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ARTICLE

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Exceptional variability in historical fire regimes across a western Cascades landscape, Oregon, USA

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Abstract
Detailed information about the historical range of variability in wildfire activity informs adaptation to future climate and disturbance regimes. Here, we describe one of the first annually resolved reconstructions of historical (1500–1900 CE) fire occurrence in coast Douglas-fir dominated forests of the west slope of the Cascade Range in western Oregon. Mean fire return intervals (MFRIs) across 16 sites within our study area ranged from 6 to 165 years. Variability in MFRIs was strongly associated with average maximum summer vapor pressure deficit. Fire occurred infrequently in Douglas-fir forest stands seral to mountain hemlock or silver fir, but fire frequency was much shorter than predicted by theory in other forest types. MFRIs within Douglas-fir stands seral to western hemlock or grand fir ranged from 19 to 45 years, and MFRIs in stands seral to Douglas-fir ranged from 6 to 11 years. There was little synchrony in fire occurrence or tree establishment across 16 sites separated by 4 km. The lack of synchrony in fire suggests that large, wind-driven fire events that are often considered to be characteristic of coast Douglas-fir forests were not an important driver of succession in our study area during the last ~400–500 years. Climate was more arid than normal during fire years in most forest types, but historical fire in stands seral to Douglas-fir was strongly associated with antecedent moisture and less strongly associated with drought. We interpret the extraordinary tempo of fire we observed in stands seral to Douglas-fir and the unique climate pattern associated with fire in these stands to be indicative of Indigenous fire stewardship. This study provides evidence of far more frequent historical fire in coast Douglas-fir forests than assumed by managers or scientists—including some of the most frequent fire return intervals documented in the Pacific Northwest. We recommend additional research across the western Cascades to create a comprehensive account of historical fire in highly productive forests with significant cultural, economic, and ecological importance.

KEYWORDS
Cascades, dendroecology, Douglas-fir, fire regimes, fire scars, Indigenous fire stewardship, tree establishment, tree rings, vapor pressure deficit, wildfire

INTRODUCTION

Wildland fire is a fundamental forest ecosystem process. Information about long-term variability in fire disturbance informs adaptation and mitigation strategies in the face of rising temperatures and dramatic recent increases in area burned (McWethy et al., 2019; Seidl et al., 2016; Swetnam et al., 1999). Long-term records of fire also provide fundamental insights about disturbance process and vegetation pattern feedbacks, successional dynamics, carbon storage potential, Indigenous land stewardship, and vulnerability to state changes (Guiterman et al., 2018; Guyette et al., 2002; Roos et al., 2022; Scholl & Taylor, 2010).

An important source of information about multi-century variability in wildfire occurrence is scars in wood tissue formed when heat from wildfire kills cambial cells that are partially or wholly covered by subsequent years' radial growth (Falk et al., 2011; Margolis et al., 2022). The calendar year in which a tree was burned by fire, and often the season, can be determined by crossdating, a procedure that compares tree ring widths on an undated wood sample to a master chronology of ring widths (Fritts & Swetnam, 1989). Hundreds of annually resolved tree ring fire histories are available across seasonally dry, fire-prone forests of the inland Western United States (dry forests) (Margolis et al., 2022).

Tree ring reconstructions of historical fire are much less common in moister and more productive forests found at high elevations, boreal regions, or in coastal zones (Daniels et al., 2017; however, see Heon et al., 2014; Heyerdahl et al., 2019; Johnston et al., 2017; Margolis & Malevich, 2016). Few trees in the moistest and most productive forest settings have "cat-face" features that contain multiple fire scars, or other visible evidence of past fire (Heon et al., 2014; O'Connor et al., 2014). Building long-term records of fire in moister forests is often further complicated by extensive cohorts of shade-tolerant tree species that are more prone to mortality from fire as well as root and bole diseases that erode tree ring evidence (Pausas, 2015; Smith et al., 2016; Stephens & Finney, 2002).

Among the regions of the United States that have few crossdated fire histories are the highly productive coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) dominated forests found from the Pacific Ocean to the crest of the Cascades in Oregon and Washington. The enormous volume of biomass that these forests accumulate over time is often assumed to be a function both of excellent conifer growing conditions as well as long intervals between wildfires (Agee, 1991, 1996; Franklin et al., 2002; Franklin & Hemstrom, 1981; Smithwick et al., 2002; Spies & Franklin, 1988; Waring & Franklin, 1979). However, several studies report complex historical fire dynamics in the central and southern portion of the Oregon Cascades. For instance, Weisberg and Swanson (2003) and Morrison and Swanson (1990) noted multiple nonlethal fire injuries on Douglas-fir stumps in western Oregon. Tepley et al. (2013) crossdated an extensive collection of tree cores from live trees in the central Oregon Cascades and inferred a variety of developmental pathways mediated by nonstand-replacing fire over the last 500 years. Merschel (2021) used both crossdated fire scars and tree establishment dates to document relatively frequent fire across a wide range of Douglas-fir dominated forest types across the Umpqua National Forest in the south-central western Oregon Cascades. Merschel (2021) suggests that Indigenous people made significant contributions to the tempo of historical fire across his study area, noting that fire at many sites abruptly ceased when the Upper Takelma and Umpqua tribes were forcibly removed to the Grand Ronde reservation in the 1850s.

The use of fire as a management tool by Indigenous people was an important driver of historical disturbance regimes and forest succession in many forest systems (Lake et al., 2017). For instance, ethnohistorical evidence analyzed by Steen-Adams et al. (2019) suggests fire was regularly employed to stimulate the production of huckleberry (*Vaccinium membranaceum*) at higher elevations in the eastern Oregon Cascades. But there has been little empirical study of Indigenous fire use in forests west of the crest of the Cascades. Several synthesis studies argue that climate and not Indigenous ignitions were the primary control on historical fire regimes of the Pacific Northwest (Walsh et al., 2015; Whitlock, 2008; Whitlock et al., 2015; Whitlock & Knox, 2002).

This study seeks to add to our knowledge of historical fire in coast Douglas-fir dominated forests of the western Oregon Cascades by evaluating multiple lines of crossdated tree ring evidence. The first specific objective is methodological: to describe methods for reconstructing historical fire across a range of forest types with multiple tree species, including large and old coast Douglas-fir that may have few outward indications of past fire. The second objective is to characterize fire frequency, seasonality, severity, and relative extent of fire across a western Cascades environmental gradient. The third objective is to quantify the relationship between historical fire frequency and biophysical variability. The final objective is to describe the relationship between historical fire occurrence and interannual variability in climate.

To accomplish these objectives, we selected a ~15,000-ha study area on the south end of the Willamette National Forest on the west slope of the central Oregon Cascades. This study area contains extensive productive coast Douglas-fir forests. It also contains forest stands with ponderosa pine (*Pinus ponderosa*) and other species typically associated with dry forests of eastern and southern Oregon—early Forest Service surveys noted this study area as the furthest northern extent of commercial quantities of pine species on the west slope of the Cascades (Langille et al., 1903). Research in this transitional area provides the opportunity to test hypotheses about the natural fire regime across diverse forest types over multiple centuries.

In addition to addressing critical knowledge gaps about disturbance ecology in an economically and ecologically significant forest type, this study will also inform the collaborative development of a range of passive and active management strategies appropriate for diverse forest types within federally managed forests (Keane et al., 2009). The Forest Service is working closely with the Southern Willamette Forest Collaborative, a stakeholder group based in Oakridge, OR, to plan a variety of restoration treatments within our study area. This research is designed to inform silviculture treatments that may serve as a model for treatments in diverse western Cascades forest communities.

METHODS

Study area and management situation

Data were collected within the upper Middle Fork Willamette River watershed on the south end of the Willamette National Forest (Figure 1). Summers in this area are warm and dry, and winters are mild and very moist. The coldest month of the year is December, with a 30-year average temperature of 1.9°C. July and August are the warmest months, with an average temperature of 18.0 and 18.2°C, respectively. The area receives between 1300 and 2000 mm of precipitation a year, most of which occurs between late fall and spring (PRISM, 2022). Topography of the area is generally very rugged, consisting of steep ridges incised by streams.

People have occupied the southern end of the Willamette National Forest for at least 10,000 years and probably much longer (Aikens et al., 2011). Many historical accounts suggest that our study area was part of the ancestral homeland of the Molalla, a culture for which there is relatively little detailed ethnographic evidence (Zenk & Rigsby, 1998). Baxter's (1986) review of archeological investigations suggests that the upper reaches of the Willamette River were an important travel corridor for people moving between western Oregon and the dry interior. A variety of Indigenous cultures, including but not limited to the Molalla, Kalapuya, Tenino, Wasco, Klamath, Northern Paiute, and Cayuse likely used our study area in the course of hunting, plant collecting, exchange of goods, and other cultural and economic activities (Baxter, 1986; Zenk & Rigsby, 1998).

Indigenous populations of western Oregon were decimated by violent dispossession of land and disease epidemics introduced by traders and settlers between 1781 and 1863 (Boyd, 1999; Lewis, 2014). Euro-American fur trappers first penetrated the upper reaches of the Middle Fork Willamette River sometime between 1812 and 1818 (Anderson, 1965; Meany, 1923). Between 1856 and 1857, most remaining members of Willamette Valley and western Oregon Cascades tribes were forcibly removed to reservations (Lewis & Kentta, 2010), although some traditional uses of the western Cascades by tribal members traveling from the Warm Springs and Klamath reservations were documented into the 1940s (Bergland, 1992). Between 1865 and 1869, the Central Oregon Military Wagon Road was constructed along the upper Middle Fork to connect eastern Oregon and the Willamette Valley (Minor & Pecor, 1977). The study area was designated as the Cascade Range Forest Reserve in 1893 and a national forest under the management of the United States Forest Service in 1907 (Rakestraw & Rakestraw, 1991).

Early Forest Service management in the study area was largely custodial and focused primarily on fire control and regulation of sheep grazing (Rakestraw & Rakestraw, 1991). Extensive clearcut logging of the Willamette National Forest began in the late 1940s and continued through the 1980s (Clary, 1986; Cox, 2010). Today, following decades of legal battles over the fate of old-growth associated species like the northern spotted owl (*Strix occidentalis caurina*), Forest Service managers are seeking fine-grained information about forest vegetation and historical disturbance dynamics to design management that promotes resilience to climate change (Davis et al., 2015; Spies et al., 2006, 2010).

Hundreds of different plant associations describe variability in forest communities in our study area and across the western slope of the Cascades. Plant associations are grouped into a "series" representing potential natural vegetation (PNV), which are named for an overstory tree species expected to eventually dominate a stand in the absence of disturbance (Daubenmire, 1968). Most forest

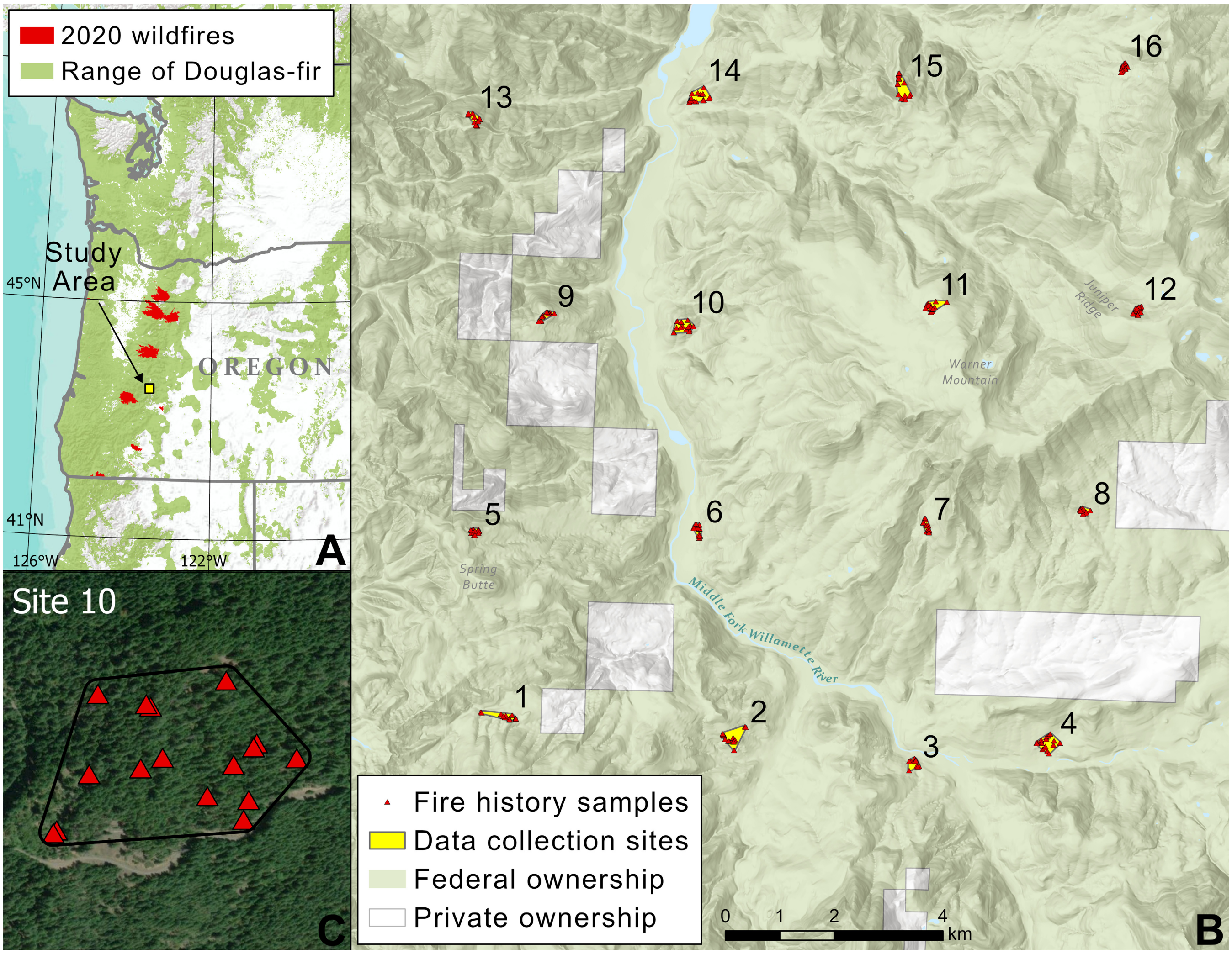

FIGURE 1 Upper Middle Fork Willamette River Study area. Study area in relation to the Pacific Northwest and 2020 Labor Day fires in Oregon (A). Location of data collection sites and samples (B). Overhead view of an example data collection site (10) (C).

series found in northwestern Oregon and western Washington are found within our study area, with the notable exception of Sitka spruce (*Picea sitchensis*), which is associated with coastal fog belts (Ruth, 1958). Most common in our study area is the western hemlock (*Tsuga heterophylla*) series, found between 500 and 1300 m in elevation where winter precipitation is a mix of rain and snow (Hemstrom et al., 1987; McCain & Diaz, 2002). Western hemlock is among the most shade-tolerant of western conifers and establishes and grows well in the understory below dominant Douglas-firs. Western hemlock is an important component of dense, multi-canopied older forests that provide habitat for northern spotted owl and other late-successional associated species (Franklin et al., 1981).

