HISTORICAL FIRE–CLIMATE RELATIONSHIPS IN CONTRASTING INTERIOR PACIFIC NORTHWEST FOREST TYPES

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ABSTRACT

Describing the climate influences on historical wildland fire will aid managers in planning for future change. This study uses existing historical climate reconstructions and a new fire history from the southern Blue Mountains in eastern Oregon, USA, to: 1) characterize historical fire-climate relationships, and 2) determine if climatic influences on fire differed among dry sites dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) and more productive sites with significant older fire intolerant grand fir (*Abies grandis* [Dougl.] Lindl.) structure. Similar to results from other fire history studies across the American West, this research documents an increased incidence of burning in the southern Blue Mountains prior to 1900 associated with more arid conditions as measured with Palmer Drought Severity Index (PDSI). Positive values of the El Niño-Southern Oscillation (ENSO) were associated with fire years when multiple sites burned within the 688 000 ha study area. Although ponderosa pine and grand fir study sites were significantly different with respect to site productivity as well as historical and contempo-

RESUMEN

Describir las influencias climáticas sobre los incendios históricos permite ayudar a los gestores de recursos a planificar cambios futuros. Este estudio usa datos de reconstrucciones climáticas existentes y nuevas historias de fuego de las montañas azules sureñas (Blue Mountains) del este de Oregón en los Estados Unidos para: 1) caracterizar las relaciones históricas entre fuego y clima, y 2) determinar si las influencias climáticas sobre los incendios difieren entre sitios secos dominados por pino ponderosa (*Pinus ponderosa* Dougl. ex Laws) y sitios más productivos con predominancia estructural de árboles maduros de abeto grande (*Abies grandis* [Dougl.] Lindl.), especie intolerante al fuego. Similar a otros estudios realizados a través del oeste de Norteamérica, esta investigación documenta un incremento en la incidencia de incendios en las montañas sureñas azules (Blue Mountains) previo al 1900, asociado con mayores condiciones de aridez medidas con el Índice de Severidad de Sequía de Palmer (PDSI). Valores positivos del Niño Oscilación del Sur (ENOS) se asociaron a años con fuego cuando incendios múltiples ocurrieron dentro de las 688 000 ha del área de estudio. Aunque los sitios de estudio con pino ponderosa fueron significativamente diferentes con respecto a la productividad y también en la composición histórica y actual

rary species composition, there were only marginal differences in historical mean fire return intervals between these forest types. There was also no significant difference in reconstructed mean temperature, precipitation, drought index, or ENSO during fire years between forest types prior to 1900 CE. However, the years prior to fire in ponderosa pine sites were moister than average, suggesting that antecedent climate was more important in the production of herbaceous fuel in ponderosa pine sites.

de especies, hubo solo diferencias marginales en relación al intervalo medio de retorno del fuego entre esos dos tipos forestales. Tampoco hubo diferencias significativas en la reconstrucción de temperaturas medias, de precipitación, del Indice de Sequía y del ENOS durante los años en que hubo incendios entre los dos tipos de bosque antes del 1900 de la era actual (CE). Por supuesto, los años previos a los incendios en los sitios dominados por pino ponderosa fueron más húmedos que el promedio, sugiriendo que el clima precedente fue más importante en la producción de vegetación herbácea en sitios con pino ponderosa.

INTRODUCTION

The relationship between climate variability and the extent of wildland fire is of increasing interest to land managers in the western United States as the economic costs of suppression grow, and climate-change modeling suggests that fire effects will be exacerbated by increasingly droughty conditions (Westerling *et al.* 2011, Attiwill and Binkley 2013, Williams 2013, Dennison *et al.* 2014, Stephens *et al.* 2014, Jolly *et al.* 2015, Abatzoglou and Williams 2016). Fire–vegetation interactions are often characterized as either fuel limited or climate limited. In fuel-limited systems, consistently dry and warm conditions are conducive to fire, and fire extent is limited by the time necessary to regenerate fuel. In climate-limited systems, moister, more productive landscapes support ample fuel to carry fire, and anomalously warm and dry conditions are necessary for fire to spread over large areas (Schoennagel et al. 2004, Meyn *et al.* 2007, Archibald *et al.* 2009, Krawchuk and Moritz 2011, Rocca *et al.* 2014).

Distinguishing between these climate–fire modes has important management implications. Fuel-reduction thinning and prescribed fire are widely accepted practices in fuel-limited systems of the western United States where extensive fuels have accumulated following fire exclusion associated with Euro-American settlement (Brown *et al.* 2004, Spies *et al.* 2006, Franklin and Johnson 2012). In contrast, active management of fuels in climate-limited systems may be inappropriate because abundant fuels are characteristic of these landscapes and significant mortality within larger fire perimeters often results in desirable ecological outcomes (Veblen 2003, Schoennagel *et al.* 2004, Meyn *et al.* 2007, Littell *et al.* 2009, Hutto *et al.* 2016).

Analysis of the modern period and dendroecological reconstructions of fire events prior to extensive Euro-American intervention on the landscape demonstrates an increased incidence of burning in the American West during warmer and drier years (e.g., Brown and Shepperd 2001; Weisberg and Swanson 2003; Heyerdahl *et al.* 2008*a, b;* Littell 2009; Liu and

Wimberly 2015). Fire extent in numerous studies varies with indices of synoptic circulation patterns (e.g., Taylor and Beaty 2005, Kitzberger *et al.* 2007, Brown *et al.* 2008, Sherriff and Veblen 2008, Trouet *et al.* 2010). In the inland Pacific Northwest, positive phases of the El Niño-Southern Oscillation (ENSO) are associated with anomalously warm and dry winters and widespread fire in summer months (Alexander *et al.* 2002, Norman and Taylor 2003, Heyerdahl *et al.* 2008*b*).

