

Post-fire landscape evaluations in Eastern Washington, USA: Assessing the work of contemporary wildfires



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ABSTRACT

In the western US, wildfires are modifying the structure, composition, and patterns of forested landscapes at rates that far exceed mechanical thinning and prescribed fire treatments. There are conflicting narratives as to whether these wildfires are restoring landscape resilience to future climate and wildfires. To evaluate the landscape-level work of wildfires, we assessed four subwatersheds in eastern Washington, USA that experienced large wildfires in 2014, 2015, or 2017 after more than a century of fire exclusion and extensive timber harvest. We compared pre- and post-fire landscape conditions to an ecoregion-specific historical (HRV) and future range of variation (FRV) based on empirically established reference conditions derived from a large dataset of historical aerial photo imagery. These four wildfires proved to be a blunt restoration tool, moving some attributes towards more climate-adapted conditions and setting others back. Fires reduced canopy cover and decreased overall tree size and canopy complexity, which moved them into, or slightly outside, the FRV ranges. Moderate- and low-severity fire generally shifted closed-canopy forest structure to open-canopy classes. Patches of high-severity fire shifted patterns of forest, woodland, grassland, and shrubland towards or beyond the HRV ranges and within the FRV ranges by increasing the total area and size of non-forest patches. However, large patches of high-severity fire in dry and moist mixed-conifer forests homogenized landscape patterns beyond FRV ranges towards simplified conditions dominated by non-forest vegetation types. Fires realigned and reconnected landscape patterns with the topo-edaphic template in some cases, but pre-existing fragmentation and spatial mismatches were compounded in many others. Patches of large-tree, closed-canopy forest were reduced by high-severity fire, and the potential to restore more climate-adapted large-tree, open-canopy forest was lost. Re-establishing landscape patterns with desired patch sizes of forest, in particular patches with large trees, will take many decades to centuries and may not occur in drier locations or where seed trees are no longer present. While large wildfires burning during extreme fire weather conditions can move some attributes towards HRV and FRV ranges, intentionally planned mechanical and prescribed-fire treatments that are integrated with strategic wildfire response will better prepare and adapt landscapes for future wildfires and climate.

1. Introduction

The interaction of extensive forest densification and expansion over

the last century, increasing wildfire and insect activity, and warming climatic conditions is driving abrupt changes across many fire- and drought-prone landscapes in the interior western US (Hessburg et al.

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2019, Hagmann et al. 2021). The need for large-scale intentional management actions to increase the resilience of landscapes to changing disturbance regimes and climate has been clearly established (Prichard et al. 2021). Although the pace and scale of mechanical and prescribed fire treatments are increasing, wildfires are modifying landscapes at far greater and increasing rates (Reilly et al. 2017, Parks and Abatzoglou 2020, North et al. 2021). Currently, there are conflicting narratives as to whether wildfires are having beneficial or detrimental effects on landscapes that have been highly altered by fire exclusion and timber harvests (Stephens et al. 2016, Haugo et al. 2019, North et al. 2021). This conflict highlights the need for improved empirical understanding of the “work” that wildfires accomplish at landscape scales (North et al. 2012, Barros et al. 2018, North et al. 2021, Stephens et al. 2021a).

Contemporary wildfires are often perceived as human and ecological catastrophes (McWethy et al. 2019). Under current fire management policies that emphasize suppression, most wildfire spread occurs during extreme-fire weather when containment is very difficult (Stephens et al. 2016). Thus contemporary wildfires often result in large and uncharacteristic patches of high-severity fire in forests that historically experienced principally frequent, low- and moderate-severity fires (Cansler and McKenzie 2014, Reilly et al. 2017, Stevens et al. 2017, Parks et al. 2018). These large patches tend to homogenize structural conditions across landscapes (Cassell et al., 2019; Singleton et al., 2021), synchronizing them for future fires and insect outbreaks and increasing likelihood of climate-driven conversion to non-forest (Davis et al. 2019, Kemp et al. 2019, Spies et al. 2019, Coop et al. 2020). High- and some moderate-severity fire also reduce populations of remaining large fire-resistant trees and patches of closed-canopy, large-tree forest structure that sustain numerous wildlife species and store significant land sector carbon (Lutz et al. 2012, Spies et al. 2018, Jones et al. 2021). Re-establishing patches of large trees will take many decades to centuries and may not be possible in significant portions of landscapes. Finally, many wildfires cause significant damage to human communities and infrastructure, and prolonged smoke exposure negatively affects human health (Liu et al. 2015).

Alternatively, some wildfires, or portions of wildfires, can accomplish many goals related to restoration and climate adaptation (Collins and Stephens 2007, Schoennagel et al. 2017, Barros et al. 2018, Haugo et al. 2019, Stephens et al. 2021b). Moderate- and low-severity fire can enhance fire and drought resistance by consuming surface fuels, killing small trees, reducing canopy cover and crown bulk density, elevating crown base height, shifting composition towards fire- and drought-tolerant tree species, promoting fire-adapted understory plants, and restoring fine scale patterns of individual trees, tree clumps, and openings (Lydersen and North 2012, Larson et al. 2013, Kane et al. 2019, LeFevre et al. 2020, Furniss et al. 2021). High-severity patches that are consistent with historically characteristic patch sizes generate biologically important early seral habitat (Swanson et al. 2011), and contribute to restoring patchworks of forest, woodland, grassland, and shrubland that have been highly altered by forest encroachment (Hessburg et al. 2016, 2019, Stephens et al. 2021b). Wildfire response strategies that utilize informed risk analysis before and during fire events can allow fires to safely achieve these positive outcomes during moderate fire weather, while suppressing and containing fires in high-risk locations or during unfavorable weather periods (Thompson et al., 2018; Young et al., 2019; Dunn et al., 2020; North et al., 2021).

The extent to which contemporary large wildfires are restoring landscape-level pattern is especially uncertain. Realigning the spatial arrangement and patch size distributions of vegetation composition and structure with the topo-edaphic conditions of a landscape is a key component of restoring the self-reinforcing and stabilizing resilience mechanisms of landscapes with active fire regimes (Moritz et al. 2011, Perry et al. 2011, Hessburg et al. 2015, 2019). Patterns of burn severity are influenced by existing vegetation, fuels, and topography (Halofsky et al. 2011, Kane et al. 2015), and are thus constrained by ecological memory that reinforces pre-fire patterns (Peterson 2002, Collins et al.

2009, Harris et al. 2020).

In landscapes where pre-fire landscape pattern was heavily fragmented by past harvesting and disconnected from the topo-edaphic template, wildfires can drive further fragmentation that can negatively affect wildlife habitat and future fire behavior (Vanbianchi et al. 2017, Zald and Dunn 2018). Conversely, extensive patches of dense forest created by fire exclusion set up dry and moist mixed-conifer forests for high-severity patches that exceed historical size distributions, especially when driven by extreme fire weather that can override local spatial controls on fire size and severity (Cansler and McKenzie 2014, Povak et al. 2020b, Prichard et al. 2020). In addition, the remaining closed-canopy forest may not be located in topo-edaphically favorable and climatically sustainable locations across the burned and unburned parts of a landscape.

Assessing the relative beneficial and detrimental “work” of wildfire necessitates the use of reference conditions that are clearly linked to similar environmental and disturbance regime settings and desired landscape-level functions. In the interior western US, active historical fire regime conditions are often used for this purpose as they represent conditions that are resilient to a wide range of disturbances and climatic fluctuations, while providing a wide range of ecological functions (Fule 2008, Keane et al. 2009, Wiens et al. 2012, Safford and Stevens 2017, Murphy et al. 2021). However, historical reference conditions (HRV) will become less useful as climate change becomes more pronounced (Littell et al. 2010, Halofsky et al. 2018). Thus, robust adaptation strategies for fire-prone ecosystems should utilize HRV conditions as a guidepost, but seek to set landscapes on a trajectory towards conditions adapted to future climates (i.e., future range of variation – FRV) (Stephens et al. 2010, Schoennagel et al. 2017, Hessburg et al. 2019).

Here, we evaluate how four recent large wildfires in eastern Washington – spanning a range of burn severity proportions and patch sizes – changed landscape-level vegetation patterns relative to HRV and FRV reference conditions within 3–22 months of each fire. We demonstrate an approach for assessing the landscape-level work of wildfires that can be used as a core component of post-fire landscape evaluations to guide post-fire management (Larson et al., 2022). Specifically, we evaluate the extent to which wildfires spanning a range of pre-fire conditions and burn severity patterns achieved four key landscape restoration and climate adaption goals (Hessburg et al. 2015). These four goals include:

1. Shift the amount and pattern of forest, woodland, and non-forest vegetation types to within the HRV and in the direction of the FRV.
2. Shift the amount and pattern of forest structure to within the HRV and in the direction of the FRV.
3. Sustain open- and closed-canopy patches with large and old trees.
4. Shift species composition towards more drought adapted, fire-tolerant species.

2. Methods

2.1. Study Area: Four fires in four subwatersheds

We conducted departure assessments at the subwatershed level (Hydrologic Unit Code 12, (Seaber et al. 1987)). Four subwatersheds were used in this study and represent four distinct landscapes that were each analyzed separately. The grain of the landscape analyses in each landscape are patches (polygons) of vegetation that are based on vegetation structure and topography with a 4 ha minimum size. The four subwatersheds were four separate analyses that together represent a range of landscape conditions and fire effects. They were not randomly selected and are not intended for pooled statistical analyses to draw global inferences. As this landscape assessment approach is conducted at the scale of subwatersheds, only the portions of each fire that fell within the selected subwatershed were included in this study. Thus, the results do not apply to the entire fire event, but to the subwatershed boundary. Each subwatershed also contains area that is outside of the fire perimeter

in varying amounts (Table 1). Evaluation of the entire landscape area is relevant to class and landscape metric comparisons of the post-fire landscape and the HRV and FRV reference conditions.