The Pacific silver fir (*Abies amabilis*) series occurs above the western hemlock series between 1100 and 1600 m elevation, where a larger percentage of winter precipitation falls as snow. Across this elevation range, Pacific silver fir replaces western hemlock as the most important shade-tolerant species associated with Douglas-fir. From around 1600 m to tree line, the Pacific silver fir series grades into the mountain hemlock (*Tsuga mertensiana*) series. Douglas-fir are absent or found only as scattered individuals within mountain hemlock forests, which are typically under snow from November through May or June. The most common tree species in stands seral to mountain hemlock in our study area were noble fir (*Abies procera*) and/or Shasta red fir (*Abies magnifica*). Noble fir likely hybridizes with Shasta red fir in our study area (see Franklin, 1983). We were unable to easily distinguish between noble fir and Shasta red fir in the field and hereafter refer to these individuals as noble/red fir or *procera*/*magnifica*.

A number of forest stands within our study area, found mostly below 1000 m, are today dominated by

Douglas-fir but also contain scattered dry forest species including ponderosa pine and Oregon white oak (*Quercus garryana*). These sites type to the Douglas-fir series. Forest Service planning documents and archeological investigations suggest that the presence of dry forest species in this area is the result of Indigenous management for open woodland habitat using fire (Baxter, 1986; USDA, 2006). Our experience working in the field suggests that the Calapooia Range, a tall ridge to the southwest likely blocks some winter and spring precipitation, which may contribute to the presence of dry forest species at lower elevations along the Middle Fork Willamette River.

The Forest Service has completed one small-scale (200 ha) project to restore more open woodland habitat believed to be present before Euro-American contact (USDA, 2006). The Forest Service is planning more extensive silvicultural treatments in stands with dry forest species which are tentatively scheduled for completion between 2025 and 2030 (USDA, 2021). We worked closely with Forest Service managers and the Southern Willamette Forest Collaborative in developing this study and sharing results with interested parties including managers, tribal members, university scientists, and residents in nearby communities (Keeler et al., 2017).

Field data collection

Field data collection was designed to build long fire histories across the full range of forest communities present within the study area. We located data collection sites at 4-km intervals at the intersection of a 12 × 12-km grid centered across the upper Middle Fork River valley, for a total of 16 different individual study sites (Figure 1, Table 1). We chose to systematically locate data collection sites to capture an elevation gradient from the river bottom to surrounding high ridges. In addition, during earlier research in eastern Oregon, we learned that many historical (circa 1500–1900 CE) fires occurred over large (>10,000 ha) areas (Merschel et al., 2018). Locating gridded fire history sites provided the opportunity to estimate the relative extent of historical fire in our study area.

Some data collection points fell on private inholdings within the Willamette National Forest; these points were relocated to national forest land. Data collection during a pilot study demonstrated that it was impractical to carry large chain saws, fuel, supplies, and wood samples that often weighed in excess of 20 kg farther than 500 m from a road, and so we relocated some data collection points to the nearest point within 500 m of an open road. We do not believe that sampling within this distance of a road biased our data collection because the road system in this part of the Willamette National Forest is extensive and provides access to almost all landforms within the study area.

Extensive reconnaissance across the upper Middle Fork Willamette study area confirmed that our network of gridded sites provided a good representation of forest conditions present with the study area. All of our sites but one were dominated by Douglas-fir. This site (12) fell within a cold/moist forest dominated by true fir and mountain hemlock. Most sites had extensive cohorts of large Douglas-fir that proved to be in excess of 300 years of age. Three sites (2, 4, and 10) were dominated by mature (<160 years old) Douglas-fir, with a number of 300+-year-old cat-faced ponderosa pine that recorded multiple cambial injuries.

We searched each of our 16 study sites for stumps and logs that potentially contained cambial scars from fire damage. We constrained our search area at each site so that wood samples were all collected within an area with similar slope, aspect, elevation, vegetation, and landform with no topographic or vegetative barriers to fire spread. The total area searched at individual sites ranged from 2 to 11 ha (mean = 5.3 ha), depending largely on the evenness of the terrain present and the availability of suitable dead wood material. We intentionally limited the size of sites so that fire histories composited from multiple trees were most likely from fires that burned across all or most of the relatively small areas where data were collected (Baker & Ehle, 2001).

The large (>100-cm dbh) and old Douglas-fir that were ubiquitous at most of our sites occasionally had charred bark but otherwise showed little outward sign of having experienced fire. After some experimentation, we learned to sample two different types of dead tree material: First, logs or stumps that had distended or oblate forms suggestive of wood growing over past fire damage. Second, large stumps where much of the wood had decomposed but a portion of the wood was preserved because extensive resin covered a wound caused by fire damage. These latter opportunities for sampling wood could be identified by probing old stumps with a steel rod or shovel. At each site, we removed one or more partial cross sections from 15 to 20 (mean = 16.8) stumps, logs, or short (<3 m tall) snags with a chainsaw outfitted with a 66 or 80-cm bar.

Whenever possible, we cut a partial cross section close to the ground that included the pith of the tree so we could estimate the date the tree was established (minimum distance of pith samples to root collar = 0 cm, maximum = 131 cm, and mean = 47 cm). We also collected 33 wood samples of different species that included the pith at the root collar and the pith at heights ranging from 10 to 100 cm above the root collar to build a statistical model that estimated the number

TABLE 1 Study site characteristics.

Site	Area (ha)	MFRI	Series (PNV)	Fire frequency type	Elevation (m)	Annual precipitation (mm)	Aspect	Slope (°)
1	6.3	81.2	ABAM	Infrequent	1099	1956	N	9
2	11.0	11.2	PSME	Very frequent	785	1344	SSW	14
3	4.0	22.2	ABGR	Frequent	666	1359	N	12
4	10.4	5.9	PSME	Very frequent	729	1403	SW	10
5	2.3	146	ABAM	Infrequent	1184	1589	NE	18
6	3.1	29.5	ABGR	Frequent	568	1359	W	12
7	2.7	27.8	ABGR	Frequent	1083	1588	SW	21
8	2.2	45.3	TSHE	Frequent	1244	1795	SW	17
9	3.4	20.7	TSHE	Frequent	880	1496	E	9
10	8.0	7.2	PSME	Very frequent	688	1422	S	26
11	5.8	130	ABAM	Infrequent	1501	1869	W	9
12	2.6	165	TSME	Infrequent	1641	1852	NW	18
13	3.9	27.9	TSHE	Frequent	935	1553	NNE	35
14	8.2	19.3	ABGR	Frequent	567	1428	SSE	19
15	8.5	30.2	TSHE	Frequent	1114	1719	N	19
16	2.0	120	ABAM	Infrequent	1300	1903	NW	13
Mean	5.2	55.6	...	...	999	1602	...	16
Min–max	2.0–11.0	5.9–165			567–1641	1344–1956		9–35

Abbreviations: ABAM, *Abies amabilis*; ABGR, *Abies grandis*; MFRI, mean fire return interval; PNV, potential natural vegetation; PSME, *Pseudotsuga menziesii*; TSHE, *Tsuga heterophylla*; TSME, *Tsuga mertensiana*.

of years between pith dates and tree germination at the mineral soil horizon.

We used Forest Service field guides to key out each site to a plant association and forest series (i.e., PNV) based on the abundance of different species of understory vegetation and overstory trees (McCain & Diaz, 2002). To help characterize variability in contemporary forest vegetation, we also measured diameter at breast height and species of trees in three 0.1-ha plots 50 m apart within or in the immediate vicinity of each site (Figure 2).

Wood sample processing and evaluation of fire scar evidence

We transported all partial cross sections to Oregon State University College of Forestry Tree Ring Laboratory facilities where we removed a thin surface from each sample. Each sample was then sanded with progressively finer sandpaper to a high polish so that the wood cellular structure could be resolved with a high-powered microscope. Each sample was visually crossdated (Fritts & Swetnam, 1989). All ring widths present on samples were measured to 0.001-mm precision using an Acu-Gage single axis linear measuring system (Acu-Gage Systems, Hudson, NH). Our Acu-Gage machine has a digital camera for measuring samples that can traverse 100 cm, which was often necessary for measuring the large partial cross sections we took from old-growth Douglas-fir stumps and logs. We verified the accuracy of our crossdating using COFECHA software or R's dplR package (Bunn, 2008; Holmes, 1983; R Core Team, 2022).

We carefully evaluated every injury present within or between tree rings of each sample. Most scars found on cat-faced ponderosa pine stumps or logs were easily determined to be caused by fire (Smith et al., 2016). Data collection and fire scar interpretation procedures for ponderosa pine samples are illustrated in Figure 3. All scars on Douglas-fir samples had been completely covered by subsequent years' growth. A variety of different kinds of scars were present between Douglas-fir tree rings, including injuries most consistent with strikes from other trees, rubbing or browsing by animals when the tree was young, or splits across ring boundaries associated with wind shear in very large and tall trees.

Two important characteristics distinguished injuries caused by fire from injuries caused by mechanical damage in large and old Douglas-fir. First, we observed

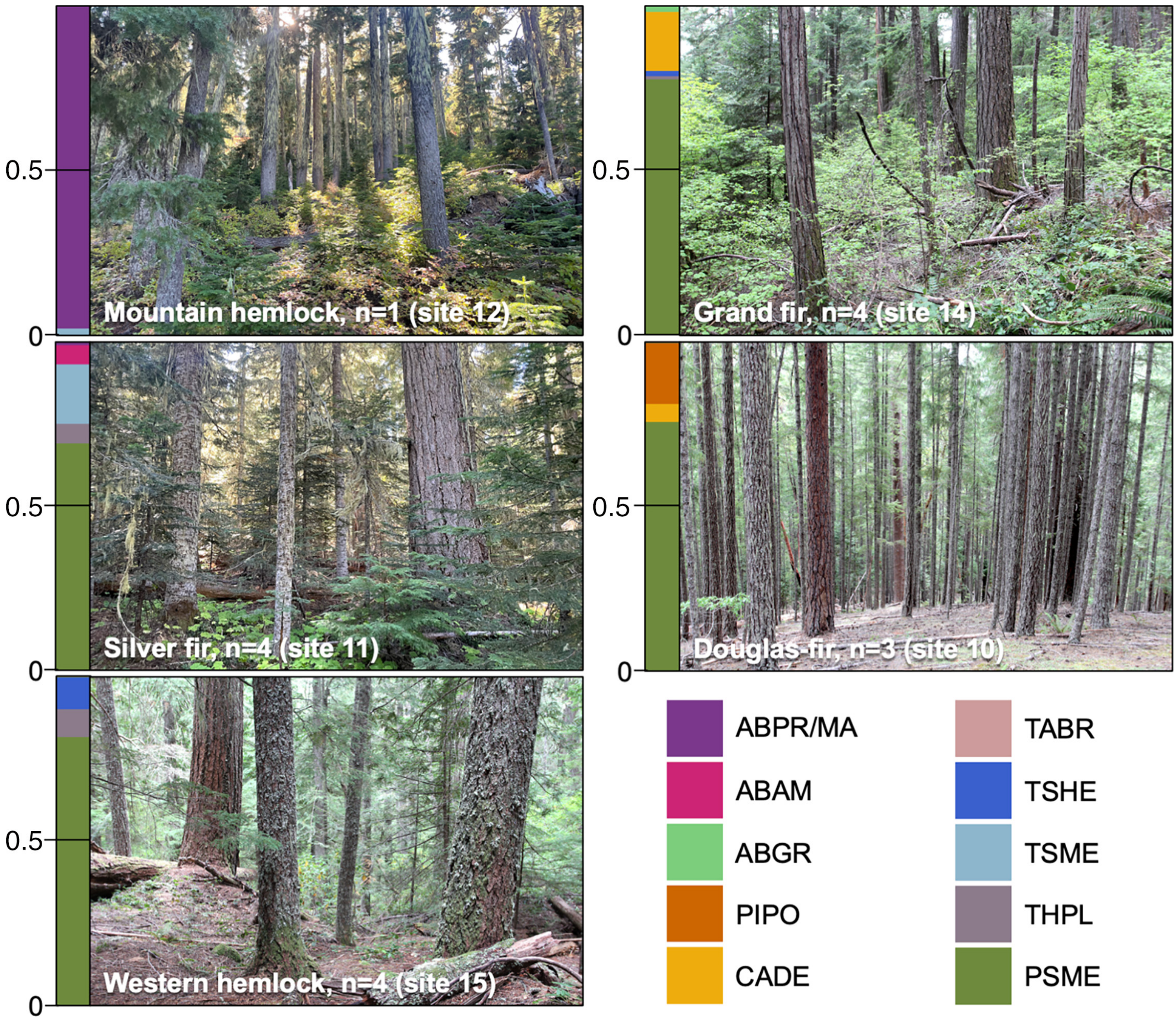

FIGURE 2 Photos representative of the five forest series/potential natural vegetation types where fire history data were collected (the site where each photo was taken is indicated in parentheses). Bars at the side of each photo indicate average basal area per hectare of different tree species as a proportion of total basal area per hectare within sites of each forest series (ABAM, *Abies amabilis*; ABGR, *Abies grandis*; ABPR, *Abies procera/magnifica*; CADE, *Calocedrus decurrens*; PIPO, *Pinus ponderosa*; PSME, *Pseudotsuga menziesii*; TABR, *Taxus brevifolia*; THPL, *Thuja plicata*; TSHE, *Tsuga heterophylla*; and TSME, *Tsuga mertensiana*). Species data were collected in three plots in unmanaged stands within or in the immediate vicinity of fire history data collection sites. Sites are keyed to forest series by virtue of characteristic assemblages of overstory and understory vegetation and not necessarily the relative abundance of different overstory tree species. See Table 1 for more detailed information about sites and forest types.

cambium death along a single-ring boundary following injury by fire. The wood underlying a fire-killed ring boundary was intact consistent with tissue necrosis from prolonged exposure to heat, and not splintered or abraded consistent with striking or rubbing (Smith, 2008; Smith et al., 2016). Second, most fire scars had a distinctive curl-over feature where subsequent years' growth converged together over fire-killed cambium (Smith et al., 2016). Data collection and fire scar interpretation procedures for Douglas-fir samples are illustrated in Figure 4.

