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Cascadia Burning: The historic, but not historically unprecedented, 2020 wildfires in the Pacific Northwest, USA

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Abstract

Wildfires devastated communities in Oregon and Washington in September 2020, burning almost as much forest west of the Cascade Mountain crest ("the westside") in 2 weeks (~340,000 ha) as in the previous five decades (~406,00 ha). Unlike dry forests of the interior western United States, temperate rain forests of the Pacific Northwest have experienced limited recent fire activity, and debates surrounding what drove the 2020 fires, and management strategies to adapt to similar future events, necessitate a scientific evaluation of the fires. We evaluate five questions regarding the 2020 Labor Day fires: (1) How do the 2020 fires compare with historical fires? (2) How did the roles of weather and antecedent climate differ geographically and from the recent past (1979–2019)? (3) How do fire size and severity compare to other recent fires (1985–2019), and how did forest management and prefire forest structure influence burn severity? (4) What impact will these fires have on westside landscapes? and (5) How can we adapt to similar fires in the future? Although 5 of the 2020 fires were much larger than any others in the recent past and burned ~10 times the area in high-severity patches >10,000 ha, the 2020 fires were remarkably consistent with historical fires. Reports from the early 1900s, along with paleo- and dendro-ecological records, indicate similar and potentially even larger wildfires over the past millennium, many of which shared similar seasonality (late August/early September), weather conditions, and even geographic locations. Consistent with the largest historical fires, strong east winds and anomalously dry conditions drove the rapid spread of high-severity wildfire in 2020. We found minimal difference in burn severity among stand structural types related to previous management in the 2020 fires. Adaptation strategies for similar fires in the future could benefit by focusing on ignition prevention, fire suppression, and community preparedness, as opposed to fuel treatments that are unlikely to mitigate fire severity during extreme weather. While scientific uncertainties remain regarding the nature of infrequent, high-severity fires in westside forests, particularly under climate change, adapting to their future occurrence will require different strategies than those in interior, dry forests.

KEYWORDS
2020 Labor Day fires, dry, east wind, fuel management, high-severity fire, moist forests, western Cascades

INTRODUCTION

The 2020 wildfire season in the western United States was not only record-setting in terms of area burned (Higuera & Abatzoglou, 2021), but large fires also affected forest types that rarely burn. The wildfires that burned through the temperate rain forests of the "westside" of the Cascade Mountain Range in the Pacific Northwest (Figure 1a) were striking in their scale, speed, and severity, as well as their devastating societal impacts. Westside forests extend from the crest of the Cascade Mountains to the Coast Range and Olympic Peninsula along the Pacific Coast and include some of the most productive and biomass-rich terrestrial ecosystems in the world, harboring unique old-growth biodiversity (Figure 1b,c; Spies et al., 2018; Waring & Franklin, 1979), as well as short-rotation Douglas fir (*Pseudotsuga menziesii* var. *menziesii*) plantations that are economically important in the region (Figure 1d). In combination with long intervals between large, severe fires, the exceptional productivity of these forests supports some of the world's largest trees and one of the most densely vegetated ecosystems globally, meaning they naturally contain substantially more biomass, carbon, and fuel than most drier, fire-prone forests elsewhere in the western United States (Smithwick et al., 2002).

While the frequency of large wildfires has increased across the western United States in recent decades (Higuera & Abatzoglou, 2021), temperate rain forests on the westside have experienced limited fire activity for more than a half a century (Reilly et al., 2017). However, between 7 and 9 September 2020, a series of wildfires (collectively known as the Labor Day fires) burned almost as much area of the westside (~292,500 ha) within a 48-h period as in the prior three decades combined (406,128 ha). Five of these in the Oregon Cascade Mountains each grew to more than 50,000 ha (Figure 2), and the fires ultimately burned a total of approximately 340,000 ha on the westside (Appendix S1: Table S1). Approximately 90,000 people were evacuated from their homes, and over half a million were placed on evacuation alert. Western Oregon experienced the worst air quality in the world for almost 2 weeks, and between US$6 and $7 billion worth of property was destroyed by fire (Oregon Office of Economic Analysis, 2020).

The 2020 Labor Day fires caught much of society by surprise, illustrating the need for an evaluation of what occurred during this event, what drove it, and to what

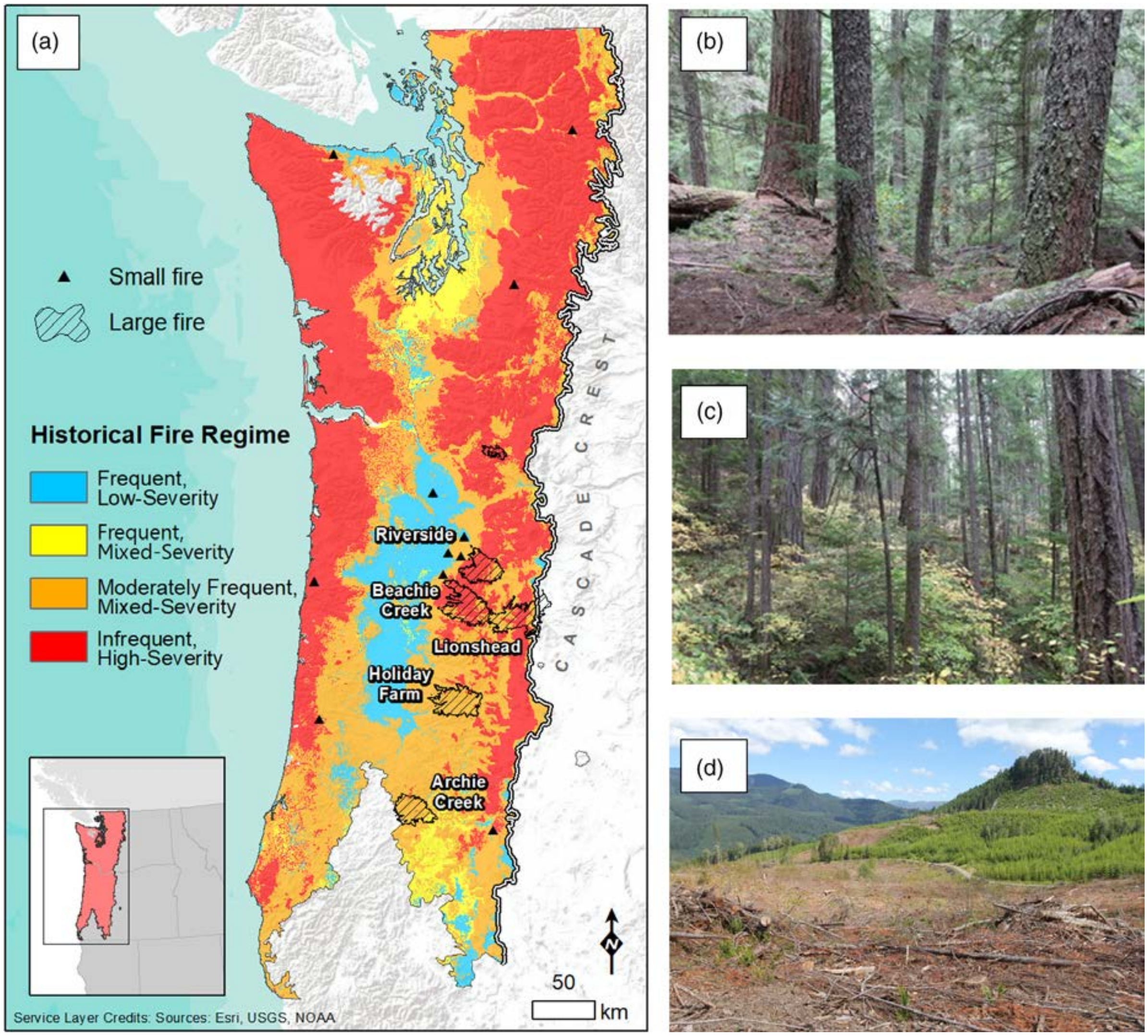

FIGURE 1 (a) Historical fire regimes (Reilly et al., 2021) and 2020 fire perimeters in western Oregon and Washington ("westside"), (b) old-growth forest structural conditions, (c) late-seral conditions with hardwood component, and (d) a recently harvested stand with a dense, young Douglas-fir plantation in background

extent such events are unprecedented. Before the smoke cleared, hypotheses proliferated in the media on the drivers of the Labor Day fires and what might be done to mitigate similar fires. These hypotheses reflect the diversity of beliefs and attitudes toward wildfire, climate change, and forest management in the Pacific Northwest. Conflicting, uncertain, and oversimplified explanations of the 2020 Labor Day fires signal how unfamiliar modern society is with wildfires in wetter forest types of the western United States, in part because much of what we know about fire, fuels, and climate in drier forests, where fires are more frequent, cannot be readily transferred to wetter forests (Halofsky et al., 2018; Spies et al., 2018).

Here, we provide a scientific examination of the 2020 Labor Day fires and evaluate their precedence in the historical record. We then explore the implications of our assessment in terms of forest management and wildfire risk reduction. Such an evaluation is essential as land managers, policy makers, and the general public begin to incorporate the future potential of such fires into their decision making. Key questions we address include the following: (1) How do the 2020 Labor Day fires compare with known historical fires on the westside? (2) How did the roles of weather and antecedent climate differ geographically and from the recent past? (3) How do fire size and severity compare to other recent fires (1985–2019), and how did forest management and prefire forest structure influence burn severity? (4) What impact will these fires have on westside landscapes? (5) How can society adapt to similar fire events in the future? We address these questions through literature review, historical observations and evidence, and new data analysis.