We selected four subwatersheds that burned in 2014, 2015, or 2017 (Table 1, Fig. 1). Initially, all subwatersheds in the study area (eastern Cascades and Okanogan Highlands areas of Washington) were identified that were more than 66% forested and had at least 33% of their area burned by 2014–2017 fires. Twenty five subwatersheds met these criteria. The four subwatersheds were then selected based on three factors. First, the subwatersheds were chosen to span a gradient of fire severities that ranged from predominantly large patches of high-severity fire (Benson Creek– 2014 Carlton Complex fire) to predominantly moderate- and low-severity fire (Scatter Creek – 2015 North Star fire) (Table 1, Fig. 2). Burn severity maps were based on satellite-measured relative differenced normalized burn ratio (RdnBR) (WA DNR 2021 following methods from Parks et al. 2018) with region-specific translation into proportional post-fire basal area (BA) loss (Saberi 2019). Second, wildfires that burned across a broad range of dry, moist, and cold forests were emphasized. Finally, subwatersheds in which the US Forest Service and other landowners where interested in incorporating the results into management planning were prioritized.

The four selected subwatersheds are located in the eastern Cascades and Okanogan Highlands areas of Washington (Fig. 1). Broad-scale climatic patterns across this area are characterized by cold-wet winters, hot-dry summers, and warm-wet transitional seasons (Table 1). Precipitation and temperature gradients driven by elevation, disturbance history, and topo-edaphic complexity create landscapes with varying intermingled forest and non-forest types and fire regimes (Agee 2003).

Table 1
Fire severity, forest type, climate, and elevation information for the four subwatersheds and their associated wildfires fires used in this study.

Subwatershed	Benson Creek	West Fork Teamaway	South Fork Boulder	Scatter Creek
Fire name & year	Carlton Complex 2014	Jolly Mountain 2017	Stickpin & Renner 2015	North Star 2015
Total area (ha)	9,824	10,149	17,840	6,367
Area burned (ha)	8,386	5,065	5,857	3,560
High Severity (%)	55 ¹	47	37	16
Moderate Severity (%)	26 ¹	37	28	19
Low Severity/ Unburned (%)	18 ¹	16	35	64
Dry forest (% of landscape)	64	38	37	26
Moist forest (% of landscape)	0	14	7	43
Cold forest (% of landscape)	0	45	54	29
Non-forest (% of landscape)	36	3	2	2
Elevation range (m)	439–1,452	682–1,964	582–2,174	655–1,562
Mean JAN temperature (°C) (sd)	−4.2 (0.4)	−2.5 (0.6)	−5.1 (0.6)	−4.9 (0.2)
Mean JULY temperature (°C) (sd)	18.1 (1.1)	15.9 (0.8)	16.6 (1.2)	17.2 (0.4)
Mean annual precipitation (mm) (sd)	424 (34)	1285 (228)	681 (49)	420 (11)

¹ The percentage area burned at different fire severities includes non-forest acres (e.g. herland, shrubland, woodland areas). A significant portion of the Carlton Complex fire in the Benson Creek subwatershed burned through pre-fire herland that maps out at moderate and low severity due to regrowth of grasses immediately after the fire. Across the subwatershed, the percentage of forested area that burned at high-, moderate- and low-severity was 67%, 18%, and 15%, respectively.

Lower elevation and south-facing slopes at mid-elevations contain shrub-steppe communities along with ponderosa pine and Douglas-fir woodlands. Low to mid elevations contain dry mixed-conifer forests (ponderosa mixed with Douglas-fir, as well as occasionally western larch or grand fir) that historically experienced low- and some mixed-severity burns at 5–25 year intervals (Everett et al. 2000, Agee 2003).

Moist mixed-conifer forests composed of western larch, Douglas-fir, grand fir, ponderosa pine, and western white pine are found at mid-elevations in valley bottoms, riparian areas, and on north-facing slopes. They experienced low- and moderate-severity burns as well, but with a greater proportion (20–25%) at high-severity, owing to occasionally longer (25–80 year) fire return intervals (Hessburg et al. 2007). Cold subalpine forests (subalpine fir, Engelmann spruce, lodgepole pine, and western larch) occupy upper elevations and typically experienced moderate- and high-severity burns at 75–150 year return intervals; however, fire-fire interactions and reburning occasionally reinforced low- or moderate-severity fire (Prichard et al. 2017). Combined with extensive aboriginal fires (Boyd 1999), the result was a multi-level patchwork of forest and non-forest vegetation conditions that conferred resistance and resilience to large-scale disturbances and climatic fluctuations (Peterson 2002, Parks et al. 2015, Hessburg et al. 2019).

Each selected subwatershed has its own unique pre-fire characteristics and fire effects that are noteworthy (Table 1). Benson Creek contains only dry mixed-conifer forest, shrub-steppe, and woodlands, with no moist or cold forest. The subwatershed is almost entirely within the Okanogan-Wenatchee National Forest (OWNF) and was extensively harvested by means of selection cutting and overstory removal treatments in the 1970s and 1980s. Extreme fire weather during the 2014 Carlton Complex fire led to a very large patch of high-severity fire that burned through most of this landscape (Fig. 2). Mechanical fuels reduction and prescribed treatments were conducted in the southeast portion of this landscape between 2008 and 2013. Most of this treated area did not burn in the Carlton Complex fire (Prichard et al. 2020).

The northern half of the West Fork Teamaway subwatershed that burned in the 2017 Jolly Mountain fire is almost entirely Inventoried Roadless Area (similar to Wilderness in management allocation) within the OWNF and contains steep, complexly dissected terrain. Fire severity was predominantly high and moderate (Fig. 2, Table 1). In contrast, the largely unburned southern half of the landscape was formerly industrial forestland and experienced extensive harvesting over the last several decades.

The South Fork Boulder Creek subwatershed is located on the east-side of the Kettle Mountain Range and has some components of Northern Rocky Mountain mixed-conifer forests such as extensive western larch in moist and cold forests, and western red cedar in moist forests. Ownership is primarily Colville National Forest (CNF). This subwatershed experienced significant past timber harvesting, but not as extensively as the other three landscapes. The Renner and Stickpin fires burned 33% of this landscape in 2015 with a relatively balanced mix of low, moderate, and high-severity patches (Table 1). Larger patches of high-severity fire dominated in upper elevation forests (Fig. 2).

Almost all of the Scatter Creek subwatershed was harvested in the 1960s–1990s with shelterwood and overstory removal treatments. This subwatershed resides primarily on the CNF and has more gentle topography than the other three. The North Star fire burned 56% of this landscape in 2015. Most of the fire (80%) burned at low-severity with small patches of moderate- and high-severity scattered throughout (Fig. 2).

2.2. Pre- and post-fire vegetation attributes

To collected pre- and post-fire vegetation attributes, we employed a well-established methodology that is currently in use for landscape-level restoration efforts in eastern Washington (Gärnter et al., 2008; Hessburg et al., 1999b, 2013; Hessburg et al., 1999a; USDA, 2012; WA DNR,

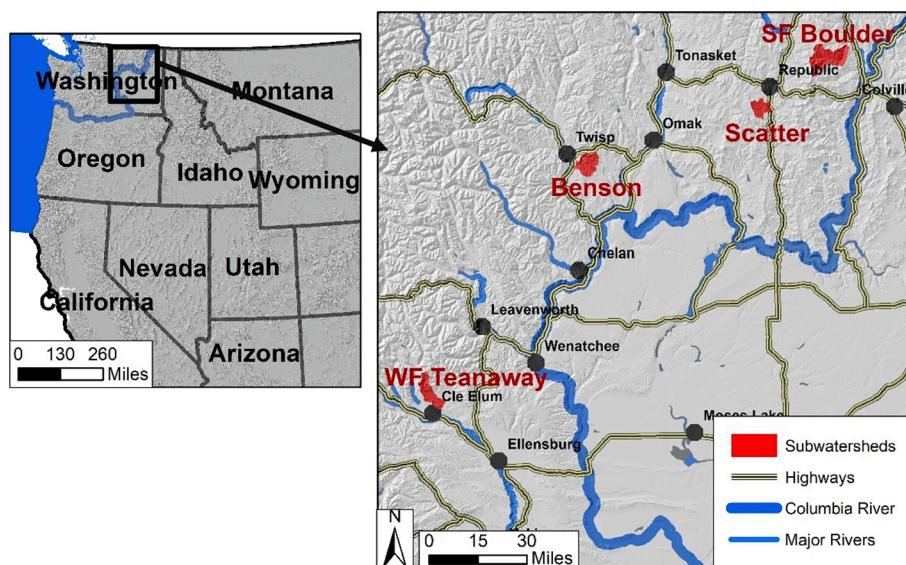


Fig. 1. Location of four subwatersheds selected for pre- and post-fire departure analysis.

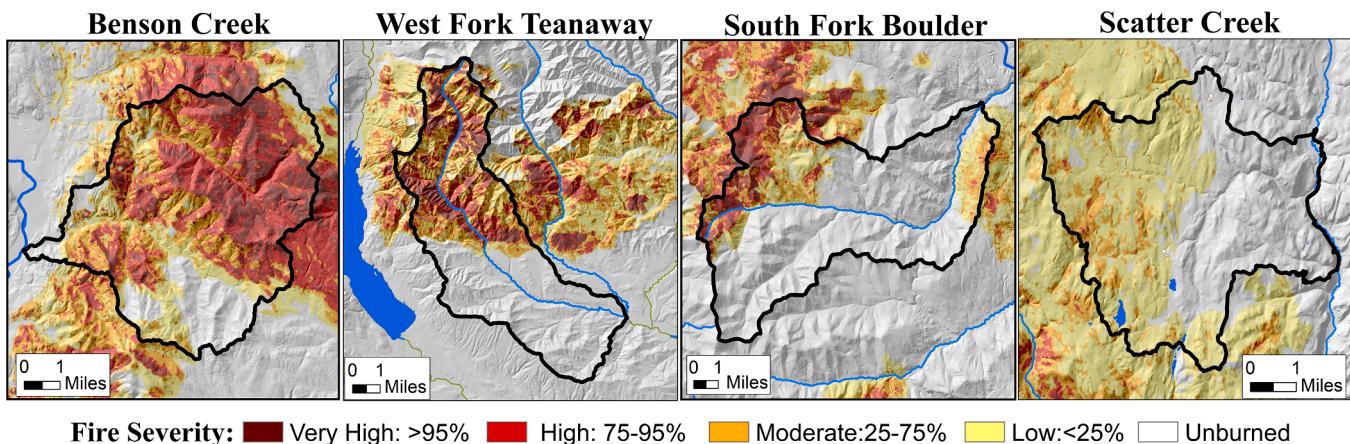


Fig. 2. Fire severity maps for four fires in the four study area subwatersheds (severity expressed as percentage of pre-fire basal area). Note the gradient from predominantly large patches of high-severity fire on the far-left panel to predominantly moderate- and low-severity fire with smaller patches of high-severity fire on the far-right panel. The large patch of high-severity fire in Benson Creek occurred in dry mixed-conifer forest, which is uncharacteristic for this forest type. Similarly, many of the large high-severity patches in the middle section of West Fork Teanaway were uncharacteristic for the moist and dry mixed-conifer types in which they occurred. Conversely, the large high-severity patches in South Fork Boulder were characteristic for the subalpine forest in which they occurred. The small to medium sized high- and moderate-severity patches in Scatter Creek were also characteristic of the predominantly dry and moist forest types in this subwatershed.