We assigned a calendar year to all fire injuries present within each wood sample. Whenever possible, we also recorded a season when fire occurred based on the position of the scar within each tree ring. Fires that formed between ring boundaries were assigned to the dormant season of the previous year. Almost all the acreage burned during contemporary (1985–2022) fires across

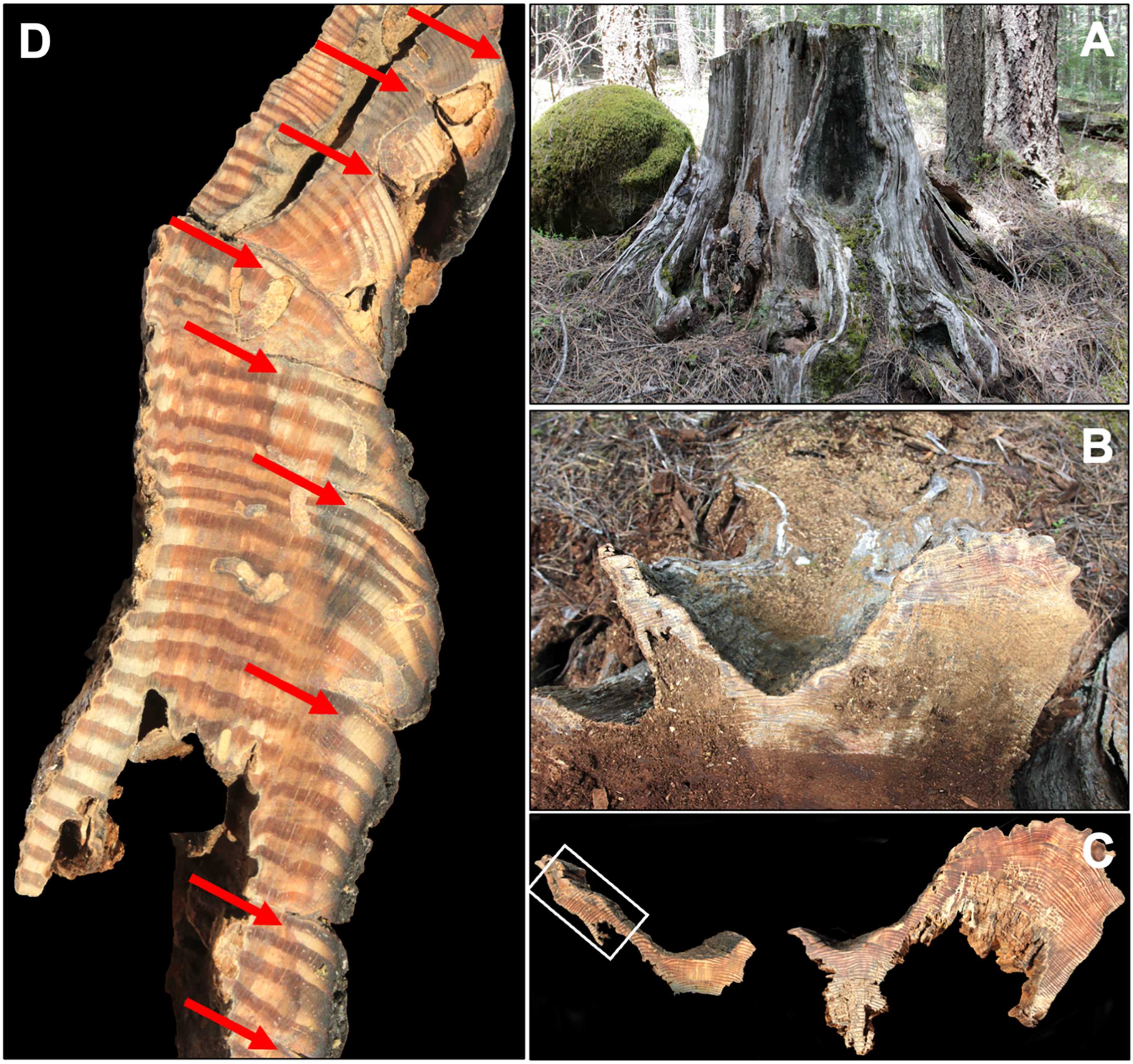

FIGURE 3 Collection and interpretation of fire scars found in ponderosa pine (in this case, from a stump found at site 4). A ponderosa pine stump with outwardly visible signs of fire scars embedded in a "cat face" (A). The cat-faced viewed from above after removing ~12 cm from the top of the stump with a chainsaw (fire scars are typically arranged in the wood that when viewed from the top is reminiscent of cat's whiskers) (B). Two samples recovered from the cat face with area shown in (D) indicated by a box (C). Fire scars in a portion of the cat face indicated by red arrows (from top to bottom: these fire scars were crossdated to the years 1874, 1858, 1849, 1839, 1833, 1829, 1822, 1815, and 1811) (D).

the western Cascades occurs from late July to late October, and it was extremely unlikely that historical fire was burning prior to the beginning of annual tree radial growth in the late winter or early spring in the mesic environments where we collected data. We assigned calendar years to other injuries that could not be positively assigned to fire damage (Figure 4D) but these injuries were excluded from further analysis.

Tree cohorts, fire severity, and fire synchrony

We characterized historical fire severity by evaluating the degree to which tree establishment derived from the pith dates found on partial cross sections constituted a coherent tree cohort. We assumed that tree cohorts were the result of moderate or high-severity fire that killed enough

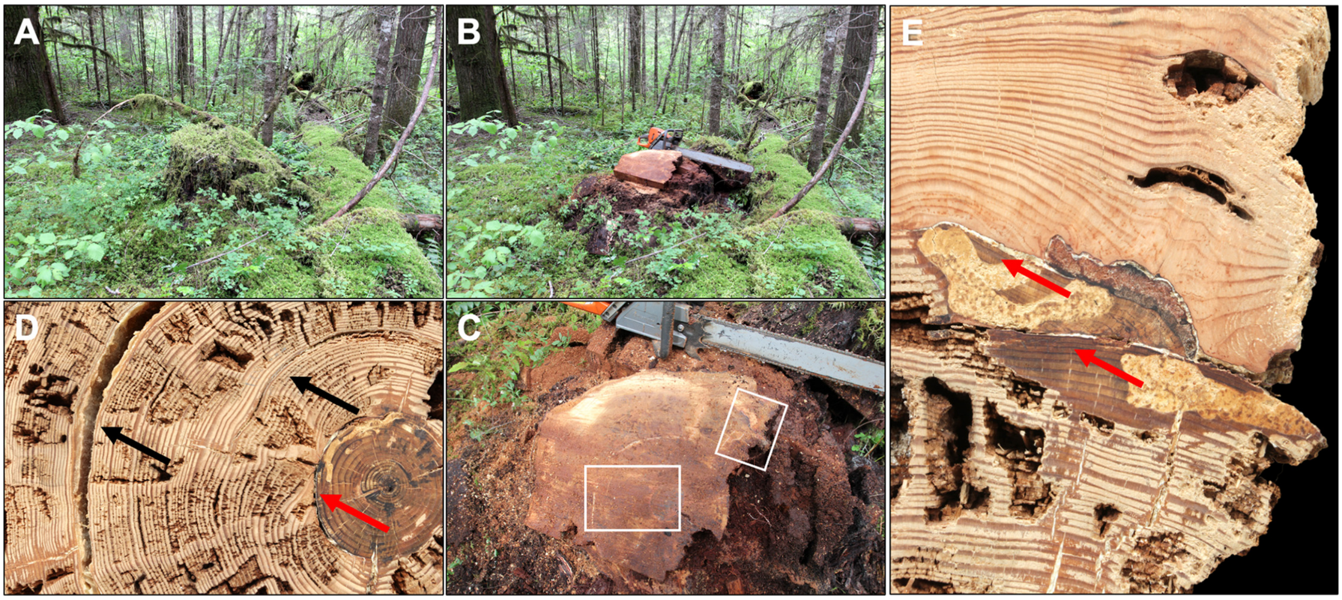

FIGURE 4 Collection and interpretation of fire scars found in Douglas-fir (in this case, from a stump found at site 6). Partially decomposed Douglas-fir stump that exhibited signs of fire hardened wood when probed with a steel bar (A). Excavation of the stump with a chainsaw (B). The resulting sample with areas shown in (D) and (E) indicated by boxes (C). Note that the pith is present and the sample was sawed quite low to the ground. Closeups of sanded and crossdated samples showing cambial injuries (D, E). Black arrows indicate cambial injuries that were not evaluated as damage from wildfires (the years 1725 and 1696 in (D)). Red arrows indicate injuries evaluated as fires (the years 1674 in (D) and 1787 and 1776 in (E)). Injuries not evaluated as fires may have resulted from fire damage, but lacked a clear "curl-over" feature and a clear scar boundary across a single ring that diagnosed fire damage.

of the overstory of forest stands to initiate the regeneration of shade-intolerant tree species like Douglas-fir. It is possible that other disturbances (e.g., windstorms) and not fire resulted in mortality of trees and subsequent regeneration. But in our coast Douglas-fir dominated study area, extensive shade-intolerant tree establishment and recruitment to the overstory are most likely following mortality of overstory trees and creation of mineral seed beds, conditions that usually only coincide following wildfire and not after storms, insect attack, and so forth (Isaac, 1943).

To precisely estimate the year of tree establishment, we first assigned a calendar year to the pith of each partial cross section where the pith was present or where we estimated the pith was within 20 years of the last ring present. We overlaid transparent concentric circles that matched the width of radial growth present on each wood sample to estimate years to pith when the pith was absent. The pith was intact on 87.5% of the samples for which we obtained pith dates. Years to pith on samples for which we had to estimate the pith ranged from 1 to 20 years (mean = 4.9). We estimated the year of tree establishment using a simple linear regression model fit with data from 33 trees that contained the pith at the root collar and the pith at different heights from the root collar. This model predicted the date of establishment of samples with pith dates as a function of sample height (distance from root collar) and the width of the 10 rings nearest the pith (a surrogate for growth rate). Estimated years between pith date and establishment date ranged from 0 to 11 years (mean = 4.7 years).

We used a simulation procedure to determine whether tree establishment dates within each site constituted a distinctive tree cohort. Our method first calculated the total number of tree establishment dates and the number of years between the first and the last establishment dates for each site. Next, we simulated tree establishment at each site by randomly selecting (with replacement) years equivalent to the total number of actual tree establishment years for each site across the same range of actual establishment years. We repeated this tree establishment resampling procedure 10,000 times for each site. For each of these 10,000 simulations, and for each time series of actual establishment dates, we calculated a binned kernel density estimate. When the density of any portion of the actual establishment dates was greater than 99% of the density of simulated establishment dates during that same time period, we considered the actual establishment dates to represent a coherent pulse of regeneration following fire disturbance rather than random establishment or episodic establishment following low-severity disturbance. A detailed rationale and explanation for this procedure is provided in Appendix S1.

Previous work in the vicinity of our study area noted extensive regeneration immediately following moderate and high-severity fire (Dunn et al., 2020; Dunn & Bailey, 2016; Johnston et al., 2019; Larson & Franklin, 2005). However, studies in other coast Douglas-fir dominated forests note that extensive Douglas-fir regeneration may be delayed until heavy seed years that typically occur every 5–7 years in this species (Williamson & Forest, 1973). Given this potential delay in tree establishment following fire, we searched for crossdated fire scars that formed 0–10 years before the first year of a distinctive tree cohort identified by our simulation procedure. We considered any crossdated fire year that fell within this window to have initiated the cohort. We summarized the lags between crossdated fires and cohort initiation to estimate the window during which a fire likely initiated the remaining tree cohorts for which we found no crossdated fire scars formed within a 10-year window prior to cohort initiation.

To characterize the degree to which fire that initiated shade-intolerant tree cohorts was synchronized across our study area we summarized the crossdated fire years that burned across multiple sites and the crossdated fires that initiated cohorts that burned across multiple sites. To further assess the degree to which large stand-replacing fire events burned across our study area, we graphed the temporal extent of fire-initiated tree cohorts, the fires that initiated these cohorts, and the range of years where fire that initiated the remaining cohorts most likely occurred.

Fire frequency and fire frequency types

We calculated a composite MFRI to quantify historical fire frequency for each site. Calculating MFRIs that represent consistent and objective estimates of fire frequency across stands with very different fire histories was challenging. Trees at some sites recorded regular fire beginning in the 1500s or 1600s through the end of the 1800s. Trees at other sites recorded just a few fires not long after a cohort-initiating event 300–500 years ago and no fires thereafter. For stands that experienced repeated fire into the 1800s, we calculated MFRI as the mean interval between all crossdated fires reconstructed at each site. For stands with long fire-free intervals that extended through the 1800s to the present day, we calculated MFRI as the mean of the intervals between the estimated date of stand-initiating fire, all crossdated fire years, and the last year in which a fire was recorded at any site (1895 CE). Truncating the final fire interval in this fashion for those sites for which we reconstructed few or no fires risks underestimating MFRIs (i.e., the true average length between fires may have been somewhat longer at some sites). But we believe this approach is justified because our research goal was to quantify historical fire regimes, and there was clearly a significant disruption to historical fire regimes in our study area beginning in the late 1800s (see *Methodological considerations and scope of inference*).

We calculated the cumulative number of fires occurring over time at each site and compared the resulting slopes to determine whether fire frequency differed between sites or between forest series/PNVs in a predictable and consistent way. We considered sites with statistically different cumulative fire slopes to belong to different fire frequency types in subsequent analysis of climate influences on fire (see *Interannual climate influence on fire*). We compared slope lines by comparing z-scores using the methods described in Clogg et al. (1995) and by constructing linear regression models with a year × fire frequency type interaction and evaluating the significance of this term with α set to 0.05.

Biophysical influences on fire

For each tree sampled, we calculated a total of 19 different environmental variables that represented climatic (e.g., 30-year normal maximum temperature) and topographic (e.g., slope) differences between sites (Table 2). We calculated the mean value of each environmental variable for all samples within each site and used the supervised machine learning algorithm Random Forest to test for the influence of these variables on composite MFRIs for each site. Many of the environmental variables we tested were highly correlated. For example, vapor pressure deficit (VPD), maximum summer temperature, and elevation all represent coupled topographic-atmospheric relationships that exert a strong control on live and dead fuel moisture content and hence fire behavior. As with traditional regression methods, variable selection using Random Forest is biased toward correlated variables (Strobl et al., 2007).

Our objective was to select from among correlated and noncorrelated variables those variables that provided statistically robust and parsimonious explanations for differences in fire frequency between sites. To accomplish this objective, we adopted the two-step Random Forest variable selection procedure recommended by Genuer et al. (2010) implemented with R's VSURF package (Genuer et al., 2015). VSURF creates a preliminary ranking of explanatory variables based on Random Forest's permutation-based variable importance scores and discards variables with relatively low predictive power. Then VSURF selects from among remaining variables those best suited for interpretation and/or prediction by constructing

TABLE 2 Variables examined as explanatory of mean fire return interval.