While complete answers to these questions will be refined over the next several years and decades of postfire

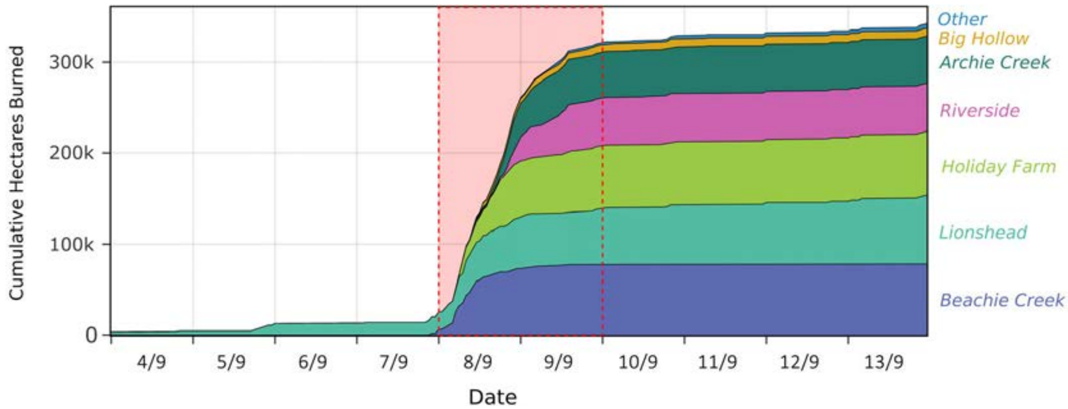

FIGURE 2 Hourly area burned in the Labor Day 2020 wildfires between 4 and 13 September based on cumulative hotspot detections within fire perimeters from the GOES-R Advanced Baseline Imager (Schmidt, 2020). The area highlighted in red represents the period of maximum fire growth where approximately 300,000 ha burned in a 48-h period. See Figure 1a for map of fire locations.

research, sufficient evidence is available in the immediate aftermath of the fires to shed light on the likely drivers and effects of the largest fires. This exploration of the larger context around the Labor Day fires provides perspectives that are missing from the dialogue, identifies key science gaps, generates hypotheses, and better distinguishes what can (and cannot) be done to mitigate and adapt to future wildfire events on the westside of the Cascade Mountains.

THE SETTING: FIRE REGIMES AND LAND-USE LEGACIES OF THE WESTSIDE

Historical fire regimes of the westside vary along gradients in summer precipitation, summer temperature, and ignition frequency (Figure 1a; Agee, 1993; Reilly et al., 2021). The climate is Mediterranean, and summer drought is the dominant pattern with warmer and drier summers at lower elevations inland and to the south. Annual precipitation ranges from over 350 cm in coastal areas and at higher elevations in the Olympic and western Cascades of Washington to approximately 100 cm at lower elevations around inland valley margins and in the southern part of the Oregon western Cascades. Most precipitation occurs during the winter, and the highest elevations receive significant snow, which often persists into June or July.

Fire history studies and observations of early 20th-century fires indicate that large, infrequent high-severity fires are characteristic of historical fire regimes in mountainous areas of the westside (Agee, 1993; Reilly et al., 2021; Spies et al., 2019). Native American burning was particularly important in and around the Willamette Valley and Puget Lowlands, which were predominated by open woodlands and/or hardwoods. Native American burning was also common in some mountainous areas to promote resources such as huckleberries (*Vaccinium* spp.) and beargrass (*Xerophyllum tenax*) (Richards & Alexander, 2006; Robbins, 1999), though the extent to which this burning affected more remote mountainous areas outside of the Puget Lowlands and Willamette Valley is less certain. We focus on the (1) infrequent, high-severity and (2) moderately frequent, mixed-severity fire regimes (Figure 1) where the vast majority of the 2020 Labor Day fires burned, and do not include the drier westside landscapes that historically experienced frequent low severity and high-frequency, mixed-severity fire regimes.

An infrequent (>125 years), high-severity fire regime (Agee, 1993) occurs across the northern, coastal, and higher elevation forests of the westside (Figure 1a), where climate is wetter and cooler, and lighting ignitions are less common. Very large fires (10^5–10^6 ha) occurred on centennial scales, with extensive patches of high-severity fire (i.e., stand replacing, with near complete tree mortality; Agee, 1993; Donato et al., 2020; Fahnestock & Agee, 1983) within a matrix of lower burn severities. Southern portions of the region (i.e., low to mid-elevations in central western Oregon) were primarily characterized by a moderately frequent (35–125 years), mixed-severity regime (Figure 1a) related to longer and more intense summer drought and greater frequency of ignition from lightning and Native American burning (Walsh et al., 2015). These forests were also occasionally subject to very large high-severity fires that reset forest succession over broad areas (Agee, 1993). However, non-stand-replacing fires occurred multiple times a century in between large stand-replacing events, diversifying pathways of structural and successional development, while maintaining a mixed-age structure of early and late-seral conifers (Tepley et al., 2013).

Most forests in the region bear legacies of European colonization in the mid- to late 1800s. Large fires ignited by colonizers for land clearing, as well as by early logging operations, occurred through the early 1900s (Morris, 1934). More than a century of clear-cut logging began at lower elevations on private lands that are currently either developed or managed under short-rotation harvests (~40–70 years) on industrial forests (Cox, 2010). Logging on federal (e.g., US Forest Service and Bureau of Land Management) lands began in the 1920s, peaked in the 1970s and 1980s, and then declined abruptly with the listing of the endangered northern spotted owl (*Strix occidentalis caurina*) in 1990 and the adoption of the Northwest Forest Plan (NWFP) in 1994 (Thomas et al., 2006). The NWFP reduced clear-cutting of older forests (>80 years) on federal lands within the range of the northern spotted owl and established an extensive system of large (10^3–10^5 ha) Late Successional Reserves (LSRs) to conserve existing and future old growth and buffer the regional distribution of old growth from large fires (Johnson & Swanson, 2009; Spies et al., 2019). While young and maturing plantations dominate much of the lower and middle elevations on private and federal lands, unlogged mature and old-growth forests, some dating back to fires in the 1500s, still remain across millions of hectares on federal lands (Spies et al., 2019).

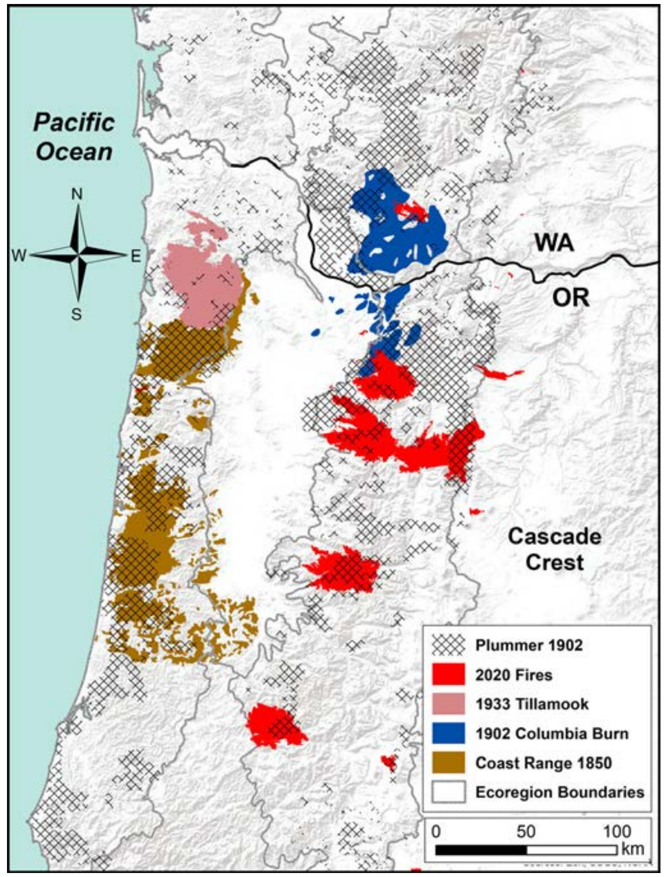

FIGURE 3 The southern portion of the Westside showing the largest of the 2020 fires along with perimeters of known large historical fires and mapped extent of "stand-replacing fire" in 1900 and 1902 (where "destruction of timber was nearly or quite complete … areas … with only a partial destruction are not here represented"). Burned forest patches in 1902 were digitized from Thompson and Johnson (1900) and Plummer et al. (1902). The complete regional extent of the 1902 burned areas is in Figure 4.

How do the Labor Day fires compare to historical fires?

Early records and 20th-century maps of burned areas indicate that the 2020 fires were not unprecedented in size and severity, and either burned within, or in close proximity to, areas that burned in large fires following European colonization (Figure 3). The Silverton Fire of the late 1860s reportedly burned >400,000 ha to the south of Mt. Hood, and the effects were likely still apparent during 1902 land surveys, but it is unknown whether this was all one versus multiple fires, as there is little historical documentation to confirm the exact location and year of the fire (Morris, 1934). The Columbia Fire in 1902 burned approximately 70,000 ha in Multnomah and Clackamas counties (Cox, 1902) near the 2020 Riverside Fire in Oregon, as well as ~180,000 ha in southwestern Washington (a.k.a. the Yacolt Fire), near the 2020 Big Hollow Fire. Other fire perimeters demonstrate that much of the area burned by the 2020 Beachie Creek, Holiday Farm, and Archie Creek Fires also burned in the early 1900s. In addition to the legendary Tillamook Burns, more than 500,000 ha burned in the Oregon Coast Range in the "Great Fires" of the 1850s and 1860s (Morris, 1934; Munger, 1944; Teensma, 1987; Zybach, 2004; Figure 3). Paleoecological records from charcoal in Battleground Lake indicate an even larger fire event in southwest Washington around 1350 AD (Walsh et al., 2008), and dendroecological records suggest large fires associated with drought on Mt. Rainier in southwest Washington since the 1200s (Hemstrom & Franklin, 1982). There is also evidence of extremely large wildfires (10^6 ha) on the Olympic Peninsula and in northern Washington in the 1100s, 1300s, 1500s, and 1700s (Appendix S2: Table S1; Henderson et al., 1989).