This study seeks to add to our knowledge of historical fire–climate relationships in the inland Pacific Northwest by comparing existing climate reconstructions to new crossdated fire histories from the southern Blue Mountains. Similar studies examine fire–climate relationships with fire histories reconstructed from a single forest type (usually forests dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) that readily record fire in cambial tissue) or pool fire records from across multiple forest types (Heyerdahl *et al.* 2002, Heyerdahl *et al.* 2008*b*). This research evaluates climate influences on fire in dry pine-dominated forests where fire is assumed to have been limited by fuel accumulation, and moister forests with significantly older cohorts of fire-intolerant, late seral species that may historically have accumulated significant fuel loads and experienced mixed-severity and high-severity, climate-limited fire (Brown *et al.* 2004, Hessburg *et al.* 2007, Baker 2012, Stine *et al.* 2014, Baker and Williams 2015).

METHODS

Study Area and Study Site Selection

All data were collected on the Malheur National Forest (MNF) in the southern Blue Mountains of eastern Oregon, USA. The MNF encompasses 688 000 ha of federal lands in the southern portion of the Blue Mountains' physiographic province, a northeast to southwest trending axis of rolling hills, plateaus,

river canyons, and occasional high ridges and peaks (Langille 1906). Convective storms are common in the summer months, and lightning from these events frequently ignites wildfires from July through September (Rorig and Ferguson 1999). Elevations below 2200 m on the MNF are dominated by conifer forests of the ponderosa pine, Douglas-fir, and grand fir vegetation series (Franklin and Dyrness 1988, Powell *et al* 2007).

Early explorers, fur traders, and settlers noted ubiquitous fire throughout the Blue Mountains, often attributed to native peoples (Work 1945, Frémont 1988, Robbins 1999, Williams 2000). The Native American population throughout eastern Oregon was significantly impacted by a series of disease epidemics between 1781 and 1863 (Boyd 1999). Traditional native lifeways on the MNF were largely abandoned after the Northern Paiute tribe was forcibly removed to reservations following the conclusion of the Bannock Indian War in 1878 (Mosgrove 1980). Unregulated grazing from the 1880s to the early part of the twentieth century also likely reduced fire extent by modifying surface fuel abundance and composition (Rummell 1951, Belsky and Blumenthal 1997).

Historical sources suggest that early Forest Service rangers working in cooperation with farmers and ranchers had considerable success in suppressing fire beginning in the early 1900s (Mosgrove 1980). By the 1920s, the MNF had extensive detection and communication systems in place and well-organized fire suppression efforts that made use of motorized pump vehicles and locally recruited hand crews (Mosgrove 1980). Pre-WWII fire suppression efforts on the MNF were likely more effective than in other parts of the Pacific Northwest because of relatively gentle topography, ease of access, and extensive use of the forest by stockmen that were enlisted in suppression efforts.

Fire histories for this study were reconstructed at 13 widely distributed sites within

the MNF (Figure 1 and Table 1). Ten sites were located by randomly selecting points within randomly selected, inventoried roadless areas. Two additional fire history sites were selected by randomly locating a point within Forest Service planning areas in which me-

chanical thinning and prescribed fire are planned within the next four years. The final site (Mosquito) was purposefully located within an area dominated by cool–moist plant association groups within a Forest Service planning area of interest to a local stakeholder
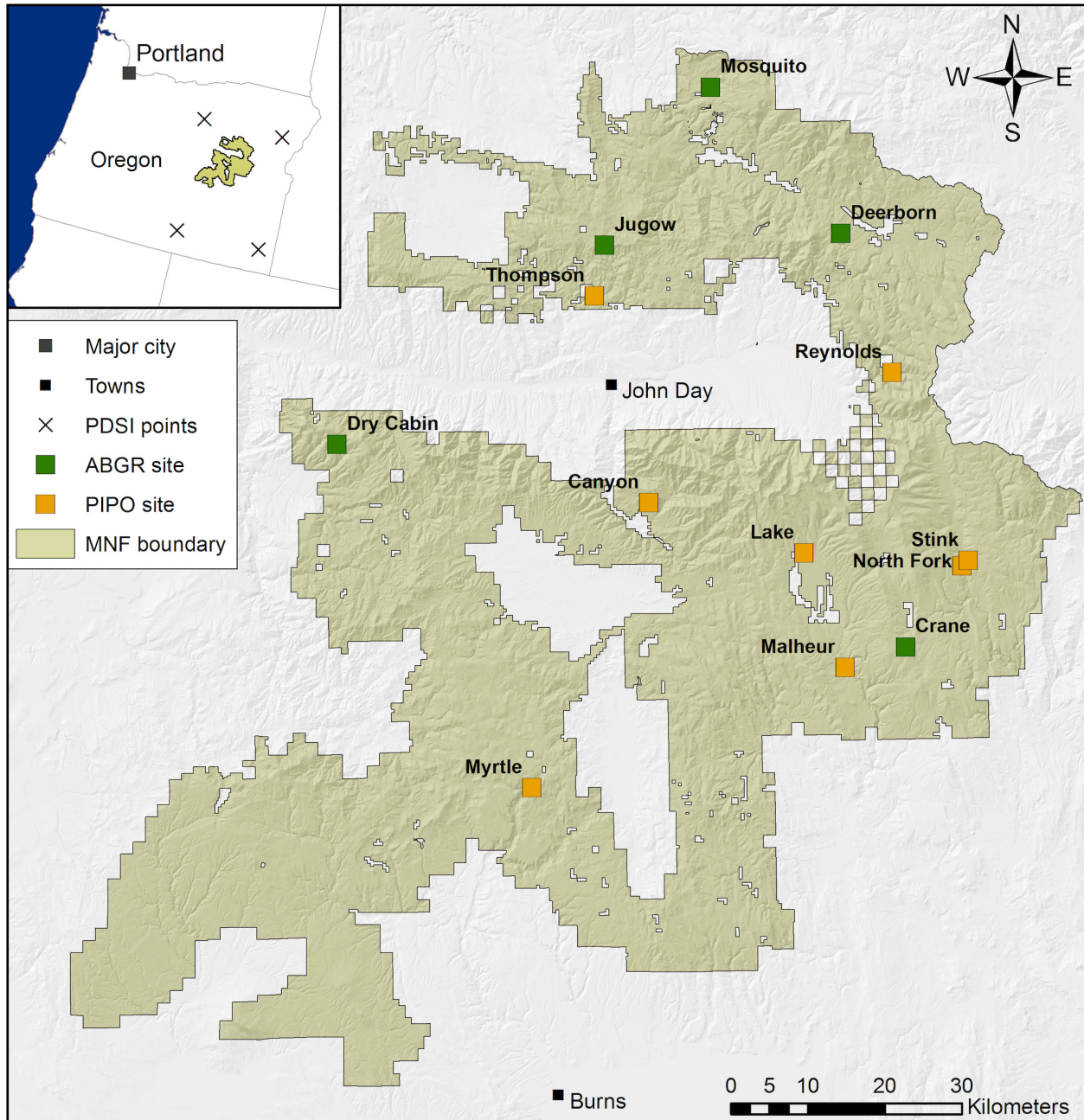