Variable	Notes and sources
Actual evapotranspiration	ArcGIS online
Annual net primary productivity	PRISM (https://www.prism.oregonstate.edu)
Annual precipitation in millimeters	PRISM (https://www.prism.oregonstate.edu)
Aspect	Aspect calculated from a 10-m digital elevation model (DEM)
Average annual maximum temperature	PRISM (https://www.prism.oregonstate.edu)
Average annual temperature	PRISM (https://www.prism.oregonstate.edu)
Average snow cover frequency from 2001 to 2019	SnowCloudMetrics (https://www.snowcloudmetrics.app)
Average snow disappearance date from 2001 to 2019	SnowCloudMetrics (https://www.snowcloudmetrics.app)
Curvature	Combination of planform and profile curvature
Elevation	Elevation calculated from a 10-m DEM
Maximum annual vapor pressure deficit (VPD)	PRISM (https://www.prism.oregonstate.edu)
Minimum annual VPD	PRISM (https://www.prism.oregonstate.edu)
Planform curvature	Curvature perpendicular to the direction of the related to the convergence and divergence of flow across a surface
Potential evapotranspiration	ArcGIS online
Profile curvature	Curvature parallel to the slope indicating the direction of maximum slope that affects the acceleration and deceleration of flow across the surface
Ruggedness	The mean difference in elevation between a central pixel and its surrounding cell calculated from a 10-m DEM
SAGA Wetness Index	Calculated from a 10-m DEM using the methods of Boehner et al. (2002)
Slope (degrees)	Slope calculated from a 10-m DEM
Topographic position index	Calculated from a 10-m DEM in QGIS

a nested collection of Random Forest models and selecting variables that contribute to models with the smallest out-of-bag error rate. We used final variables selected by VSURF to build mixed linear models and simple linear models that provided estimates of the effect of environmental variables selected by VSURF on fire frequency.

Interannual climate influence on fire

Based on previous fire history research in Oregon (e.g., Johnston et al., 2017), we anticipated that fire years reconstructed in our study area, and particularly fire years that burned multiple sites or that initiated cohorts, would be strongly associated with anomalously dry climate. We tested this hypothesis using superposed epoch analysis (SEA) and reconstructed historical Palmer Drought Severity Index (PDSI; Cook et al., 2010; grid point 33). SEA evaluates the degree to which climate before, during, and after event years departs from average values based on confidence limits for the departure obtained by bootstrapping (Guiterman et al., 2019). We used the sea function in the R package burnR to evaluate individual fire years as well as the four years prior to fire and the two years following fire (Malevich et al., 2018). We considered PDSI in any of these years to be anomalously arid or moist when it exceeded either 95% or 99% CIs obtained from 1000 bootstraps. We tested for significant departures from mean reconstructed PDSI for all fire years, all fire years that burned across multiple sites, all fire years that initiated cohorts, and fire years burning at sites belonging to different fire frequency types (see *Fire frequency and fire frequency types*).

RESULTS

We collected, processed, and crossdated 351 partial cross sections from 311 dead trees (21 logs, 17 snags, and the remainder stumps). A total of 226 (73%) of trees sampled were coast Douglas-fir. Ponderosa pine, noble/red fir, incense cedar, and mountain hemlock made up 13%, 5%, 4%, and 4% respectively of trees sampled. Western red cedar, sugar pine, and western hemlock combined represented less than 1% of trees sampled.

We crossdated a total of 147,588 tree rings in which we identified 672 cambial injuries, 479 of which we classified as fire scars. These crossdated fire scars allowed us to reconstruct 130 different fire years that occurred at one or more of our 16 study sites between 1500 and 1895 CE. All sites had sufficient dead old trees available to build multi-century records of fire and tree establishment, and we crossdated at least one fire scar at every site except site 12. Figure 5 displays the results of our reconstructions, including tree establishment dates, crossdated fires, and shade-intolerant tree cohorts at each of our 16 sites. The vast majority (92%) of fire scars for which we could assign a season of fire were found within the latewood or after the end of radial growth, indicating fires that burned sometime between the middle of summer and fall, which is consistent with the contemporary fire season. The remaining scars were found in the late portion of the early wood, indicating fires that burned in late spring or early summer. All late early wood scars were found in trees sampled within Douglas-fir series sites.

Composite MFRIs differed significantly among sites, ranging from 6 years (site 4) to 165 years (site 12). Examination of the range of MFRIs reconstructed within sites belonging to different forest series suggested there were three distinct historical fire frequency types across our study area. MFRIs in grand fir and western hemlock series sites ranged from 19 to 45 years. MFRIs for Douglas-fir series sites were approximately twice as short, ranging from 6 to 11 years. MFRIs for silver fir and mountain hemlock series forests were generally more than twice as long, ranging from 81 to 165 years (Table 3). A regression of the cumulative number of fires by year, essentially a measure of the rate of accumulation of fires at sites over time, also clearly distinguished the slope of grand fir and western hemlock series forests from other forest series (Figure 6). Hereafter, we refer to Douglas-fir series sites as the very frequent fire type, grand fir and western hemlock series forests as the frequent fire type, and silver fir and mountain hemlock series forests as the infrequent fire type.

Although our cohort detection simulation procedure made use of a relatively small number of pith dates, we were able to identify a total of 16 distinctive tree establishment cohorts comprised primarily of shade-intolerant species at 12 different sites (Figure 5). Four sites, including a western hemlock series site (13), two grand fir series sites (3 and 7), and a Douglas-fir series site (10) exhibited some coherence in tree establishment, but our simulation procedures provided no statistically robust evidence of tree cohort initiation following fire. Two Douglas-fir series sites (2 and 4) and a grand fir site (14) experienced frequent or very frequent fire and had relatively uneven-aged structure but also showed evidence of one tree establishment cohort. All silver fir series sites, the one mountain hemlock series site, and all but one western hemlock series sites experienced at least one fire that initiated a tree cohort, and three of these sites (16, 1, and 15) experienced multiple fire events that initiated cohorts (Figure 5).

The fire history evidence we assembled provided little evidence of large stand-replacing fires that burned across multiple sites separated by ~4 km. Of the 130 fire years we reconstructed, 80 fire years (62%) were reconstructed at only one of our 16 data collection sites. A total of 36 fire years (28%) were reconstructed at two different sites, and 10 fire years (8%) burned at three different sites. The 1706 and 1783 fire years were recorded at four sites, the 1776 fire year was recorded at five sites, and the 1849 fire year was recorded at six sites (Figure 5, lower panel). A total of eight fire years reconstructed from crossdated scars occurred between 0 and 7 years (mean = 3 years) before the initiation of a tree cohort, and we considered it most likely that these fires were responsible for initiating those cohorts. None of these crossdated cohort-initiating fire years were recorded at more than one site. There was also little temporal overlap between tree establishment cohorts across sites (Figure 7). One notable exception was cohorts initiated between 1659 and 1679 at sites 2, 4, 14, 15, and 16. But the fires that most likely initiated these cohorts burned in different years, suggesting these cohorts formed during several decades of heightened fire activity but were not burned in one large fire.

Variable selection with VSURF procedures indicated that maximum summer VPD was sufficient to explain the MFRI response without the inclusion of other explanatory variables in models. Elevation or average snow cover frequency also would have provided parsimonious models explaining variability in the MFRI response among sites. Linear model building confirmed that VPD was the best predictor of the MFRI response and that adding additional variables did not increase model performance. A simple linear model for VPD explained 76% of the MFRI response. A 1-hPa decrease in VPD was associated with a 26.7-year (95% CI = 18.2–35.2 years) increase in MFRI (i.e., less frequent fire) (Figure 8). Our sample units (individual fire history sites, $n = 16$) were not independent in a strict sense, although our analysis of fire synchrony above suggests that fire at one site had little predictive power of fire at another site. We also fit mixed models with site and site within forest series as random effects to account for the lack of independence in sample units. But these models provided little improvement as measured by variance explained or AIC, and the effect of VPD on MFRI with mixed models was nearly identical to the simple linear model.

SEA demonstrated that fire occurrence within our study area was associated with different climate signals across forest types. There was modest evidence of

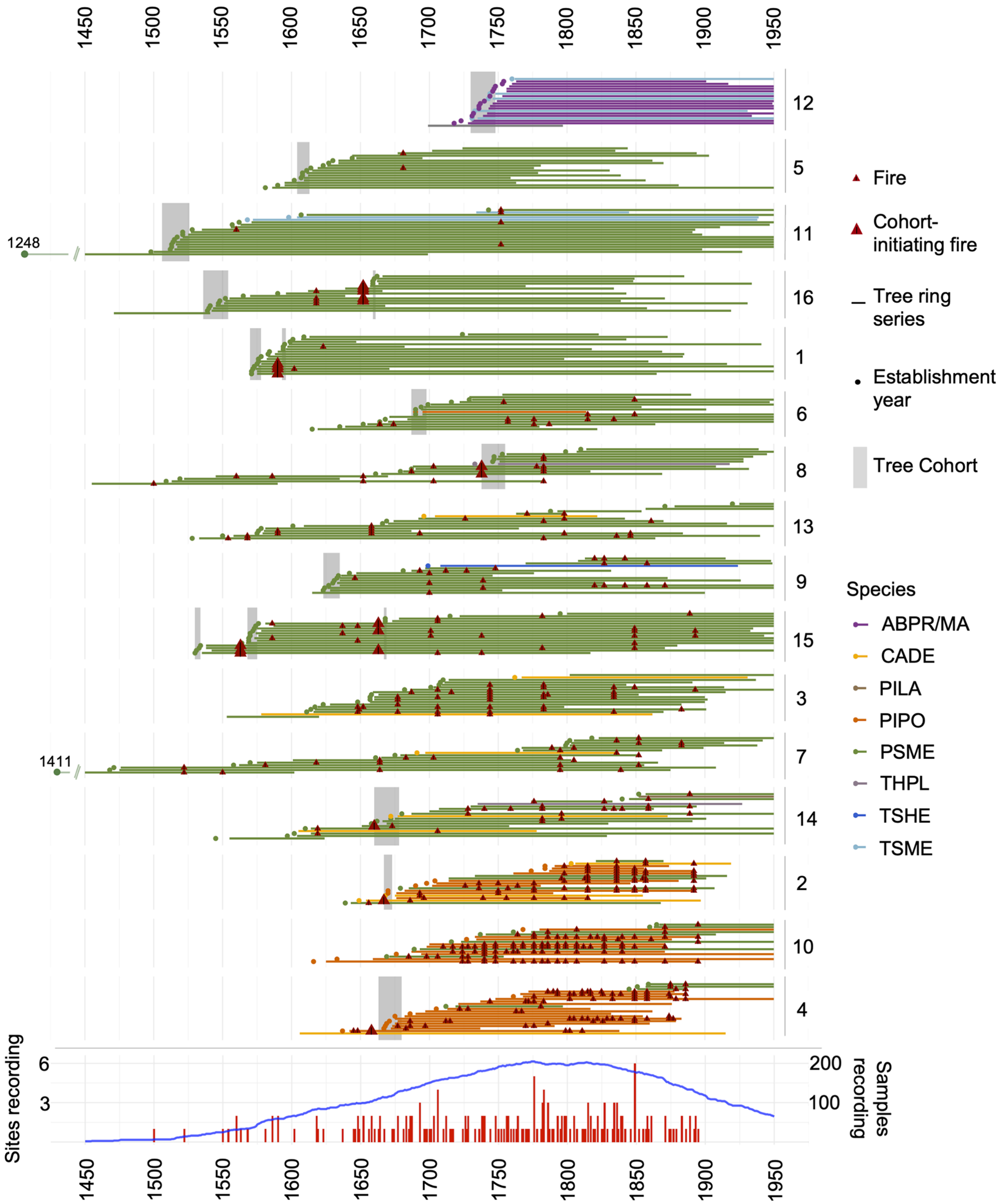

FIGURE 5 Legend on next page.

anomalously arid conditions in the year of fire and moister conditions in the year immediately preceding fire when evaluating all crossdated fire years (Figure 9A). There was strong evidence of anomalously arid conditions in the year of fire and no evidence of an effect of antecedent moisture when considering fire years that were recorded at more than one site (39% of total fires; Figure 9B).

The magnitude of drought during fire years that initiated cohorts was similar to the magnitude of drought during fire years that burned more than one site, although there were likely too few replicates of cohort-initiating fires ($n = 8$) to make robust inferences about the significance of this departure (Figure 9C). Similarly, only eight fire years were reconstructed within infrequent fire types (silver fir series), and there was little evidence of a strong climate control on fire occurrence during these fire years (Figure 9D). There was very strong evidence that fire was associated with arid years in frequent fire types (grand fir and western hemlock series) and no evidence of an effect of antecedent moisture (Figure 9E). There was modest evidence that fire years in very frequent fire types (Douglas-fir series) were more arid than normal, and strong evidence that these fires were preceded by anomalously moist conditions (Figure 9F).

DISCUSSION

Historical fire in a coast Douglas-fir forest

This study and Merschel (2021) are the first to use annually resolved tree ring records to quantify long-term fire occurrence in productive coast Douglas-fir dominated landscapes of the western Oregon Cascades. Our methods reveal extraordinary complexity in historical fire regimes in the western Cascades, ranging from stands that experienced a stand-replacing fire many centuries ago and no fires since that time, to stands with few if any stand-replacing fires and chronic nonstand-replacing fire for hundreds of years until cessation of fire in the late 1800s. Climate influences on fire also varied within a relatively small (15,000 ha) study area. Approximately half of the fires we reconstructed were associated with anomalously arid climate. The remaining fires are more strongly influenced by moist years prior to fire.

We anticipated that systematically locating fire history sites across our study area would allow us to detect evidence of past large wind-driven fire events that are considered archetypal of coast Douglas-fir forests (Agee, 1996; Donato et al., 2020; Franklin et al., 2002; Halofsky et al., 2018; Reilly et al., 2022). Further, we assumed that we would be able to obtain a rough estimate of the size of some of these events by observing the degree to which tree cohorts or cohort-initiating fires were reconstructed at multiple sites. But this study provides little evidence of large, wind-driven fires of the sort that burned 50,000–75,000 ha in the watersheds immediately to the north and to the south of our study area in 2020 (Figure 1).

Although we cannot precisely estimate the size of historical fires given the extent and grain of our sampling grid, the fact that only 39% of fire years were recorded at more than one site, only 11% of fire years were recorded at more than two sites, and only 3% of fire years were recorded at more than three sites strongly suggests that most historical fires were relatively small. Few if any of the shade-intolerant tree cohorts that we reconstructed at 16 sites within a ~15,000-ha area appear to have originated as a result of the same fire event (Figures 5 and 7), suggesting that stand-replacing patches were also limited in spatial extent. Interestingly, the few fires that almost certainly burned relatively large areas—the 1849 fire that was recorded at six sites, the 1776 fire that was recorded at five sites, and the 1783 and 1706 fires that were recorded at four sites—did not reset succession at those sites or initiate any tree establishment cohorts that we were able to detect.