Common to both the infrequent, high-severity and the moderately frequent, mixed-severity westside fire regimes, there appears to be a clear "recipe" for the largest fire events: late-summer drought, an ignition, and perhaps most importantly, a strong synoptic east-wind event (Agee, 1993). First-hand accounts of 20th-century fires tell a consistent story of strong, dry east winds as the key driver of large, high-severity fires that initially began as small slash and land-clearing fires ignited by early European colonizers (Dague, 1929; Joy, 1923; Morris, 1934). Instrumental records quantifying wind conditions in historical fires are, however, limited. First-hand observations of the Tillamook Burn in the Oregon Coast Range (~105,000 ha) note low relative humidity (<25%) and average wind speeds from the east greater than 8 m/s during a period in which ~90,000 ha burned in a single 30-h period on the 25 and 26 August 1933 (Dague, 1934; Morris, 1934). Most of the Yacolt Fire (~180,000 ha) in southwest Washington burned during an east-wind event on the night of 11 September 1902 (Morris, 1934). Although fires were less widespread than in 1902, drought and fire weather conditions were worse in 1929, when ~19,000 ha burned from 6 to 8 September in Marion County, Oregon (Dague, 1929), and ~85,000 ha of the Yacolt Fire were reburned by the Siouxon Fire on 15 September. Numerous accounts from the late 1800s and early 1900s document extensive fires in late summer and early fall that shrouded the westside in smoke, threatening lives, and infrastructure, with details and timing bearing eerie similarity to the 2020 Labor Day fires (Morris, 1934).

Dry, east winds are rare early in the summer, but increase in frequency in mid-August and continue through September until the fall rains begin. This wind pattern was documented more than a half a century ago when Cramer (1957) examined data from the Portland airport (1931–1941 and 1948–1954) and identified a specific window of vulnerability to dry, east-wind days, defined by two or more hours with relative humidity <36% and wind speed >4 m/s. When applied to gridded weather reanalysis data, this threshold highlights distinctive geographic patterns of dry, east-wind frequency, duration, and magnitude during the late summer on the westside (Figure 4). Historical fire perimeters around the Columbia River Gorge and the central Cascade Mountains correspond well with regional hotspots of relatively frequent occurrence of dry, east winds. Dry, east winds are less frequent and generally lower in speed and duration in the cooler and wetter northern part of the Washington western Cascades and Olympic Peninsula, where there were fewer large fires following early European colonization. In the Oregon Coast Range, where large fires occurred in the 1850s and again in the Tillamook Burns from 1933 to 1951 (Figure 4), dry, east winds are infrequent but exceptionally strong. The influence of dry, east winds on fire size is complex, and even locations where events are rare can still be vulnerable

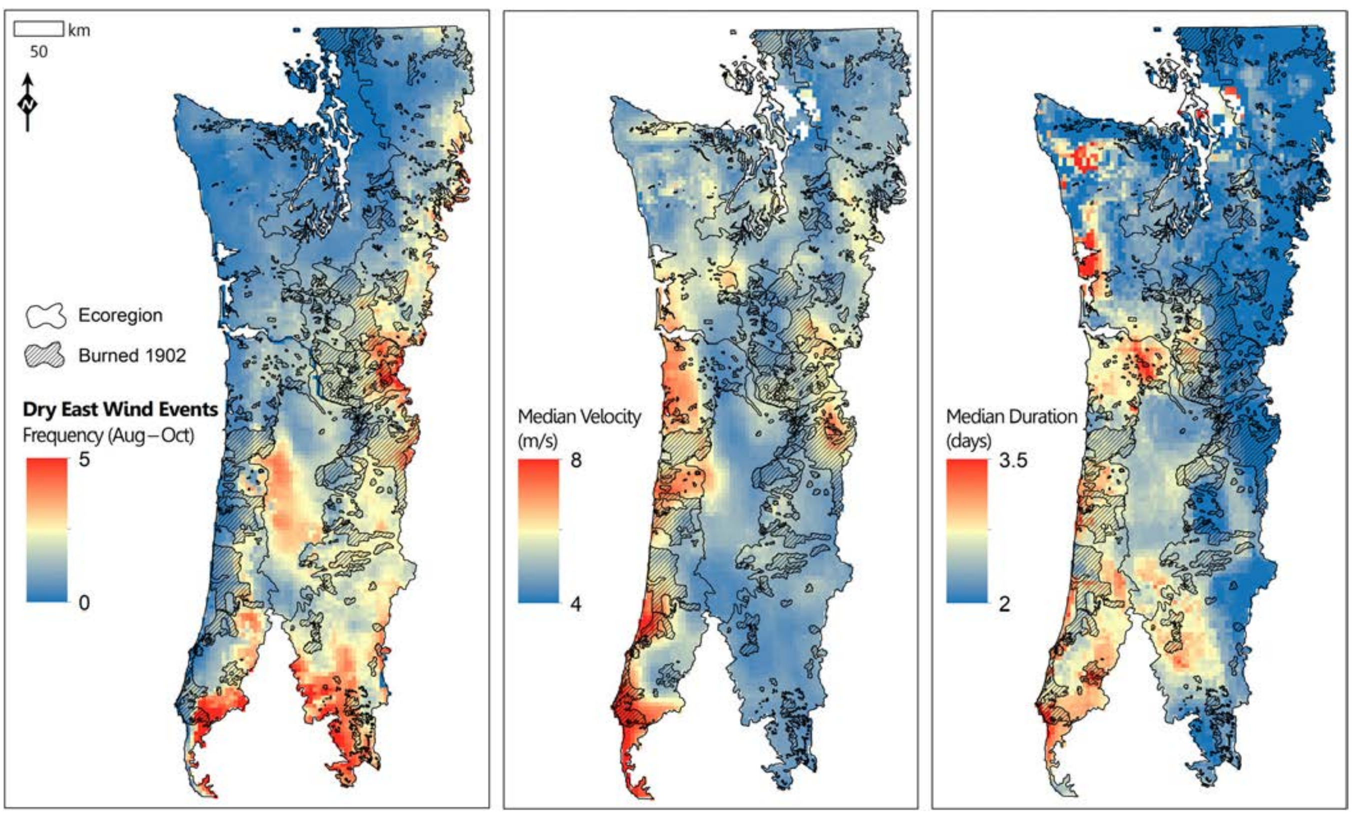

FIGURE 4 Geographic patterns of the annual frequency, magnitude, and duration of dry, east-wind events from August to October 1979–2021, and patches of "stand-replacing fire" in 1902 (Thompson and Johnson 1900, Plummer et al. 1902; see Figure 3 for more details on 1902 perimeters). Dry east-wind events were characterized following Cramer (1957), and the map was derived from gridMET data from 1979–2021 (Abatzoglou 2013). Event days are based on Cramer (1957) "major east wind day criteria" and do not specifically represent regional wind events such as the one that drove the 2020 fires. These maps also likely underestimate wind at high elevations, mountain passes, and other areas subject to topographic channeling of winds.

to large, high-severity fires, particularly if winds are stronger and events last longer.

While the 2020 Labor Day fires were unprecedented with respect to human time scales and societal impacts (i.e., generational events), there is substantial evidence from both historical and paleoecological records that very large, severe fires like the 2020 fires are characteristic of historical fire regimes on the westside. The seasonal timing, locations, fire sizes, and conditions of the 2020 fires were all consistent with historical evidence of past fires that reached similar and even larger sizes, producing heavy, persistent smoke and resetting forest ages across large parts of the region.

How did the roles of weather and antecedent climate differ geographically and from the recent past (1979–2019)?

Analysis of the climatic and weather conditions leading to the Labor Day fires in Oregon shows that they were driven by a highly anomalous combination of drought and wind conditions (Abatzoglou et al., 2021; Mass et al., 2021), but less is known about how these varied across the region. Why did fires in some portions of the region "blow up" while others did not? As atmospheric conditions for a regional wind event developed during the first week of September, several fires were burning in western Oregon and Washington. Five of these in the Oregon Cascades quickly grew to >50,000 ha (Figure 2), while others in the Coast Range and Washington Cascades caused substantial losses but remained relatively small. Given the rarity of such regional fire events on the westside, a retrospective analysis on how geographic variability in drought and wind speed contributed to differences in fire size can help increase understanding of the potential for similar events in the future.

Despite near normal precipitation and snowpack in the region during the prior winter (early April snow water equivalent was 109% of median in Oregon and 113% of median in Washington; Bumbaco et al., 2021), an exceptionally warm spring resulted in rapid snowmelt and effectively lengthened the fire season. By late summer, warm temperatures and low precipitation resulted in anomalous drought conditions across the region relative to 1979–2019 (Figure 5). Two commonly used air and fuel moisture metrics directly related to wildfire potential, Evaporative Demand Drought Index (EDDI; Hobbins et al., 2016; McEvoy et al., 2019) and energy release component (ERC; Bradshaw et al., 1984), were high across the region compared with recent decades. Both metrics intensified over the 2 months leading up to the fires, especially in the 2 weeks immediately preceding the fires (Figure 5).