2020). This approach employs standard photo-interpretation (PI) techniques with a specific protocol that was originally developed for the Interior Columbia Basin Ecosystem Management Project (Hessburg et al. 1999a).

Pre-fire patches (polygons) were first manually delineated for each subwatershed based on vegetation structure and topography with a 4 ha minimum size. Photo-interpreted raw attributes - canopy cover, overstory and understory size class and tree species, number of canopy layers, and snag density - were then estimated for each polygon, along with other attributes (See Hessburg et al. 2013 for a complete list). Using imagery from the closest year after the fire, this PI process was repeated for the burned area of each subwatershed using the pre-fire polygons and raw attributes as a reference to minimize re-measurement error. Polygons were reconfigured as needed to capture post-fire conditions. Polygons in the unburned portion of the subwatershed were checked for any significant change in conditions. The acquisition dates of the pre-fire imagery for the four subwatersheds ranged from 1 to 14 months before fire, while post-fire imagery ranged from 3 to 22 months after fire.

Using these raw attributes, three derived attributes were calculated

for each patch (polygon): physiognomic type, structure class, and cover type. Classification criteria for the physiognomic type and structure class attributes are shown in Table 2. Cover types are based on overstory and understory tree species using the classification key described in Hessburg et al. (2013). A number of class and landscape metrics (McGarigal 2012) were then generated for each of the three derived attributes (See Hessburg et al. (2013) for a full list). Three class metrics –percent land (percentage of the landscape area- PL), area-weighted mean patch size (MPS), and cumulative patch size distributions– were selected to parsimoniously capture the primary changes from the fires in a parsimonious manner (Cushman et al. 2008).

Digital imagery for 2013, 2015, and 2017 was obtained from the Washington Department of Natural Resources for this project, which purchases a stereo, higher resolution (40 cm) version of NAIP (National Agricultural Imagery Program) from the vendor that produces NAIP imagery. Digital, “heads up” stereo digitizing software was used for PI (DAT/EM System International 2019).

Table 2

Classification criteria for physiognomic type and forest structure class. Canopy cover is total overhead tree crown cover, as estimated by the photo-interpreter for a polygon. Tree size is the estimated diameter at breast height of the dominant and co-dominant trees, derived from photo-interpreted overstory and understory size class and canopy cover attributes for a polygon. See Hessburg et al. (1999a) for additional information on photo-interpreted attributes and shrub and herb/forb cover types.

Attribute	Class	Definition
Physiognomic Type	Forest	≥25% canopy cover
	Woodland	5–24% canopy cover
	Shrubland	<5% canopy cover, shrub species dominant
	Herbland	<5% canopy cover, herb or forb species dominant
	Non-Vegetated	Post-fire bare ground, rock, water, developed, or other non-vegetated types
Forest Structure Class	Open	<5% canopy cover (includes non-forest and non-vegetated types); or 5–44% cover and overstory ≤ 25.4 cm
	Small-Closed	≥45% canopy cover and tree size < 25.4 cm
	Medium-Open	5–44% canopy cover and tree size 25.4–50.8 cm
	Medium-Closed	≥45% canopy cover and tree size 25.4–50.8 cm
	Large-Open	5–44% canopy cover and tree size > 50.8 cm
	Large-Closed	≥45% canopy cover and tree size > 50.8 cm

2.3. Departure analysis

We quantified departure by comparing the pre- and post-fire conditions of each subwatershed to an ecoregion-specific historical (HRV) and future range of variation (FRV). HRV is based on empirically established reference conditions derived from a large dataset of historical aerial stereo imagery that was generated as part of the Interior Columbia Basin Ecosystem Management Project (Hessburg et al. 1999a). Class and landscape metrics are quantified and analyzed at the subwatershed level. These metrics are derived from photo-interpreted raw attributes that are collected for polygons (minimum 4 ha size) within a subwatershed (Hessburg et al. 1999a). We utilized the same PI protocol for this study that was used for this historical dataset. Historical imagery has also been used to quantify landscape-level departure from reference conditions in other regions using similar methods (Skinner 1995, Scull et al. 2017, Lydersen and Collins 2018, Calbi et al. 2020).

To establish HRV ranges for metrics for a specific subwatershed, historical data from 10 to 16 reference subwatersheds within the same ecological sub-region are used (Hessburg et al. 2000). The FRV is obtained by using the same historical dataset, but with a climate change analogue, “space for time substitution landscape sampling” approach (Gärnter et al. 2008). A second set of 10–16 reference subwatersheds from a warmer and drier ecological sub-region are selected to form the FRV. Climate projections from the RCP 4.5 greenhouse gas emissions scenario (Stocker et al., 2014) were used to select ecological sub-regions for the FRV for each target subwatershed (see Hessburg et al. 2013 for a full description of this approach).

For each of the derived attributes (physiognomic type, structure class, and cover type), PL and MPS were graphically compared to the HRV and FRV ranges to assess which types were below, within, or above the reference ranges before and after the fire. The lower and upper values for the HRV and FRV reference ranges were based on the 20th and 80th percentile values for each metric from the 10–16 subwatersheds that formed the HRV and FRV ranges, respectively. Only percent land departures for cover types are presented here. Pre- and post-fire cumulative patch size distributions for forest structure class were also graphically compared to the HRV and FRV distributions.

In addition to analyzing changes in the three derived attributes, we used a principal components analysis (PCA) ordination to assess the

overall direction of changes caused by wildfire in relation to the reference ranges. We selected six raw attributes to define the PCA axes: total canopy cover, overstory canopy cover, number of canopy layers, over-story tree size, understory tree size, and snag density. The reporting units were individual forested polygons of HRV, FRV, pre-fire, and post-fire datasets, with contributions to the PCA weighted by polygon area. We visualized data in ordination space by plotting area-weighted centroids of HRV and FRV subwatersheds overlain with pre- and post-fire centroids for analysis subwatersheds. We also plotted the six structure classes (Table 2) for reference by using area weighted mean values of all the polygons from the historical and current subwatersheds for each structure class.

To assess how different wildfire severities affected the work of wildfire, we examined the pre- to post-fire transitions in forest structure class caused by low-, moderate-, and high-severity fire. The goal was to better understand how different burn severities across all four of the fires shifted forest structure classes. We combined burn severity maps (Fig. 2) with pre- and post-fire forest structure maps and then pooled the results across all four landscapes. We generated flow diagrams for low-, moderate-, and high-severity fire to report these results. Minor transitions (<2% of the area for each severity class) were not shown. All analyses for the entire study were conducted in R version 3.6.1 (R Development Core Team 2020).

3. Results

As the individual fires in each subwatershed were analyzed independently, results are presented for each subwatershed separately. Figures for two of the landscapes with contrasting results are included here, while figures for the other landscapes are provided in Appendix A. The last section reports combined results for structure class transitions from different burn severities.

3.1. Benson Creek

Driven by extreme fire weather, the 2014 Carlton Complex fire burned over 3,000 ha of forest at high-severity. This high-severity patch merged with adjacent pre-fire native herland and shrubland areas to create a 6,822 ha herland patch (Fig. 3), thereby flipping this landscape from forest to herland dominated (Figs. 3 & 4). Post-fire, the percent land (PL) and area-weighted mean patch size (MPS) of herland is well above the HRV and FRV reference ranges. The MPS of forest shifted from well above HRV and FRV to within the HRV and FRV reference ranges (Fig. 4). The fire also converted most of the woodland to herland thereby pushing woodland area and patch sizes to the lower end of both HRV and FRV reference ranges.

The wildfire shifted the PL and MPS for most of the forest structural classes to the lower end of the HRV and FRV reference ranges (Fig. 4), especially the large-tree, closed-canopy and medium-tree, closed-canopy classes. The extreme weather driven runs of the fire converted almost of the large-tree, open-canopy patches to the open class, while moderate- and low-severity fire created new patches of large-open (Figs. 3 & 4). The net result was no change in the PL for this class and a slight increase in MPS. The fire reduced PL of ponderosa pine and Douglas-fir cover types and converted most of these sites to herland (Table 3). No shifts from one forest cover type to another were detected.

Overall, the Carlton Complex fire shifted forest structure conditions from outside to within the HRV and FRV reference ranges, but right to the lower limit of forest cover (Fig. 4E). The large patch of high-severity fire that merged with adjacent pre-fire herland patches now occupies 70% of the landscape (Fig. 3). This coarsened and homogenized the landscape pattern, reducing the once higher abundance of small- to medium-sized patches (Fig. 4F).

