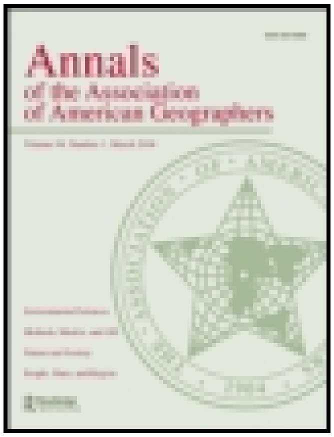

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A Regional Perspective on Holocene Fire–Climate–Human Interactions in the Pacific Northwest of North America

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Wildfire plays an important role in ecosystems of the Pacific Northwest, but past relationships among fire, climate, and human actions remain unclear. A multiscale analysis of thirty-four macroscopic charcoal records from a variety of biophysical settings was conducted to reconstruct fire activity for the Pacific Northwest (PNW) during the past 12,000 years. Trends in biomass burning and fire frequency are compared to paleoenvironmental and population data at a variety of temporal and spatial scales to better understand fire regime variability on centennial- to millennial-length time scales. PNW fire activity in the early Holocene is linked to climatic and vegetation changes; however, increased fire activity in the middle to late Holocene is inconsistent with long-term trends in temperature and precipitation. Two hypotheses are explored to explain the rise in fire activity after ca. 5,500 calendar years before present, including greater climate variability and increased human use of fire. Climatic changes such as increased El Niño/Southern Oscillation event frequency during the past approximately 6,000 years could have led to hydrologic shifts conducive to more frequent fire events, despite overall trends toward cooler and moister conditions. Alternatively, increasing human populations and their associated uses of fire might have increased biomass burning. Centennial-scale changes in fire activity, such as during the Medieval Climate Anomaly and the Little Ice Age, closely match widespread shifts in both climate and population, suggesting that one or both influenced the late-Holocene fire history of the PNW. *Key Words: biomass burning, charcoal, El Niño/Southern Oscillation, Native Americans/First Nations, wildfire.*

森林大火在太平洋西北地区的生态系统中扮演重要的角色，但过去的火灾、气候和人类行为之间的关係却不甚清楚。本文对各种物理条件中的三十四个巨视性炭屑纪录进行跨尺度分析，以对太平洋西北地区（PNW）过去一万两千年来的火灾活动进行重构。本文将生物体燃烧和火灾频率的趋势，与在各种时间及空间尺度的古环境及人口数据进行比较，以更佳地理解火域在百年与千年时间尺度中的变异。全新世早期的PNW火灾活动，与气候和植物变迁相关；但全新世中期至晚期增加的火灾活动，与温度及降雨的长期趋势不符。本文探讨两种假说，以解释火灾活动大约于今日之前的五千五百曆年后增加的原因，包含更大的气候变异和人类用火的增加。大约过去六千年来，诸如圣婴南方振动现象所增加的事件频率之气候变迁，可能已导致水文转变，引发了频率更高的火灾事件，儘管总体的趋势趋向更凉爽和潮湿的条件。抑或增加的人类人口，及其相关的用火，可能已增加了生物体燃烧。百年尺度的火灾活动变迁，诸如在中世纪气候异常和小冰期期间，同时与气候和人口的广泛转变紧密相符，意味着其中一者或两者共同影响了PNW全新世晚期的火灾历史。 *关键词： 生物体燃烧，炭，圣婴南方振动现象，美洲原住民／第一民族，森林大火。*

El incendio forestal juega un papel importante en los ecosistemas del Noroeste del Pacífico, aunque las pasadas relaciones entre fuego, clima y acciones humanas siguen siendo poco claras. Se llevó a cabo un análisis a escala múltiple de treinta y cuatro registros macroscópicos de carbón vegetal, extraídos de una variedad de escenarios biofísicos, para reconstruir la actividad de incendios forestales en el Noroeste del Pacífico (PNW) durante los pasados 12.000 años. Las tendencias de quemas de biomasa y frecuencia de los incendios se comparan con datos paleoambientales y de población a una variedad de escalas temporales y espaciales para entender mejor la variabilidad del régimen de fuego a escalas de tiempo de centenarias a milenarias. La actividad del fuego en el PNW a principios del Holoceno se vincula con cambios climáticos y vegetacionales; sin embargo, el incremento de esta actividad de fuego desde el Holoceno medio hasta el tardío es inconsistente con tendencias de temperatura y precipitación a largo plazo. Se exploraron dos hipótesis para explicar el incremento en la actividad del fuego