Both ERC and EDDI indicated greater wildfire potential in Oregon than Washington. Energy release component percentile values showed a latitudinal gradient in the western Cascades, with the most extreme conditions toward the south in Oregon and less extreme conditions to the north in Washington (Figure 5). One week before the fires, ERC values across most of western Oregon exceeded the 80th percentile, with several areas exceeding the 95th and 98th percentiles. Similarly, the EDDI for much of western Oregon exceeded the 98th percentile at the time of the fires. Both metrics were also high in western Washington, but drought conditions developed later in the season and were not as extreme as in western Oregon at the time of the fires.

Beginning late on Sunday, 6 September, a large high-pressure system, stretching from the northeastern Pacific Ocean into northern Alberta, separated into two distinct high-pressure centers. The eastern center, moving over the Rocky Mountains and south over Canada, brought low moisture, subarctic air into the region. At this time, winds over the Oregon Cascades were light and variable in direction. However, by early afternoon on 7 September, a low-pressure system moved around the east flank of the eastern high-pressure center. Traveling from northeast to southwest with cold, dry continental air from the interior, this uncommon atmospheric trajectory initiated a synoptic east-wind event that started on 7 September (Figure 6; Mass et al., 2021). Although uncommon, this atmospheric trajectory is characteristic of the region and creates critical fire weather conditions, as the cool air warms and further dries as it descends the west slope of the Cascades (Schroeder et al., 1964).

Automated weather stations (Remote Access Weather Stations [RAWS]) in the vicinity of several of the fires (Figure 6) recorded anomalously dry, east winds that persisted for 3–4 days in some parts of the region. The duration of the event differed considerably across the westside (Figures 6 and 7); duration was longest around the Columbia River Gorge and at higher elevations along the Cascade Crest from central Washington to central Oregon. Winds persisted for up to 3 days in other mountainous areas of the westside but were relatively short-lived in areas in the Willamette Valley and Puget Trough, especially toward the valley margins adjacent to the western Cascades.

Wind gusts peaked at >25 m/s on slopes and ridges at upper elevations but declined toward the lower elevation flanks along the Willamette Valley margin (Figure 7d) around the Beachie Creek, Lionshead, and Riverside Fires, where both the drought and fuel metrics were highly anomalous. In the southern part of the Oregon Cascades, where drought was most intense, the lower elevation Archie Creek and Holiday Farm Fires experienced

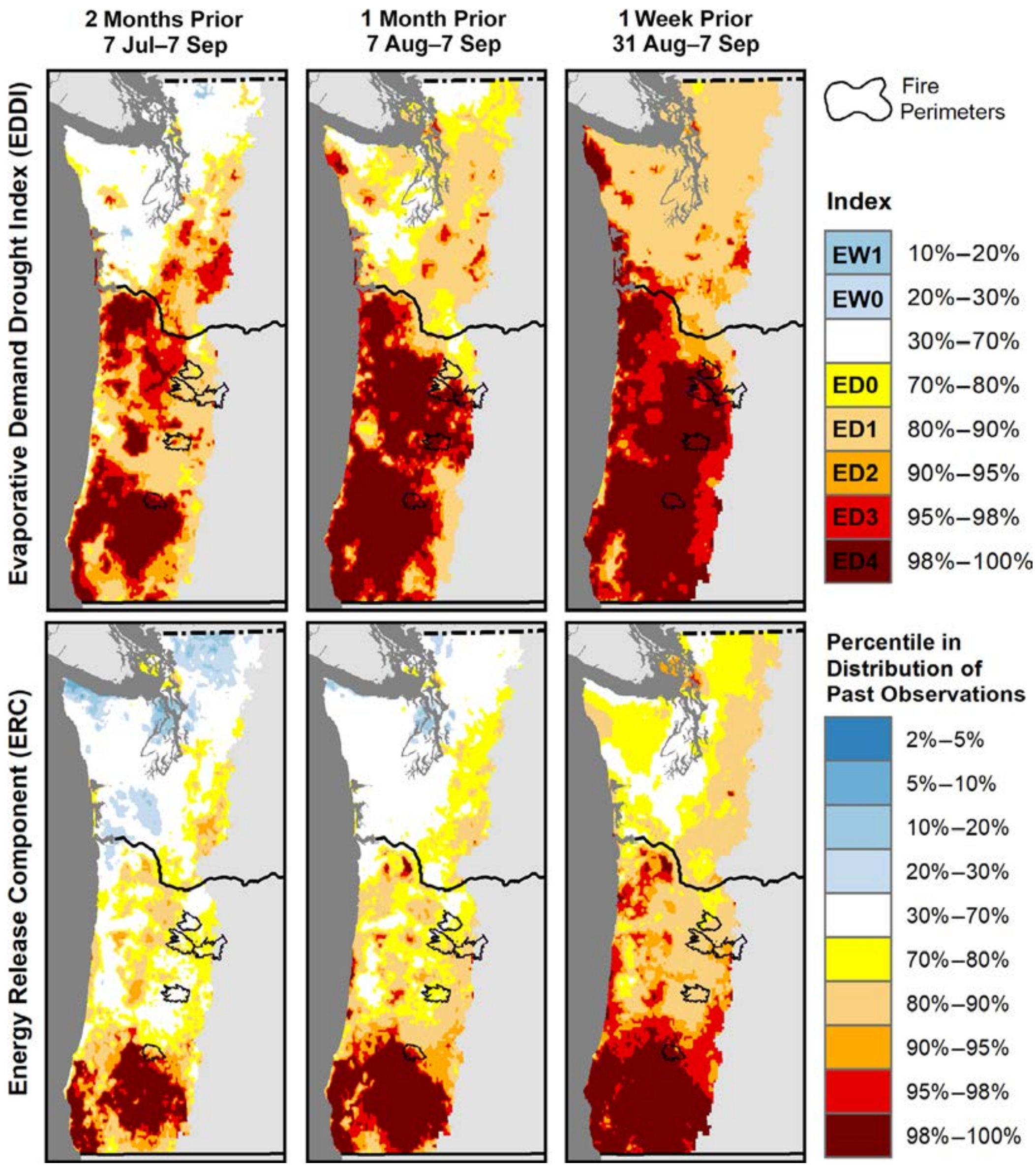

FIGURE 5 Evaporative demand and fuel condition metrics for 7 July to 7 September 2020 based on gridMET meteorological data (Abatzoglou, 2013). Values are shown as percentiles for 1979–2020. The Evaporative Demand Drought Index (EDDI) measures moisture conditions at the atmosphere–surface interface and is physically based on evaporative demand, the amount of water that would be evaporated from the land or transpired by plants if soil water was unlimited. It is a standardized index (−2.5 to 2.5) assigned to categories based on percentiles, as used by the US Drought Monitor. For example, category ED 4 (>2.0) indicates 98th percentile moisture conditions. Energy release component (ERC) is a measure of the amount of energy that can be released by combusting fuel based on a composite measure of live and dead fuel moisture. Higher ERC values indicate greater potential fire intensity for the season.

more moderate winds (Figure 7e,f) but grew to similar sizes as the fires to the north in Oregon. Despite similarly high winds in areas immediately to the south and east, the Big Hollow Fire remained relatively small. Drought conditions were less extreme there, and it appears that a ridge on the eastern flank of the fire reduced wind speed and redirected winds toward the northwest (Figure 7b). In the Oregon Coast Range and northern Washington Cascades, drought and wind speed were lower in the vicinity of fires, which remained small (Figure 7a,c).

While coincident drought and dry, east winds are associated with these large wildfire events, the regionally heterogeneous patterns of drought, fuel conditions, wind, and fire size in the 2020 fires illustrate a more complex mechanism than the simple co-occurrence of drought and wind. The largest burns occurred where seasonal drought and fuel conditions were most intense and synoptic east winds were the strongest, helping to explain why fires in the Oregon Cascades were so much larger than fires in other parts of the region. However, other

