Fire Ecology – Case Study Low-intensity wildfire in old-growth Douglas fir and western hemlock forest consumed deep duff, thinned from below, and created challenges for fire management – a case study from the west slopes of the Cascades

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Case Report

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Abstract

Background

Wind-driven wildfires on the west slopes of the Cascade Range create large areas of stand-replacing (SR) effects at multi-century timescales but less intense and more frequent non-stand-replacing (NSR) fires are now known to generate a complex array of stand structures and forest dynamics pathways in old growth, independent of, or in interaction with, SR fire. We report on the effects of low-intensity fire based on plot-based measurements of fuels and vegetation, fire behavior, and immediate and overwinter impacts in old-growth Douglas-fir and western hemlock forest (*Pseudotsuga menziesii* var *menziesii* and *Tsuga heterophylla* (Raf.) Sarg.) on the 2023 Lookout Fire.

Results

In low intensity wildfire, high duff loadings, often in linear piles derived from downed logs, were largely consumed (89%, 247 Mg ha^{-1}). While towering, overstory Douglas-fir were minimally affected, 32% of poles, 7% of canopy trees (≥ 15.2 cm diameter), and 32% of snags of all sizes fell during or shortly after the fire. Most live trees fell from combustion impacts on primary roots which, for western hemlock, the most common tree species, was associated with how much duff was consumed. Further, 15% of live poles and 32% of live canopy trees, mostly western hemlock, experienced significant primary root heating. Western hemlock was particularly vulnerable to root impacts because its primary roots tended to grow exposed at the top of the mineral soil, especially where they were "perched" from having regenerated on nurse logs. Monitoring in the early growing season 7–8 months after the fire showed that, of trees alive before and standing immediately after the fire, 28% of poles and 6% of canopy trees fell and 31% of poles and 14% of canopy trees died standing with mortality strongly related to the extent of canopy injury from the fire. All told, 60% of poles and 13% of canopy trees had died by the early growing season after the fire. Primary root and root-collar heating was not significantly related to mortality of standing trees 7–8 months after the fire, but we expect that many trees will die from that cause in the coming years. Though high duff loadings were consumed by the fire and there was substantial thinning from below, the overstory of large Douglas-fir and other old-growth characteristics persisted, including most downed woody debris in large-diameter logs which will be augmented by fire-killed trees that have already fallen or will fall in the future.

Conclusions

NSR fire can cause substantial effects below the Douglas-fir overstory in old-growth on the west slopes of the Cascades, contributing to pyrodiversity in these ecosystems. Our coordinated pre-, active-, and post-wildfire measurements led to mechanistic insights about how these effects occur. Treefall during and immediately after fire and high loadings of duff and downed logs challenged fire suppression operations but treefall hazards for firefighters might be mitigated along shaded fuel breaks before fires ignite, guided by an understanding of why trees fall.

Introduction

Large stand replacing (SR) fires on the west slopes of the Cascade Range have occurred sporadically over the centuries (Reilly et al. 2022), leading to extensive Douglas-fir regeneration and setting the stage for development of old-growth conditions (Franklin et al. 1981). While SR fires are an important driver of forest dynamics in moist forests of the Pacific Northwest, mounting evidence shows that non-stand-replacing (NSR) fires with mixed effects introduce complexity to forest dynamics, often repeatedly re-working stands that originated from SR fire (Weisberg 2004, Tepley et al. 2013, Johnston et al. 2023, Merschel et al. 2024). Further, some study sites have shown no evidence of SR fire and others showed little to no NSR fire after stand initiating SR fire (Tepley et al. 2013, Johnston et al. 2023). While mortality of the fire-resistant Douglas-fir (*Pseudotsuga menziesii var menziesii*) overstory is limited in NSR fires, these fires have a substantial effect on forest structure and tree recruitment below the overstory (Tepley et al. 2013, Merschel et al. 2024).

NSR fire effects occur extensively on wildfires that spread under low-wind conditions, responding primarily to fuels and topography. Under these conditions, NSR effects often re-occur through multiple re-burns (Downing et al. 2021). Hotter and drier conditions are expected in the future in the Cascade Range and are expected to substantially increase area burned (Dye et al. 2024). Many of these fires will be fuels- and terrain-driven and NSR (Johnston et al. 2023) and it is important to understand their effects as ecosystems adapt to changing environmental conditions and an increase in fire (Halofsky et al. 2018).

The 2023 Lookout Fire provided an opportunity to describe relationships among fuels, low-intensity fire (i.e., fireline intensity, the frontal heat release rate) (Byram and 1959), and fire effects. The areas we studied were in a part of the fire's footprint that burned under low-wind conditions during drought in Douglas-fir and western-hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forests with old-growth characteristics (hereafter old-growth) including large trees, large snags, large logs, and high structural complexity (Franklin et al. 1981). Although wildfire effects are routinely inferred from fire severity maps based on pre-fire and either immediate (Miller and Quayle 2015) or 1-year post-fire space-based reflectance measurements (Miller et al. 2009), dense tree canopies dominate the reflectance signal, thereby limiting information on soil, understory, and mid-story effects which are a focus of ground-based monitoring (Birch et al. 2023).

Understanding the mechanisms by which wildfires cause their effects (Johnson 1984) is a primary benefit of ground-based, coordinated pre-, active-, and immediate post-fire measurements (Miesel et al. 2018, Birch et al. 2023), providing information that cannot be gained from satellite remote sensing or ground measurements made years after fire (Weisberg 2004). Moreover, comparisons of pre- and post-wildfire data are extremely rare in the literature. A review of fire-focused studies in the Pacific Northwest found that just 5% of studies included both pre- and post-fire data, with a majority of these from prescribed fire (Betts et al., unpublished data). We report on fire behavior and effects in old-growth and consider implications for remote sensing, fire management, and old-growth forest stewardship.