Figure 1. Map of study area showing location of study sites. PDSI = Palmer Drought Severity Index; the PDSI site is the location where the weather was used to calculate PDSI. MNF = Malheur National Forest. ABGR site (green square) refers to a grand fir dominated site. PIPO site (orange square) refers to a ponderosa pine dominated site.

Table 1. Environmental and physical characteristics of study sites. The PIPO group is the ponderosa pine group, and the ABGR group is the grand fir group. ELGL = *Elymus glaucus* Buckley; CARU = *Calamagrostis rubescens* Buckley; CAGE2 = *Carex geyeri* Boott; and LIBO3 = *Linnaea borealis* L. PAG is plant association group, which describes the relative temperature and moisture regime of sites (Powell *et al.* 2007). ABGR 1890 % refers to grand fir as a proportion of total reconstructed basal area in the year 1890. Sites ranged in size from 4 ha to 12 ha. Variables were calculated as the average of values for 15 systematically located plots in each site.

Site	Longitude W Latitude N	Group	Dominant plant association	Dominant PAG	ABGR 1890 %	MFRI	Elevation (m)	Aspect	Slope (%)
Thompson	118°58'42" 44°31'16"	PIPO	PIPO–ELGL	Hot–dry	0	14.9	1248	NW	9
North Fork	118°23'10" 44°11'53	PIPO	PIPO–CARU	Warm–dry	0	10.6	1490	E	10
Myrtle	119°5'23" 43°56'48"	PIPO	PIPO–CAGE2	Warm–dry	0	10.7	1641	W	15
Stink	118°22'32" 44°12'17"	PIPO	PSME–CARU	Warm–dry	0	13.1	1550	NW	18
Malheur	118°34'44" 44°4'56"	PIPO	PSME–CARU	Warm–dry	0	11.0	1497	E	17
Reynolds	118°29'39" 44°25'34"	PIPO	ABGR–CAGE2	Warm–dry	0	18.0	1588	SW	26
Lake	118°38'33" 44°13'1"	PIPO	ABGR–CAGE2	Warm–dry	1	18.4	1619	NA	0
Canyon	118°53'39" 44°16'43"	PIPO	ABGR–CAGE2	Warm–dry	1	18.3	1545	SE	20
Crane	118°28'49" 44°6'17"	ABGR	ABGR–CARU	Warm–dry	24	15.8	1863	NW	9
Dry Cabin	119°24'2" 44°21'1"	ABGR	ABGR–CAGE2	Warm–dry	38	19.2	1785	NW	15
Jugow	118°57'37''' 44° 34'48"	ABGR	ABGR–LIBO3	Cool–moist	28	11.8	1730	NW	5
Deerborn	118°34'25" 44°35'22"	ABGR	ABGR–LIBO3	Cool–moist	46	21.2	1460	NE	11
Mosquito	118°46'59" 44°45'47 "	ABGR	ABGR–LIBO3	Cool–moist	24 to 46[1]	18.0	1366	NE	20

[1] These coverages were estimated from an opportunistic sample of only 23 old (>150 yr) trees because of time and funding constraints.

group. Each site consisted of an area of relatively consistent slope and aspect that varied in size from 4 ha to 12 ha.

The sites were more than seven kilometers apart except for two sites (North Fork and Stink), which were one kilometer apart (maximum distance between sites = 39 kilometers, average distance between sites = 16 kilometers). Although these two sites were in close proximity to one another and may have burned during the same fire events, they were analyzed separately because they were separated by a major river (the North Fork of the Malheur River) that may have impeded the spread of many historical fires.

Fire Histories

Each site was systematically searched for evidence of fire. Partial cross sections from a

minimum of 10 fire-scarred trees (maximum = 22, mean = 15) were removed with a chain saw from each site. Sampled trees were well distributed across each site. Wood samples were given a fine polish with progressively finer grades of sandpaper and visually cross-dated using a master chronology developed for a related study of successional dynamics in the southern Blue Mountains (Stokes and Smiley 1968, Holmes 1983, Johnston 2016). All samples were measured to 0.001 mm precision using a computer-controlled Velmex or Acu-Gage linear measuring system (Velmex, Inc., Bloomfield, New York, USA; Acu-Gage Systems, Hudson, New Hampshire, USA). Cross-dating accuracy was verified using COFECHA software (Grissino-Mayer 2001).

Each fire scar found in partial cross sections was assigned to a calendar year. Fire scars found in the boundary between rings were assigned to the earlier ring because almost all contemporary fires burn in July to October during the late growing season or dormant season, and <1 % of fire scars were found in the early growing season portion of annual growth rings. Site mean fire return intervals (MFRIs) were calculated as the arithmetic mean of the intervals between fire years. Weibull median fire return intervals (Grissino-Mayer 1999) were virtually identical to the arithmetic mean intervals, so arithmetic mean intervals are reported throughout this study.

Historical fire return intervals were calculated for the period 1650 CE to 1900 CE because fire had been effectively excluded from most sites by 1900, and several sites had few live or dead trees that recorded fire prior to 1650 (Figure 2). Only fire years recorded by at least two trees that were more than 200 m apart were used in calculating MFRIs and in statistical analysis. This approach ensured that all fires considered in analyses spread across each site and also eliminated false positive detections in samples from species like grand fir in which charcoal does not readily bind to fire scars.