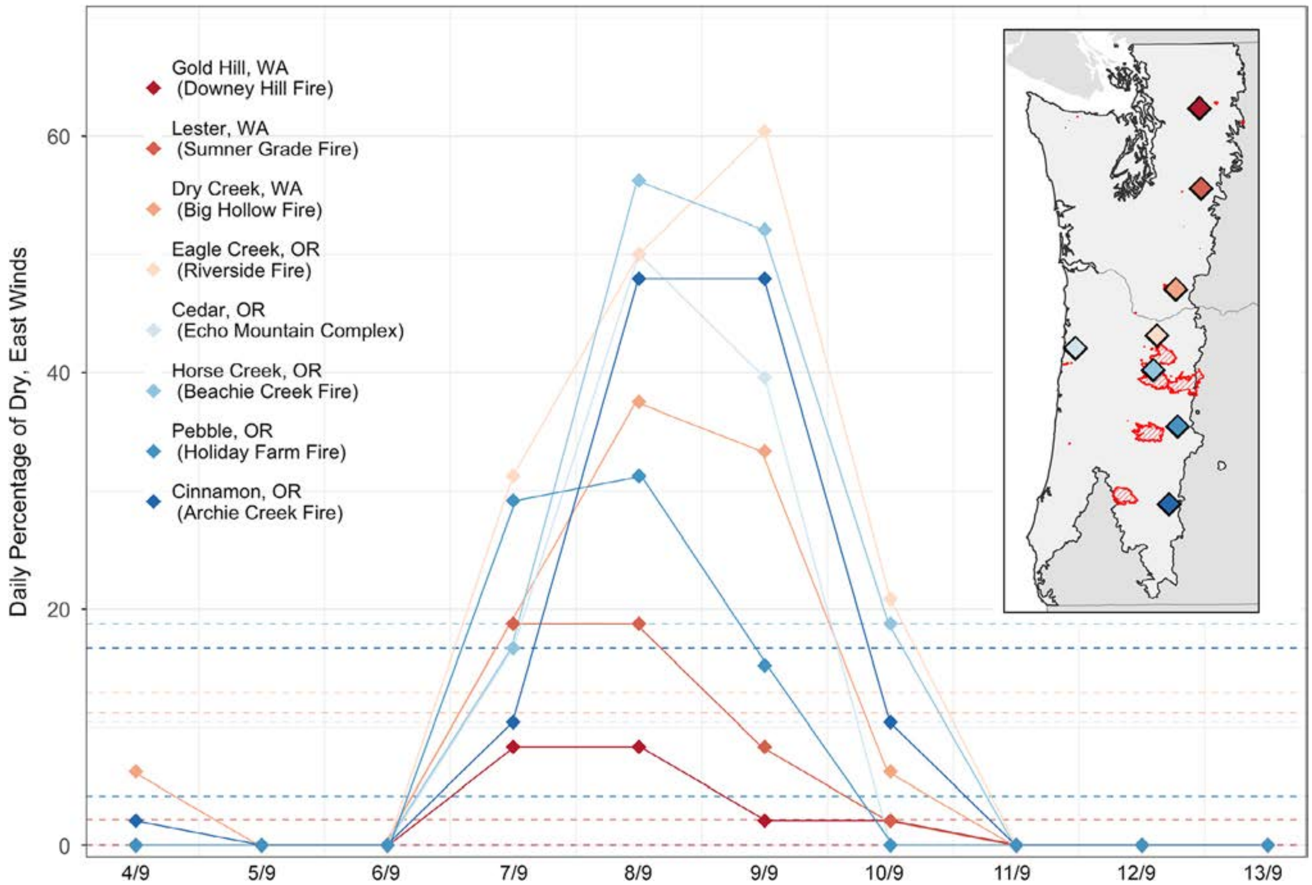

FIGURE 6 Duration and magnitude of the dry, east-wind event at six Remote Access Weather Stations (RAWS) from 4 to 13 September 2020. Magnitude is given as daily percentage of hours recording fast, dry, and east winds. An hourly record is considered fast, dry, and east when either 10-min average or gust speed exceeds 4 m/s, wind direction is between 15° and 165°, and relative humidity drops below 36%, per criteria proposed in Cramer (1957). Remote Access Weather Stations (Appendix S4: Table S1) are listed latitudinally from north to south, roughly corresponding to the general location of eight wildfires that were burning during this event. Horizontal dashed lines indicate the historical 90th percentile of the daily percentage of fast, dry, and east winds from 4 to 13 September for the long-term record (~20–30 years depending on the station). Each RAWS exceeds its 90th percentile during 7–10 September 2020, the period of highest spread for the Labor Day fires.

factors likely played a role. Mesoscale modification of synoptic wind patterns by the terrain in mountainous areas and along valley margins also appears to have affected fire growth and spread, potentially explaining why some fires remained small and others grew very large (Figure 7). Identification of critical fire weather and climate thresholds based on interactions among wind speed, relative humidity, drought, and live and dead fuel aridity is clearly needed to refine predictive capability for large westside fires.

How do the 2020 Labor Day fires compare to contemporary fires, and how did forest management and prefire forest structure influence burn severity?

The 2020 Labor Day fires were exceptional in their size and severity compared to other contemporary westside fires (1985–2019). Five of the 2020 fires were far larger than previous contemporary fires, including almost twice as much high-severity fire (>75% basal area mortality) as most fires, 70% of which burned in patches >10,000 ha (Figure 8a,b). These large patches of high-severity fire in 2020 may have qualitative ecological differences from those in other smaller contemporary fires (Figure 8c), particularly in terms of regeneration dynamics where seeds have a longer distance to travel and recolonize the interior of large patches (Romme et al., 1998).

Although several fires have occurred since the early 1980s, east-wind events of similar magnitude to 2020 were limited during this time (Abatzoglou et al., 2021; Mass et al., 2021). Approximately 60% of the 19,750-ha Eagle Creek fire in 2017 burned in a 2-day period from 4 to 5 September, and while relative humidity was low (<25%) during this period, wind speeds from a local RAWS station were much weaker (approximately 1.8 m/

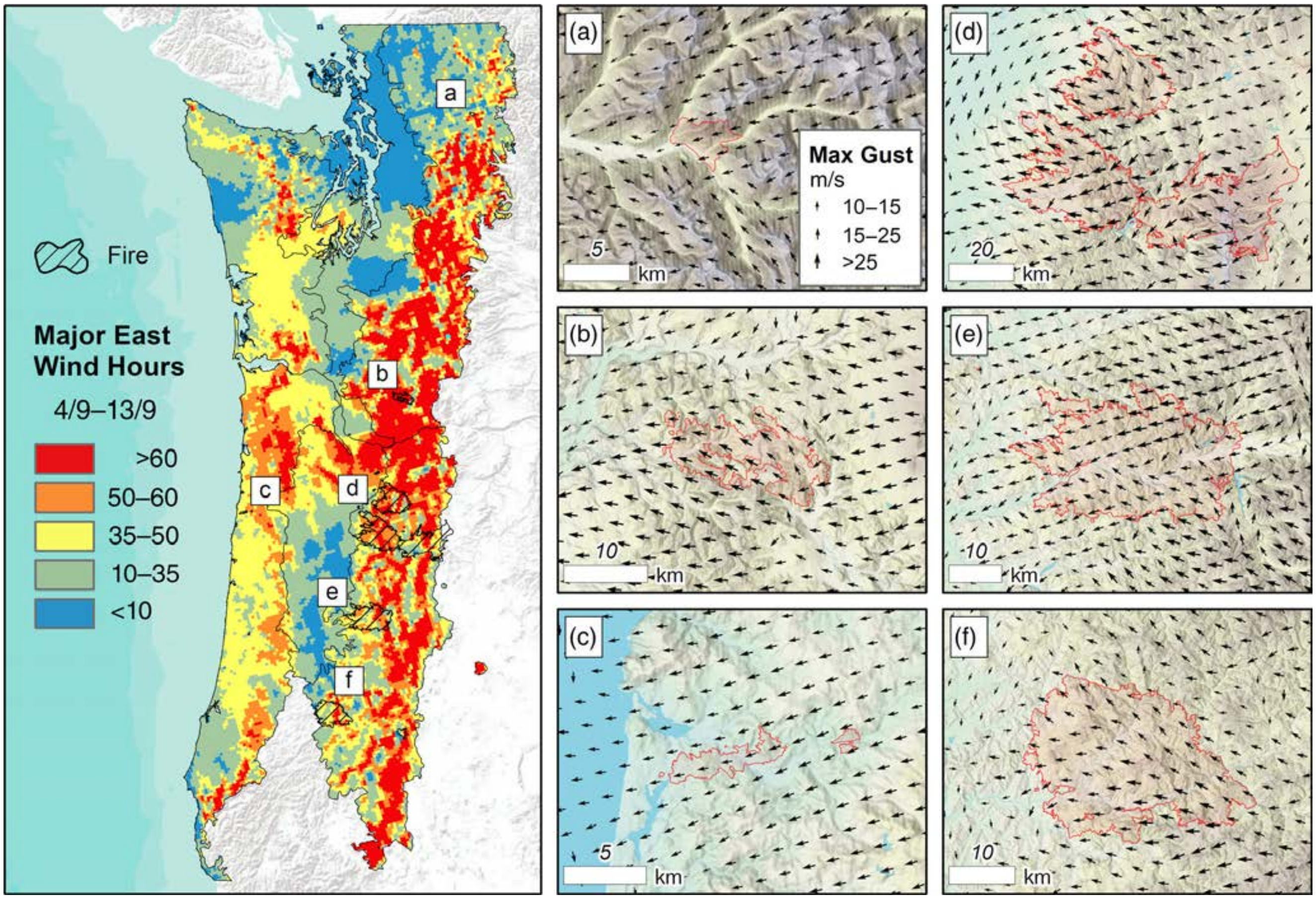

FIGURE 7 The map on the left depicts regional patterns of the duration of the September 2020 dry, east-wind event (total number of hours between 4 and 13 September) across the westside following the Cramer (1957) threshold based on hourly weather data from the Real-Time Mesoscale Analysis dataset (RTMA; De Pondeca et al., 2011) accessed through Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog/NOAA_NWS_RTMA). Inlays to the right depict maximum gust speed and wind direction for the (a) Downey Creek Fire, (b) Big Hollow Fire, (c) Echo Mountain Complex Fire, (d) Riverside, Beachie Creek, and Lionshead fires, (e) Holiday Farm Fire, and (f) Archie Creek Fire. Arrows represent the direction and velocity of the maximum estimated gust at a given location between 8 and 9 September from RTMA data.

s; A. Dye, unpublished data; Appendix S4: Figure S1) than those that drove the Labor Day fires. Most previous westside fires have been relatively small (<10,000 ha) mixed-severity or high-severity fires (Reilly et al., 2017). These differences highlight three broad types of fires that characterize the contemporary fire regime on the westside (Figure 8c): relatively small (<10,000 ha) and moderately sized (10,000–50,000 ha) (1) mixed-severity and (2) high-severity fires that occur in the absence of synoptic wind events, and (3) large, high-severity fires driven by winds during synoptic regional events.