Methods

The Lookout Fire ignited by lightning on August 5th, 2023, on the H. J. Andrews Experimental Forest (HJA) within the Willamette National Forest in Oregon. Immediate fire effects within the fire's footprint were mixed (Supplementary Material: Figure S1), ranging from slope-driven runs causing SR effects at a hillslope scale to fires backing downslope in ground (duff) and surface fuels (litter, downed woody material, and understory vegetation) and causing minimal effects on the Douglas-fir overstory. Predicted basal area loss from the Rapid Assessment of Vegetation Condition after Wildfire (RAVG) mapping for the Lookout Fire was primarily low (0–25%), covering 54% of the footprint, while moderate (25–50%), high (50–75%), and very high (75–100%) were predicted for 20, 12, and 14% of the fire footprint, respectively (Supplementary Material: Figure S1). The Fire Behavior Assessment Team (FBAT) characterized low intensity fire in old-growth dominated by Douglas-fir and western hemlock and with scattered western redcedar (*Thuja plicata* Donn ex D. Don) and Pacific yew (*Taxus brevifolia* Nutt.). We established plots in sites with tall trees and limited canopy gaps and, as a safety precaution, avoided sites with snags that were assessed to present high post-fire safety risks. We therefore report minimal snag data here. Past snag felling had occurred in and around some plots near roads or clearcut blocks. Fire histories derived from old-growth Douglas-fir stumps in nearby clearcuts show that the overstory originated in SR fire and typically had experienced multiple NSR events subsequently (Weisberg 2004). Fire scars and charred wood and bark observed in some plots confirm the occurrence of NSR fires. Plots 1–5 and 11 and 12 burned while plots 6–10 did not and are not considered further in this study. Burned plots were at elevations ranging from 1990 to 2420 m above sea level.

FBAT collects plot-based, pre-fire fuels and vegetation data, installs instruments to measure fire behavior, and returns after fire to re-measure fuels and assess direct fire effects (Birch et al. 2023). Details can be found in the FBAT report for the Lookout Fire (see (Dickinson et al. 2024)). Local fire spread rates and flame lengths were estimated from plot video in reference to in-scene standard poles. Rate of spread and transit time over a plot that has a nominal diameter of 30 m were estimated from an array of 5 fire arrival sensors. A minimum of three arrival times are required to estimate a spread rate. If no spread rate could be calculated, no transit time was reported either. Landscape-scale time-lapse imagery shows the character of the fire between 21 August and 17 October 2023, capturing the area and timeframe in which the southernmost FBAT plots nearest to Lookout Creek (1, 5, 6, and 12) burned. Links to landscape and plot video are available in (Dickinson et al. 2024).

We used a bulk density of 1.75 kg m^{-2} cm^{-1}, the average mixed-conifer value from (VanWagtendonk et al. 1996), to estimate duff loading from depth at 3 locations along each of three 15.2 m transects. We used line-intercept sampling to estimate downed wood loading along transects (Brown 1974) using specific gravities of 0.47 and 0.36 for sound and rotten (yet structurally intact) logs, respectively, the average mixed-conifer values from (VanWagtendonk et al. 1996). Here, we report data on the larger downed wood (> 7.6 cm diameter, also known as the 1000 + hour timelag class, material that would take roughly 1000 hr or more to equilibrate to changes in atmospheric conditions). Intensity was calculated from the product of rate of spread, consumption of fuels that typically contribute to flame front spread in surface fires (i.e., litter, 1-100 hr downed wood, and understory vegetation), and a constant heat of combustion (18,600 kJ kg^{-1}).

Canopy (≥ 15.2 cm diameter at breast height, DBH) and pole-sized (2.5 to < 15.2 cm DBH) trees were characterized in fixed-radius plots. We quantified bole charring and crown injury post-fire. The percentage of pre-fire live crown volume that was affected by the fire is assessed along with the percentage charred or consumed ("torched") canopy volume. Subtracting percentage torched from affected approximates percent canopy scorched. Trees were classified pre-fire by expected vulnerability to fire-caused injury and after fire by observed effects using a list of codes from the (Service 2003). We added codes for structural failure (treefall) caused by weakening of the primary roots (e.g., from duff combustion), base (on stem below DBH, e.g., from fire scar burnout), or stem (above DBH, e.g., from wound burnout). Significant structural weakening to primary roots, bases, and stems from wood combustion were assessed visually. Structural weakening at the roots was assessed if there appeared to be extensive root heating from combustion of deep duff that would cause tree death and, as dead roots rotted, structural failure. For bases and stems, extensive consumption of rotten wood from past wounding often led to an assessment of structural weakening. We summarized fire weather using data from HJA and Remote Access Weather Stations (Supplementary Material: Table S1). Cooler temperatures and rain ended on 4 September 2023 and fire entered seven of the 12 plots installed between 14 and 19 September while the study area dried and transitioned from moderate back to severe drought (National Drought Mitigation 2023).

We used Rapid Assessment of Vegetation Condition after Wildfire (RAVG) maps based on pre- and post-fire LANDSAT reflectance for comparison with ground measurements (Service 2023). We report classified basal area and canopy cover loss derived from the Relative Differenced Normalized Burn Ratio (RdNBR).

In April and May 2024, approximately 7–8 months after plots burned, we assessed live status on individual trees standing in burned plots. A standing tree was assumed to be dying if its canopy foliage was yellow or mostly yellow. The set of trees that fell after the immediate post-fire sample was inferred from the difference between the trees that were alive before the fire and standing immediately after fire and the trees that were standing alive or dead in April and May. Trees that were snags pre-fire are not included in this assessment.

R (version 4.4.2) was used to test hypotheses, specifically the binomial test (dbinom), non-parametric Wilcoxon rank sum test (wilcox.test), and logistic regression using the general linear model function (glm) in base R. For logistic models of tree impacts, the response variable was binary (alive or dead) and the error distribution was specified as binomial.