It is likely that collecting additional tree establishment data would provide evidence of additional shade-tolerant or shade-intolerant tree establishment cohorts at our sites. Merschel (2021) reconstructed almost twice as many tree establishment cohorts per data collection site on the Umpqua National Forest to the south of our study area

FIGURE 5 Fire history from 1450 to 1950 CE at 16 data collection sites across the upper Middle Fork study area. Upper panels show individual tree ring series (horizontal lines), tree establishment dates (small points), crossdated fire years (small triangles), crossdated fire years that initiated cohorts (large triangles), and establishment dates that constitute distinct tree cohorts (shaded polygons) for each site. Sites are ordered from the fewest to the most fires reconstructed. Tree ring series and establishment dates are color coded by species (ABPR/MA, *Abies procera/magnifica*; CADE, *Calocedrus decurrens*; PILA, *Pinus lambertiana*; PIPO, *Pinus ponderosa*; PSME, *Pseudotsuga menziesii*; THPL, *Thuja plicata*; TSHE, *Tsuga heterophylla*; and TSME, *Tsuga mertensiana*). Two establishment dates that preceded 1450 CE are shown on the far left of the upper panels. Bottom panel shows the number of sites recording fire in each year as red bars (minimum of zero and maximum of six sites recording fire between 1450 and 1950) and the total samples capable of recording fire in a given year as a blue line (minimum of 2 and maximum of 216 samples capable of recording fire between 1450 and 1950).

TABLE 3 Summary of mean fire return intervals (MFRIs) calculated for five forest series (i.e., potential natural vegetation).

Series	No. sites	Average MFRI	MFRI range
PSME	3	8.1	6–11
ABGR	4	24.7	19–30
TSHE	4	31.0	21–45
ABAM	4	119.3	81–146
TSME	1	165.0	...

Abbreviations: ABAM, *Abies amabilis*; ABGR, *Abies grandis*; PSME, *Pseudotsuga menziesii*; TSHE, *Tsuga heterophylla*; TSME, *Tsuga mertensiana*.

using a larger data set consisting of establishment dates derived from tree cores. Our sparser data were likely sufficient to identify the tree cohorts that constitute the dominant older overstory trees at our sites. Reconstructing additional tree cohorts with a larger tree establishment data set would likely indicate that historical successional and disturbance dynamics were even more complex than we report.

Neither theory nor widely used management frameworks account for the tremendous variability in frequency, severity, and climate drivers of historical fire at the fine spatial scales documented by this study. For instance, widely used fire regime mapping products (e.g., LANDFIRE; see Rollins, 2009) and recent science syntheses of western Cascades forests (Spies et al., 2018) divide all of our ~15,000-ha study area into just one or two natural fire regime classifications (e.g., "infrequent high-severity" or "moderately frequent—mixed-severity"). To adapt forests to future change, scientists and managers require far greater detail about historical fire at much finer spatial scales than anticipated by any existing fire regime framework. Effective adaptive management of other coast Douglas-fir dominated forests will benefit from detailed fire history research that elucidates fine-scale variability in successional and disturbance dynamics.

Management implications

An important finding of our study is the abrupt cessation of fire across our study area coincident with the establishment of forest reserves and modern management regimes in the late 1800s. The timing of the termination of burning is similar to the timing of fire exclusion in dry forests of eastern and southern Oregon (Heyerdahl et al., 2019; Johnston et al., 2017; Merschel et al., 2018; Metlen et al., 2018). In dry forests, fire exclusion has resulted in significant increases in forest density, fuel loading, and fuel connectivity, and these forests are vulnerable to loss of critical ecosystem function from uncharacteristically severe fire (Hagmann et al., 2021; Hessburg et al., 2021; Prichard et al., 2021). A large portion of our study area is also departed from the historical range of variability

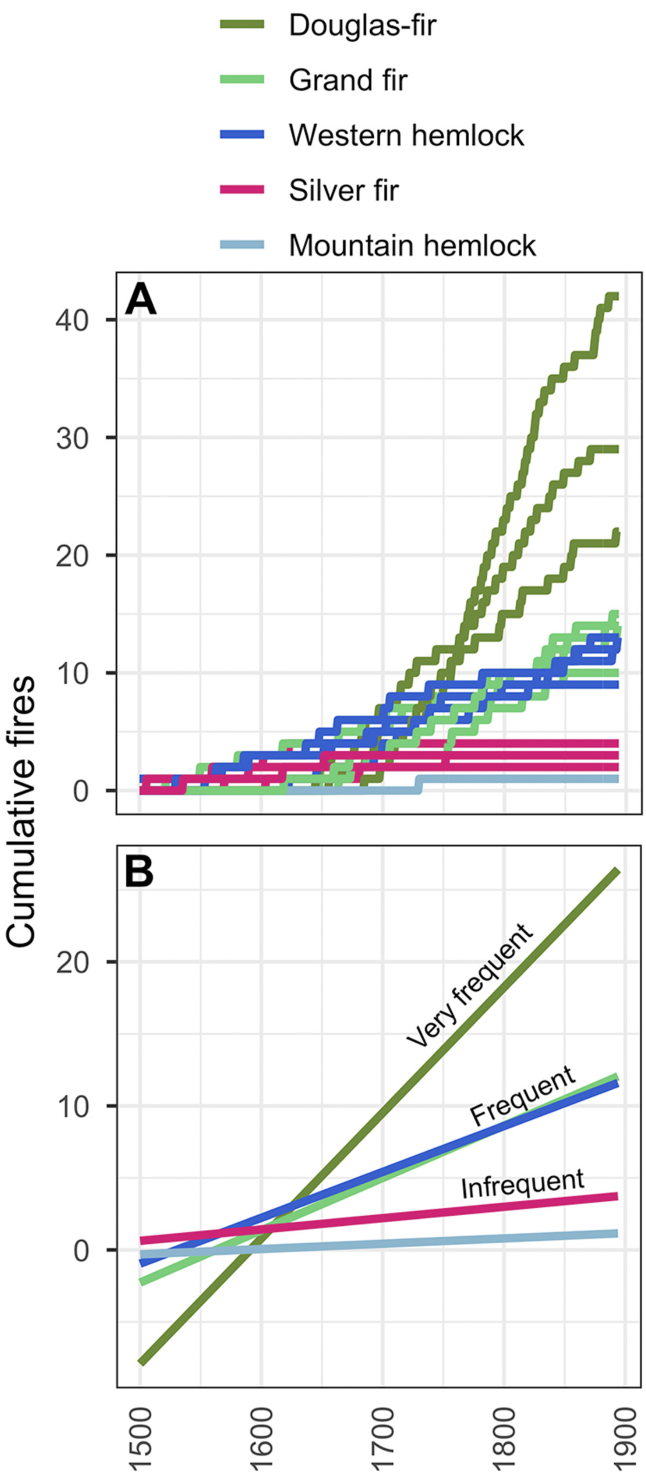

FIGURE 6 Cumulative fires over time for 16 sites (A) and the slopes of the cumulative fire over time regression for all sites of each forest series (B). The slopes of grand fir and western hemlock series sites were significantly different from Douglas-fir series and silver fir and mountain hemlock series sites ($p < 0.01$) and were the basis for dividing sites into very frequent, frequent, and infrequent fire types.

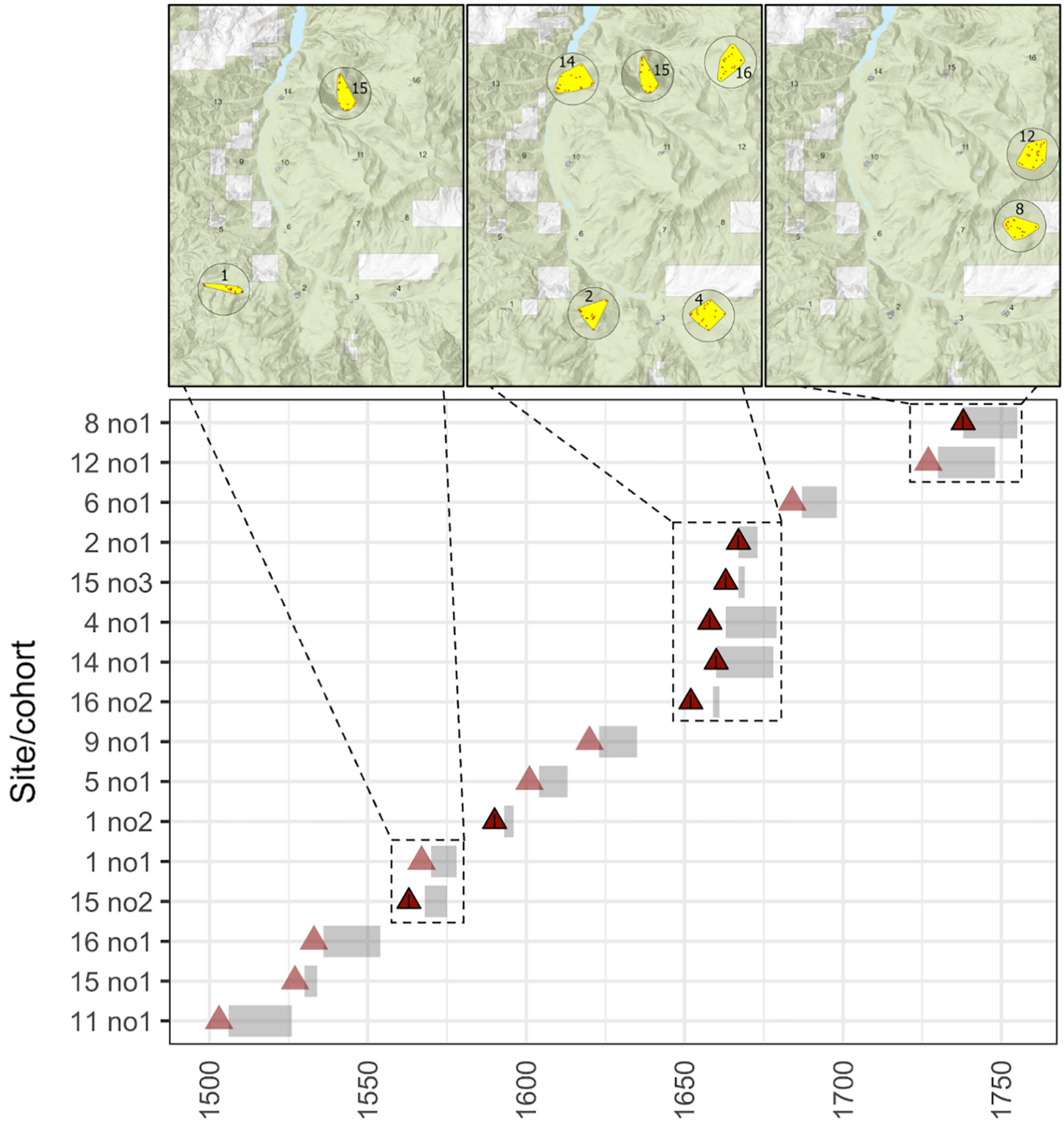

FIGURE 7 Synchrony of shade-intolerant tree cohorts and cohort-initiating fires across sites. The lower panel shows tree establishment cohorts (gray polygons), cohort-initiating fires reconstructed from crossdated fire scars (dark red triangles with black line showing year of fire), and the likely range (0–7 years prior) of cohort-initiating fires that we were unable to reconstruct using fire scars (transparent red triangles). Upper panels exaggerate sites with cohorts that overlapped temporally.

in fire frequency. However, we urge managers to make decisions about restoration treatments within our study area based on a broader set of considerations than simply the difference between historical and contemporary fire frequencies.

Several observations lead us to believe that Douglas-fir series stands in our study area require silvicultural intervention to maintain critical ecological functions. First, we noted significant forest compositional and structural change. Most of these stands have a few old (>300 years old) Douglas-fir, but the vast majority of contemporary basal area in these stands is young and mature (≤150 year old) Douglas-fir that were established beginning in the late 1800s when fire was excluded. Our field observations, as well as one study conducted in a nearby site (Day, 2005), demonstrate that Douglas-fir series forests in our study area are significantly denser today than they were 150+ years ago. Second, these structural and

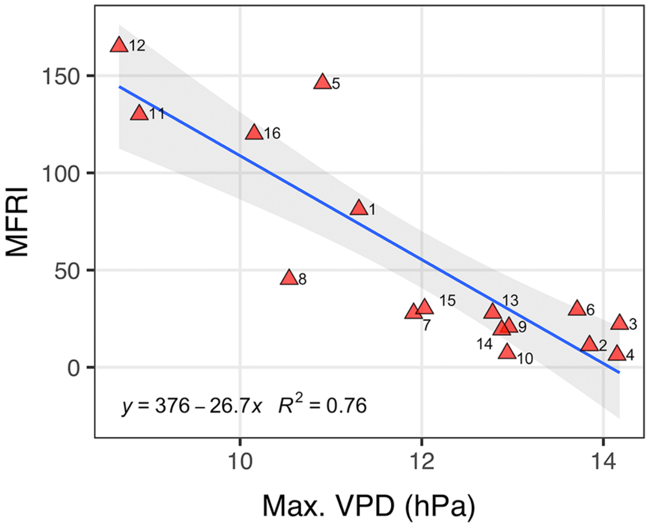

FIGURE 8 Relationship between maximum summer vapor pressure deficit (VPD) and mean fire return interval (MFRI). Labeled red triangles are individual sites.

compositional changes are clearly resulting in significant mortality of old-growth pines and oaks. Providing a detailed account of mortality dynamics is beyond the scope of this study, but during field data collection, we estimated that approximately a quarter of extant old-growth ponderosa pine had died in the last 20 years. Dead Oregon white oak stems beneath 25–35 m tall Douglas-fir canopies were commonplace. Without thinning to release pines and oaks, most old-growth historical forest structure will be lost to competition from young and mature Douglas-fir.

Grand fir series stands in our study area appear to have undergone some change in the last 150 years, but these changes were more subtle than the change in Douglas-fir series stands. All of the stands where we collected data appear to historically have been dominated by Douglas-fir with sugar pine and incense cedar as the two most common secondary species. All of the older sugar pine in these stands were dead when we collected data in 2020. We believe that more collaborative research is needed to craft management objectives for these stands and determine if silvicultural intervention can achieve forest resilience objectives.

All western hemlock stands in our study area and possibly some silver fir stands have missed one or more natural fire cycles, and it is likely that these stands have somewhat more shade-tolerant and fire-sensitive species cover than they did historically. But our field observations do not suggest that significant structural or compositional changes in these stands have occurred. And there is no evidence from our field observations or other research in these forest types to suggest that old-growth structure is at heightened risk from uncharacteristic disturbance as a result of fire exclusion policies (Franklin & Johnson, 2012). There is little reason to believe that silvicultural interventions that have been successful in relinking critical pattern-process feedbacks in dry forests (see Lindsay & Johnston, 2020; Prichard et al., 2021; Tepley et al., 2020; Vernon et al., 2023) would achieve forest resilience objectives in older western hemlock or silver fir series forests on the west slope of the Cascades (Halofsky et al., 2018). Although we do not recommend thinning or other types of restoration forestry in western hemlock or silver fir series forests, additional research is warranted to investigate the degree to which changes to fire management policies are appropriate to facilitate future fire in these forest types.