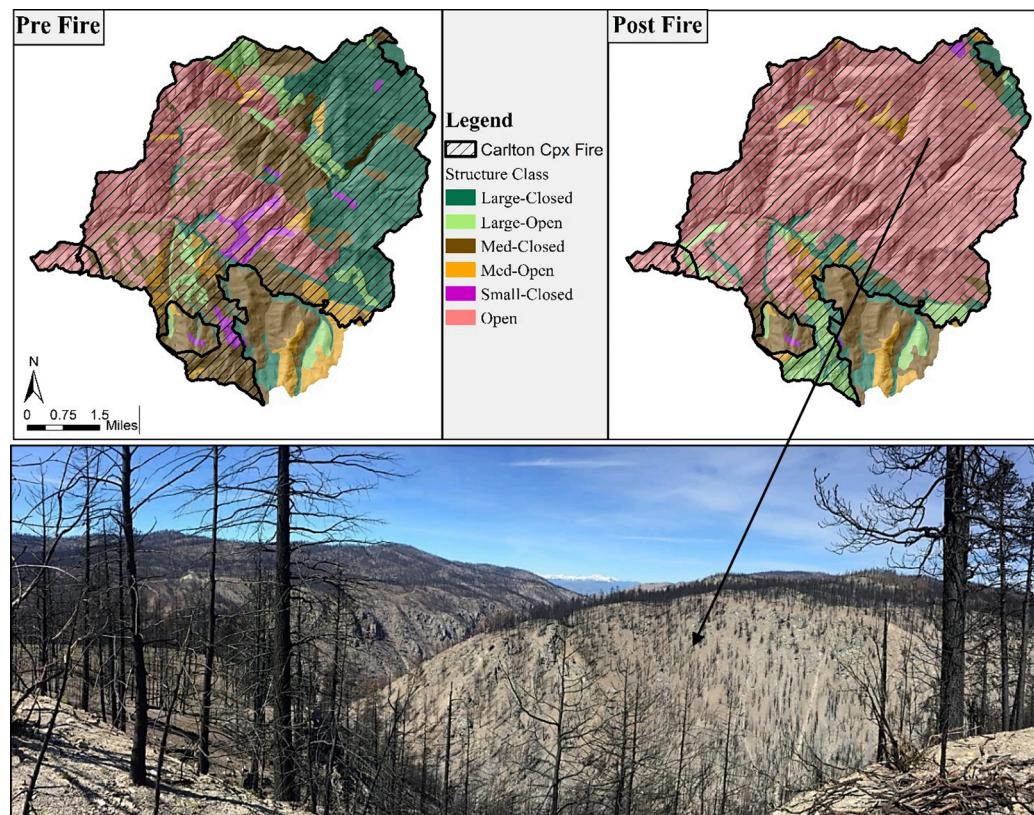


Fig. 3. Top panel: pre- (left) and post-fire (right) forest structure classes in Benson Creek. Lower panel: >3,000 ha patch of high-severity fire created by the Carlton Complex Fire in 2014 in Upper Finley Canyon within the Benson Creek subwatershed. Note that high-severity burn patches occurred in uncharacteristic dry forest biophysical settings after a long period of fire exclusion and selection cutting of the largest fire-tolerant trees. See Table 2 for structure class definitions. Photo: Susan Prichard.

3.2. South Fork Boulder Creek

Despite burning only 33-percent of this subwatershed, the 2015 Renner fire and 2015 Stickpin fire moved this landscape in the direction of the FRV reference ranges. High-severity fire in the western, upper elevation portion of the subwatershed significantly reduced the PL and MPS of forest by breaking up a very large patch of forest (Fig. A1, A2). Post-fire, non-vegetated PL and MPS were above both reference ranges, but many of these patches are forest that burned at high-severity and will quickly transition to shrubland, hermland, or young forest. The post-fire landscape remains predominantly forested (78% of the area), at the high end of FRV range. The MPS of forest is still well above both ranges (Fig. A2).

The fires converted the medium-closed and small-closed structure classes that were at the high end of FRV range to the open and medium-open classes (Fig. A2). The large-open and large-closed classes were minimally affected. The area of Douglas-fir, subalpine fir, and lodgepole pine cover types were all reduced from a pre-fire condition that was above or at the high end of the HRV reference range towards the FRV range and converted them to non-forest types (Table 3), while ponderosa pine and western larch cover increased slightly.

Overall, the fire shifted forest structure conditions from the HRV to the FRV reference ranges by reducing canopy cover and tree size/canopy complexity (Fig. A2E). In the pre-fire condition, the patch size distribution of forest patches was dominated by smaller patch sizes relative to most of both reference ranges (Fig. A2F). Post-fire, we observed that high- and moderate-severity fire patches had broken up some larger patches of forest, which further fragmented the landscape.

3.3. West Fork Teanaway

The 2017 Jolly Mountain fire burned at a range of severities and fire severity patch sizes (Table 1, Fig. 5). Moderate- and high-severity fire converted patches of forest to woodland and non-vegetated

physiognomic types (burned ground), shifting the PL of forest to the lower end of both reference ranges (Fig. 6). Many of the post-fire non-vegetated patches (burned ground) are likely to quickly transition to shrubland, hermland, or in some cases young forest.

The primary effect of the fire on structural classes was to convert the large-closed class to the open class and medium-open class (Figs. 5, 6). Interestingly, the MPS of the large-closed class increased, while the PL of declined from 46 to 31%. As only very small patches of large-closed are left within the fire perimeter, the remaining large patches in the unburned area increased the MPS. The subalpine fir cover type was significantly reduced and converted to non-forest (Table 3), while the Douglas-fir cover type increased modestly.

Overall canopy cover and forest structural conditions were outside of both reference ranges before and after the fire due to low canopy cover (Fig. 6E). The fire moved tree size/complexity from the upper edge to the middle of both reference ranges. Pre-fire, the patch size distribution was skewed towards smaller patches (left side of the envelope in Fig. 6F), relative to both reference ranges. The Jolly Mountain fire broke up the few existing larger patches of forest, further fragmenting the landscape to the point where the patch size distribution is now slightly outside of both reference ranges.

3.4. Scatter Creek

The predominantly low-severity 2015 North Star fire shifted some vegetation attributes in the direction of the FRV reference range while moving other attributes in the opposite direction. The PL of the forest physiognomic type was reduced to below the HRV reference range, but well within the FRV range (Fig. A4). Similarly, PL of herland and woodland increased above the HRV range, but within the FRV range. The fire reduced the MPS of forest by breaking up large patches, but only slightly increased the MPS of herland and woodland patches (Fig. A4).

The fire shifted medium-closed PL and MPS from the upper end of the HRV and FRV ranges to the middle of those range (Fig. A4), converting it

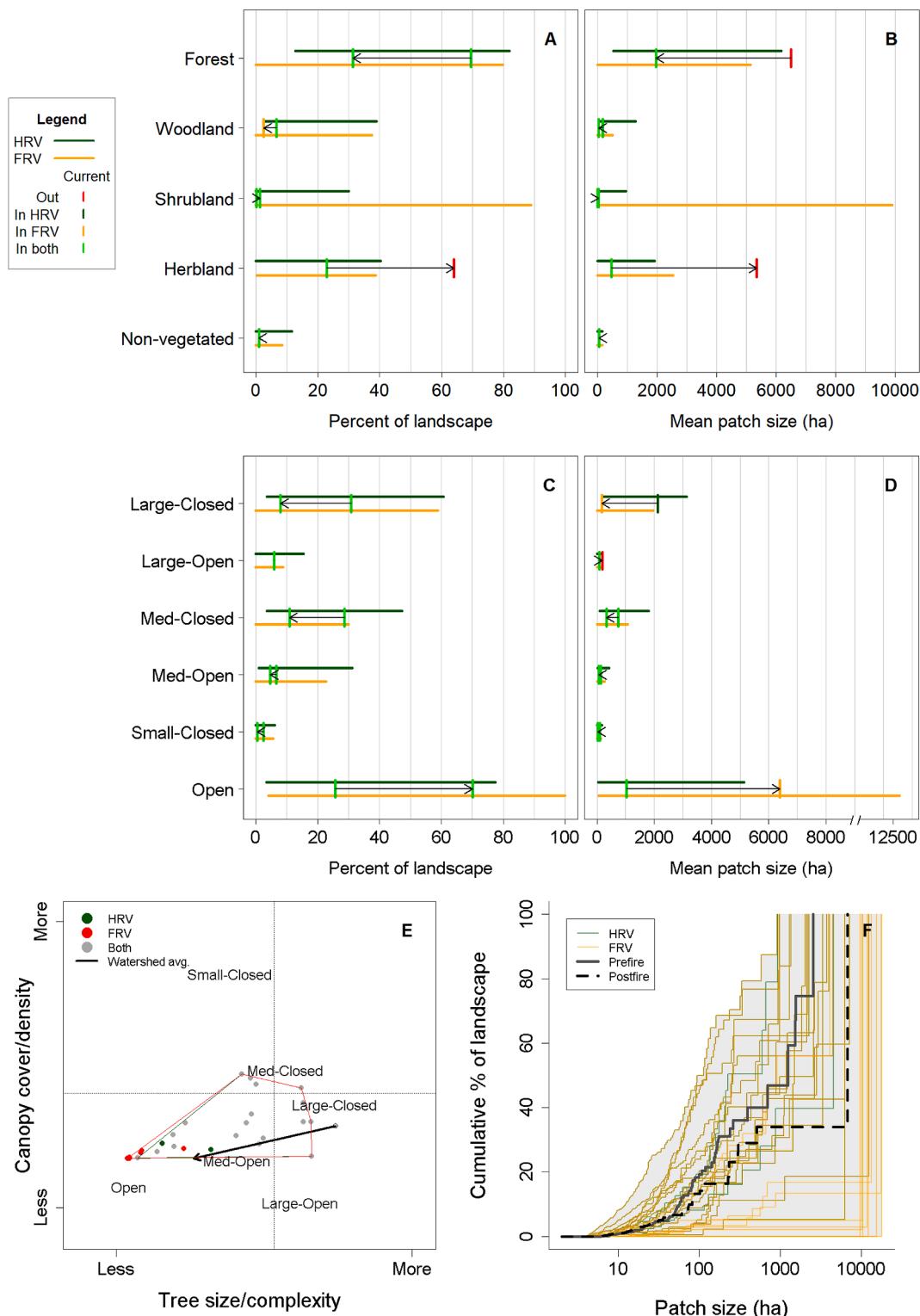


Fig. 4. Pre- and post-fire pattern metrics for the Benson Creek subwatershed. The upper and middle rows display the percentage of landscape area (left) and area weighted mean patch size (right) for physiognomic types (A,B) and forest structure classes (C,D) relative to the historical (HRV) and future (FRV) reference ranges. Arrows show the direction of change from pre to post-fire conditions. “Out” indicates that the current condition for the metric of interest is outside of both reference ranges. “In” indicated that the current condition for the metric of interest within one or more reference ranges. Panel E shows principal components analysis (PCA) of 6 forest structural attributes. Green and red dots show area-weighted centroids of the HRV and FRV sample subwatersheds of an ecological subregion. The arrow shows the fire-caused forest structural change in PCA space, with the arrow pointing from the pre-fire centroid to the post-fire centroid. Panel F displays cumulative patch size distributions of structure classes for pre- and post-fire patches. Each yellow (FRV) and green (HRV) line within panel F shows the cumulative patch size distribution for an individual reference subwatershed. See Table 2 for physiognomic type and forest structure class definitions.