Results

Fire weather and behavior

Fire progressed through plots as surface fire with low rates of spread and transit times. Transit times across ~ 30 m plots averaged 33 hours (Table 1, Supplementary Material: Table S2). Local spread rates estimated from video ranged from < 1.8 to 24 m hr^{-1} while spread rates estimated over entire plots from fire-arrival sensors ranged from 0.18 to 4.8 m hr^{-1} reflecting uneven and often patchy spread at the plot scale. Because of low spread rates, fireline intensities were exceedingly low, averaging 22 kW m^{-1}. For context, surface fires typically range up to 2000 kW m^{-1} (Johnson 1986). In Plot 5, the plot with the highest rate of spread, fire spread vertically on overstory tree boles in bark and moss, lofting embers that ignited spot fires (Fig. 1). We observed this behavior 10 days after rain when air temperature was 28° C, relative humidity was 21%, and fire was backing against a 4 km hr^{-1} wind with gusts up to 10 km hr^{-1} measured on the plot. Plots began to burn 10–15 days after rainfall when moisture content of logs in the 1000 hr timelag class (15.2–19.2 cm diameter) was predicted to be 16.4% (Supplementary Material: Table S1).

Table 1
Fire behavior summary for burned plots on the Lookout Fire. Flame lengths and ROS were estimated from video. ROS was also estimated from the array of fire-arrival sensors and, in combination with surface fuel consumption data, was used to estimate intensity. Transit time was estimated from the array of fire-arrival sensors.

Variable	Plots (N)	Average	Std. Dev.	Min.	Max.
Flame length (cm)	5	37	31	15	91
ROS (m hr^{-1}) – Video	5	11	13	2.0	26.4
ROS (m hr^{-1}) - Sensors	7	1.6	1.2	0.2	4.6
Intensity (kW m^{-1})	7	22	22	2	61
Transit time (hr)	5	33	35	1.5	82

Table 2
Pre-fire loading and consumption of duff and 1000 + hr wood (≥ 15.2 cm diameter) across burned plots (N = 7).

Statistics	Pre-Fire Loading (Mg ha^{-1})			Consumed loading (Mg ha^{-1})[1]			Consumption (%)		
	Duff	Wood	All	Duff	Wood	Total	Duff	Wood	All
Avg.	270	137	445	247	45	322	89	38	71
Std. dev.	150	79	222	148	35	180	7	26	17

[1]Consumed loading is the difference between pre- and post-fire loading.

[2]All fuels includes all ground and surface fuels (duff, all woody material, litter, herbs, shrub, and tree seedlings) but not canopy fuels given these were surface fires.

Fuel loading and consumption

Average duff loadings were high (270 Mg ha^{-1}) and 89% of duff was consumed (Table 2, Fig. 1). Average duff depth around the bases of canopy trees was 20 cm and ranged from 2.5–69 cm (median 15 cm, std. dev. 14 cm). The deepest duff appeared to be derived from downed logs, occurring in linear piles. Sound and rotten (yet structurally intact) woody material ≥ 7.6 cm diameter was the second largest component of pre-fire surface fuel loading but only 38% of the material consumed (Table 2, Fig. 1). Mean pre- and post-fire diameters of 1000 + hr woody material were 34 (range 9–78) and 38 (range 8–78) cm, respectively.

Fire effects on trees

Live poles (109 trees ha^{-1}, 32% of all poles) and canopy trees (21 trees ha^{-1}, 7% of all canopy trees) fell during or immediately after the fire (Table 3). Additional trees felled by chainsaw to mitigate risk right after the fire are not included in this sample. A high density of poles (60 trees ha^{-1}, 18% of all poles) and canopy trees (122 trees ha^{-1}, 42% of all canopy trees) did not fall but were visually assessed to be structurally weakened or injured to an extent that death and failure would ensue in the years following the fire (i.e., delayed mortality, Table 3, Figs. 2 and 3). For snags, 32% fell during or immediately after the fire. Snag sample size was low (N = 19) and snags are not considered further. Four poles and two canopy trees had broken stems caused by the fall of another tree. In the spring re-sampling, additional poles were observed to have suffered this fate over the winter. All Douglas-firs were overstory trees and only three (18% of 17) experienced significant structural damage, all from combustion of rotten stem wood. No Douglas-fir failed structurally.

Table 3
Incidence of live pole and canopy tree structural failure (treefall) or structural weakening and injury caused by combustion and associated root and stem heating. The total number of poles and canopy trees was 81 and 75, respectively. The table includes all species.

Tree size	Structural failure?	Tree part affected	Damage code[1]	Number of trees	Damaged trees (%)	All trees (%)	Density (trees/ha)
Poles	Yes	Root	RSTR	16	47.1	23.5	79
		Base	BSTR	6	17.6	8.8	30
		Stem	SSTR	0	0.0	0.0	0
	Sum - structural failure			22	64.7	32.3	109
	No	Root	RBRN	10	29.4	14.7	50
		Base	BBRN	1	2.9	1.5	5
		Stem	SBRN	1	2.9	1.5	5
	Sum - weakening & injury			12	35.2	17.7	60
	Sum - root impacts (RSTR & RBRN)			26	76.5	38.2	129
	Sum over all codes			34	100	50.0	169
Overstory	Yes	Root	RSTR	4	11.8	5.8	17
		Base	BSTR	1	2.9	1.4	4
		Stem	SSTR	0	0.0	0.0	0
	Sum - structural failure			5	14.7	7.2	21
	No	Root	RBRN	22	64.7	31.9	93
		Base	BBRN	0	0.0	0.0	0
		Stem	SBRN	7	20.6	10.1	30
	Sum - weakening & injury			29	85.3	42.0	122
	Sum - root impacts (RSTR & RBRN)			26	76.5	37.7	110
	Sum over all codes			34	100	49.3	143

[1]RSTR, BSTR, SSTR – wood combustion that caused structural failure at the roots, at the base of the stem, or along the stem above breast height, respectively. RBRN, BBRN, SBRN – intense heating and/or wood combustion that caused or is expected to cause significant structural weakening at the roots, at the base of the stem, or along the stem above breast height, respectively.