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después de *ca.* 5.500 años calendario antes del presente, incluyendo una más grande variabilidad del clima y mayor uso humano del fuego. Cambios climáticos tales como la agudización en la frecuencia del evento El Niño/Oscilación del Sur durante aproximadamente los pasados 6.000 años podrían haber llevado a variaciones hidrológicas conducentes a eventos de fuego más frecuentes, no obstante las tendencias generales hacia condiciones más frescas y húmedas. Alternativamente, el crecimiento de las poblaciones humanas y el incremento de usos del fuego asociados pudieron incrementar la quema de biomasa. Los cambios en actividad del fuego a escala centenaria, tal como lo ocurrido durante la Anomalía Climática Medieval y la Pequeña Edad del Hielo, de cerca emparejan los cambios generalizados tanto en clima como población, sugiriendo que tanto el uno como la otra, o ambos, influyeron la historia del fuego del Holoceno tardío en el PNW. *Palabras clave: quema de biomasa, carbón vegetal, El Niño/Oscilación del Sur, nativos americanos/primeras naciones, incendio forestal.*

Wildfire is an important ecological process in many Pacific Northwest (PNW) ecosystems and can have extensive and lasting effects on vegetation composition and structure, nutrient cycling, biodiversity, and other key ecosystem properties (Agee 1993; McKenzie et al. 2004). Advanced technologies like remote sensing have greatly accelerated modern fire science, yet past interactions among fire, climate, and human activities on multidecadal and longer time scales in the PNW remain poorly understood. Better understanding the relationship between Holocene (the past 12,000 years) fire regime change, climate variability, and human actions will provide forest managers, scientists, and policymakers with relevant information that can be used to anticipate how forests and fire disturbance will respond to future climate change and intensified human activities (Mote and Salathé 2010).

Based on accounts and documents of Native American/First Nations (hereafter Native American) land-use practices (Douglas 1959; Knox 2000), it is likely that pre-Euro American settlement fire regimes in the PNW were influenced by human actions for millennia (Johannessen et al. 1971; Boyd 1999; Vale 2002; Lepofsky, Hallett, et al. 2005). Yet in many paleoecological studies, comparisons of past climatic changes with fire proxy data from fire-scarred trees and sediment charcoal reveal strong fire–climate relationships (e.g., Hessl, McKenzie, and Schellhaas 2004; Brunelle et al. 2005; Kitzberger et al. 2007; Heyerdahl et al. 2008; Whitlock et al. 2008). For example, studies from many sites in the United States and Canada generally argue that since the middle Holocene, declining summer insolation, an associated decline in summer temperature, and increasing effective moisture in the late Holocene increased fuel moisture and thus reduced fire frequency over millennia (e.g., Walsh, Whitlock, and Bartlein 2008; Hély et al. 2010), leaving little room for human agency in explaining past fire-regime changes (but see Lepofsky et al. 2003; Wray and Anderson 2003; Lepofsky, Lertzman, et al. 2005; Walsh, Pearl, et al. 2010).

Climate changes and human actions cannot both have been the primary influence on the wildfire trends evident in the paleofire data. It is possible that either climatic changes or human impacts were dominant or that they were coupled, leading to reinforcing or synergistic effects (Brown and Hebda 2002b; Lepofsky, Lertzman, et al. 2005; Walsh, Whitlock, and Bartlein 2010). Likely, climate and human actions worked at different spatial and temporal scales to influence fire regimes, with the former at broad spatial and long temporal scales and the latter at finer spatial and shorter temporal scales (Bowman et al. 2011). Vegetation changes also played a key role in determining fire regimes during the Holocene (Lynch et al. 2003; Marlon, Bartlein, and Whitlock 2006; Higuera et al. 2009). As a starting point to better understand these relationships, we conduct a multiscale analysis of past fire activity in the PNW—a region that contains an unusually dense network of paleofire sites.

