit Trail Fire footprint, which restricted our ability to generalize stand-structure and fuel relationships across the full environmental range represented by the North Star, Summit Trail, and Swawilla fires. Because pre-fire fuel conditions were unavailable, we could not fully separate the effects of planted stand structure from pre-existing differences in site productivity, accessibility, treatment history, or landscape position. The non-random placement of planted western larch stands also raises the possibility that some observed burn severity differences reflect underlying environmental variation rather than planted-stand conditions alone.

The burn severity analysis also depends on the accuracy and transferability of the remotely sensed CBI model used to estimate fire effects. Although this model provides a powerful tool for compar-

ing burn severity across large fire footprints, local field calibration would strengthen confidence in the magnitude of the reported differences, particularly for more recent fires and for specific forest types within the Colville Reservation. Future work should prioritize independent post-fire field plots, model sensitivity analyses, and comparisons with additional burn severity metrics to evaluate the robustness of the observed larch-associated patterns across sensors, fire years, and vegetation types (Dumroese et al., 2020; Radcliffe et al., 2024).

In Chapter 3, the primary limitation involves scaling laboratory combustion results to field-scale fire behavior. The laboratory experiments isolated species-level differences in litter flammability under controlled conditions. Still, fire behavior at stand and landscape scales also reflects canopy structure, wind, topography, live fuel moisture, horizontal fuel continuity, and vertical fuel arrangement. Previous studies have documented systematic discrepancies between laboratory and field fire behavior across fuel types and wind conditions, reinforcing the need for caution when extrapolating laboratory results to operational fire behavior (Schiks & Wotton, 2015; Kolaitis et al., 2023).

Experimental prescribed burns in larch-dominated and pine-dominated stands would provide an important next step for testing whether the litter-level differences documented here translate into measurable differences in field-scale fire behavior (Finney, 1998; Finney et al., 2015). Researchers and managers should treat the approximate 50% western larch response observed in Chapter 3 as a laboratory-derived hypothesis rather than a management threshold. Field experiments across stands with varying western larch abundance, spatial arrangement, and thinning histories would help determine whether similar compositional responses occur under realistic fire weather, fuel moisture, and stand-structure conditions.

Additional uncertainty concerns litter age and decomposition. Chapter 3 used senescence litter recently, but natural fuel beds contain material from multiple years at different stages of decomposition. As litter decomposes, microbial activity, particle breakdown, and chemical changes can alter fuel bed structure, moisture relations, and smoldering behavior. These processes may either maintain or reduce the low-flammability characteristics observed in fresh western larch litter over longer accumulation periods (Keane, 2008; Sikkink et al., 2017; Bryanin et al., 2020). Long-term

decomposition and flammability experiments would clarify whether western larch continues to modify surface fuel conditions as litter ages.

More broadly, this thesis points toward several unresolved ecological questions. Future research should examine how western larch fire performance changes as planted stands mature toward older, more structurally complex conditions; how much larch-dominated forest is needed to influence fire behavior at broader landscape scales; and how spatial arrangement affects fire spread, severity mosaics, and treatment effectiveness. Research should also evaluate whether projected increases in drought and atmospheric moisture demand alter the moisture-retention differences observed between western larch and pine litter. If increasingly severe drought reduces litter moisture across all species, the relative flammability advantage of western larch may narrow under some future fire weather conditions (Westerling, 2016; Hessburg et al., 2021).

Finally, future work should test whether the mechanisms documented here apply across the full elevation and compositional range of western larch restoration on the Colville Reservation. Western larch co-occurs with multiple conifer and broadleaf species beyond the ponderosa pine and lodgepole pine mixtures tested in this study. Expanding laboratory, field, and prescribed fire experiments across additional species combinations would improve understanding of how larch interacts with broader mixed-conifer fuel complexes. Addressing these questions will help translate the multi-scale findings of this thesis into adaptive restoration strategies that remain responsive to changing fire regimes, site conditions, and Tribal forest management priorities.

4.6 Conclusions

The findings of this thesis have several implications for ongoing western larch restoration efforts on the Colville Reservation, particularly in landscapes where reducing high-severity fire risk is one management objective among broader priorities related to timber production, watershed protection, wildlife habitat, cultural resources, and natural resource stewardship.

First, our results suggest that western larch may need to represent a substantial component of the surface fuel matrix before its litter traits produce measurable fire-dampening effects. In Chapter

3, mixed-species combustion experiments showed that fuel beds containing low proportions of western larch produced relatively limited reductions in flammability. In contrast, fuel consumption and combustion intensity declined more strongly when western larch represented approximately half or more of the litter mixture.

This pattern supports a testable hypothesis: western larch may need to become sufficiently abundant to alter fuel bed structure, packing density, and moisture dynamics before it substantially changes combustion behavior. However, because this result comes from controlled laboratory mixtures constructed by litter mass, we should not interpret it as a direct stand-level planting threshold. Planting prescriptions that include western larch only as a minor component within pine-dominated stands may provide more limited surface-fuel moderation. Additional field studies and tradeoff analyses across western larch proportions, site types, and stand structures are needed before translating this laboratory pattern into operational guidance.

Second, the results reinforce the importance of stand development and thinning history in shaping fire behavior within planted western larch stands. Species composition alone did not ensure lower burn severity across all fire contexts. Young planted stands approaching canopy closure without thinning may develop elevated structural vulnerability through dense stem packing, ladder fuel development, and increased vertical and horizontal fuel continuity. These conditions are consistent with the transitional period of elevated fire hazard often observed during mid-successional canopy closure in dry and mixed-conifer forests (Graham et al., 2004; Agee & Skinner, 2005; Chiono et al., 2012). Maintaining appropriate thinning schedules and reducing ladder fuel continuity will likely be important for sustaining the fire-moderating potential of western larch restoration over time.

Finally, the findings suggest that western larch restoration may complement low-intensity prescribed fire and Tribal-led fire-based management where site conditions, fuels, and management objectives support the reintroduction of frequent surface fire. Mature western larch stands with elevated crown base heights, reduced ladder fuel continuity, and compact lower-flammability litter layers may provide fuel conditions more compatible with low-severity surface fire than dense pine- or fir-dominated stands with continuous surface and ladder fuels. These conditions could

support understory heterogeneity, reduce canopy fire potential, and contribute to the restoration of fire-adapted forest structure (Lake et al., 2017; Wynecoop et al., 2019; Hessburg et al., 2021; Dumroese et al., 2020).

In this context, managers should not treat western larch restoration as a substitute for prescribed fire, mechanical thinning, or other fuel treatments. Instead, western larch restoration can function as one component of a broader landscape strategy that restores species composition, stand structure, and fuel conditions more compatible with frequent low- to moderate-severity fire. Its value lies not in eliminating fire from these landscapes, but in helping managers create forest conditions in which fire can burn with greater variability, lower fuel continuity, and more ecologically desirable effects.

5.0 References

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