Forest management, through its influence on forest structure, is often a major driver of fire behavior (Agee & Skinner, 2005; Thompson et al., 2007; Zald & Dunn, 2018). The 2020 fires burned through a diverse mix of forest age classes on the westside, which in large part reflected different management histories. Structural classes varying in live biomass, tree size, and canopy cover (CC; Appendix S6: Figure S1) experienced similarly high fire severity, and more than half of all classes burned at high severity (Figure 9). The sparse structural class with low biomass and less than 10% CC had slightly higher levels of burn severity than other classes, but severity was consistently high in open stands with low biomass, moderate biomass plantations (sapling/pole and small/medium), and older, higher biomass forests (large, large/giant). These patterns differ from those observed on the westside in previous studies under more moderate weather conditions (i.e., no east-wind event) that found higher fire severity in young plantations than in more mature, higher biomass conditions (Zald & Dunn, 2018).

We further assessed the role of prefire structure, along with fire weather, fuel moisture, and topography on burn severity in the 2020 fires (Appendix S6), using random forest (De'ath & Fabricius, 2000), a common statistical framework for modeling burn severity (e.g., Dillon et al.,

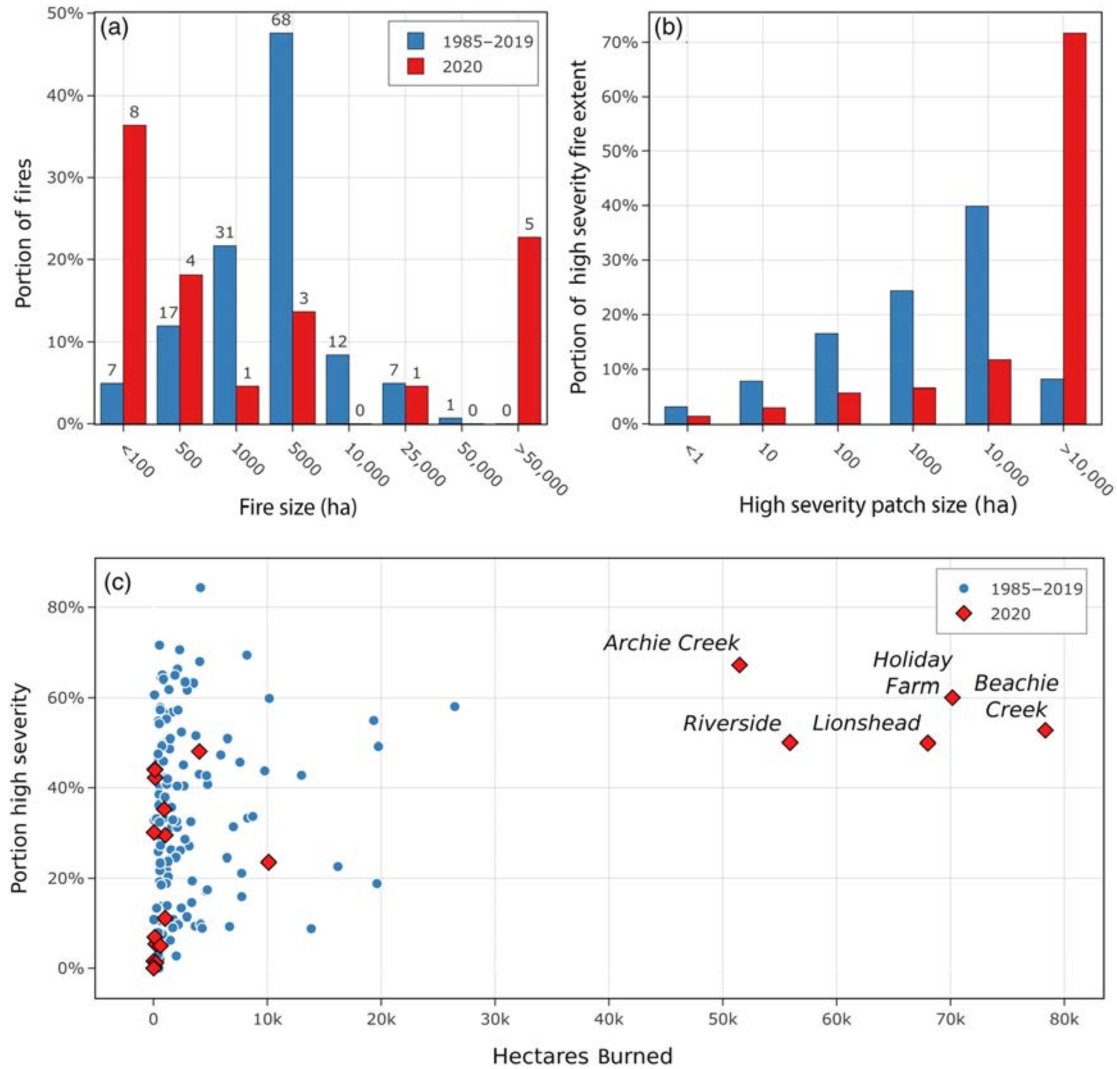

FIGURE 8 (a) Distribution of westside fire sizes between 1985 and 2019 compared to the 2020 Labor Day fires, based on perimeters from the Monitoring Trends in Burn Severity program (https://mtbs.gov) and the National Interagency Fire Center (NIFC; https://data-nifc.opendata.arcgis.com). The number of fires is noted above each bar. (b) High-severity (>75% basal area mortality) patch size distributions as a proportion of all area burned at high severity from 1985 to 2019 and 2020. (c) Fire size and proportion of area burned at high severity from 1985 to 2020 on the westside. Maps of high-severity fire are based on the relative difference in the normalized burn index (RdNBR) from imagery 1 year before and 1 year after the fire, with a threshold of 75% basal area mortality (Appendix S5; Reilly et al., 2017).

2011; Taylor et al., 2021; Zald & Dunn, 2018). The model accounted for 19.1% of the variance in burn severity and maximum gust played the most important role, followed by climate and fuel moisture variables (Appendix S6: Figure S2). Stand structure and topographic variables were less important though fire severity increased on steeper slopes and windward east-facing aspects (Appendix S6: Figure S3). While there remains further work to be done on this topic, our results are consistent with theory and existing studies in stand-replacing fire regimes of other regions that document a limited role of stand structure and topography in forests which consistently experienced 40%–50% high-severity fire (e.g., Bessie & Johnson, 1995; Turner et al., 1994; Turner & Romme, 1994).

Our findings reinforce that the Labor Day fires were fundamentally a weather-driven event (Abatzoglou et al., 2021; Mass et al., 2021). The influence of forest management on fire severity was minimal and variation in forest structure or fuels played relatively little role. These results provide little evidence to support the use of fuel treatments to mitigate fire severity under extreme fire weather conditions on the westside. Hazardous fuel reduction, a prominent wildfire risk reduction strategy in dry forests of the western United States (Stephens et al., 2021), can mitigate fire effects and tree mortality in dry forests during low and moderate fire weather conditions, and even in some topographic positions during extreme conditions (Prichard et al., 2020; Prichard &

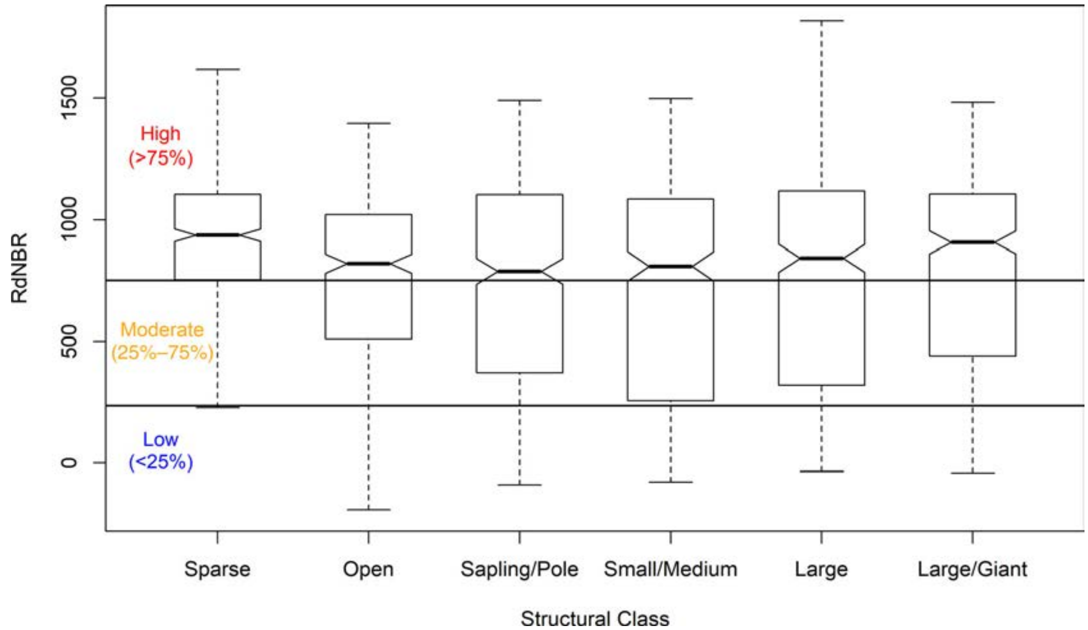

FIGURE 9 Patterns of burn severity for six structural classes in 2020, illustrating the majority of all structural classes burned with high severity. Structural classes are based on canopy cover (CC) and quadratic mean diameter (QMD) of dominant trees and were mapped using the gradient nearest neighbor (GNN) method (Appendix S6: Figure S1; Bell et al., 2021). Burn severity maps were created using the relative change in the normalized burn index (RdNBR) based on a composite of the maximum RdNBR from immediately after the fire and the following growing season. Fire severity thresholds follow Reilly et al. (2017).