Our research suggests a need for active management in young tree plantations of all forest types. Almost all older stands in our study area originated with a series of fires (Poage et al., 2009; Poage & Tappeiner, 2002; Tepley et al., 2014). These results suggest an explanation for long periods of Douglas-fir establishment noted by other studies. For instance, Freund et al. (2014) reported Douglas-fir establishment periods of up to 99 years (averaging 50–70 years) across 18 sites in western Oregon and Washington. These prolonged periods of regeneration likely do not represent continuous Douglas-fir establishment after stand-replacing fire, but rather episodic regeneration following a series of reburns. Reburns following cohort initiation in our study area were almost certainly associated with prolonged early successional habitat and dynamic allocation of resources to residual tree structure (Davis et al., 2007; Kroll et al., 2020). Where creation of complex habitat is a management objective, fire or thinning disturbance in plantations that have experienced just one stand-replacing disturbance (logging) should be a priority for managers (Franklin & Johnson, 2012).

Methodological considerations and scope of inference

This study demonstrates that very large and old coast Douglas-fir are capable of recording multiple fire events and are probably underutilized by dendroecologists for fire history research (Figure 4). In our experience, most sites in the western Oregon Cascades have stumps and dead logs sufficient to reconstruct detailed fire histories, but working with this material poses unique challenges. Many of our samples were taken from stumps or logs that exceeded 120 cm in diameter (the largest stump sampled was 223 cm in diameter). Many partial cross sections from dead trees had significant water content and usually weighed in excess of 15 kg (several samples from

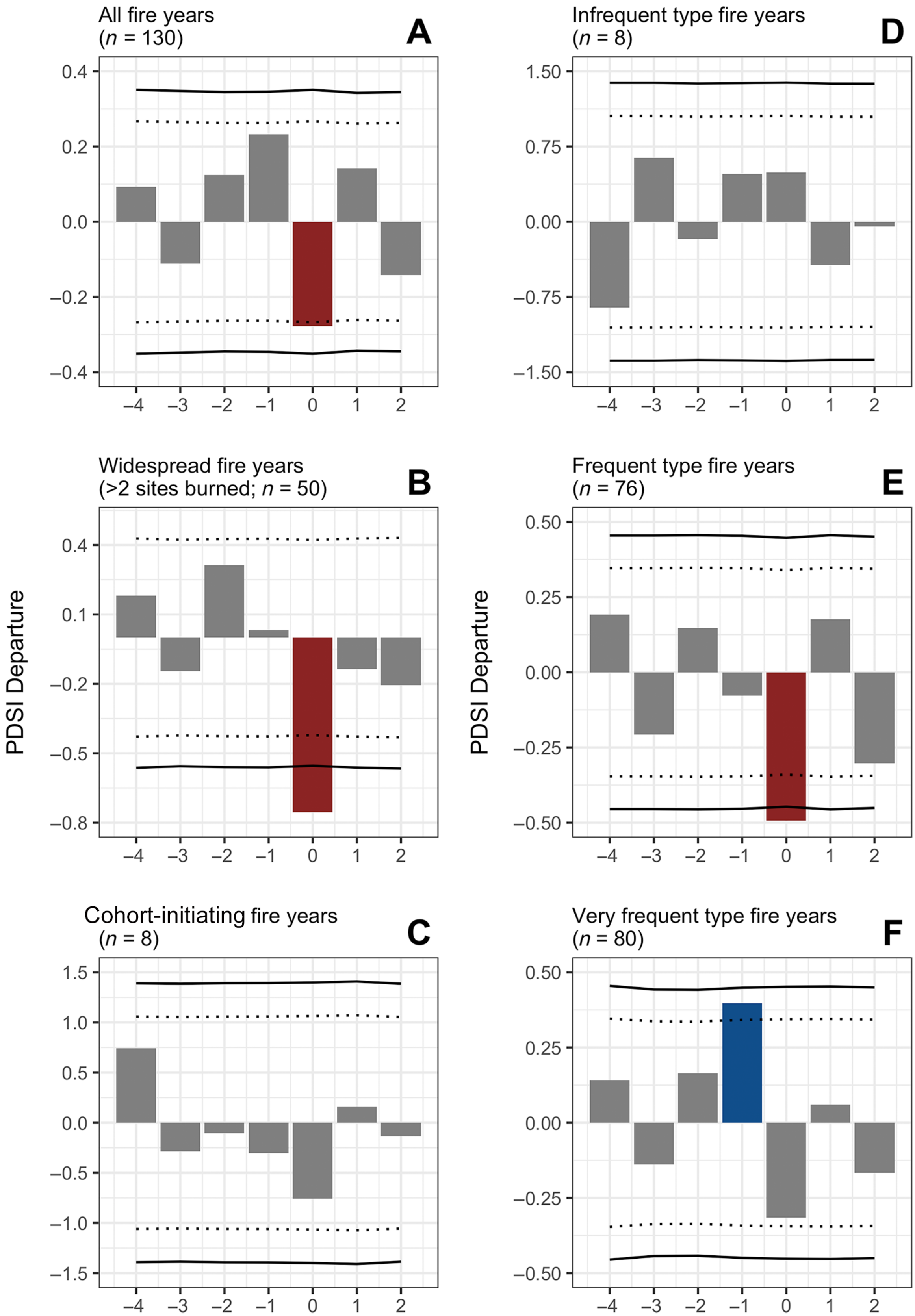

FIGURE 9 Results of superposed epoch analysis. Bars indicate mean Palmer Drought Severity Index (PDSI) value during year of fire (0 on the *x*-axis) and four years before and two years after fire. PDSI values during year of fire that are significantly departed from mean values at either 95% or 99% CIs (dotted and solid horizontal lines, respectively) are colored red (significantly negative PDSI values indicating aridity) or blue (significantly positive PDSI values indicating cool and moist conditions).

waterlogged stumps that weighed in excess of 25 kg were left in the field for a year to dry).

We found that collecting smaller partial cross sections was often not possible when fire scars covered a large portion of the tree bole or when we needed long pieces of wood to ensure adequate rings were present for crossdating radial growth. Collecting and processing this type of material requires highly trained field crews and expensive equipment that can be difficult to operate and maintain. In particular, to the best of our knowledge, the relatively expensive (~US $20,000) Acu-Gage system is the only system well suited for precise measurement of tree rings in wood samples of this size.

Our methods for calculating MFRIs (see *Fire frequency and fire frequency types*) differed somewhat depending on the type of site evaluated. For most sites, we derived MFRI as the mean interval between crossdated fire scars. Some of these composite records have relatively large gaps between fires that may reflect a lack of fire but, especially in stands seral to Douglas-fir, most likely reflect periods during which few if any trees had open cat-faces recording fire (see, e.g., the gap in fire in the early 1700s at site 2 and the gap in fire in the mid-1700s at site 4 shown in Figure 5). In those cases, we likely overestimated MFRI, that is, fire historically occurred even more frequently than we report. On the other end of the fire frequency gradient, we derived MFRI as the interval between an estimated year of stand-initiating fire, any crossdated fire scars present, and the year 1895. In those cases, truncating the length of the last interval at the year 1895 may have resulted in underestimates of MFRI; that is, fire historically occurred somewhat less often than we report. Our estimate of fire frequency in stands seral to mountain hemlock is especially suspect (Table 3), since we only collected data at one mountain hemlock site, and there was only one fire return interval that was somewhat arbitrarily determined.

We believe that our methods for calculating MFRI in stands with few or no reconstructed fires were appropriate for several reasons. First, there is considerable evidence that management of our study area underwent significant change in the late 19th and early 20th centuries with the establishment of a forest reserve (later a national forest) and adoption of modern forest management practices including fire exclusion (Clary, 1986; Rakestraw & Rakestraw, 1991). It is undoubtedly significant that we were unable to reconstruct any wildfires at any of our sites after the year 1895, and so the use of this year as the endpoint of the last fire return interval calculated for sites where fire burned infrequently is logical. Although we almost certainly did not reconstruct every fire that occurred in study sites over the past 500 years, our relative estimates of differences in fire frequency between stands and forest types should be reliable. There is no reason to believe that trees in stands that recorded fires during an early period were not capable of recording fires during a later period had fires occurred, particularly since trees of the same size, age, and species at other sites were recording fire (Figure 5). Although it stands to reason that young coast Douglas-fir are more easily damaged by fire (many 5- to 75-year-old trees recorded fire), many trees that recorded fire when they were young also frequently recorded fire when they were hundreds of years old (Figure 5).

As noted above (*Historical fire in a coast Douglas-fir forest*), our evaluation of tree cohorts and the relationship between tree cohorts and fires used a relatively small number of tree establishment dates (10–20 establishment dates per site). These relatively sparse data make it unlikely that we describe the full range of fire-mediated tree establishment dynamics present within sites across our study area. Collection and processing of wood samples from large and old dead Douglas-fir poses unique challenges and the resources available for this research did not permit us to significantly increase sample sizes. Our evaluation of tree cohorts was also limited by the amount of dead wood present within a relatively small area. We could have sampled across larger areas, but topography in our study area was highly dissected and features such as steep ridges and incised streams may have presented barriers to historical fire spread. Compositing fire histories at larger spatial scales across these barriers risks spurious inference about historical fire frequency.

We believe that our study design—reconstruction of composite fire histories using 15–20 samples within relatively small areas (2–11 ha) roughly the same distance apart was an appropriate balance of spatial extent and sampling intensity given limited resources. And we believe this study design accurately describes relative differences in historical fire frequency and severity across forest types. Importantly, our study area contains most of the forest types present within the western Oregon Cascades. But inferences outside our study area should be made with caution. Research in areas further north with shorter fire seasons and cooler summer temperatures will likely yield less variability in fire frequencies and generally longer fire return intervals along an evaporative demand gradient.

Large stand-replacing fires may be a more prominent feature of Douglas-fir forests further north where the low fuel moistures required for fire spread depend on anomalously hot, dry, and windy fire weather. In addition, there may be different mesoscale topographic controls on fire further north. Our study area is somewhat unusual for the western Oregon Cascades in that the upper Middle Fork Willamette River flows north to south for almost

30 km and is enclosed on all sides by mountainous topography (Figure 1). This topography is probably less conducive to sustained directional wind flows since prevailing winds are typically along a west–east axis. Today, closed-canopy forests dominate our study area. But prior to the establishment of forest reserves in the late 1800s, interactions of terrain, weather patterns, and ignitions appear to have interdigitated open-canopy forest with structurally complex closed-canopy forest.

Further to the north, forests were likely historically more uniformly closed canopy because major river valleys are oriented primarily from west to east and directly exposed to Pacific Ocean weather patterns that carry significant moisture over the flat terrain of the Willamette Valley and Puget Trough. These large river valleys also tend to funnel hot dry air from eastern Oregon when the prevailing wind patterns reverse themselves during foehn type wind events (Cramer, 1957). It is possible that large, wind-driven fire events (Donato et al., 2020; Halofsky et al., 2018; Reilly et al., 2022) are characteristic of terrain with significant exposure to both moisture-laden onshore flows and rare but powerful late-season offshore flows that can develop sustained wind velocities in major river canyons.

Indigenous fire stewardship

Much of the variability in historical fire frequency in our study area is explained by a single environmental variable—maximum summer VPD—which exerts a strong mechanistic control on fire by modulating live and dead fuel moistures. But the very high tempo of fire within Douglas-fir series forests in our study area is striking. MFRIs reconstructed for this forest series, which receive 1350–1450 mm of annual precipitation in our study area, are shorter than MFRIs we have reconstructed for sites in eastern Oregon with 450–700 mm annual precipitation (Johnston et al., 2017; Merschel et al., 2018). Our eastern Oregon sites also have longer fire seasons, higher maximum summer temperatures, receive more lightning ignitions, and have experienced far more area burned in contemporary fires (Reilly et al., 2017; Rorig & Ferguson, 1999). To the best of our knowledge, no other published fire history from the Western United States has documented more frequent historical fire in biophysical settings as moist and productive as our Douglas-fir series sites (see Margolis et al., 2022).

As noted in the methods (*Study area and management situation*), the lower elevation stands where we reconstructed very frequent fire may be drier and more fire prone because a tall ridge to the southwest blocks winter and spring storm tracks. Another explanation for this very frequent fire regime is intentional use of fire by Indigenous communities. A number of observations besides the very high tempo of fire in our study area provide support for this hypothesis.

First, the course of the Middle Fork Willamette River leads both to the rich resources of the Willamette Valley and to one of the lowest points of the crest of the Cascade Mountains in Oregon. This route was used extensively both during the prehistorical and historical periods for movement between eastern and western Oregon (Baxter, 1986). Second, the archeological literature for western Oregon (e.g., Aikens et al., 2011; Baxter, 1986) reports a high density of pre-Euro-American campsites and food and tool processing sites within our study area. Third, while conducting fieldwork for this project, we observed more than 100 "culturally modified" trees (see Mobley & Eldridge, 1992) with large scars left from the removal of bark with stone tools. Although we have occasionally seen culturally modified trees in the course of other research in the Pacific Northwest, we have never observed such a high density of these features, suggesting intensive use of this area. Fourth, the relatively small size of most of the fires we reconstructed (see *Historical fire in a coast Douglas-fir forest*) is consistent with previous research that shows that ignitions by Indigenous communities result in smaller burned areas than ignitions by lightning (Bliege Bird et al., 2012).

A final reason to believe that Douglas-fir series stands in our study area were burned regularly by Indigenous people is the relationship between climate and fire years in Douglas-fir series stands relative to stands belonging to different forest series in our study area and other study areas in the Pacific Northwest. Previously published fire history reconstructions in the Pacific Northwest note a strong relationship between aridity and fire occurrence (Hessl et al., 2004; Heyerdahl et al., 2002, 2008; Johnston et al., 2017). Similar to these other studies, fire years in our upper Middle Fork study area were drier than normal, although the aridity signal was much less pronounced in Douglas-fir series stands. Instead, the year prior to fire in Douglas-fir series stands was significantly moister than normal.

Above-average moisture several years before fire years and drought during fire years is typical of the American southwest and is consistent with increased herbaceous fuel production during wet years that is subsequently cured by drought and provides a continuous fuel bed that carries fire over large areas. Roos et al. (2022) refer to this climate signal as the "canonical pattern." These authors evaluated areas of modern-day Arizona and New Mexico where the archeological record provides evidence of intensive use by Indigenous peoples during certain time periods and less intensive use related to population decline and warfare in other time periods. They consider a less pronounced canonical fire–climate pattern during periods of more intensive use to be evidence of anthropogenic ignitions dampening climate controls on fire. The somewhat muted influence of drought in the year of fire in Douglas-fir series stands in our study area may indicate that human fire use decoupled otherwise strong fire–climate relationships.