Analysis of Fire-Climate Relationships

Preliminary analysis of fire–climate relationships prior to 1900 made use of a variety of existing tree-ring-based climate reconstructions. In cases for which multiple reconstructions existed for a climate variable of interest, the reconstruction with the best correlation with PRISM climate data from the study area during the months of May through August over the period 1895 to 2010 was used in subsequent analysis (PRISM 2015; Table 2). PRISM data for the period 1895 to 2010 overlapped with historical reconstructions, and temperature and precipitation in May through August is most strongly correlated with contemporary (1985 to 2015) fire extent.
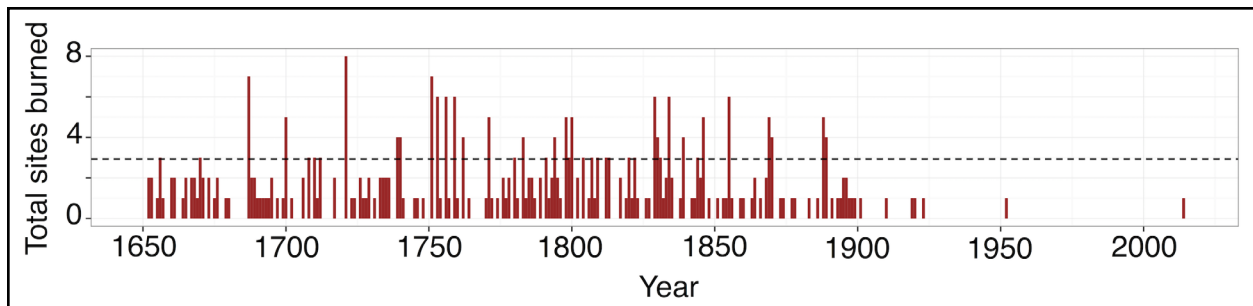

Figure 2. Fire extent in the southern Blue Mountains shown as the number of sites (13 total) recording fire (maximum = 8, minimum = 0) in each year between 1650 and 2015. The earliest recorded was in the year 1278, but fires before 1650 are not shown because many sites recorded few fires before 1650 due to a lack of older trees. Fire years above the dashed horizontal line burned more than three sites.

Table 2. Historical climate reconstructions used in this study. PDSI = Palmer Drought Severity Index; ENSO = El Niño–Southern Oscillation; PDO = Pacific Decadal Oscillation.

Climate reconstruction	Record	Source
Precipitation	1706 to 1978	Garfin and Hughes 1996
Summer temperature	1600 to1983	Briffa *et al.* 1992
PDSI	400 to 2003	Cook *et al.* 2004
ENSO	1301 to 2005	Li *et al.* 2013
PDO	1565 to 2004	D'Arrigo and Wilson 2006

Superposed epoch analysis (SEA) was used to investigate the relationship between historical fire occurrence and reconstructed climate records. SEA used bootstrap resampling (5000 trials) of annual climate time series to determine if departures from mean annual values were statistically significant in the year of fire and for five years before and four years after fire (Haurwitz and Brier 1981, Touchan *et al.* 1996, Swetnam and Betancourt 1998, Heyerdahl *et al.* 2002, Adams *et al.* 2003). The significance of the departure from mean annual climate values during fire years was calculated at both a 95 % and a 99 % confidence interval. SEA was used to test the influence of climate in years in which fires burned any of 13 study sites, and in years in which fire was widespread across the MNF. Fire years in which at least 4 of 13 sites recorded fire were considered widespread fire years because, during an average year in which fire was recorded, approximately one quarter of sites (3 out of 13 sites) experienced fire.

SEA may provide spurious estimates of statistical significance when the time series tested are autocorrelated at the same lag window as the SEA analysis (Prager and Hoenig 1992, Schoennagel 2007). Climate time series were tested for autocorrelation by linear regression of each climate reconstruction year with consecutive years and by visual examination of autocorrelation function plots (acf), which were lagged by 5 years (the same window as SEA analysis) created using the acf function in R (R Core Team 2015). Palmer Drought Severity Index (PDSI) and precipitation reconstructions exhibited no autocorrelation ($P \geq 0.11$). The selected ENSO and temperature reconstructions exhibited strong autocorrelation ($P = < 0.01$) and were pre-whitened by fitting the series to a differenced second-order autoregressive integrated moving average (ARIMA) model in R, and using model residuals in subsequent analysis (Heyerdahl *et al.* 2008*b,* R Core Team 2015).

Forest Types

Differences in historical forest composition were used to divide study sites into forest types that the ecological literature suggests were characterized by different fire regimes and climate drivers of fire. Historical forest composition was determined by systematically coring a minimum of 135 live trees of different species and size classes at 12 of the 13 fire history sites. At least half of these trees were estimated in the field to be older than 150 years of age based on morphological characteristics. Only 23 older (>150 years old) trees were opportunistically cored at the last site (Mosquito) because of time and funding constraints. All tree cores were crossdated and basal area and species composition were reconstructed for the year 1890 by subtracting basal area between 1890 and the year the tree was cored from total basal area (Johnston *et al.* 2016). Reconstructed 1890 basal area was used to classify each site as either a ponderosa pine (PIPO) or grand fir (ABGR) site (Figure 3).

Figure 3. Examples of a ponderosa pine site (Myrtle) dominated by ponderosa pine, and a grand fir (*Abies grandis* [Dougl.] Lindl.) site (Jugow) dominated by grand fir, western larch (*Larix occidentalis* Nutt.), lodgepole pine (*Pinus contorta* Dougl. ex Loud), and scattered Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco).