The goal of this study is to examine millennial- and centennial-scale patterns of fire activity in the PNW during the Holocene to better explain past fire regimes. To do this, thirty-four published and unpublished macroscopic charcoal records from the region were analyzed (Figure 1), and a regional biomass burning curve was produced. Additionally, a spatial comparison of fire activity is presented for the past 6,000-year and 3,000-year periods, during which time human populations are thought to have increased dramatically in the PNW (Lepofsky, Hallett, et al. 2005; Prentiss et al. 2005; Campbell and Butler 2010). We developed a classification system that groups sites into coarse climatic, elevation, and vegetation regions (Table 1) to highlight how fire varies among ecological settings. The analyses presented aim to elucidate whether changes in fire regimes during the past 12,000 years were consistent with climatic events, changes in vegetation, anthropogenic activity, or

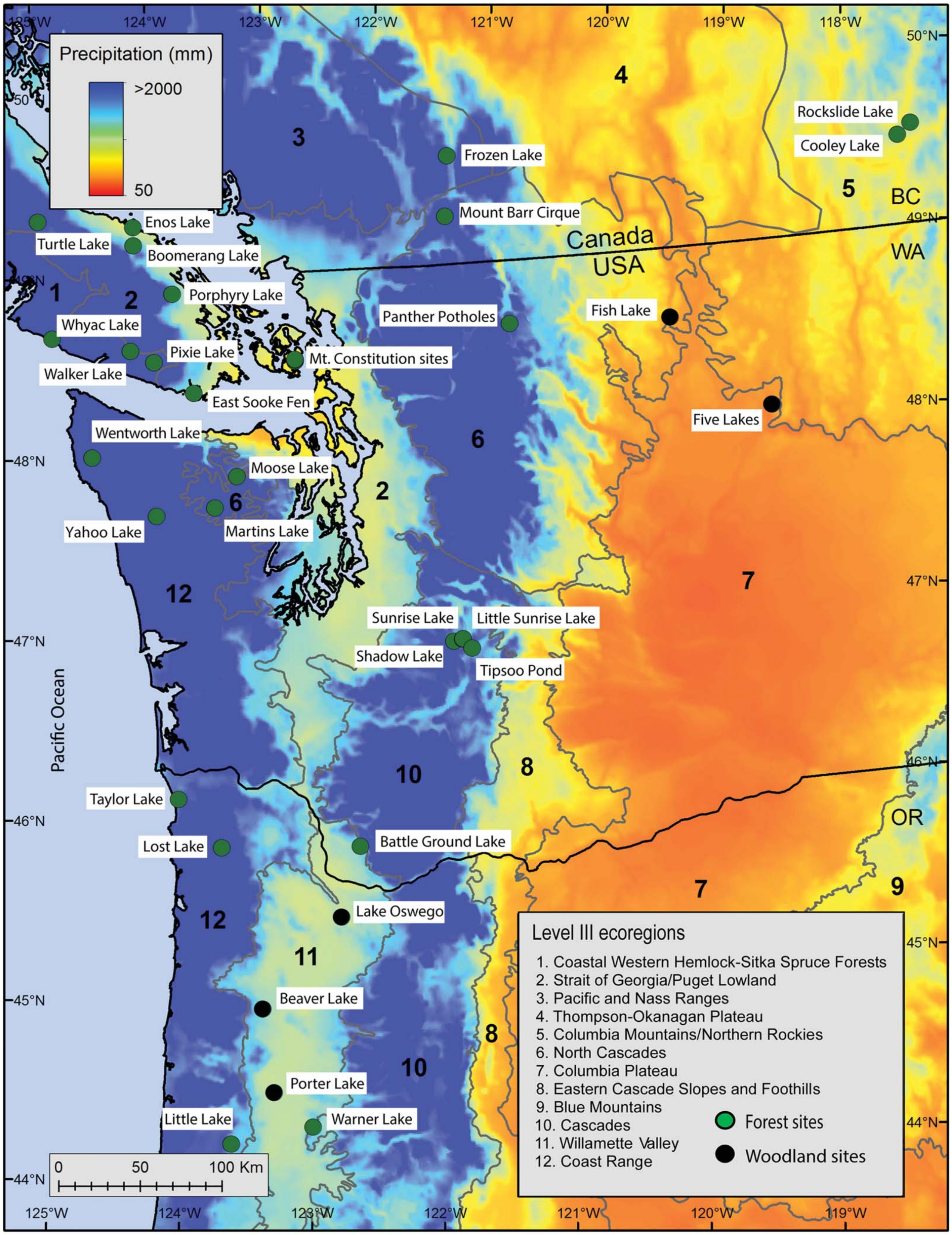

Figure 1. Map of the thirty-four charcoal study sites in the Pacific Northwest. Green circles indicate forested sites; black circles indicate woodland sites. Ecoregions are marked with numbers and are based on Olson et al. (2001). Base layer is the PRISM precipitation data (PRISM Climate Group 2014). (Color figure available online.)