Of live trees that either fell or were weakened structurally, primary roots were the most common point of failure or weakening, accounting for 62% and 69% of poles and canopy trees in this subset, respectively

(Table 3, Fig. 3). In contrast, trees were less likely to fall or be structurally weakened from effects on the stem (either at the base or above breast height) accounting for 38% and 31% of pole and canopy trees that fell or were weakened, respectively. Western hemlocks accounted for 60% and 65% of poles and canopy trees, respectively, and accounted for more of the fallen or structurally weakened trees than expected (likelihood that the incidence in western hemlock was different than that for other species is $P = 0.0005$ by binomial test). How much duff was consumed was modestly associated with root impacts to western hemlock canopy trees (Table 5) but not for the larger sample that included all species.

Table 5
Logistic regression testing whether root impacts in live western hemlock overstory trees were related to duff consumption (Mg ha^{-1}). The sample included root impacts that either caused the tree to fall or would be expected to cause structural weakening and delayed mortality.

Model	Estimate	Std Error	Z value	Pr(>|z|)
Intercept	-1.35	0.59	-2.30	0.022
Duff consumption	0.16	0.07	2.22	0.027

Of the 21 canopy trees standing post-fire which experienced heating and combustion of their primary roots and were expected to die standing or fail structurally in coming years, 14 (16% of all canopy trees, all being western hemlock except one) were perched, that is, their primary roots were above the mineral soil (Fig. 2). We assume that these trees had regenerated (germinated and grew) on nurse logs. Western hemlock were not more likely to have experienced high levels of basal duff consumption than other species (Wilcoxon rank sum test, $W = 476$, $P = 0.92$).

Foliage impacts (both from injury and consumption) occurred more extensively on poles (43% of pre-fire live crown volume) than on canopy trees (13%, Table 4, detail in Supplementary Material: Table S3). Average foliage consumption on poles (3% of pre-fire live crown volume) and canopy trees (2%) was minimal, consistent with low fireline intensities. Average maximum char height across all canopy trees was 5 m and the greatest char heights (39 m average across all trees on the plot) occurred on Plot 5 where we observed fire spread vertically up tree boles (Fig. 1). Moss on boles and branches was recorded on 39 of 74 canopy trees in the sample (42%).

Table 4

Direct (immediate) fire effects on pole (2.5 to < 15.2 cm DBH) and canopy trees (> 15.2 cm DBH). Effects based on averages across all trees in a plot. Bole char can be an indicator of intensity though the highest bole charring in this case was caused by fire spreading up the boles of trees. Plot-level results are provided in Supplementary Material, Table S3.

Tree Diameter Class	Statistic	Bole Char (m)		Crown Effects (%)					
				Total affected[1]			Torch		
		Avg min	Avg max	Avg	Min	Max	Avg	Min	Max
Poles	Avg.	0.2	1.2	43	18	71	3	0	14
	Std. dev.	0.2	1.1	38	37	43	6	0	21
Canopy	Avg.	0.7	5.1	12.6	0	39	2	0	14
	Std. dev.	0.7	5.0	17	0	44	6	0	38

[1]Total affected is the sum of injured (“scorched”) and consumed or charred (“torched”) foliage.

RdNBR for plots (Supplementary Material: Figure S1) averaged 59 (range 5–109, std. dev. 41) which classifies to a Composite Burn Index (CBI) of 1, expected canopy cover loss of 0%, and a low percentage of basal area loss (0–25%). Ground-based measurement of canopy cover loss on burned plots was 13%. Including both poles and canopy trees, basal area loss from treefall was 2.5% and basal area loss including both trees that fell and all trees assessed to be structurally weakened (and expected to exhibit delayed mortality) was 36%.

We used the spring assessment (7–8 months after fire) of tree live status to examine relationships with immediate post-fire injury and structural impacts. Live trees that were standing immediately post-fire and that were standing dead in spring (Fig. 4) had experienced greater live-crown effects than trees that were alive in spring (Table 6). There was a marginal (but non-significant) relationship between 7–8 month mortality and the extensive root injury and damage assessed visually right after the fire for all trees and for western hemlock alone.

Table 6
The relationship between tree mortality in spring (7–8 months after fire) and canopy impacts and duff depth for pole and canopy trees combined. Note that we only measured post-fire basal duff depth for canopy trees and, as such, we use pre-fire duff depth here instead of consumption. The relationship between tree mortality and duff consumption is similar to these results when only canopy trees are considered. Each tree is a replicate.

Model	Estimate	Std Error	Z value	Pr(>|z|)
Intercept	0.73	0.66	1.10	0.27
Duff depth (cm)	0.06	0.04	1.67	0.10
Affected (%)[1]	-0.04	0.01	-3.72	0.0002

[1]Total affected is the sum of injured ("scorched") and consumed or charred ("torched") foliage.

Discussion

A growing body of literature is unveiling the pyrodiversity of old-growth Douglas-fir dominated forests on the west slopes of the Cascades. The prevailing view had been that stand-replacing (SR) fires set the stage for a centuries-scale dynamic dominated by endogenous successional processes. However, recent studies have found a wide range of disturbance histories and associated variability in forest structure and species composition related to climatic setting, topography, fuels, and Indigenous fire stewardship (Tepley et al. 2013, Merschel et al. 2024). Our case study in an old-growth Douglas-fir and western hemlock forest shows how low-intensity fires cause substantial ecological effects below the Douglas-fir overstory. Effects ranged from combustion of heavy duff loadings, structural failure (fall) of live trees, standing mortality from canopy heating, and injury and damage from root heating and combustion that, we expect, will ultimately lead to delayed mortality. Western hemlocks were the most common canopy tree below the fire-resistant Douglas-fir overstory and were more affected by root impacts than expected from their abundance relative to other species. High rates of tree fall were a significant impediment to fire suppression efforts and, given our data on why trees fall, we consider how those risks could be mitigated.

Low-intensity fire caused high rates of mortality and injury below the canopy

By coordinating measurements of pre-fire fuels and vegetation, active-fire behavior, fuel consumption, and immediate post-fire effects (Birch et al. 2023), we quantified substantial impacts from low intensity wildfire below an old-growth Douglas-fir overstory on the west slopes of the Cascades. Although fire intensities were low, fire energy (Birch et al. 2023) was high, primarily because of consumption of deep duff that was often in linear piles being derived from downed logs and, secondarily, from consumption of downed logs that were still intact at the time of the fire (Figs. 1 and 2). Plots burned 10–15 days after rain under mostly moderate fire-weather conditions (Supplementary Material: Table S1) helping to explain low fireline intensities. Transit times on plots averaged more than one day (Plot 1) because of slow and uneven spread. The fire area was in moderate to severe drought when plots burned which accounts for high rates of duff consumption.