Differences between sites were further investigated by calculating differences in forest productivity within 15 0.1 ha plots systematically located within each study site using stand data collected in the field and existing geospatial data sets. Current (as of 2014 or 2015) forest density and proportion of total plot basal area consisting of grand fir—a fire-intolerant, shade-tolerant species associated with moister and more productive sites—was used to characterize the moisture gradient of study sites (Franklin and Dyrness 1988, Agee 1994). The average maximum vapor pressure deficit and available soil water of plots within each study site was used to characterize environmental constraints on tree growth and establishment. Maximum vapor pressure deficit, the average difference between actual vapor pressure and saturation vapor pressure during June and July from 1975 to 2015, was derived from PRISM (http://prism.oregonstate.edu, accessed 1 June 2015) data sets. Available soil water—the average total growing season water holding capacity of the soil column estimated from soil depth, soil texture, and parent material—was derived from NRCS 2014 data sets (Carlson 1974).

Non-parametric pivotal bootstrap regression techniques were used to test for differences in site productivity between sites (Racine 1997, Hayfield and Racine 2008). Non-parametric regression was also used to test whether mean fire return intervals differed between forest types. Finally, to investigate climate drivers of fire between forest types, non-parametric regression and SEA was used to compare reconstructed climate indices during fire years in ponderosa pine and grand fir sites.

RESULTS

Fire–Climate Relationships across Sites

Fire was recorded within at least one study site during 149 different years during the period 1650 to 1900. Fire was recorded at more than half of the 13 study sites in the southern Blue Mountains during three different years (1687, 1721, and 1751), and more than a third of sites during 25 different years. SEA demonstrated that fire years in the southern Blue Mountains prior to 1900 were characterized by significantly higher than average reconstructed temperature, lower than average reconstructed precipitation, and lower than average recon-

structed PDSI values (Figure 4 and 5). Of these three strongly correlated ($r^2 \geq 0.71$) measures of annual temperature and precipitation
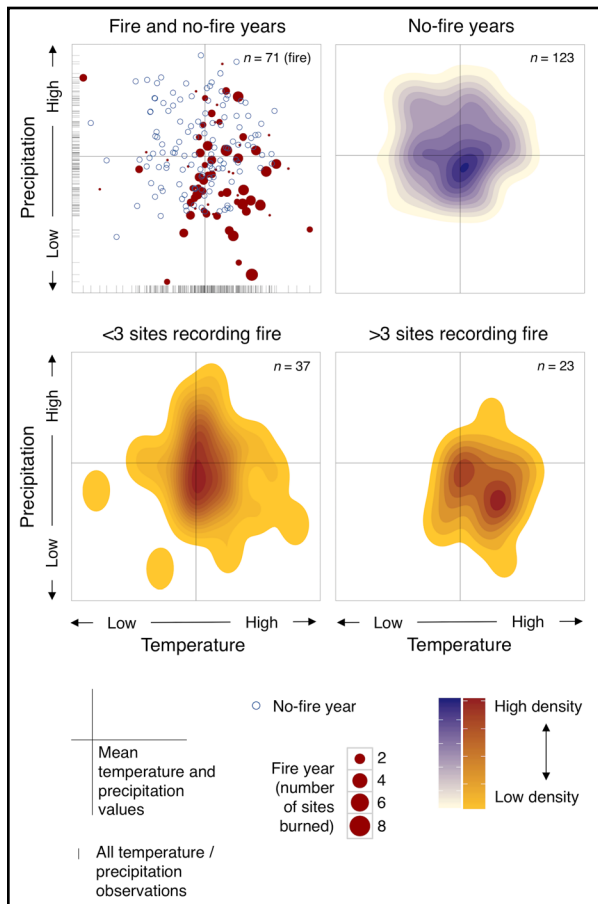

Figure 4. Relationship between fire occurrence and reconstructed temperature and precipitation in the Blue Mountains of the Malheur National Forest, Oregon, USA. Top left panel shows each annual precipitation and temperature reconstruction between 1706 and 1900 as small hash marks on the *y*-axis and *x*-axis, respectively (fire histories were reconstructed to 1650, but precipitation reconstructions only extend to 1706). The position of hollow blue circles (no fire year) and solid red circles (fire year) on the *y*- and *x*-axes correspond to the reconstructed precipitation and temperature value for that year. The size of red circles corresponds to the number of sites recording fire. The remaining panels show: the density of years in which no fire was recorded (upper right), density of years in which fire was recorded at less than 3 sites (lower left), and density of years in which fire was recorded at more than 3 sites (lower right).

variability, the Cook *et al.* 2004 PDSI reconstruction was more explanatory ($r^2 = 0.54$) of fire occurrence when evaluated with pivotal bootstrap resampling techniques than any currently available temperature ($r^2 \leq 0.42$) or precipitation ($r^2 \leq 0.38$) reconstruction. Because of the stronger explanatory power of this reconstruction, and because it integrates the influence of both temperature and precipitation, reconstructed PDSI was used in most subsequent graphical and statistical analyses.

ENSO values during fire years prior to 1900 did not depart significantly from mean ENSO values, although years in which fire was widespread (at least four sites recording fire) were associated with positive ENSO (El Niño) values. Years in which no fire was recorded were associated with negative ENSO (La Niña) values (Figure 5).

Fire−Climate Relationships in Ponderosa Pine Versus Grand Fir Sites

Reconstructed 1890 basal area in ponderosa pine sites consisted primarily of ponderosa pine (71 % to 100 % of total reconstructed basal area). Some ponderosa pine sites had modest amounts of Douglas-fir (0 % to 20 % of total site reconstructed basal area), or western larch (0 % to 9 % of total site reconstructed basal area). Less than 1 % of 1890 reconstructed basal area in ponderosa pine sites consisted of fire-intolerant, shade-tolerant grand fir. In contrast, grand fir made up 24 % to 46 % of reconstructed 1890 basal area in grand fir sites. Besides grand fir, other species present in grand fir sites in order of proportion of total reconstructed basal area were Douglas-fir, western larch, ponderosa pine, and lodgepole pine.