Table 3

Pre- and post-fire cover type transitions caused by wildfire for four study subwatersheds in reference to the historical (HRV) and future ranges of variation (FRV). Values are percentage area of the forested landscape. The OTHER class includes post-high-severity fire conditions with bare ground. Post-high-severity fire areas in Boulder and Teanaway are shown as OTHER, while these areas were classified as HERB in Benson and Scatter due to the presence of herbaceous cover by the time of the postfire imagery. Note that the name of the cover type is the name of the dominant tree species, but other associated species may also be present. For more information on cover type classifications see Hessburg et al. (1999a, 2013).

Cover Type	Benson Creek			South Fork Boulder			West Fork Teanaway			Scatter Creek		
	Pre → Postfire	HRV	FRV	Pre → Postfire	HRV	FRV	Pre → Postfire	HRV	FRV	Pre → Postfire	HRV	FRV
PIPO	62 → 22	5–73	0–63	7 → 7	0–29	5–73	42 → 41	0–11	13–71	14 → 15	24–62	5–73
LAOC	–	–	–	3 → 4	5–71	0–5	–	–	–	1 → 2	0–19	0–5
PSME	12 → 9	2–43	0–39	51 → 44	13–62	2–43	35 → 38	5–54	9–46	57 → 52	8–49	2–43
PICO	–	–	–	15 → 12	0–12	0–7	0 → 0	0–6	0–7	–	–	–
ABLA	–	–	–	22 → 19	0–5	0–4	17 → 5	3–39	0–32	20 → 17	0–12	0–4
HERB	25 → 67	0–40	0–44	–	–	–	0 → 0	0–4	0–15	4 → 13	1–17	0–40
SHRUB	0 → 1	0–39	0–88	0 → 0	0–0	0–39	0 → 0	0–8	0–9	–	–	–
OTHER	1 → 1	0–10	0–2	1 → 14	0–8	0–10	5 → 13	1–63	0–32	3 → 1	0–6	0–4

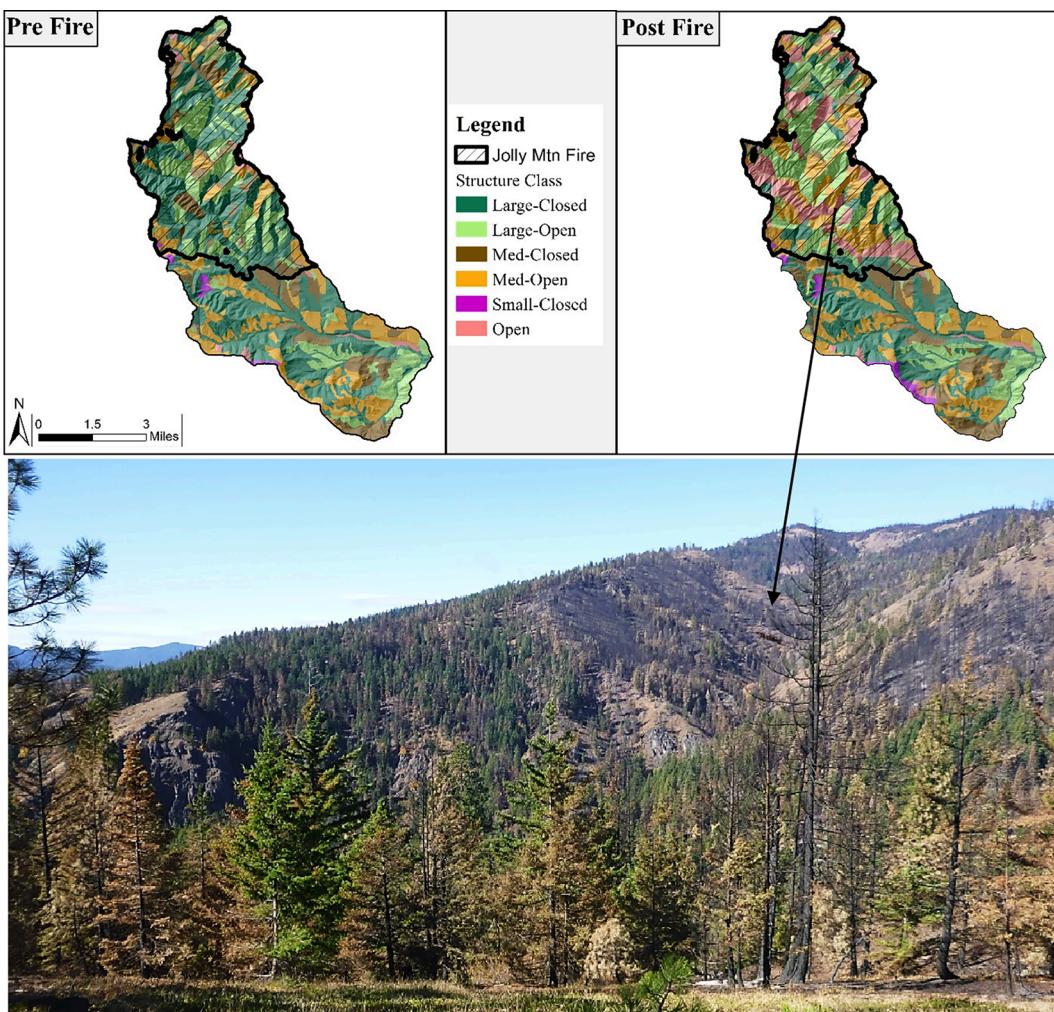


Fig. 5. Top panel: pre- (left) and post-fire (right) forest structure classes in the West Fork Teanaway subwatershed. The wildfire reinforced and further compounded the pre-fire fragmentation of this landscape relative to the HRV and FRV. Bottom panel shows photo of high-, moderate-, and low-severity patches created by the Jolly Mountain Fire in 2017 in the West Fork Teanaway subwatershed. See Table 2 for structure class definitions. Photo: Scott Downes.

to the large-open, medium-open, and open classes. However, the large-open class is still relatively rare (5% PL), and the MPS is at the low end of the HRV and FRV ranges. While not affected much by the fire, the large-closed class occupies less than 10-percent of the landscape, which is below the HRV and at lower end of the FRV reference range. Likewise, the MPS of large-closed is lower than both reference ranges. Douglas-fir and subalpine fir cover types were reduced and mostly converted to

herbland (Table 3), but are still above both reference ranges. Ponderosa pine and western larch increased slightly.

Overall, the fire shifted forest conditions in the direction of lower canopy cover and reduced tree size and canopy complexity (Fig. A4E). Pre-fire, the landscape was already below the HRV range for tree size and canopy complexity, but at the upper end of both reference ranges for canopy cover. Medium and larger size patches of closed-canopy forest