Kennedy, 2014). However, our results suggest that manipulation of stand structure is unlikely to mitigate fire effects in wind-driven fires on the westside given the minimal differences in burn severity among stand structure classes.

Landscape-scale fuel treatments are already a challenge in slower growing, drier forests of the interior western United States (North et al., 2012), and even if temporarily successful under moderate fire weather conditions, implementing treatments would require exceedingly frequent maintenance given the high productivity of westside forests (Halofsky et al., 2018). Landscape-scale treatments could produce largely novel broad-scale forest conditions without any historical precedent or analog and could also promote invasions of non-native plant species (Ares et al., 2009; Bailey et al., 1998), compromising many of the diverse socio-ecological values currently connected with these forests (Spies et al., 2019). While landscape-scale fuel treatments may not be applicable across much of the area encompassed by this review, small-scale fuel treatments will still likely play a role around high-value resources and homes as a risk reduction strategy during non-wind events (further discussed below).

Although stand structure played little role in driving burn severity under extreme weather conditions in 2020, recent studies on the role of stand structure and fire severity on the westside suggest that older, closed-canopy forests with higher biomass are more fire resistant than young plantations with smaller trees under more moderate weather conditions (Lesmeister et al., 2019; Lesmeister et al., 2021; Zald & Dunn, 2018). Small trees with thinner bark are more exposed to lethal temperatures than large trees with thicker bark, even in low- and moderate-severity fire (Dunn & Bailey, 2016; Johnston et al., 2018), and moist westside, old-growth forests maintain substantial levels of live fuel moisture even during severe drought (Jiang et al., 2019). Thus, promoting late-successional and old-growth conditions dominated by large, fire-resistant trees could foster resistance to high-severity fire under less extreme fire weather (Agee & Skinner, 2005).

What ecological impact will these fires have on western Cascades landscapes?

Large disturbances have unique and long-lasting effects on the landscapes they affect (Foster et al., 1998; Turner et al., 1998). Major ecological concerns focus on losses of forest habitat for threatened and rare species dependent on late-successional and old-growth forests (LSOG). Initial estimates indicate that at least 73,842 ha of LSOG severely burned (>75% basal area mortality) in the 2020 Labor Day fires. This equates to 2.1% of the LSOG on the westside, and approximately as much LSOG as was lost to fire between 1986 and 2019 (Appendix S7: Table S1). Stands that experienced high-severity fire and maintained residual large trees could retain some old-growth characteristics, but these biological legacies will likely be reduced due to delayed mortality (Brown et al., 2013). Within LSRs established by the NWFP on the westside, approximately 12,606 ha of LSOG burned at high severity in 2020, accounting for 52% of the total burned extent within LSRs. Large proportional losses at landscape scales are consistent with simulation studies of the historical range of variability (HRV) at the scale of late-successional reserves in the Coast Range and western Cascades of Washington (Donato et al., 2020; Wimberly et al., 2000). In some cases, single LSRs may suffer large proportional losses during large fire events. However, when viewed regionally, the well-dispersed network of large block LSRs buffered losses across the NWFP area, with only 1.4% of the total area of LSOG in westside LSRs experiencing high-severity fire in 2020. Despite being buffered from losses at regional scales, the impacts of the 2020 fires will add to prior losses from contemporary fire and further increase the deficit in, and fragmentation of, old-growth forests from 20th-century logging (Davis et al., 2015; Spies et al., 2018). This is particularly the case in the western Cascades of Oregon, where high-severity fires in 2020 affected 5.4% of the remaining LSOG.

High-severity fires will likely foster biodiversity through the creation of structurally complex, early seral habitats (i.e., pre-canopy closure communities), which are of conservation interest on the westside (Kroll et al., 2020; Reilly & Spies, 2015; Spies et al., 2019; Swanson et al., 2011). Maps of burned areas in the early 1900s (Figure 2; Appendix S8: Table S1) suggest approximately 20% of westside forests was in a fire-created, early seral state following an active fire period starting in the 1800s (Weisberg & Swanson, 2003). Forests were apparently very resilient with prompt regeneration and fire-created, early seral conditions declined to 5% by the 1930s (Harrington, 2003). By the early 2000s, westside fire rotations were >1000 years and structurally complex, early seral conditions were one of the rarest habitats on the westside, comprising <1% of all westside forests (Reilly & Spies, 2015). High-severity fire across 3.2% (329,759 ha) of westside forests from 1986 to 2020 suggests postfire early seral conditions may now be at the lower end of the range of available estimates of the HRV in parts of the westside region (long-term average is ~6%, ranging from 1% to 30%) (Donato et al., 2020; Wimberly et al., 2000). Fire-created, early seral conditions in the Oregon western Cascades are now slightly greater than available estimates from wetter westside ecoregions (10.2%) but remain in deficit compared to the HRV across most of the rest of the region (Donato et al., 2020; Reilly & Spies, 2015).

Research on ecological response following westside fires is limited, but existing studies on post-fire vegetation following historical and contemporary fires generally document a prompt regeneration response and resilience to single large, high-severity fires. Revegetation of native vegetation communities following the 1933 Tillamook and 1902 Yacolt Fires was rapid, with abundant conifer regeneration (Gray & Franklin, 1997; Isaac & Meagher, 1938), and most late-seral plant species in adjacent old forests were also present following the Tillamook Burn (Neiland, 1956). Regeneration studies following contemporary fires are also limited to a few well-studied fires in the early 1990s (e.g., 1991 Warner Creek Fire), but demonstrate similar forest resilience (Brown et al., 2013; Dunn, Johnston, et al., 2020; Larson & Franklin, 2005), with seedling abundance and richness peaking at moderate levels of severity at middle and upper elevations in the Oregon western Cascades (Dunn, Johnston, et al., 2020). Some higher elevation forests have shown resilience to high-severity fire (Acker et al., 2017). However, in other high-elevation forests, single and repeated high-severity fires at short intervals have reduced regeneration and shifted composition toward that of drier, lower elevation forests (Busby et al., 2020).

While an increase in early seral conditions can promote biodiversity, there may be increased risk of reburns, given their historical precedence following early 20th-century fires (Figure 10). The 1902 Yacolt Fire experienced 15 partial reburns in the following 50 years (Figure 10a), the 1933 Tillamook Burn experienced five partial reburns in the following 20 years (Figure 10b), and much of the fire activity in the mid- and late 1800s has been attributed to reburning in large fires (Morris, 1934). Following one of the Tillamook Burns, Neiland (1956) found that maximum daytime summer temperatures were approximately 11°C warmer with 10% lower relative humidity in burned areas than in adjacent old-growth forests. Warmer, drier conditions may increase the potential for burning in early seral landscapes where post-fire regeneration and vegetation establish in abundance rapidly.

Invasive species were also abundant following the Tillamook Burns (Neiland, 1956), including the seedbank-forming, pyrophyllic shrub Scotch broom (*Cytisus scoparius*), which is already present across ~5% of westside forests (Gray, 2005). Gorse (*Ulex europeaus*), a closely related invasive species common to coastal areas, was implicated as a major driver of a fast-moving fire that burned the city of Bandon in the Oregon Coast Range in September of 1936 during a dry, east-wind event (Isaac, 1940). In addition to increasing fire risk, non-native species can have detrimental effects on early seral floral and pollinator communities and are common across westside landscapes along roads and in previously managed areas (Bailey et al., 1998; Gray, 2005).

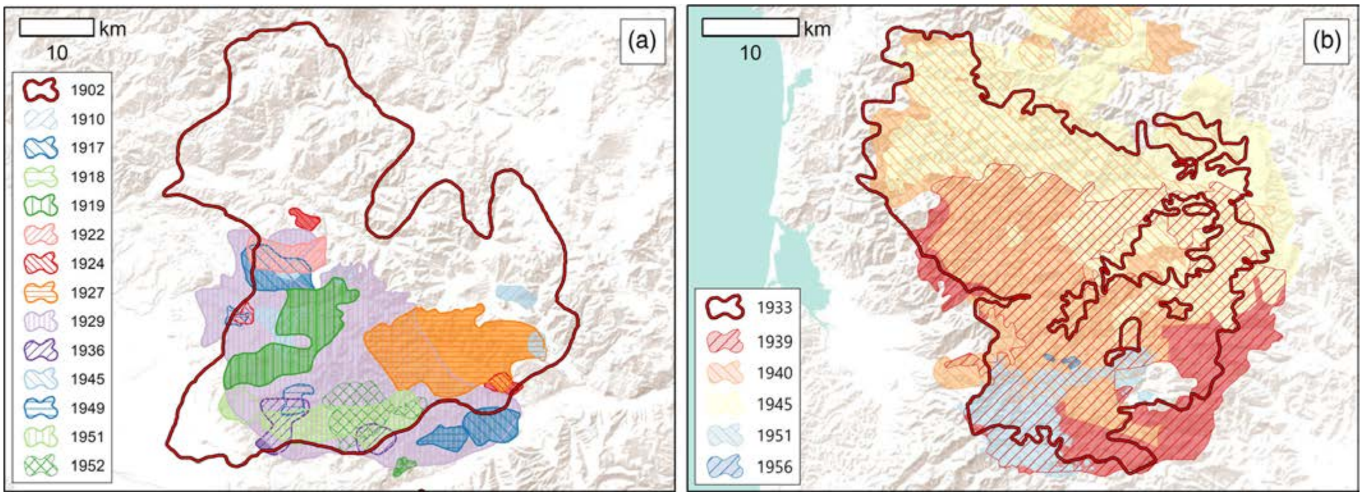

FIGURE 10 Reburns following (a) the 1902 Yacolt Fire in the western Washington Cascades and (b) the 1933 Tillamook Burn in the Oregon Coast Range. See Figure 3 for location of fires in Oregon and Washington.