Although only 23 trees older than 150 years of age were opportunistically cored within the Mosquito site, it was added to the grand fir group because the site was dominated by old (>150 yr) grand fir, and most of the older trees cored were grand fir. This site also keyed to the same plant association
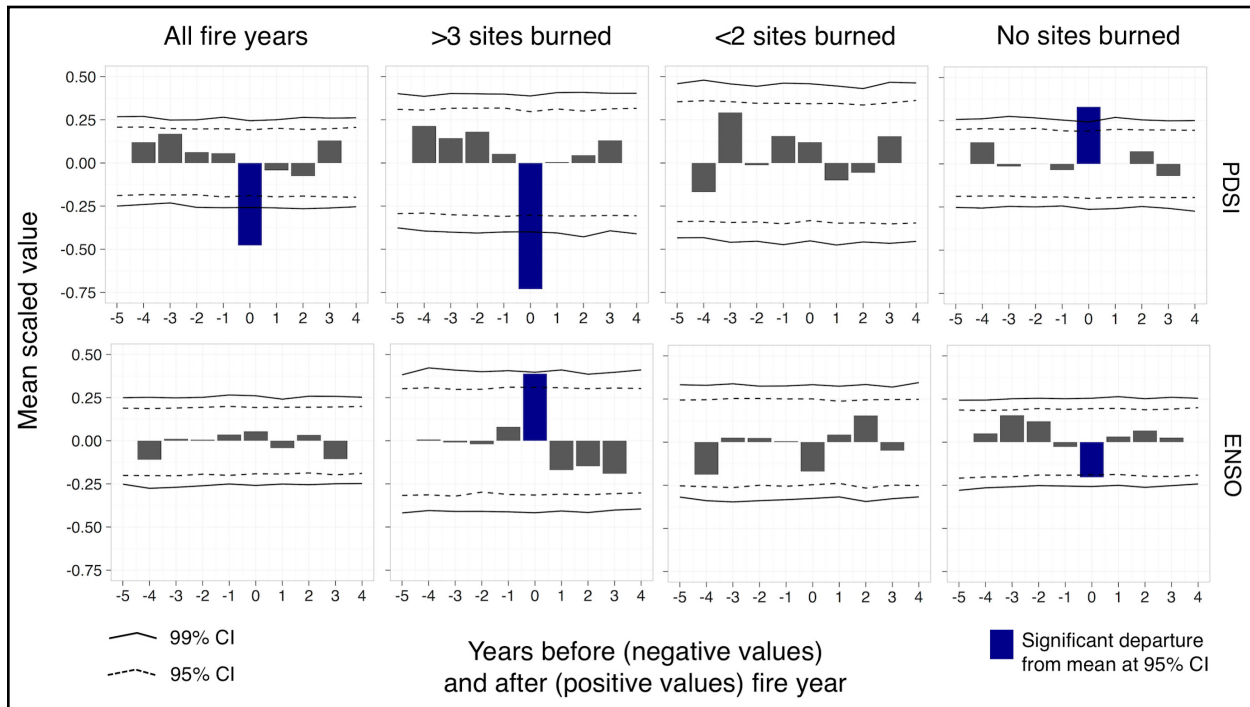
Figure 5. Superposed epoch analysis of fire occurrence and PDSI and ENSO. The *y*-axis shows scaled mean values of each of two climate indices during the year of fire (year 0 on the *x*-axis), for five years before the year of fire (negative values on the *x*-axis), and for four years after fire years (positive values). Blue colored bars indicate a value of a climate index in that year that is significantly departed from mean climate values at the 95 % confidence interval (CI).

(grand fir−twinflower [*Linnaea borealis* L.]) as the moistest and most productive of the grand fir sites in which 1890 basal area was reconstructed from a larger collection of systematically sampled tree cores (Johnson and Clausnitzer 1992, Powell *et al.* 2007, Powell 2011; Table 1).

Ponderosa pine sites included sites that belonged to ponderosa pine, Douglas-fir, and warm-dry grand fir plant associations that historically had little or no grand fir. Grand fir sites consisted of sites that belong to cool-moist grand fir plant associations and warm-dry grand fir plant associations that had significant grand fir structure in the late 1800s (Table 1). Between 93 % to 100 % of the fire history samples collected from ponderosa pine sites were from ponderosa pine trees. Ponderosa pine made up between 10 % to 56 % of samples from moist grand fir sites, with western larch, Douglas-fir, grand fir, and lodgepole pine making up the remainder.

There were statistically significant differences in most measures of site productivity between ponderosa pine and grand fir sites. Grand fir sites are today significantly denser than ponderosa pine sites and have a significantly higher proportion of grand fir basal area. Grand fir sites have higher available soil water holding capacity. Grand fir sites experience significantly lower summer maximum vapor pressure deficits (Figure 6).