Merschel (2021) also noted very frequent fire attributable to Indigenous ignitions in a study site on the North Umpqua River to the south of our study area. We believe that multidisciplinary investigations that synthesize traditional ecological knowledge, dendroecology, archaeology, and ethnography throughout the western Oregon Cascades will help define the extent and intensity of Indigenous fire use. Additional research may also reveal the degree to which Indigenous fire use was associated with unique cultural systems, influenced stand and landscape scale biodiversity, attenuated disturbance modulated shifts in forest structure and composition, and protected communities and focal resources from high-severity fire (Bliege Bird et al., 2008; Hoffman et al., 2021; Long et al., 2021; Trauernicht et al., 2015). We recommend fire history reconstructions in a variety of Douglas-fir dominated western Cascades settings where Indigenous fire stewardship may have influenced forest successional pathways. Describing the degree to which our Middle Fork site is anomalous with respect to frequent fire in the heart of the western Oregon Cascades, or, alternately, part of a larger network of fire-stewarded forests may result in important new models of coupled human–natural systems (sensu Liu et al., 2007).

CONCLUSIONS

Coast Douglas-fir dominated forests of the western Cascades are nationally and globally significant resources. We present methods for inferring the frequency and seasonality of historical fire as well as approximations of the relative size and severity of historical fires across diverse forest types in this region. Our methods demonstrate that historical fire regimes in a ~15,000-ha study area were extraordinarily complex, characterized by a broad range of fire frequencies and fire severities. Additional research at broader spatial scales will contribute to understanding the influence of Indigenous fire stewardship, the range of historical fire sizes, the relative importance of large wind-driven fire events, and the relationship between fire history and stand development in coast Douglas-fir forests.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

R code and tree establishment data to evaluate tree cohorts (Johnston, 2023) are available from Zenodo: https://doi.org/10.5281/zenodo.10055945. All fire scar data are available from the North American Tree Ring Fire Scar Network: https://www.sciencebase.gov/catalog/item/61326384d34e40dd9c0ac70d.

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REFERENCES

Agee, J. K. 1991. "Fire History of Douglas-Fir Forest in the Pacific Northwest." In *Wildlife and Vegetation of Unmanaged Douglas-Fir Forests*. USDA Forest Service General Technical Report PNW-GTR-285, 512 pp. Corvallis, OR: Pacific Northwest Research Station.

Agee, J. K. 1996. *Fire Ecology of Pacific Northwest Forests*. Washington, DC: Island Press.

Aikens, C. M., T. J. Connolly, and D. L. Jenkins. 2011. *Oregon Archaeology* 149–209. Corvallis, OR: Oregon State University Press.

Anderson, V. J. 1965. "Fur Trade on the Umpqua." Umpqua Trapper 1:1-4 (publication of the Douglas County Historical Society, available from the authors).

Baker, W. L., and D. Ehle. 2001. "Uncertainty in Surface-Fire History: The Case of Ponderosa Pine Forests in the Western United States." *Canadian Journal of Forest Research* 31(7): 1205–26.

Baxter, P. 1986. "Archaic Upland Adaptations in the Central Oregon Cascades." Dissertation, University of Oregon.

Bergland, E. O. 1992. "Historic Period Plateau Culture Tree Peeling in the Western Cascades of Oregon." *Northwest Anthropological Research Notes* 25(2): 31–53.

Bliege Bird, R., D. W. Bird, B. F. Codding, C. H. Parker, and J. H. Jones. 2008. "The "Fire Stick Farming" Hypothesis: Australian Aboriginal Foraging Strategies, Biodiversity, and Anthropogenic Fire Mosaics." *Proceedings of the National Academy of Sciences of the United States of America* 105(39): 14796–801. https://doi.org/10.1073/pnas.0804757105.

Bliege Bird, R., B. F. Codding, P. G. Kauhanen, and D. W. Bird. 2012. "Aboriginal Hunting Buffers Climate-Driven Fire-Size Variability in Australia's Spinifex Grasslands." *Proceedings of the National Academy of Sciences of the United States of America* 109(26): 10287–92.

Boehner, J., R. Koethe, O. Conrad, J. Gross, A. Ringeler, and T. Selige. 2002. "Soil Regionalisation by Means of Terrain Analysis and Process Parameterisation." In *Soil Classification 2001*. Research Report No. 7, EUR 20398 EN, edited by E. Micheli, F. Nachtergaele, and L. Montanarella, 213–222. Luxembourg: European Soil Bureau.

Boyd, R. 1999. *The Coming of the Spirit of Pestilence: Introduced Infectious Diseases and Population Decline among Northwest Coast Indians, 1774-1874*. Seattle, WA: University of Washington Press.

Bunn, A. G. 2008. "A Dendrochronology Program Library in R (dplR)." *Dendrochronologia* 26(2): 115–124.

Clary, D. A. 1986. *Timber and the Forest Service*. Lawrence, KS: University Press of Kansas.

Clogg, C. C., E. Petkova, and A. Haritou. 1995. "Statistical Methods for Comparing Regression Coefficients between Models." *American Journal of Sociology* 100(5): 1261–93.

Cook, E. R., R. Seager, R. R. Heim, Jr., R. S. Vose, C. Herweijer, and C. Woodhouse. 2010. "Megadroughts in North America: Placing IPCC Projections of Hydroclimatic Change in a Long-Term Palaeoclimate Context." *Journal of Quaternary Science* 25: 48–61.

Cox, T. R. 2010. *The Lumberman's Frontier: Three Centuries of Land Use, Society, and Change in America's Forests*. Corvallis, OR: Oregon State University Press.

Cramer, O. P. 1957. "Frequency of Dry East Winds over Northwest Oregon and Southwest Washington." (No. 24). Pacific Northwest Forest and Range Experiment Station, Forest Service, US Department of Agriculture.

Daniels, L. D., L. L. Yocom Kent, R. L. Sherriff, and E. K. Heyerdahl. 2017. "Deciphering the Complexity of Historical Fire Regimes: Diversity among Forests of Western North America." In *Dendroecology* 185–210. Cham: Springer.

Daubenmire, R. F. 1968. *Plant Communities*. New York: Harper & Row. 300 pp.

Davis, L. R., K. J. Puettmann, and G. F. Tucker. 2007. "Overstory Response to Alternative Thinning Treatments in Young Douglas-Fir Forests of Western Oregon." *Northwest Science* 81(1): 1–14.

Davis, R. J., J. L. Ohmann, R. E. Kennedy, W. B. Cohen, M. J. Gregory, Z. Yang, and T. A. Spies. 2015. *Northwest Forest Plan—The First 20 Years (1994-2013): Status and Trends of Late-Successional and Old-Growth Forests*. General Technical Report PNW-GTR-911. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. 112 pp.

Day, J. W. 2005. "Historical Savanna Structure and Succession at Jim's Creek, Willamette National Forest, Oregon." Doctoral diss., University of Oregon.

Donato, D. C., J. S. Halofsky, and M. J. Reilly. 2020. "Corralling a Black Swan: Natural Range of Variation in a Forest Landscape Driven by Rare, Extreme Events." *Ecological Applications* 30(1): e02013.

Dunn, C. J., and J. D. Bailey. 2016. "Tree Mortality and Structural Change Following Mixed-Severity Fire in *Pseudotsuga* Forests of Oregon's Western Cascades, USA." *Forest Ecology and Management* 365: 107–118.

Dunn, C. J., J. D. Johnston, M. J. Reilly, J. D. Bailey, and R. A. Miller. 2020. "How Does Tree Regeneration Respond to Mixed-Severity Fire in the Western Oregon Cascades, USA?" *Ecosphere* 11(1): e03003. https://doi.org/10.1002/ecs2.3003.

Falk, D. A., E. K. Heyerdahl, P. M. Brown, C. Farris, P. Z. Fulé, D. McKenzie, T. W. Swetnam, A. H. Taylor, and M. L. Van Horne. 2011. "Multi-Scale Controls of Historical Forest-Fire Regimes: New Insights from Fire-Scar Networks." *Frontiers in Ecology and the Environment* 9: 446–454. https://doi.org/10.1890/100052.

Franklin, J. F. 1983. *Ecology of Noble Fir*. Seattle, WA: College of Forest Resources, University of Washington.

Franklin, J. F., K. Cromack, Jr., W. Denison, A. McKee, C. Maser, J. Sedell, F. Swanson, and G. Juday. 1981. *Ecological Characteristics of Old-Growth Douglas-Fir Forests*. General Technical Report PNW-GTR-118. Portland, OR: USDA Forest Service, Pacific Northwest Research Station.

Franklin, J. F., and M. A. Hemstrom. 1981. "Aspects of Succession in the Coniferous Forests of the Pacific Northwest." In *Forest Succession: Concepts and Application*, edited by D. C. West, H. H. Shugart, and D. B. Botkin, 212–229. New York: Springer-Verlag. Chapter 14.

Franklin, J. F., and K. N. Johnson. 2012. "A Restoration Framework for Federal Forests in the Pacific Northwest." *Journal of Forestry* 110(8): 429–439.

Franklin, J. F., T. A. Spies, R. Van Pelt, A. B. Carey, D. A. Thornburgh, D. R. Berg, and J. Chen. 2002. "Disturbances and Structural Development of Natural Forest Ecosystems with Silvicultural Implications, Using Douglas-Fir Forests as an Example." *Forest Ecology and Management* 155(1–3): 399–423. https://doi.org/10.1016/S0378-1127(01)00575-8.

Freund, J. A., J. F. Franklin, A. J. Larson, and J. A. Lutz. 2014. "Multi-Decadal Establishment for Single-Cohort Douglas-Fir Forests." *Canadian Journal of Forest Research* 44(9): 1068–78.

Fritts, H. C., and T. W. Swetnam. 1989. "Dendroecology: A Tool for Evaluating Variations in Past and Present Forest Environments." *Advances in Ecological Research* 19: 111–188.

Genuer, R., J. M. Poggi, and C. Tuleau-Malot. 2010. "Variable Selection Using Random Forests." *Pattern Recognition Letters* 31(14): 2225–36.

Genuer, R., J. M. Poggi, and C. Tuleau-Malot. 2015. "VSURF: An R Package for Variable Selection Using Random Forests." *The R Journal* 7(2): 19–33.

Guiterman, C. H., E. Q. Margolis, C. D. Allen, D. A. Falk, and T. W. Swetnam. 2018. "Long-Term Persistence and Fire Resilience of

Oak Shrubfields in Dry Conifer Forests of Northern New Mexico." *Ecosystems* 21: 943–959.
Guiterman, C. H., E. Q. Margolis, C. H. Baisan, D. A. Falk, C. D. Allen, and T. W. Swetnam. 2019. "Spatiotemporal Variability of Human–Fire Interactions on the Navajo Nation." *Ecosphere* 10(11): e02932.
Guyette, R. P., R. M. Muzika, and D. C. Dey. 2002. "Dynamics of an Anthropogenic Fire Regime." *Ecosystems* 5: 472–486.
Hagmann, R. K., P. F. Hessburg, S. J. Prichard, N. A. Povak, P. M. Brown, P. Z. Fulé, R. E. Keane, et al. 2021. "Evidence for Widespread Changes in the Structure, Composition, and Fire Regimes of Western North American Forests." *Ecological Applications* 31(8): e02431.
Halofsky, J. S., D. C. Donato, J. F. Franklin, J. E. Halofsky, D. L. Peterson, and B. J. Harvey. 2018. "The Nature of the Beast: Examining Climate Adaptation Options in Forests with Stand-Replacing Fire Regimes." *Ecosphere* 9(3): e02140.
Hemstrom, M. A., S. E. Logan, and W. Pavlat. 1987. *Plant Association and Management Guides for the Willamette National Forest*. R6-Ecol-257-1986. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 312 pp.
Heon, J., D. Arseneault, and M. A. Parisien. 2014. "Resistance of the Boreal Forest to High Burn Rates." *Proceedings of the National Academy of Sciences of the United States of America* 111: 13888–93.
Hessburg, P. F., S. J. Prichard, R. K. Hagmann, N. A. Povak, and F. K. Lake. 2021. "Wildfire and Climate Change Adaptation of Western North American Forests: A Case for Intentional Management." *Ecological Applications* 31(8): e02432.
Hessl, A. E., D. McKenzie, and R. Schellhaas. 2004. "Drought and Pacific Decadal Oscillation Linked to Fire Occurrence in the Inland Pacific Northwest." *Ecological Applications* 14(2): 425–442.
Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2002. "Annual and Decadal Climate Forcing of Historical Fire Regimes in the Interior Pacific Northwest, USA." *The Holocene* 12(5): 597–604.
Heyerdahl, E. K., R. A. Loehman, and D. A. Falk. 2019. "A Multi-Century History of Fire Regimes along a Transect of Mixed-Conifer Forests in Central Oregon, USA." *Canadian Journal of Forest Research* 49(1): 76–86.
Heyerdahl, E. K., D. McKenzie, L. D. Daniels, A. E. Hessl, J. S. Littell, and N. J. Mantua. 2008. "Climate Drivers of Regionally Synchronous Fires in the Inland Northwest (1651–1900)." *International Journal of Wildland Fire* 17(1): 40–49.
Hoffman, K. M., E. L. Davis, S. B. Wickham, K. Schang, A. Johnson, T. Larking, P. N. Lauriault, N. Q. Le, E. Swerdfager, and A. J. Trant. 2021. "Conservation of Earth's Biodiversity Is Embedded in Indigenous Fire Stewardship." *Proceedings of the National Academy of Sciences of the United States of America* 118(32): 1–6.
Holmes, R. L. 1983. "Computer-Assisted Quality Control in Tree-Ring Dating and Measurement." *Tree-Ring Bulletin* 43: 69–78.
Isaac, L. A. 1943. *Reproductive Habits of Douglas-Fir*. Washington, DC: Charles Lathrop Pack Forestry Foundation. 107 pp.
Johnston, J. D. 2023. "johnstja/cohort_sim: Tree Cohort Identification Procedure (cohort_sim)." Zenodo. Data and Code. https://doi.org/10.5281/zenodo.10055945.
Johnston, J. D., J. D. Bailey, C. J. Dunn, and A. A. Lindsay. 2017. "Historical Fire-Climate Relationships in Contrasting Interior Pacific Northwest Forest Types." *Fire Ecology* 13(2): 18–36.
Johnston, J. D., C. J. Dunn, and M. J. Vernon. 2019. "Tree Traits Influence Response to Fire Severity in the Western Oregon Cascades." *Forest Ecology and Management* 433: 690–98.
Keane, R. E., P. F. Hessburg, P. B. Landres, and F. J. Swanson. 2009. "The Use of Historical Range and Variability (HRV) in Landscape Management." *Forest Ecology and Management* 258(7): 1025–37.
Keeler, B. L., R. Chaplin-Kramer, A. D. Guerry, P. F. Addison, C. Bettigole, I. C. Burke, B. Gentry, et al. 2017. "Society Is Ready for a New Kind of Science—Is Academia?" *Bioscience* 67(7): 591–92.
Kroll, A. J., J. D. Johnston, T. D. Stokely, and G. W. Meigs. 2020. "From the Ground Up: Managing Young Forests for a Range of Ecosystem Outcomes." *Forest Ecology and Management* 464: 118055.
Lake, F. K., V. Wright, P. Morgan, M. McFadzen, D. McWethy, and C. Stevens-Rumann. 2017. "Returning Fire to the Land: Celebrating Traditional Knowledge and Fire." *Journal of Forestry* 115(5): 343–353.
Langille, H. D., F. G. Plummer, A. Dodwell, T. F. Rixon, and J. B. Leiburg. 1903. *Forest Conditions in the Cascade Range Forest Reserve, Oregon*. With an introduction by Henry Gannett. Washington, DC: Department of the Interior U.S. Geological Survey. Professional Papers No. 9 (298, with maps and pl.), 29 cm.
Larson, A. J., and J. F. Franklin. 2005. "Patterns of Conifer Tree Regeneration Following an Autumn Wildfire Event in the Western Oregon Cascade Range, USA." *Forest Ecology and Management* 218(1–3): 25–36.
Lewis, D. G. 2014. "Four Deaths: The Near Destruction of Western Oregon Tribes and Native Lifeways, Removal to the Reservation, and Erasure from History." *Oregon Historical Quarterly* 115(3): 414–437.
Lewis, D. G., and R. Kentta. 2010. "Western Oregon Reservations: Two Perspectives on Place." *Oregon Historical Quarterly* 111(4): 476–485.
Lindsay, A. A., and J. D. Johnston. 2020. "Using Historical Reconstructions of Moist Mixed Conifer Forests to Inform Forest Management on the Malheur National Forest." In *The 2019 National Silviculture Workshop: A Focus on Forest Management-Research Partnerships*, L. S. Pile, R. L. Deal, D. C. Dey, D. Gwaze, J. M. Kabrick, B. Palik, and T. M. Schuler, comps. General Technical Report NRS-P-193 23–33. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. https://doi.org/10.2737/NRS-GTR-P-193-paper4.
Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, and W. W. Taylor. 2007. "Complexity of Coupled Human and Natural Systems." *Science* 317(5844): 1513–16.
Long, J. W., F. K. Lake, and R. W. Goode. 2021. "The Importance of Indigenous Cultural Burning in Forested Regions of the Pacific West, USA." *Forest Ecology and Management* 500: 119597.
Malevich, S. B., C. H. Guiterman, and E. Q. Margolis. 2018. "Burnr: Fire History Analysis and Graphics in R." *Dendrochronologia* 49: 9–15.