The very large fire extents and large patches of high-severity fire in the Labor Day fires have raised many ecological concerns regarding the current and future trajectory of these areas. Along with the record of similar fires occurring historically, available evidence suggests that westside forests are generally resilient (i.e., they have a high capacity to return to a predisturbance state), and populations of late-seral wildlife species (e.g., the northern spotted owl) have persisted through past regional fire events. However, contemporary landscapes are influenced by ownership patterns (Kroll et al., 2020) and bear the legacies of past forest management. Novel stressors, including fragmented landscapes, climate change, and invasions of non-native plant species, may further reduce resilience to future fires and increase fire risk in early seral landscapes.

How can westside communities adapt to similar fire events in the future?

As the area affected by large wildfires has increased in the western United States, so has scientific consensus on the need to adapt and live with fire (Dunn, O'Connor, et al., 2020; Moritz et al., 2014; North et al., 2015; Thompson et al., 2015). Current policies addressing wildfire risk recognize the need to maintain or improve forest resilience, create fire-adapted communities, and increase the safety and effectiveness of wildfire response (Wildland Fire Leadership Council, 2014). Regionally specific approaches to addressing wildfire risk are needed (Schoennagel et al., 2017), but most scientific and management effort is currently focused on dry forests, where the effects of fire exclusion are greater. Less is known about the effectiveness of these dry-forest fuel reduction strategies in westside forests (Halofsky et al., 2018).

Infrequent, stand-replacing fires are low-probability, high-consequence events akin to other natural hazards that westside communities face, such as earthquakes and tsunamis (McEvoy et al., 2021). These events are rare, difficult to forecast, and result in profound negative consequences to human communities. Given the wide range of factors that contribute to infrequent, high-severity fires on the westside (e.g., climate, weather, topographic setting), and the highly stochastic nature of wildfire in general, forecasting the time and location of future disasters is not a viable risk reduction strategy except at very short time scales (i.e., days). Instead, effective planning for rare events embraces inherent uncertainty in forecasting and seeks to find solutions that are robust across a range of plausible events (Hulse et al., 2016; Lempert et al., 2002; Witter et al., 2013). Fire managers and community planners can draw strategies from similar preparations for "the Big One," a massive earthquake that is generally anticipated along the Pacific Northwest coastline (Cramer et al., 2018; Flynn et al., 1999). This approach is less common for wildfires, potentially leading to distorted risk perception and complacency in community adaptation (e.g., Aven & Krohn, 2014; Kates & Clark, 1996; Kunreuther et al., 2001). Given the potentially high consequences and relatively low wildfire risk to communities, westside communities face considerable challenges in accessing and allocating resources to effectively plan for and mitigate low-probability, high-consequence events (McEvoy et al., 2021).

Achieving resilience and protecting communities on the westside may be more effective if focused on social strategies rather than fuels management. Given that much of the westside is prone to rare, wind-driven fire events, hazardous fuel reduction strategies are unlikely to be effective at preventing disastrous consequences. Thus, homeowner-focused and community-level strategies are essential tools for community resilience (Calkin et al., 2014). Dry forest strategies are predominantly focused on altering fire severity and behavior in the event of a fire, whereas for the westside, ignition management to strategically prevent fire starts may be the most effective and ecologically congruent tool to reduce the risk of large, high-severity fires (Halofsky et al., 2018). Westside fires are overwhelmingly the result of human-caused ignitions (Short, 2017), which, when coincident with severe fire weather, can lead to large fires (Abatzoglou et al., 2018). Improved understanding of where and under what weather conditions human-caused ignitions can lead to large fires will facilitate opportunities to strategically manage risk.

Fire managers are essential agents in mitigating risk to valued resources and assets, with direct influence on the safety and effectiveness of wildfire response and suppression. Risk management provides an important suite of tools for managing wildfires before, during, and after the event (Thompson et al., 2019). Decisions can be made by leveraging quantitative wildfire risk assessments and spatial representations of where suppression efforts are more likely to be successful and in accordance with protecting valued resources (Dunn, O'Connor, et al., 2020; O'Connor et al., 2017; Rodriquez y Silva et al., 2020; Thompson et al., 2016). Given the potential for low-probability dry, east-wind events (Figure 3), a risk management framework can be used to strategically allocate firefighting resources across regional and national scales. Wildfire response will remain a significant risk mitigation strategy since hazardous fuel treatments are unlikely to be successful in wind-driven events.

When large, wind-driven fires do occur, westside communities would be well served by investments in public awareness and evacuation planning based on existing risk information (Cova et al., 2011; Dye et al., 2021; McCaffrey et al., 2018; Whittaker et al., 2020). While a red flag warning of the possibility of large wildfire was known days in advance of the 2020 events (Mass et al., 2021), the novelty and implications of such a warning were lost across much of the westside region. The success of planning and evacuations could be improved with a public awareness campaign of what to do under such a situation, akin to tsunami warnings (Jin & Lin, 2011; Li et al., 2019). Finally, the consequences of wildfire disasters may be mitigated, especially when winds are less intense, through management of fuels near homes and other high-value resources, structural hardening, and strategic land-use planning and development aimed at increasing survivability and reducing losses (Braziunas et al., 2021; Calkin et al., 2014; Syphard et al., 2012; Syphard et al., 2017).

CONCLUSIONS

The 2020 Labor Day fires were a wake-up call to many scientists, forest managers, policy makers, and the public on the westside of Oregon and Washington. The fires were unprecedented relative to the recent fire record in terms of human impact, burn severity, and size, but were well within the bounds of historical records and natural fire regimes that shaped westside landscapes historically. The major difference between the 2020 fires and previous contemporary fires was the occurrence of a rapid, extreme drying period and a regional-scale dry, east-wind event that corresponded with multiple ignitions. Geographic patterns of drought and wind speed appear to explain some of the variability in fire size and highlight a more complex "recipe" for large westside fires than just the simultaneous occurrence of wind and drought.

While there is consensus among statistical and process-based models that area burned in westside forests is likely to increase as the climate warms and summers become drier (Davis et al., 2017; Halofsky et al., 2020; McEvoy et al., 2020; Rogers et al., 2011; Sheehan et al., 2015), the effects of climate change on dry, east winds now and in the future are uncertain and just beginning to be explored (Brewer & Mass, 2016a, 2016b). Recent work using downscaled regional climate models projected a modest decrease in the frequency of east-wind events on the westside (Mass et al., 2022). However, it is unclear if climate change effects on other drivers of wildfire (e.g., drier fuels and longer fire seasons) will partially compensate for any decline in frequency. Even if wind events decrease in frequency, more small and moderately sized fires are likely to be burning in late summer and early fall, potentially serving as catalysts for larger fires when wind events do occur.

Forest management and fuel treatments are unlikely to influence fire severity in the most severe wind-driven fires. However, implemented in strategic locations, fuel treatments may still be beneficial under low and moderate fire weather conditions by reducing fire spread, increasing the effectiveness of fire suppression, limiting the consequences of fire in the wildland–urban interface, and providing some protection to communities and infrastructure. Similarly, implementing Firewise USA principles (www.nfpa.org) around structures and structural-hardening techniques may help reduce losses during low and moderate fire weather. With the inherent limitations in using fuels management to mitigate large, wind-driven westside fires, adaptation strategies that are more likely to be successful include those that focus on managing ignitions, fire suppression, and community preparedness. Knowledge of seasonal and geographic patterns of dry, east-wind events may help inform communities at risk, help prioritize suppression, and plan evacuations when there are multiple ignitions coinciding with extreme weather conditions. Aggressive fire suppression will continue to be a necessary tool to reduce risk of wildfires of all sizes on the westside and, with naturally longer fire-return intervals, has fewer negative ecosystem consequences compared to dry forests where fire was historically frequent (Halofsky et al., 2018).

The Labor Day fires will leave a lasting imprint on the western Cascades, reducing and fragmenting remaining old-growth forest and habitat for associated species. Large patches of early seral habitat that have been absent from the region for decades will likely foster biodiversity but may promote invasions of non-native species and increase the likelihood of reburns in the next few decades. Available studies on Westside fires indicate forest regeneration will likely be abundant following the 2020 fires. However, opportunities exist for increasing species and genetic variability that may be better suited to future conditions where planting is required to meet management objectives and desired outcomes. Having plans in place before future events can accelerate the process of post-fire management activities that vary among ownerships with different management objectives.

Further study of the 2020 Labor Day fires is needed to address many uncertainties that still exist and provide critical knowledge on rare, large fire events. However, our assessment of the current science and context surrounding the 2020 fires demonstrates that this watershed event for human communities was entirely consistent with historical behavior for the regional landscape in which many communities are embedded. Like tsunamis and earthquakes, it was inevitable that events like those of 2020 would eventually occur. And like other rare natural disturbances, these kinds of wildfire will occur again, as they are an inherent characteristic of these ecosystems. Effectively managing and adapting to future westside fires will require that such "black swan" events (Donato et al., 2020) are factored into natural resource and community planning efforts.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Reilly & Zuspan, 2022) are available from Zenodo: https://doi.org/10.5281/zenodo.6266566. Other data used are cited herein or provided in the appendices.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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