The fire caused 32 and 7% of pole and canopy trees, respectively, to fail structurally during or immediately after the fire (Fig. 3). The amount of duff consumption was particularly consequential for western hemlock (Fig. 2, Tables 3 and 5). Whether a tree that was alive at the time of the fire was assessed to be dead or dying in spring (Fig. 4) was strongly related to immediate canopy impacts (Tables 4 and 6) but not root impacts. We were surprised by the lack of relationship between root heating and standing mortality for western hemlock given how visually striking its effects were (Fig. 2). However, we expect high rates of delayed mortality for western hemlock that experienced extensive root heating yet were survived into spring (Fig. 4).

Low incidence of stem damage (whether at the base or above DBH) prevents us from assessing its relationship to tree mortality (Table 3, Fig. 3). Because fire spread up tree boles (Fig. 1) was facilitated by moss and bark, bole charring in this forest (Table 4) is not directly related to fireline intensity. We expect that injury caused by bark and moss combustion is not common because few trees had vertical scarring from past fires.

Western hemlock is highly susceptible to primary root heating and damage because of its habit of root growth above mineral soil (Uchytil and 1991) and regeneration on nurse logs (Franklin et al. 1981) that have long-since rotted into duff (Fig. 2). In contrast, overstory Douglas-fir appeared to be resistant to fire effects because their primary roots grow below-ground and canopies are elevated (Tesky 1992). The effects of consumption of deep duff and intact logs around the bases of a few Douglas-firs could not be assessed immediately post-fire and might lead to basal wounding.

Low levels of basal area and canopy cover loss estimated shortly after fire from space-based, optical measurements (Supplementary Material: Figure S1) paint a picture of limited fire effects. Our data suggest that space-based estimates of basal area and canopy cover loss (Supplementary Material: Figure S1) are likely to be underestimates because the dramatic effects on trees growing below the fire-resistant Douglas-fir overstory are obscured (Miller et al. 2009, Miller and Quayle 2015). Long-term effects will also likely be larger than expected because of delayed mortality from, especially, western hemlock that were vulnerable to root impacts. Additionally, ice storm effects in the winter following the Lookout Fire were observed on the HJA, but not quantified in this study, and likely contributed to tree failure observed after the fire (Fig. 4). Combining optical sensing with active remote sensing (e.g., Light Detection and Ranging) could improve remotely-sensed assessments by providing more information on structural effects below the overstory.

Our results generally support previous assessments of the substantial effects of NSR fire in old-growth Douglas-fir and western hemlock forests on the HJA measured years after fires (Weisberg 2004). The value of pre-, active-, and immediate post-fire assessments such as ours is that they reveal the hidden processes behind the effects of repeated NSR fires (Downing et al. 2021). Given the high injury and mortality rates of trees growing below the overstory, we expect simplification of forest structure, including thinning from below (Fig. 4) resulting in an increase in the average size of surviving trees (Weisberg 2004). In contrast, the Douglas-fir overstory showed high resistance to low-intensity fire. While duff consumed at high rates and downed logs consumed modestly (Fig. 1), trees that fell or will fall in the future because of the fire will add to the large pool of downed logs (Table 3) and perpetuate old-growth character (Franklin et al. 1981).

The modest consumption of downed logs we observed may contrast with their greater consumption during wind-driven SR fire when, as hypothesized, sustained ventilation of the combustion process occurs (Stephens et al. 2022). Preliminary data from the long-term log-decomposition experiment at the HJA suggests interactive effects of state of decomposition and fire severity on consumption of large diameter logs (0.5 m in diameter; Harmon et al. unpublished data). Of the three log-decomposition plots that burned during the Lookout Fire, plots with minimal canopy effects (suggesting a low intensity creeping fire) had more complete combustion of heavily decomposed logs relative to plots with complete consumption of the canopy. Clearly, mysteries remain to be explored.

Facilitating old-growth stewardship

Fire suppression tactics that help reduce fire size will continue to be of ecological and social value (Reilly et al. 2022) given historical loss of old-growth, expected increases in burning in the Pacific Northwest (Dye et al. 2024), and the ineffectiveness of fuel treatments in altering the ecological impacts of wind-driven fires in west-slopes of the Cascades ecosystems (Reilly et al. 2022). High loadings of downed logs and deep duff and high rates of treefall during NSR fires in old-growth complicate use of direct fire suppression tactics (e.g., building fireline at the fire’s edge). Consequently, indirect suppression tactics, such as holding operations along containment features and using ignition operations to burn fuels between the main fire and containment lines (as was done on the 2023 Lookout Fire) may often be the only practical way to limit area burned in old-growth. Establishing and maintaining shaded fuelbreaks along containment lines with the highest probabilities of holding during suppression operations, that is, along Potential Operational Delineations, is an emerging strategy (Thompson et al. 2022). Use of shaded fuel breaks may provide opportunities for indirect suppression along the flanks and heels of wind-driven fires, during periods of low wind during large fire events, or for NSR fires like the 2023 Lookout Fire where fire behavior was governed by fuels and topography (Halofsky et al. 2018). A risk associated with fuel breaks is that they may create drier microclimatic conditions in forest beyond the breaks themselves, which may in turn increase fire risk during dry periods in what are typically wet and productive west-slopes Cascades ecosystems (Halofsky et al. 2018). Removal of trees that are prone to failure combined with maximum retention of other canopy trees could help mitigate microclimatic impacts of shaded fuel breaks and reduce risk to firefighters during fire management operations. Fire spread up tree boles aided by moss that causes short-range spotting (Fig. 1, Supplementary Material: Table S2) is a known challenge to fire containment on the west slopes of the Cascades. It is unclear that risks from spotting can be mitigated while, at the same time, maintaining old-growth characteristics along fuel breaks.