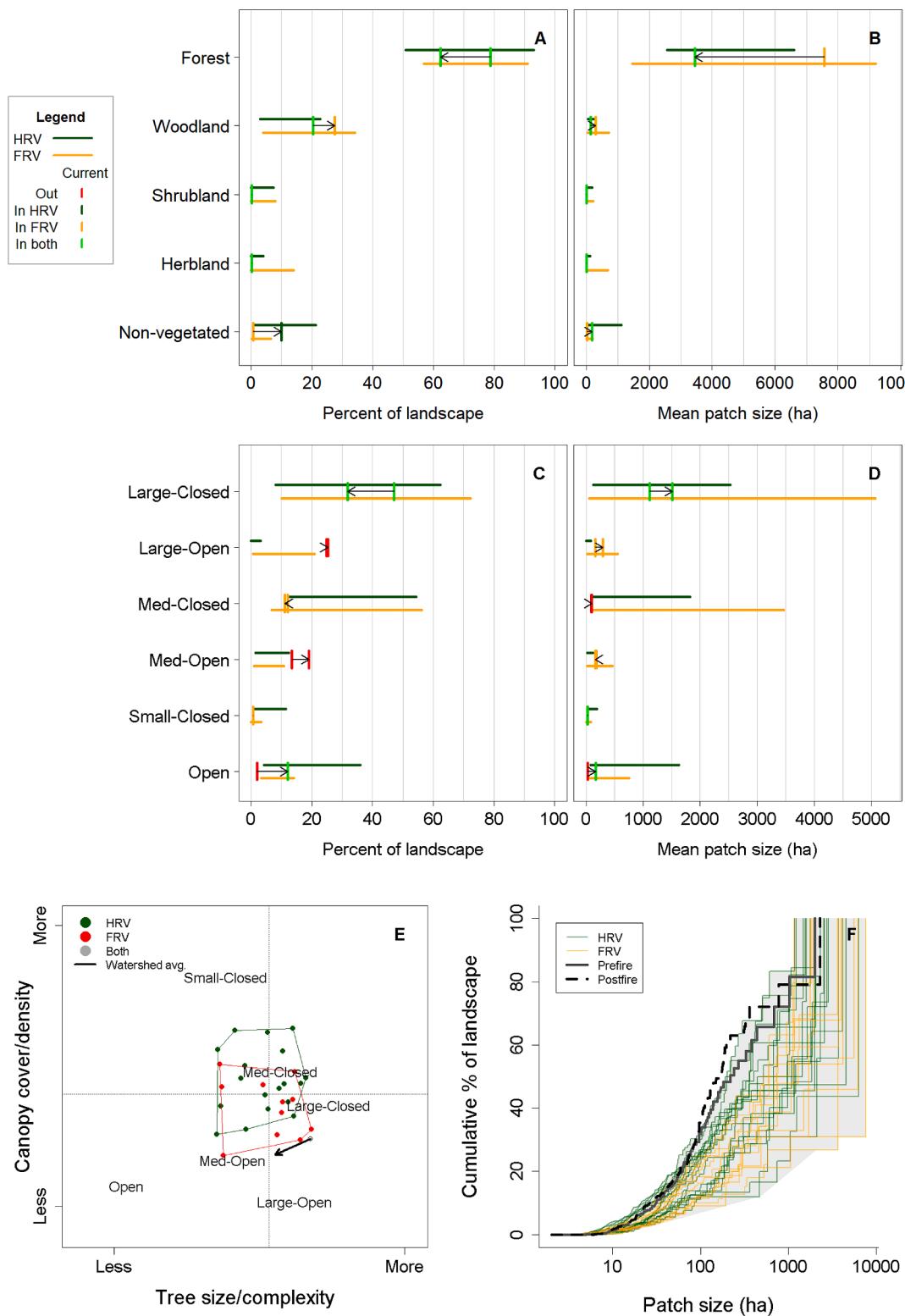


Fig. 6. Pre- and post-fire pattern metrics for the West Fork Teanaway subwatershed. The upper and middle rows display the percentage of landscape area (left) and area weighted mean patch size (right) for physiognomic types (A,B) and forest structure classes (C,D) relative to the historical (HRV) and future (FRV) reference ranges. Arrows show the direction of change from pre to post-fire conditions. “Out” indicates that the current condition for the metric of interest is outside of both reference ranges. “In” indicated that the current condition for the metric of interest within one or more reference ranges. Panel E shows principal components analysis (PCA) of 6 forest structural attributes. Green and red dots show area-weighted centroids of the HRV and FRV sample subwatersheds of an ecological subregion. The arrow shows the fire-caused forest structural change in PCA space, with the arrow pointing from the pre-fire centroid to the post-fire centroid. Panel F displays cumulative patch size distributions of structure classes for pre- and post-fire patches. Each yellow (FRV) and green (HRV) line within panel F shows the cumulative patch size distribution for an individual reference subwatershed. See Table 2 for physiognomic type and forest structure class definitions.

were broken apart by generally small patches of high- and moderate-severity fire (Fig. 2, Fig. A3). This further fragmented the landscape, which was already close to the fragmented side of the patch size distribution relative to both the HRV and FRV ranges prior to the fire (Fig. A4F).

3.5. Effect of burn severity on forest structure class transitions.

Wildfires burning at different severities drove predictable transitions in forest structural classes (Fig. 7). Most of the area that burned at low-severity across all four subwatersheds remained in the same structure class. However, low-severity fire did shift the medium-closed class to medium-open in some cases, and also caused transitions from medium-to large-size classes. Moderate-severity fire had a wide range of effects, including shifting dense, medium-and large-tree forest to medium-open and large-open classes. The medium- and large-tree open classes generally remained in the same class, but tree size was changed in some cases in both directions. The predominant effect of high-severity fire was to move the closed classes into the open class. The large-open classes that burned at high-severity often remained in the same class, although some patches were converted to open. Also, the large open was shifted to medium-open in some cases.

4. Discussion

Wildfire proved to be a blunt restoration tool. The mixed effects were

not surprising given that the wildfires we assessed burned during hot and dry conditions in landscapes that had experienced over a century of fire exclusion, extensive timber harvest, and minimal mechanical fuels reduction and prescribed fire treatments. The fires shifted some landscape-level attributes towards or within the bounds of the HRV and FRV reference ranges, while other fire effects reinforced or compounded prevailing departures or created new ones. The wide variation in fire effects we observed was expected, yet common themes emerged from our evaluations. By design, our analysis was conducted shortly after each fire. Some of the fire induced changes will be mediated by rapid vegetation re-growth, while others will persist for many decades or longer.

By comparing the effects of wildfires on landscapes with different topo-edaphic conditions, pre-fire vegetation, and fire weather conditions, we gained insight into the extent to which wildfires of different severities achieved four key landscape restoration principles (Hessburg et al., 2015; Larson et al., 2022). The following sections describe the work of each wildfire in light of these principles:

4.1. Progress towards shifting the amount and pattern of forest, woodland, and non-forest vegetation types to within the HRV and in the direction of the FRV.

Three of the four wildfires (in the Boulder, Teanaway, and Scatter subwatersheds) reversed, to varying degrees, the increase in forest and loss of woodland, grassland, and shrubland patches that were

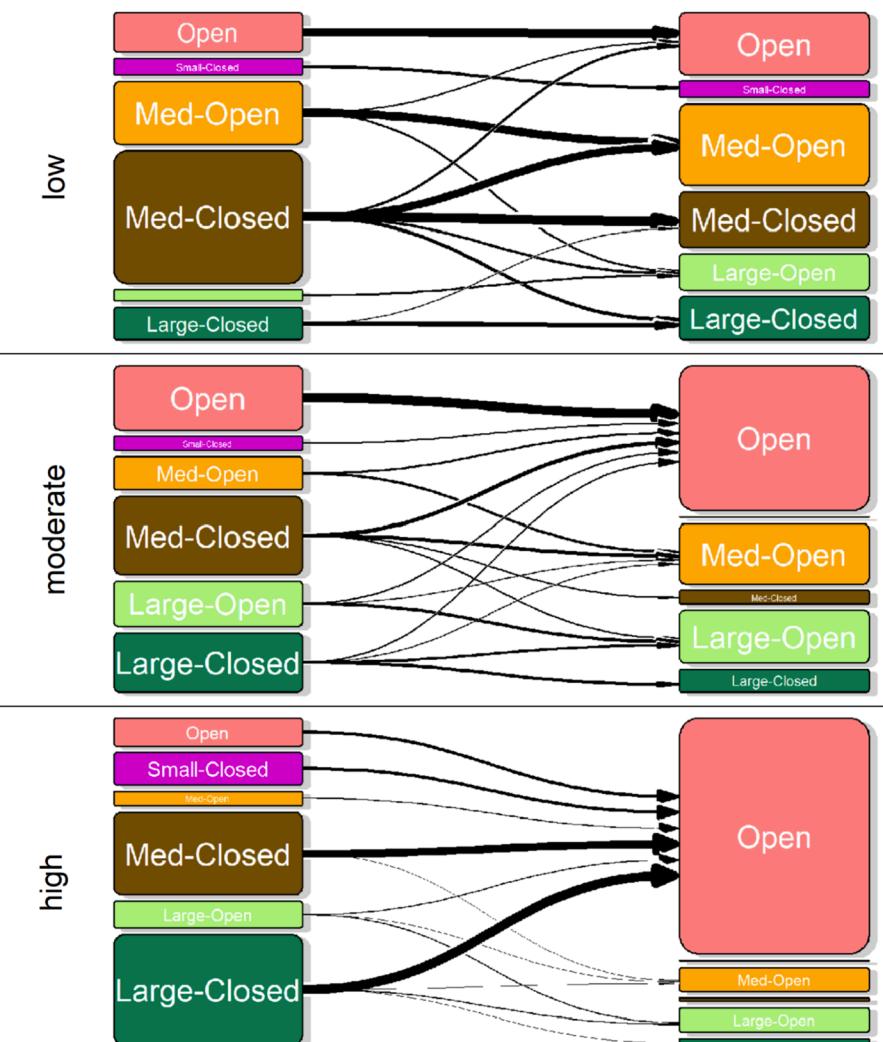


Fig. 7. Flow diagrams showing transitions in forest structural classes caused by three wildfire severities pooled across the four study subwatersheds. The lines with arrows show the transition pathways. The width of the lines are proportional to the amount of area that followed each pathway. The height of the boxes are proportional to the total area of each structure class in the pre- (left side) and post-fire (right side) pooled sub-watersheds for each fire severity class. Low severity is 0–25%, moderate severity is 25–75%, and high severity is 75–100% of pre-fire basal area consumed, respectively. Minor transitions (<2% of the area) are not shown in order to enhance the readability of the figure. See Table 2 for structure class definitions.

historically common in the Interior Columbia Basin and elsewhere in western North America (Dickinson 2014, Hessburg et al. 2019, Coop et al. 2020 p. 2016, Bielski et al. 2021, Hagmann et al. 2021). These fires generally shifted physiognomic patterns towards or beyond the HRV ranges and to within the FRV ranges. These fires burned with a relatively balanced range of high- and moderate-severity fire patch sizes. Sufficient forest area and patch sizes were maintained due to the substantial area that burned at low- to moderate-severity.

By reducing the dominance of large forest patches ($\geq 25\%$ tree cover) and increasing the number and size of other physiognomic patch types, these fires likely enhanced the hydrological and wildlife habitat functions associated with non-forest patches (Stephens et al. 2021b). In addition, the more varied patchworks of different vegetation types, forest structure, and fuel profiles will promote heterogeneous severity patterns in future fires (Collins et al. 2009, Coop et al. 2016, Stevens-Rumann et al. 2016). Depending on size and location, these non-forest patches will likely encourage a more climate adapted fire regime by facilitating spread of low-intensity, short flame length fire to surrounding forest patches, thereby inhibiting the spread of high-severity fire and insect outbreaks (Hessburg et al. 2019).

Post-fire, early-seral conditions are highly dynamic (Swanson et al. 2011), especially in moist and cold forests. Given that most of the high-severity patches are in moist and cold forest types in these three landscapes, we expect that many areas will transition back to forest or woodland within 10–20 years due to high regeneration rates in these forest types and the smaller sizes of some high-severity patches (Povak et al. 2020a). Yet some of these high-severity areas will likely become long-term shrublands, grasslands or broadleaf deciduous forest patches (Shinneman et al. 2013), depending on conifer seed rain availability from surviving trees, adjacency to forest patches, subsequent reburns, and future climatic conditions (Kemp et al. 2016, Stevens-Rumann and Morgan 2016, Cansler et al. 2018). Broadleaf deciduous forest patches, especially quaking aspen, were another key to forest landscape resilience under historically active fire regimes, owing to the moist site and fuel conditions associated with them (Hagmann et al. 2021).