MFRIs calculated using fire years recorded in two or more trees more than 200 m apart ranged from 10.6 yr to 18.4 yr within the eight ponderosa pine sites, and from 11.8 yr to 21.2 yr within the five grand fir sites. There was no statistically significant difference in fire frequencies between these two forest types. There was also no statistically significant difference in the mean value of reconstructed temperature, precipitation, PDSI, or ENSO during fire years in ponderosa pine and grand fir sites ($P \geq 0.14$; Figures 6, 7, and 8). All
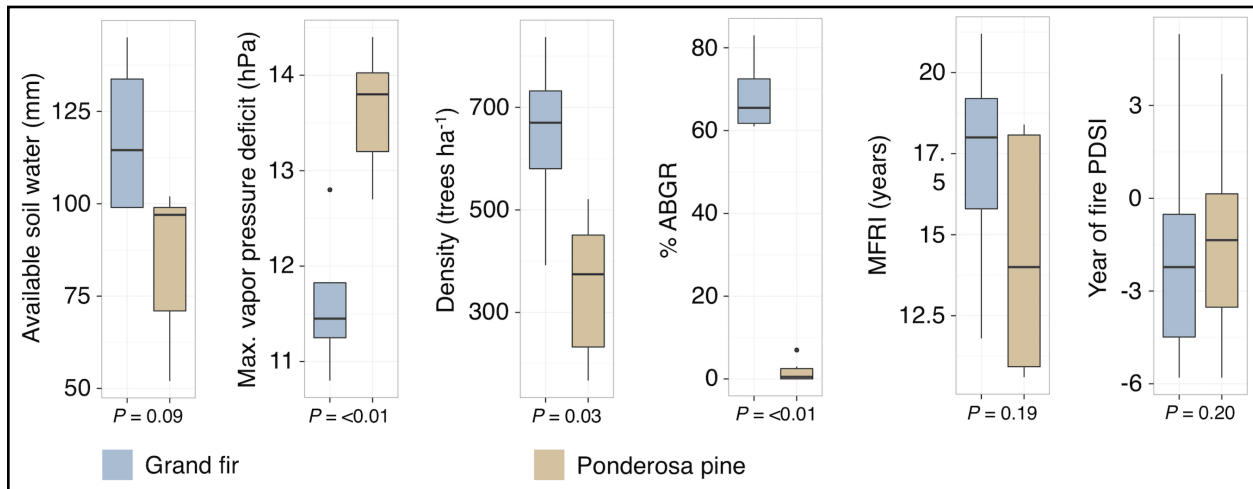
Figure 6. Box and whisker plots of biophysical and fire disturbance characteristics of ponderosa pine and grand fir study sites in the Blue Mountains of the Malheur National Forest, Oregon, USA. Available soil water refers to the maximum potential depth that water can be held in a soil column modeled from mapped soil depth, texture, and parent material (Carlson 1974). Maximum vapor pressure deficit refers to the thirty-year average maximum difference between actual vapor pressure and saturation vapor pressure at the same temperature during June and July (PRISM 2015). Density and proportion of total stand basal area consisting of grand fir were calculated within study sites in 2014 and 2015 and serve as indicators of inherent site productivity. MFRI and reconstructed PDSI during fire years were calculated for the period 1650 to 1900.

fire-climate relationships during fire years between forest types examined with SEA and non-parametric pivotal bootstrap resampling techniques were similar, although SEA documented moister than average climate in ponderosa pine sites prior to fire years (Figure 8).

DISCUSSION

Aridity and Historical Fire Occurrence

This study is similar to other studies in the inland Pacific Northwest that demonstrate a strong relationship between aridity and historical fire extent (Heyerdahl *et al.* 2002, Hessl *et al.* 2004, Heyerdahl 2008*b*). Although fires burned during a wide range of climate conditions in the southern Blue Mountains prior to 1900, widespread fire was more common during years that were warmer and drier than average. Conversely, years without fire were generally moister and cooler than average (Figures 4 and 5). ENSO variability was a weak predictor of fire occurrence, although years without fire and years during which fire burned multiple sites were associated with statistically significant departures from mean ENSO values (Figure 5).

This study does not address other ocean–atmosphere teleconnections like the Pacific Decadal Oscillation (PDO) that may have influenced historical fire extent by modulating centennial scale temperature and precipitation patterns. Although past studies suggest that PDO influences fire extent at the scale of the entire Pacific Northwest (Gedalof *et al.* 2005), this influence may be dampened in drier interior forests in which fire typically consumed fuel at temporal scales shorter (<20 yr) than an average PDO period (20 yr to 30 yr). It is also difficult to analyze the effect of PDO on historical fire occurrence because there is poor agreement between PDO reconstructions (Kipfmueller *et al.* 2012).
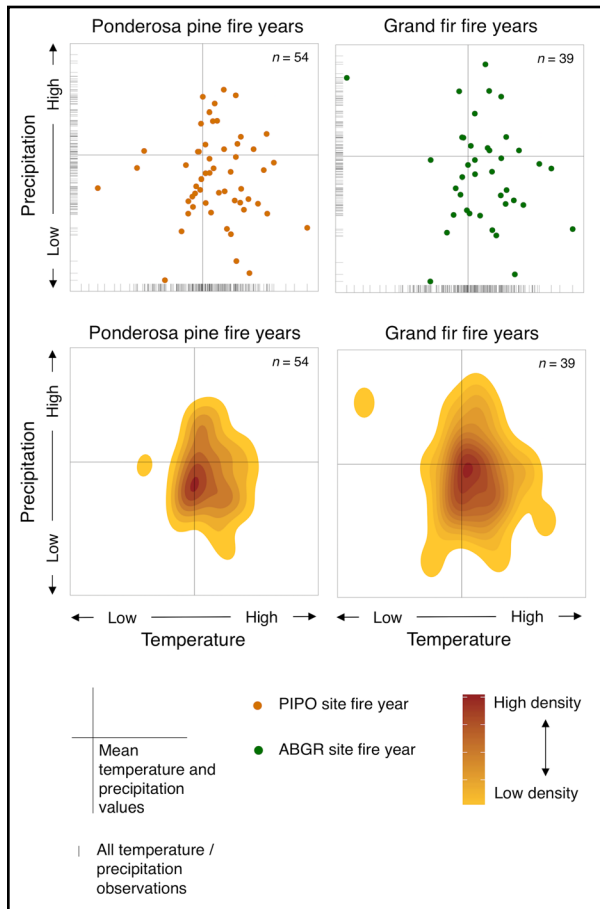
Figure 7. Relationship between fire occurrence and reconstructed temperature and precipitation for ponderosa pine and grand fir sites in the Blue Mountains of the Malheur National Forest, Oregon, USA. Top panels show annual precipitation and temperature reconstructions between 1706 and 1900 as small hash marks on the *y*-axis and *x*-axis, respectively (fire histories were reconstructed to 1650, but precipitation reconstructions only extend to 1706). The position of points on the *y*-axis and *x*-axis correspond to the reconstructed precipitation and temperature value in a year in which fire was recorded in a ponderosa pine (orange point) or grand fir (green point) site. The bottom panels show the density of years in fire was recorded in ponderosa pine (lower left) and grand fir (lower right) sites.