Future research and directions

The substantial duff consumption we documented and the structural impacts on trees growing below the Douglas-fir overstory illustrate the value of pre-, active-, and immediate post-fire sampling for describing the mechanisms by which fires cause their effects (Johnson 1984). The sampling opens the door to understanding delayed mortality that we expect to occur from root impacts, particularly on western hemlock, and will support an on-going study on carbon cycling, including a focus on pyrogenic carbon. Local sampling of fuel properties (e.g., mass and bulk densities of duff and woody fuels, respectively) will increase accuracy of loading estimates in future studies. Pre-, active-, and post-fire data on more fires in old-growth on the west slopes of the Cascades will help refine our understanding of fire effects on trees as it relates to species and size, weather, and local climate. Greater understanding will help improve predictions of how ecosystems are likely to adapt to increased fire risk in the future (Halofsky et al. 2018) and add richness to our interpretation of remotely-sensed fire severity maps.

Declarations

Ethics declarations

Ethics approval and consent to participate - Not applicable

Consent for publication - Not applicable

Competing interests - The authors declare that they have no competing interests.

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Figures

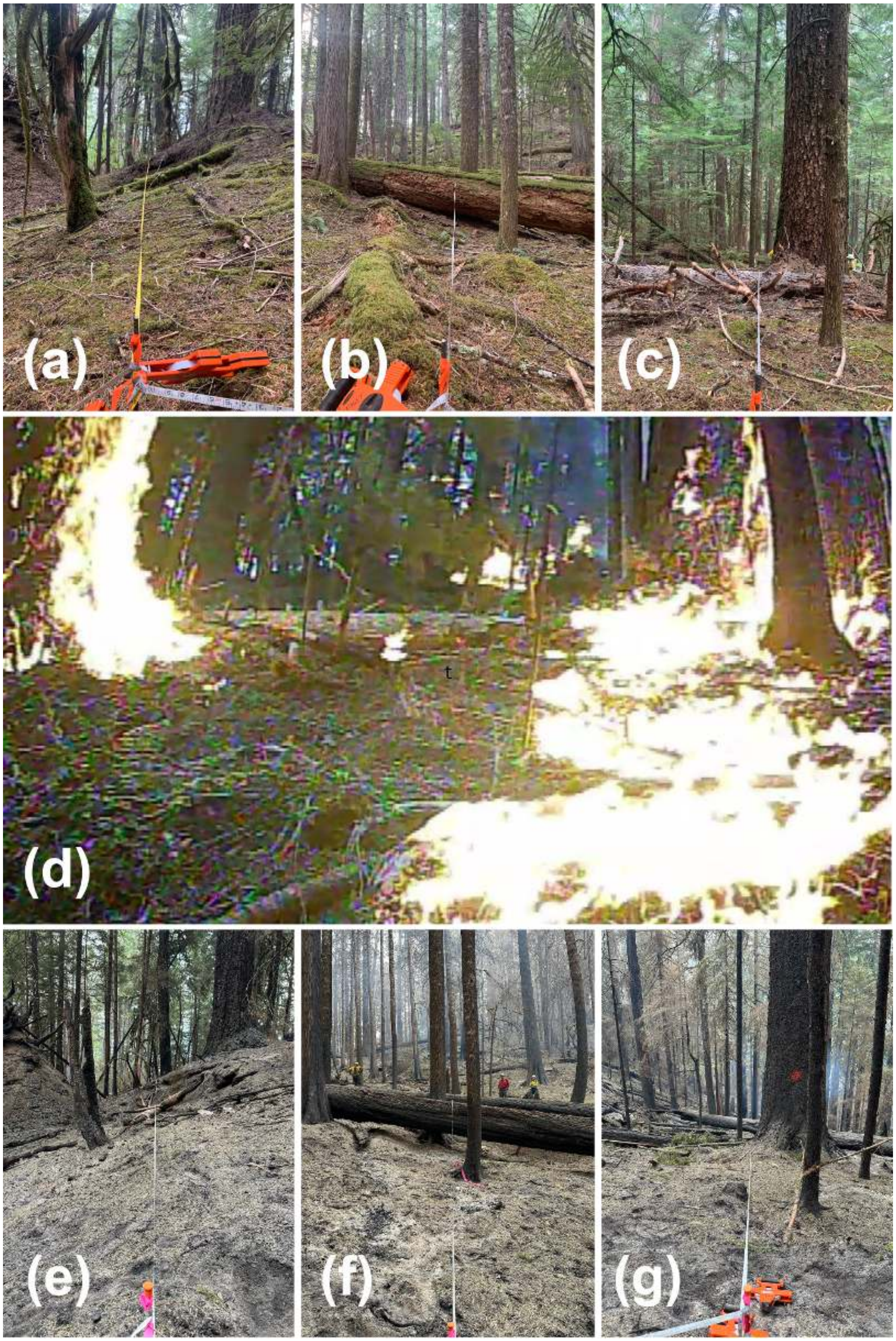

Figure 1

Pre-fire, active-fire, and post-fire images of Plot 5, which burned at the highest rate of spread and intensity. Between paired pre- (a, b, c) and post-fire images (e, f, g), note the moss-covered log in the middle image that had rotted into the duff and was consumed while intact logs showed less consumption (Table 2). The active-fire image (d) shows fire spread up the boles of trees and instances of spot fires ignited by short-range ember transport. The active fire image's field of view includes plot center but is not aligned with any transect. Photo credits: FBAT.