In contrast, the extreme fire weather driven Carlton Complex fire in the dry forest dominated Benson Creek landscape moved physiognomic conditions away from more climate adapted conditions by homogenizing landscape pattern (Prichard et al. 2020). The 6,822 ha patch of herland created by the fire pushed the area weighted mean patch size (MPS) and percent land (PL) of herland well beyond the HRV and FRV references ranges. Pre-fire patches of woodland were also consumed and eliminated from this large burn patch. While patches of high-severity fire provide important habitat elements for many species (Swanson et al. 2011), large ($\geq 10^3$ ha) high-severity burn patches in pine and dry mixed-conifer forest were very rare historically (Hagmann et al. 2021) and can lead to declines in wildlife diversity (Jones et al. 2021, Steel et al. 2021).

Much of the herland patch will not likely return to a woodland or forest condition due to a lack of nearby conifer seed rain and the current and projected high moisture deficits for this area (see moisture deficit projections in (Larson et al., 2022)). Furthermore, surface fuel beds will quickly rebuild due to a combination of grass accumulation and woody fuels from fire-killed trees (Lutz et al. 2020). This will facilitate future reburns that will likely kill most small trees that are able to establish, further reducing the likelihood of forest recovery (Coppoletta et al. 2016, Stevens-Rumann and Morgan 2016, McIver and Ottmar 2018, Lydersen et al. 2019, Cansler et al. 2022). The snags and early-seral plant communities in this patch will provide habitat for post-fire specialists for one to two decades (Hutto 2006) until the dead wood decomposes or is consumed by future fires.

Options to facilitate a gradual transition to a more climate-adapted patchwork of forest, woodland, herland, and shrubland in this landscape are now greatly limited. The US Forest Service did replant a significant portion of the high-severity burn areas several years after the fire. However, multiple years of dry spring and summer conditions after

replanting are likely to greatly lower survival (North et al. 2019). Future accumulation of fuels and reburns are likely to further impede forest recovery (McIver and Ottmar 2018). The homogenized landscape pattern is thus likely to persist and the functions associated with a more forested landscape will be absent. This combination of increasing moisture stress and large patches of high-severity wildfire are precipitating expansion of non-forest vegetation types across the western US (Chambers et al., 2016; Coop et al., 2020; Coppoletta et al., 2016; Davis et al., 2019; Kemp et al., 2019; Savage and Mast, 2005; Stevens et al., 2021). Monitoring of these high-severity patches is warranted to assess replanted areas, as well as natural tree regeneration and other plant communities that establish.

A potential post-fire management strategy for fire-converted patches is assisted migration of drought-adapted oak species that often increase in abundance after high-severity fires in other regions (Halofsky et al. 2011, Guiterman et al. 2018). While not locally present, populations of Gary oak (aka Oregon white oak; *Quercus garryana*) are present approximately 180 km to the south and west of this area (Pellatt and Gedalof 2014), and could be introduced if the projected future climate is deemed suitable (Case and Lawler 2016).

4.2. Progress towards shifting the pattern and amount of forest structural conditions to within the HRV and FRV.

Wildfires reduced overall forest canopy cover and tree size-canopy complexity in all four burned landscapes to within or slightly outside of the FRV ranges. High-severity fire drove the greatest degree of change by converting closed-canopy structure classes that were at the upper or middle end of both reference ranges to early-seral forest and non-forest vegetation types (open structure class). The open structure class was shifted from the lower end of both ranges to within the FRV ranges or upper end of the HRV ranges in most cases. Moderate- and low-severity fire also shifted some closed-canopy structural classes to more fire- and drought-tolerant medium- and large-tree, open-canopy structural classes, but patch sizes were not significantly increased. Overall, the PL of medium-closed or large-closed structure classes was shifted from the middle or upper end of both reference ranges to the middle or lower end. Patch sizes of closed-canopy classes were generally reduced, but the MPS of these classes remained within the middle to lower end of the HRV and FRV reference ranges.

The large HRV and FRV ranges for many of the structure classes represent a relatively wide array of possible conditions across a landscape. Different parts of the ranges provide different combinations of ecosystem functions that can be more or less resilient to future disturbances. While large high-severity patches in dry and moist mixed-conifer forests, such as occurred in Benson Creek, may abruptly move aggregate canopy cover and forest structure into the FRV, they can set landscapes on a self-reinforcing trajectory towards simplified conditions dominated by young forests and non-forest vegetation types that may lead beyond FRV ranges when future wildfires occur (Cassell et al., 2019; Coop et al., 2016; Rammer et al., 2021; Steel et al., 2021; Stevens et al., 2021). In contrast, wildfires that burn primarily at moderate- and low-severity, such as occurred in Scatter Creek, can increase the area and patch size of large- and medium-tree, open-canopy forest while maintaining sufficient patches of closed-canopy forest. Small- and medium-sized high-severity patches can restore patchworks of forest and non-forest. Such fires result in more biologically diverse landscapes where future fires are more likely to act as stabilizing feedbacks and enhance landscape resilience (Kane et al. 2019, Murphy et al. 2021, Prichard et al. 2021, Taylor et al. 2021, Berkey et al. 2021, Cansler et al. 2022).

Restoring landscape pattern by realigning the spatial arrangement and patch size distributions of forest structure with the topo-edaphic template is another critical aspect of climate adaption (North et al. 2009, Hessburg et al. 2015). The four fires proved to be an imprecise tool in accomplishing this goal. In the Teanaway landscape, extensive timber

harvests in the unburned southern half of the landscape had already fragmented and reduced medium- and large-closed forest. Extensive high-severity fire within the Jolly Mountain fire greatly reduced and further fragmented the remaining closed forest in the northern half the landscape, pushing the cumulative patch size distributions to the very edge or just outside of both reference ranges. Many of the patches of large-closed forest that burned at high-severity were located on climatically favorable sites that are projected to have moisture deficit levels that will support dense, moist mixed-conifer forest in the future (WA DNR 2020). In contrast, most of the closed-canopy forest that remains is located on drier biophysical settings where future climate projections indicate high drought vulnerability and risk of high-severity fire.

This mismatch of forest structure and topo-edaphic conditions will make sustaining a sufficient area, as well as larger patches, of closed-canopy forest very challenging in the future (Spies et al. 2019). Mechanical or fire based treatments to lower fire risk and drought vulnerability in the remaining dense forest will further reduce and fragment closed-canopy forest and push the landscape beyond the FRV range for overall canopy cover. Re-growth of large-closed forest from medium-open or large-open classes will take several decades, if not longer, and future fires are likely to set this back. Similarly, Benson Creek is now vulnerable to a future wildfire moving forest landscape conditions beyond FRV range for canopy cover and structural conditions, particularly as the dense unburned portion of the landscape remains vulnerable to drought (Larson et al., 2022).

The 2015 North Star fire made some progress in reconnecting patterns of forest structure with the topo-edaphic template, but more work is needed. Past overstory removal treatments in the Scatter Creek landscape, combined with fire exclusion, greatly reduced and fragmented large-closed structure to the lower end of the FRV reference range and well below the HRV range, resulting in a pre-fire landscape dominated by medium-closed forest. Low and moderate-severity fire transitioned some medium-closed forest to medium- and large-open forest on south facing slopes and other drier sites, but fire also broke up the larger patches of dense forest in the most favorable topo-edaphic locations.

The Scatter Creek landscape still resides at the upper end of both ranges for canopy cover, however, with a relatively large amount of medium-closed and medium-open forest remaining. Options exist for mechanical and fire-based treatments to further align vegetation with the topo-edaphic template by building larger patches of medium- and large-open forest in drier topo-edaphic locations through treatment of adjacent medium-closed forest (Larson et al., 2022). To fully restore fuelbeds and fire resistance, these large patches can then be treated with prescribed fire or managed wildfire to reduce post-fire fuel accumulation and consume activity fuels from mechanical treatments.

The two wildfires in the Boulder subwatershed moved the amount of open-canopy forest towards the HRV and FRV ranges and helped to reconnect structural conditions with the topo-edaphic template. Low- and moderate-severity fir created somewhat larger patches of open-canopy forest at lower elevations and on south facing slopes, while high-severity fire restored missing early-seral forest at higher elevations. The fires only burned a third of this landscape, however, and more work is needed.

4.3. Progress with conserving closed- and open-canopy patches with large and old trees.

Large and old trees of fire resistant species are the structural backbone of fire-dependent forests and a critical component of forest ecosystem resilience (Franklin and Johnson 2012, Lutz et al. 2012, 2018, Hessburg et al. 2015). Populations of old trees contain high levels of resistance to wildfires (Cansler et al. 2020) and contain a broad base of genetic diversity (Hamrick et al. 1989, de la Mata et al. 2017) that can facilitate regeneration and establishment of climate-adapted tree

provenances, thus aiding forests to naturally adapt to a shifting climate after disturbances (Storfer et al. 2007, Luo and Chen 2013).

Congruent with many other studies, patches of open-canopy, large-tree forest proved to be relatively resistant to wildfire in each of the four landscapes (Stephens et al. 2008, Prichard et al. 2010, Safford et al. 2012, Pawlikowski et al. 2019). Even when this structural class experienced high-severity fire, enough large trees survived to avoid conversion to the open class in many cases. Some large-open patches were converted to non-forest by the extreme weather driven fire in Benson Creek, as well as on steep slopes in the Teanaway subwatershed. However, the overall abundance and MPS of the large-open class remained stable or increased in both subwatersheds due to fire driven transitions from medium- and large-closed to this class.

In contrast, the closed-canopy, large-tree structure class was prone to high- and moderate-severity fire owing to its high vulnerability to crown fire initiation and spread. In the Benson and Teanaway landscapes, fires shifted the PL and MPS of this structure class to the lower to middle end of both reference ranges. Loss of large-tree, closed-canopy forest has been a common feature of many other large wildfires (Taylor and Skinner 1998, Agee and Skinner 2005, Spies et al. 2006, 2018).