Margolis, E. Q., C. H. Guiterman, R. D. Chavardès, J. D. Coop, K. Copes-Gerbitz, D. A. Dawe, D. A. Falk, et al. 2022. "The North American Tree-Ring Fire-Scar Network." *Ecosphere* 13(7): e4159.

Margolis, E. Q., and S. B. Malevich. 2016. "Historical Dominance of Low-Severity Fire in Dry and Wet Mixed-Conifer Forest Habitats of the Endangered Terrestrial Jemez Mountains Salamander (*Plethodon neomexicanus*)." *Forest Ecology and Management* 375: 12–26.

McCain, C., and N. Diaz. 2002. "Field Guide to the Forested Plant Associations of the Westside Central Cascades of Northwest Oregon: Willamette N.F., USFS; Mt Hood N.F., USFS; Salem District BLM; Eugene District, BLM." USDA Forest Service PNW Region, Technical Paper R6-NR-ECOL-TP-02-02.

McWethy, D. B., T. Schoennagel, P. E. Higuera, M. Krawchuk, B. J. Harvey, E. C. Metcalf, and C. Kolden. 2019. "Rethinking Resilience to Wildfire." *Nature Sustainability* 2(9): 797–804.

Meany, E. S. 1923. "The Journal of John Work, A Chief-Trader of the Hudson's Bay Company." *Washington Historical Quarterly* 14(4): 307–8.

Merschel, A. G. 2021. *Historical Forest Succession and Disturbance Dynamics in Coastal Douglas-Fir Forests in the Southern Western Cascades of Oregon*. Corvallis, OR: Oregon State University.

Merschel, A. G., E. K. Heyerdahl, T. A. Spies, and R. A. Loehman. 2018. "Influence of Landscape Structure, Topography, and Forest Type on Spatial Variation in Historical Fire Regimes, Central Oregon, USA." *Landscape Ecology* 33(7): 1195–1209.

Metlen, K. L., C. N. Skinner, D. R. Olson, C. Nichols, and D. Borgias. 2018. "Regional and Local Controls on Historical Fire Regimes of Dry Forests and Woodlands in the Rogue River Basin, Oregon, USA." *Forest Ecology and Management* 430: 43–58.

Minor, R., and A. F. Pecor. 1977. "Cultural Resource Overview of the Willamette National Forest, Western Oregon."

Mobley, C. M., and M. Eldridge. 1992. "Culturally Modified Trees in the Pacific Northwest." *Arctic Anthropology* 29: 91–110.

Morrison, P. H., and F. J. Swanson. 1990. *Fire History and Pattern in a Cascade Range Landscape*. USDA Forest Service General Technical Report. PNW-254. Corvallis, OR: Pacific Northwest Research Station.

O'Connor, C. D., D. A. Falk, A. M. Lynch, and T. W. Swetnam. 2014. "Fire Severity, Size, and Climate Associations Diverge from Historical Precedent along an Ecological Gradient in the Pinaleno Mountains, Arizona, USA." *Forest Ecology and Management* 329: 264–278.

Pausas, J. G. 2015. "Bark Thickness and Fire Regime." *Functional Ecology* 29(3): 315–327.

Poage, N. J., and J. C. Tappeiner, III. 2002. "Long-Term Patterns of Diameter and Basal Area Growth of Old-Growth Douglas-Fir Trees in Western Oregon." *Canadian Journal of Forest Research* 32: 1232–43.

Poage, N. J., P. J. Weisberg, P. C. Impara, J. C. Tappeiner, and T. S. Sensenig. 2009. "Influences of Climate, Fire, and Topography on Contemporary Age Structure Patterns of Douglas-Fir at 205 Old Forest Sites in Western Oregon." *Canadian Journal of Forest Research* 39(8): 1518–30.

Prichard, S. J., P. F. Hessburg, R. K. Hagmann, N. A. Povak, S. Z. Dobrowski, M. D. Hurteau, V. R. Kane, et al. 2021. "Adapting Western North American Forests to Climate Change and Wildfires: 10 Common Questions." *Ecological Applications* 31(8): e02433.

PRISM Climate Group. 2022. "Oregon State University." http://www.prism.oregonstate.edu.

R Core Team. 2022. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing. https://www.R-project.org/.

Rakestraw, L., and M. Rakestraw. 1991. *History of the Willamette National Forest*. Eugene, OR: U.S. Department of Agriculture, Willamette National Forest, 272 pp.

Reilly, M. J., C. J. Dunn, G. W. Meigs, T. A. Spies, R. E. Kennedy, J. D. Bailey, and K. Briggs. 2017. "Contemporary Patterns of Fire Extent and Severity in Forests of the Pacific Northwest, USA (1985–2010)." *Ecosphere* 8(3): e01695.

Reilly, M. J., A. Zuspan, J. S. Halofsky, C. Raymond, A. McEvoy, A. W. Dye, and B. K. Kerns. 2022. "Cascadia Burning: The Historic, but Not Historically Unprecedented, 2020 Wildfires in the Pacific Northwest, USA." *Ecosphere* 13(6): e4070.

Rollins, M. G. 2009. "LANDFIRE: A Nationally Consistent Vegetation, Wildland Fire, and Fuel Assessment." *International Journal of Wildland Fire* 18(3): 235–249.

Roos, C. I., C. H. Guiterman, E. Q. Margolis, T. W. Swetnam, N. C. Laluk, K. F. Thompson, and L. Whitehair. 2022. "Indigenous Fire Management and Cross-Scale Fire-Climate Relationships in the Southwest United States from 1500 to 1900 CE." *Science Advances* 8(49): eabq3221.

Rorig, M. L., and S. A. Ferguson. 1999. "Characteristics of Lightning and Wildland Fire Ignition in the Pacific Northwest." *Journal of Applied Meteorology and Climatology* 38(11): 1565–75.

Ruth, R. H. 1958. *Silvical Characteristics of Sitka Spruce* (No. 8). Portland, OR: Pacific Northwest Forest and Range Experiment Station, US Department of Agriculture, Forest Service.

Scholl, A. E., and A. H. Taylor. 2010. "Fire Regimes, Forest Change, and Self-Organization in an Old-Growth Mixed-Conifer Forest, Yosemite National Park, USA." *Ecological Applications* 20: 362–380.

Seidl, R., T. A. Spies, D. L. Peterson, S. L. Stephens, and J. A. Hicke. 2016. "Searching for Resilience: Addressing the Impacts of Changing Disturbance Regimes on Forest Ecosystem Services." *Journal of Applied Ecology* 53(1): 120–29.

Smith, K. T. 2008. "An Organismal View of Dendrochronology." *Dendrochronologia* 26(3): 185–193.

Smith, K. T., E. Arbellay, D. A. Falk, and E. K. Sutherland. 2016. "Macroanatomy and Compartmentalization of Recent Fire Scars in Three North American Conifers." *Canadian Journal of Forest Research* 46: 535–542.

Smithwick, E. A., M. E. Harmon, S. M. Remillard, S. A. Acker, and J. F. Franklin. 2002. "Potential Upper Bounds of Carbon Stores in Forests of the Pacific Northwest." *Ecological Applications* 12(5): 1303–17.

Spies, T. A., and J. F. Franklin. 1988. "Old-Growth Forest Dynamics in the Douglas-Fir Region of Western Oregon and Washington." *Natural Areas Journal* 8: 190–201.

Spies, T. A., T. W. Giesen, F. J. Swanson, J. F. Franklin, D. Lach, and K. N. Johnson. 2010. "Climate Change Adaptation Strategies for Federal Forests of the Pacific Northwest, USA:

Ecological, Policy, and Socio-Economic Perspectives." *Landscape Ecology* 25(8): 1185–99.

Spies, T. A., M. A. Hemstrom, A. Youngblood, and S. Hummel. 2006. "Conserving Old-Growth Forest Diversity in Disturbance-Prone Landscapes." *Conservation Biology* 20(2): 351–362.

Spies, T. A., P. A. Stine, R. Gravenmier, J. W. Long, M. J. Reilly, and R. Mazza. 2018. *Synthesis of Science to Inform Land Management within the Northwest Forest Plan Area*. General Technical Report PNW-GTR-970. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 186 pp.

Steen-Adams, M. M., S. Charnley, R. J. McLain, M. D. Adams, and K. L. Wendel. 2019. "Traditional Knowledge of Fire Use by the Confederated Tribes of Warm Springs in the Eastside Cascades of Oregon." *Forest Ecology and Management* 450: 117405.

Stephens, S. L., and M. A. Finney. 2002. "Prescribed Fire Mortality of Sierra Nevada Mixed Conifer Tree Species: Effects of Crown Damage and Forest Floor Combustion." *Forest Ecology and Management* 162: 261–271.

Strobl, C., A. L. Boulesteix, A. Zeileis, and T. Hothorn. 2007. "Bias in Random Forest Variable Importance Measures: Illustrations, Sources and a Solution." *BMC Bioinformatics* 8(1): 1–21.

Swetnam, T. W., C. D. Allen, and J. L. Betancourt. 1999. "Applied Historical Ecology: Using the Past to Manage for the Future." *Ecological Applications* 9(4): 1189–1206.

Tepley, A. J., S. M. Hood, C. R. Keyes, and A. Sala. 2020. "Forest Restoration Treatments in a Ponderosa Pine Forest Enhance Physiological Activity and Growth under Climatic Stress." *Ecological Applications* 30(8): e02188.

Tepley, A. J., F. J. Swanson, and T. A. Spies. 2013. "Fire-Mediated Pathways of Stand Development in Douglas-Fir/Western Hemlock Forests of the Pacific Northwest, USA." *Ecology* 94(8): 1729–43. https://doi.org/10.1890/12-1506.1.

Tepley, A. J., F. J. Swanson, and T. A. Spies. 2014. "Post-Fire Tree Establishment and Early Cohort Development in Conifer Forests of the Western Cascades of Oregon, USA." *Ecosphere* 5(7): 1–23.

Trauernicht, C., B. W. Brook, B. P. Murphy, G. J. Williamson, and D. M. J. S. Bowman. 2015. "Local and Global Pyrogeographic Evidence that Indigenous Fire Management Creates Pyrodiversity." *Ecology and Evolution* 5(9): 1908–18. https://doi.org/10.1002/ece3.1494.

United States Department of Agriculture, Forest Service (USDA). 2006. *Jim's Creek Savanna Restoration Environmental Assessment*. Oakridge, OR: Middle Fork Ranger District, Willamette National Forest.

United States Department of Agriculture, Forest Service (USDA). 2021. *Youngs Rock Rigdon Draft Environmental Impact Statement*. Oakridge, OR: Middle Fork Ranger District, Willamette National Forest.

Vernon, M. J., J. D. Johnston, T. D. Stokely, B. A. Miller, and D. R. Woodruff. 2023. "Mechanical Thinning Restores Ecological Functions in a Seasonally Dry Ponderosa Pine Forest in the Inland Pacific Northwest, USA." *Forest Ecology and Management* 546: 121371.

Walsh, M. K., J. R. Marlon, S. J. Goring, K. J. Brown, and D. Gavin. 2015. "A Regional Perspective on Holocene Fire–Climate–Human Interactions in the Pacific Northwest of North America." *Annals of the Association of American Geographers* 105(6): 1135–57.

Waring, R. H., and J. F. Franklin. 1979. "Evergreen Coniferous Forests of the Pacific Northwest: Massive Long-Lived Conifers Dominating these Forests Are Adapted to a Winter-Wet, Summer-Dry Environment." *Science* 204(4400): 1380–86.

Weisberg, P. J., and F. J. Swanson. 2003. "Regional Synchroneity in Fire Regimes of Western Oregon and Washington, USA." *Forest Ecology and Management* 172: 17–28.

Whitlock, C. 2008. "Long-Term Relations among Fire, Fuel, and Climate in the North-Western US Based on Lake Sediment Studies." *International Journal of Wildland Fire* 17(1): 72.

Whitlock, C., and M. A. Knox. 2002. "Prehistoric Burning in the Pacific Northwest: Human versus Climatic Influences." In *Fire, Native Peoples, and the Natural Landscape*, edited by R. Vale, 195–231. Washington, DC: Island Press.

Whitlock, C., D. B. McWethy, A. J. Tepley, T. T. Veblen, A. Holz, M. S. McGlone, G. L. W. Perry, J. M. Wilmshurst, and S. W. Wood. 2015. "Past and Present Vulnerability of Closed-Canopy Temperate Forests to Altered Fire Regimes: A Comparison of the Pacific Northwest, New Zealand, and Patagonia." *Bioscience* 65(2): 151–163.

Williamson, R. L., and P. N. Forest. 1973. "Coastal Douglas-Fir. Silvicultural Systems for the Major Forest Types of the United States." *Agriculture Handbook* 445: 8–10.

Zenk, H. B., and B. Rigsby. 1998. "Molalla." *Handbook of North American Indians* 12: 439–445.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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