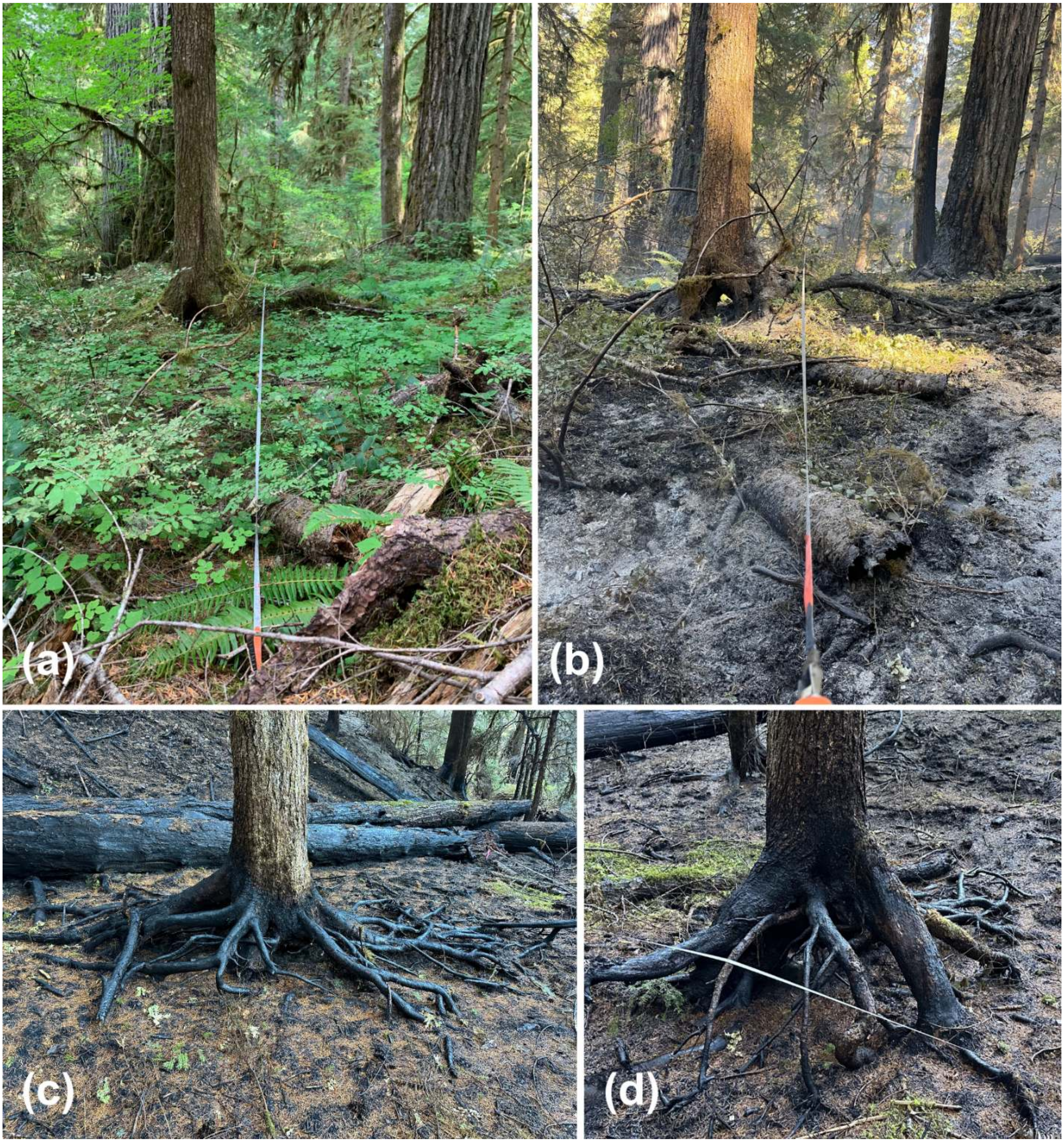

Figure 2

Fire effects on Plot 4 on a bench above Lookout Creek. Paired pre- (a) and post-fire (b) images show that the western hemlock in the left foreground is "perched" on its primary roots above the mineral soil as is visible after the duff consumed (b), suggesting regeneration on a nurse log. In contrast, a Douglas-fir with its roots below the mineral soil is in the right background. Post-fire detail (c, d) on two western hemlocks that experienced significant root heating. The tree on the right (d) had, apparently, regenerated on a nurse log while the one on the left (c) appears to have regenerated on, at least, deep duff. Photo credits: FBAT.