The option to treat a portion of the large-closed structure class that burned at high-severity and convert it into more fire- and drought-resistant large-tree, open-canopy forest has been lost (Restaino et al. 2019, Churchill 2021). Intentional, landscape-level restoration treatments prior to these wildfires could have realigned landscape pattern with the topo-edaphic template. Proactive thinning and prescribed burning treatments could have expanded the amount and patch sizes of the large-open class in the more fire- and drought-prone portions of the landscape (Hessburg et al., 2015; USDA, 2012), which would have reduced the likelihood of crown fire transmission to the remaining large-closed patches (Ager et al. 2007, Tubbesing et al. 2019). Furthermore, large-closed structure in the most favorable topo-edaphic and future climatic locations could have been selected for retention (Camp et al., 1997; Spies et al., 2019; Larson et al., 2022), promoting a higher future abundance of fire refugia (Meddens et al. 2018, Krawchuk et al. 2020, Meigs et al. 2020). Promotion of refugia patches on the landscape could potentially be a cost-effective solution to retain a variety of ecosystem services.

Not all of the large-closed structure class burned at high- to moderate-severity, however. The PL and MPS of large-closed forest remained stable in the Boulder and Scatter Creek landscapes. High-severity fire did convert this structural condition to non-forest in some places. This was offset in other locations, however, by low-severity fire shifting medium-closed to this class by thinning out smaller trees and increasing average tree size while maintaining adequate canopy cover ($\geq 50\%$ cover). Other large-closed patches experienced low-severity fire and did not change structural class. In Benson Creek, a number of closed-canopy patches in the southern portion of the subwatershed that had received thinning and prescribed fire treatments persisted through the wildfire (Prichard et al. 2020). These results suggest that large-tree, closed-canopy forest can be sustained in some locations in an active fire regime, and that probable burn severity is more important than burn probability in defining fire refugia (Krawchuk et al. 2020, Meigs et al. 2020).

4.4. Progress with shifting species composition towards drought-adapted, fire-tolerant species.

Wildfires offer an opportunity to transition composition in towards climate- and wildfire-adapted species and phenotypes. Drought- and fire-intolerant species were reduced by the four wildfires in our study, but this reduction was mostly driven by conversion to non-forest by high-severity fire. These early-seral patches offer an opportunity to shift to more drought and fire-tolerant species or phenotypes provided that seed sources are available (Povak et al. 2020a). Alternatively, planting can assist these transitions (Chmura et al. 2011, North et al. 2019) where

forest is likely to persist in the future and is desirable from a physiognomic pattern perspective (see Section 4.1, Larson et al., 2022).

Moderate- and low-severity fire slightly increased the amount of ponderosa pine and western larch cover types in several of the landscapes by reducing understory fire-intolerant species composition. This effect is likely underestimated by photo-interpretation (Lydersen and Collins 2018), as well as other remote sensing methods (Jeronimo et al. 2018, Furniss et al. 2020), because – when observing conditions from above – it is difficult to detect changes in understory structure and composition beneath an overhead canopy, or in the shadows of larger trees. Continued monitoring with field and remote sensing methods could provide longer-term information about regeneration and establishment of desired species after fire (Cansler et al. 2022).

4.5. Study limitations

Quantifying HRV or FRV reference ranges for evaluating landscape-level structural and compositional patterns is challenging in any landscape. While understanding of tree- to stand-level structure and pattern in historical and contemporary frequent-fire forests is well developed (Larson and Churchill 2012, Churchill et al. 2013, 2017, Pawlikowski et al. 2019, LeFevre et al. 2020, Murphy et al. 2021), landscape-level reference data do not exist for many vegetation types across the interior West (Johnstone et al. 2016). Historical imagery is an established empirical data source for establishing reference conditions over large areas, and for quantifying landscape changes (Skinner 1995, Scull et al. 2017, Lydersen and Collins 2018, Calbi et al. 2020). Other sources of reference data, such as simulation modeling (Hemstrom et al. 2014, Keane et al. 2018, McGarigal et al. 2018), early timber inventories (Hagmann et al. 2013, 2014, 2021, Stephens et al. 2018), and LiDAR data from contemporary landscapes with restored fire regimes (Jeronimo et al. 2019) all have advantages, but also their own set of limitations and uncertainties (Keane et al. 2009, Hagmann et al. 2018), particularly with regards to landscape pattern (Keane et al. 2002).

The imagery used to create the historical dataset used in this study is from the 1930 s–1950 s period (Hessburg et al. 1999a). A statistical imputation process was used to replace any harvested trees, as evidence of prior harvesting and type of harvest were photo-interpreted attributes (Hessburg et al. 2013). However, decreased fire frequency in the early part of the 20th century led to increases in forest cover by the 1930–1950 s in many locations in the interior western US (Hagmann et al. 2021). Thus, the HRV and FRV ranges used in this study likely over-represent forest cover, especially in the understory, relative to landscapes with active fire regimes (Hagmann et al. 2017, Lydersen and Collins 2018, Jeronimo et al. 2019). Interpretation of the results of this study should thus be mindful of this reality. We focused on the lower end of HRV and FRV ranges for closed-canopy conditions and the upper end for open-canopy classes to account for this issue. For future studies, both the HRV and FRV reference conditions could be adjusted down for amounts and patch sizes of the forest physiognomic type and closed-canopy structural classes and increased for woodland and open-canopy structural classes. Additional proxy records and simulation modeling discussed in the above paragraph could be used for this purpose.

4.5.1. Management implications and Conclusions

Wildfires in seasonally dry forests of the western US are an inevitable fact of the 21st century. The goal of adaptive forest treatments is to prepare them for climate change and increases in wildfire activity. In the context of wildfire prepared landscapes, most wildfires will function as maintenance treatments, reinforcing the good work of more characteristic wildfires and adaptive treatments. The four wildfires we assessed, however, burned under hot and dry conditions in landscapes that had experienced over a century of fire exclusion, extensive timber harvest, and minimal mechanical fuel reduction and prescribe fire treatments. The results from the work of these four fires provide five important

implications for restoration and climate adaptation efforts.

- 1. Wildfire is a blunt tool in fire-excluded, untreated landscapes.** Wildfires that burn with a characteristic mix of severities and patch sizes can shift landscape towards more climate-adapted, resilient conditions. However, large, uncharacteristic high-severity patches can push landscapes towards simplified conditions outside of FRV ranges. Wildfires often reduce the number and size of large-tree patches and diminish options to restore large tree, open-canopy forest.
- 2. Moderate- and low-severity fire can be a good first entry.** These fires tend to shift closed-canopy forest conditions to more fire resistant and resilient, open-canopy structural conditions and more fire-tolerant species. However, additional fire and/or mechanical treatments are typically needed within 10–20 years to reduce future fuel loads and achieve desired compositional and structural conditions (Prichard et al., 2021; Larson et al., 2022).
- 3. High-severity fire can restore or homogenize patchworks of forest, woodland, grassland, and shrublands.** Large patches of high-severity fire in dry and moist mixed-conifer forests homogenize physiognomic patterns by converting large forest areas to grassland or shrubland (Stevens et al., 2017; Singleton et al., 2021), raising their vulnerability to short interval reburning and limiting future developmental trajectories. Small-, as well as some medium-sized, high-severity patches can restore self-reinforcing patchworks of forest and non-forest vegetation that build resistant to future large, high-severity fires.
- 4. Wildfires can compound pre-existing departures in landscape patterns.** Wildfires burning during extreme fire weather conditions are unlikely to realign forest conditions that have been disconnected from the topo-edaphic template by past timber harvesting and fire exclusion. Instead, they can reinforce existing mismatches by compounding overly homogeneous or fragmented patterns (Zald and Dunn, 2018). Mechanical treatments that heavily reduce canopy cover over large areas and overly fragment landscape pattern – further mismatching conditions to the topography – may result in wildfires that reduce the amount and patch sizes of closed-canopy forest beyond FRV ranges. Alternatively, treatments that are heavily focused in one part of the landscape, while leaving large patches of closed-canopy forest in fire- and drought-prone locations, can set up landscapes for future high-severity disturbances.
- 5. Integration of landscape-level restoration treatments with strategic wildfire response can best adapt landscapes to future climate.** Mechanical and prescribed fire treatments that intentionally prepare landscapes for fire by following landscape restoration principles (Hessburg et al., 2015; Stephens et al., 2021a) will likely result in more positive outcomes from coming wildfires, which can then be allowed to do further adaptive work (Hessburg et al. 2021, North et al. 2021). This is analogous to how a combination of mechanical thinning and prescribed fire are the most effective stand-level treatments (Hudak et al. 2011, Safford et al. 2012, Cansler et al. 2022). When wildfires occur in untreated or partially treated landscapes, wildfire response strategies based on informed risk analysis can allow fires to accomplish positive work during moderate fire weather, while suppressing and containing fires in high-risk locations or during unfavorable weather periods (Young et al., 2019; Dunn et al., 2020). Post-fire management can then further the good work of wildfires where necessary or ameliorate negative effects (Meyer et al., 2021; Stevens et al., 2021; Larson et al., 2022).

While the work ahead is daunting, time tested knowledge and tools exist to prepare landscapes for a warmer and drier future with more fire (WA DNR 2020, Prichard et al. 2021). Over time, these methods can help re-establish wildfire as a helpful ecosystem process that also maintains safer landscapes for people, instead of a catastrophe to be feared and suppressed.

CRediT authorship contribution statement

Derek J. Churchill: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Formal analysis, Visualization, Data curation, Funding acquisition. **Sean M.A. Jeronimo:** Conceptualization, Methodology, Formal analysis, Visualization, Data curation, Writing – review & editing. **Paul F. Hessburg:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Project administration. **C. Alina Cansler:** Conceptualization, Writing – review & editing. **Nicholas A. Povak:** Conceptualization, Methodology, Writing – review & editing. **Van R. Kane:** Writing – review & editing, Project administration. **James A. Lutz:** Conceptualization, Writing – review & editing. **Andrew J. Larson:** Supervision, Project administration, Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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