Historical Fire Occurrence in Different Forest Types

This is one of the few studies that explicitly examines potential differences in climate
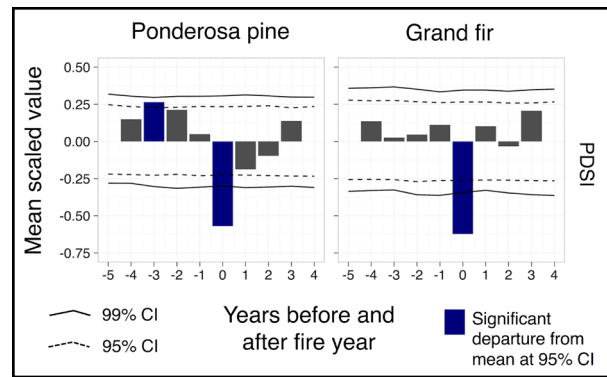
Figure 8. Superposed epoch analysis of Palmer Drought Severity Index (PDSI) and fire years in ponderosa pine and grand fir study sites in the Blue Mountains of the Malheur National Forest, Oregon, USA. The *y*-axis shows scaled mean values of PDSI in the year of fire (year 0 on the *x*-axis), for five years before the year of fire (negative values on the *x*-axis), and for four years after fire years (positive values). Blue colored bars indicate a value of a climate index in that year that is significantly departed from mean climate values at the 95% confidence interval (CI). Note moister antecedent conditions in ponderosa pine sites.

drivers of historical fire occurrence between different forest types found within the same landscape in the inland Pacific Northwest. Other authors suggest that forests that historically had a large component of fire-intolerant, shade-tolerant late seral trees (e.g., species of the *Abies* genus) were climate-driven systems that burned irregularly under more extreme weather conditions than drier ponderosa pine dominated forests (Brown *et al.* 2004, Hessburg *et al.* 2007, Baker 2012, Baker and Williams 2015). Although there were marked differences in current tree density and historical and contemporary species composition between ponderosa pine and grand fir sites for which fire histories were reconstructed, there was no statistically significant difference in fire return intervals or climate drivers of fire between these forest types (Figure 6).

The dendroecology methods utilized in this study do not provide precise estimates of historical structure or composition because dead trees that were alive during the 1890 re-

construction period were not included in reconstructions. However, systematic sampling of extant live forest structure is a reasonable basis for inferring relative differences in historical composition. There are distinct and dramatic differences between the two forest types identified in this study: ponderosa pine sites today have little or no evidence of fire-intolerant grand fir structure that was alive in 1890, whereas grand fir was clearly a major component of grand fir sites in the late 1800s (Table 1, Figures 3 and 6).

Relatively short fire return intervals reconstructed at all sites suggest that both ponderosa pine and grand fir sites in the southern Blue Mountains were fuel-limited systems that generally burned whenever ignitions were coincident with sufficient fuel to carry fire. Although there was no statistically significant difference between fire return intervals calculated between ponderosa pine and grand fir sites, fire return intervals in grand fir sites were slightly longer than ponderosa pine sites. It is possible that a larger sample size would demonstrate a small but meaningful difference in fire return intervals between ponderosa pine and grand fir sites. It is also possible that the calculated fire return intervals in grand fir sites are artificially lengthened because these sites contain fewer species like ponderosa pine that readily record fire in cambial tissue and a higher proportion of fires that burned grand fir sites did not leave fire scar evidence.

Unlike climate in grand fir sites, climate in the years before fire in ponderosa pine sites was significantly moister for several years before fire, a climate signal consistent with increased production of perennial grass (Swetnam and Betancourt 1998, Veblen *et al.* 2000, Littell *et al.* 2009, Rother and Grissino-Mayer 2014). This fast regenerating fuel type may have been less extensive or less contiguous in grand fir stands with higher tree leaf areas and less light available to understory vegetation, or within cooler topographic positions unsuitable for graminoids. Although there was no differ-

ence in temperature or precipitation in the year of fire between ponderosa pine and grand fir sites, it is possible that grand fir sites provide more shade or occupy shadier topographic positions that maintain lower fuel moistures that impede fire spread. Future studies should investigate the spread of historical fire between contrasting forest types.

Management Implications

There are two important differences between historical and contemporary fire patterns in the southern Blue Mountains. First, frequent fire recorded at all sites prior to 1900 indicates that historical fires usually burned over areas with fuel loads that had usually accumulated over 10 yr to 20 yr since the previous fire, whereas contemporary fires burn through fuels that, in most cases, have accumulated over more than 100 yr. Second, the fact that multiple sites experienced fire in the same year prior to 1900 (an average of a quarter of sites burned during fire years) and the fact that frequent fire was characteristic of diverse forest types, suggest that historical fires often burned over a significant proportion of the total area of the MNF. In contrast, the two largest fire years in the southern Blue Mountains in the last 35 years (2001 and 2007) each burned less than 9 % of the forest. During the average fire year in the last 30 years in which more than 500 ha burned, less than 2 % of the total area of the forest burned (Monitoring Trends in Burned Severity data, http://mtbs. gov).

Restoring characteristic fire regimes on more than 11 million hectares of federal forestland in the American West is a major goal of federal, state, and local policy makers (WGA 2002, Carroll 2007, GAO 2009, Schultz *et al.* 2012). However, some authors suggest that more than 40 % of restoration treatments are taking place in forest types in which historical fire dynamics and, therefore, the need for fuels reduction, are largely unknown

(Schoennagel and Nelson 2010). In the inland Pacific Northwest, efforts to accelerate the pace and scale of restoration on national forest land have been criticized for targeting treatments in forest types in which thinning is thought to be inappropriate because severe climate-driven fires were historically common (Brown *et al.* 2004, Baker 2012, Baker and Williams 2015).

This study, however, demonstrates that fire frequencies and climate drivers of fire were similar across a broad gradient of productivity including moister and more productive grand fir sites. Management practices appropriate for drier ponderosa pine sites, including mechanical thinning to reduce overall stand density and remove ladder fuels prior to reintroduction of fire, would therefore also be appropriate for productive mixed conifer stands (Margolis and Malevich 2016). Reintroduction of fire on a spatial scale many orders of magnitude greater than the current combined extent of prescribed and wildland fire may be necessary to restore historical surface fuel levels.

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