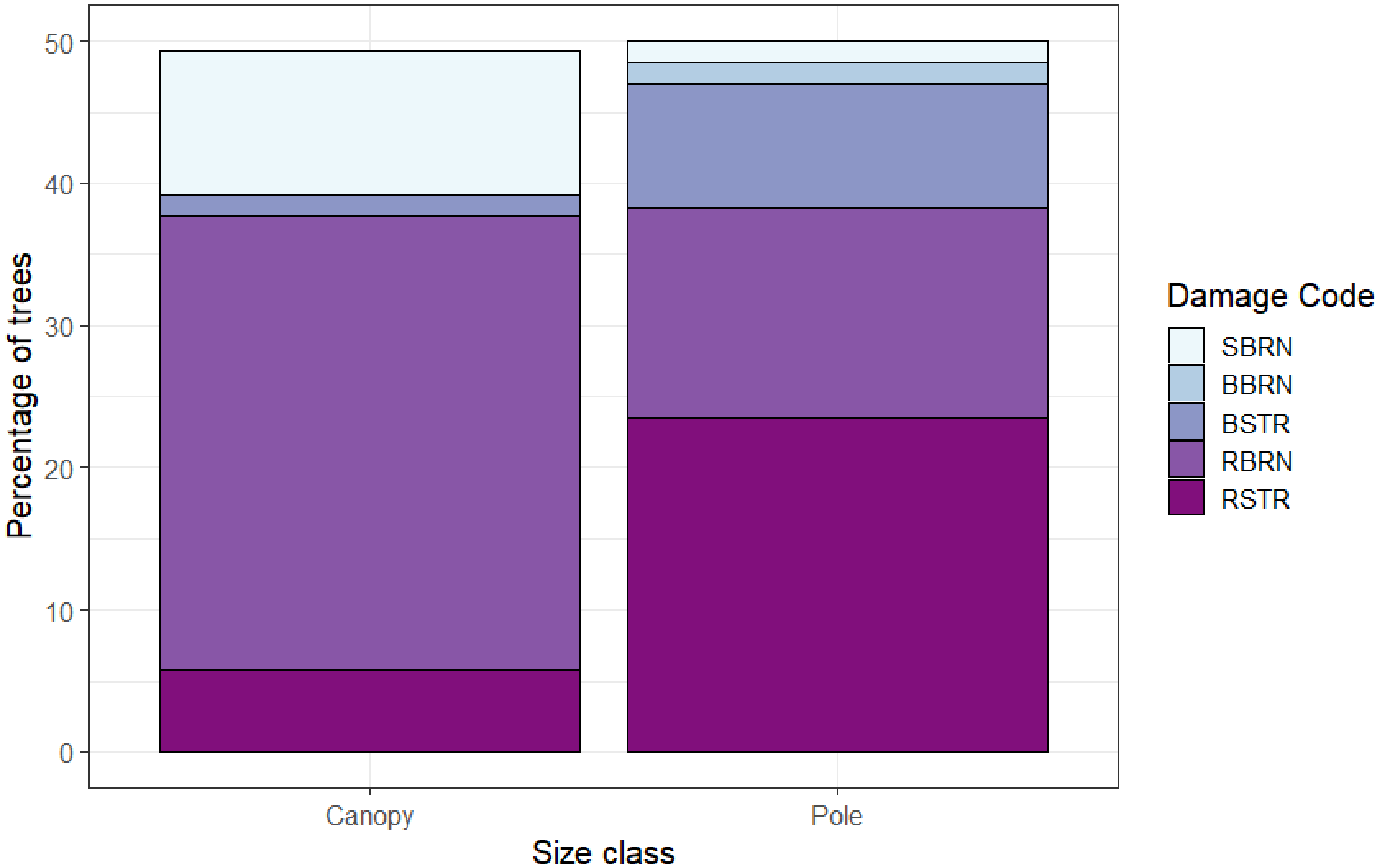

Figure 3

Distribution of damage codes between canopy and pole trees across all species (see also Table 3). Structural failure (tree fall, STR) occurred at the roots (R) and at the tree base below DBH (B) from combustion effects (probably combustion of dead wood). Heating and combustion effects that did not cause structural failure but were assessed to be significant enough to kill the tree in the future (BRN) affected roots, stem bases, and stems above DBH (S).

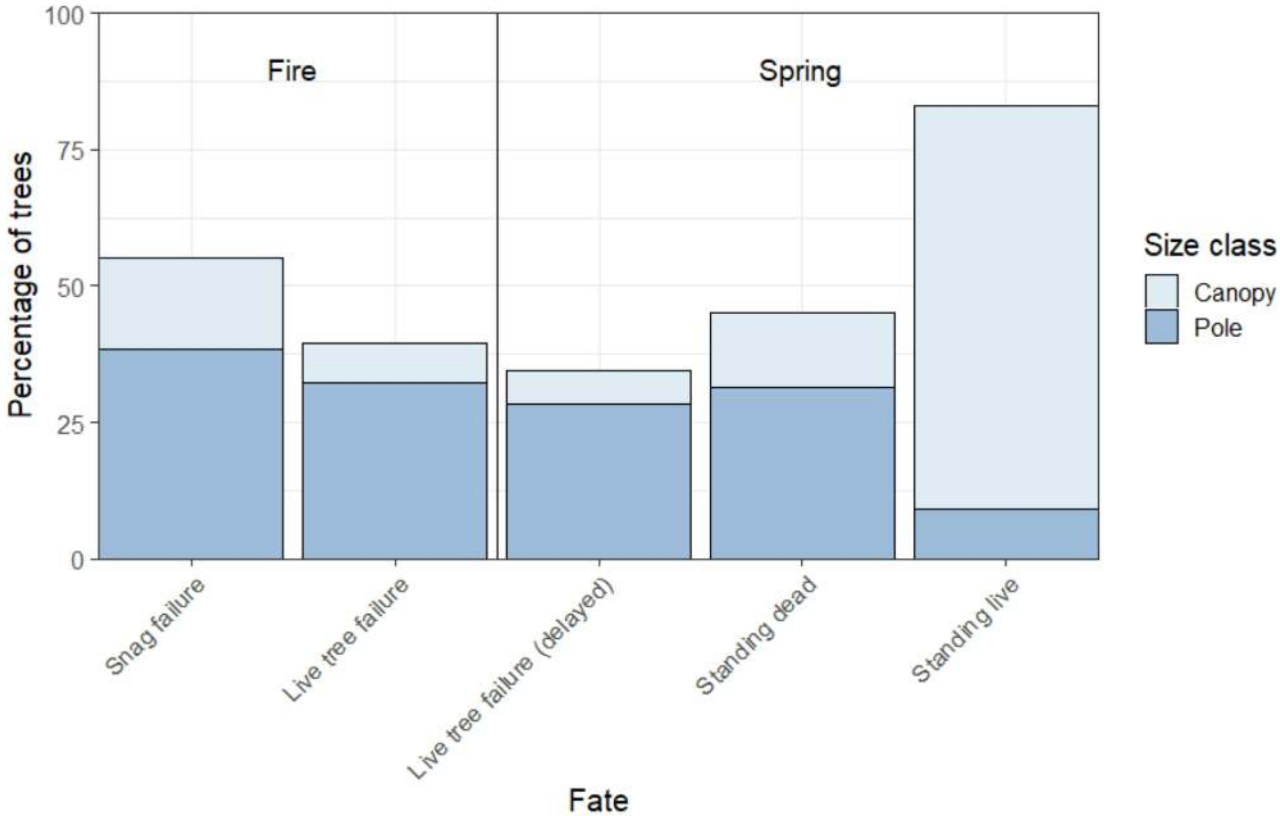

Figure 4

Tree fates shortly after the fire and in the following spring/early summer. Live trees that did not fail at the time of the fire or shortly thereafter were re-assessed in spring. The subset of these trees that failed before the spring sampling are shown as “Live tree failure (delayed)”. Trees that were alive before the fire and were either standing dead or standing alive in spring are shown in the rightmost columns. We expect that many trees standing live in the spring will die because of the impacts of root heating and combustion.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- FireEcologySupplementaryMaterialDickinsonetal26November2025.docx