Table 1. Location, elevation, record length, and analysis categorization of the thirty-four study sites listed in order from highest to lowest latitude

Site	Latitude, longitude	Elevation (m)	Record length (years)[d]; average sample resolution (cm/yr)	High/low elevation	Coastal/ inland	Forest/ woodland	Wet/ dry forest	Reference
Frozen Lake, BC, Canada[a,b,c]	49.60°N, −121.47°W	1,180	12,340/0.02	High	Inland	Forest	Wet	Hallett et al. (2003)
Rockslide Lake, BC, Canada[a,b,c]	49.55°N, −117.52°W	1,539	4,970/0.04	High	Inland	Forest	Dry	Gavin et al. (2006)
Cooley Lake, BC, Canada[a,b,c]	49.49°N, −117.65°W	1,515	7,500/0.06	High	Inland	Forest	Dry	Gavin et al. (2006)
Turtle Lake, BC, Canada[c]	49.32°N, −124.95°W	80	12,090/0.04	Low	Coastal	Forest	Wet	Brown and Hebda (2002b)
Enos Lake, BC, Canada[c]	49.28°N, −124.15°W	50	16,030/0.07	Low	Coastal	Forest	Dry	Brown and Hebda (2002b)
Mount Barr Cirque, BC, Canada[a,b,c]	49.26°N, −121.52°W	1,376	7,660/0.08	High	Inland	Forest	Wet	Hallett et al. (2003)
Boomerang Lake, BC, Canada[c]	49.18°N, −124.15°W	360	13,420/0.04	Low	Coastal	Forest	Dry	Brown and Hebda (2002b)
Porphyry Lake, BC, Canada[c]	48.91°N, −123.83°W	1,100	14,980/0.02	High	Coastal	Forest	Dry	Brown and Hebda (2003)
Whyac Lake, BC, Canada[c]	48.67°N, −124.84°W	15	16,600/0.03	Low	Coastal	Forest	Wet	Brown and Hebda (2002a)
Panther Potholes, WA, U.S.[a,b]	48.65°N, −121.03°W	1,100	10,540/0.09	High	Inland	Forest	Wet	Prichard et al. (2009)
Fish Lake, WA, U.S.[a,b]	48.62°N, −119.70°W	550	3,780/0.09	Low	Inland	Woodland	—	Walsh (data collected 2011)
Pixie Lake, BC, Canada[c]	48.60°N, −124.20°W	70	15,330/0.06	Low	Coastal	Forest	Wet	Brown and Hebda (2002a)
Walker Lake, BC, Canada[c]	48.53°N, −124.00°W	950	15,400/0.04	High	Coastal	Forest	Wet	Brown and Hebda (2003)
Mt. Constitution C32, WA, U.S.[b]	48.52°N, −122.83°W	735	7,210/0.02	High	Coastal	Forest	Dry	Sugimura et al. (2008)
Mt. Constitution C38, WA, U.S.[b]	48.52°N, −122.83°W	735	3,820/0.02	High	Coastal	Forest	Dry	Sugimura et al. (2008)
Mt. Constitution C11, WA, U.S.[b]	48.51°N, −122.83°W	735	7,590/0.02	High	Coastal	Forest	Dry	Sugimura et al. (2008)
East Sooke Fen, BC, Canada[c]	48.35°N, −123.68°W	155	13,680/0.09	Low	Coastal	Forest	Dry	Brown and Hebda (2002a)
Five Lakes, WA, U.S.[c]	48.08°N, −118.93°W	780	1,530/0.10	High	Inland	Woodland	—	Scharf (2010)
Wentworth, WA, U.S.	48.08°N, −118.93°W	47	16,330/0.04	Low	Coastal	Forest	Wet	Gavin and Brubaker (2015)
Moose Lake, WA, U.S.[c]	47.88°N, −123.35°W	1,508	10,240/0.06	High	Coastal	Forest	Wet	Gavin et al. (2001)
Martins Lake, WA, U.S.[c]	47.71°N, −123.54°W	1,415	12,010/0.03	High	Coastal	Forest	Wet	Gavin et al. (2001)
Yahoo Lake, WA, U.S.[a,b]	47.41°N, −124.01°W	710	14,660/0.03	High	Coastal	Forest	Wet	Gavin, Brubaker, and Greenwald (2013)
Little Sunrise Lake, WA, U.S.[a,b]	46.92°N, −121.58°W	1,698	7,630/0.03	High	Inland	Forest	Wet	Lukens (2013)
Sunrise Lake, WA, U.S.[a,b]	46.92°N, −121.59°W	1,748	14,510/0.02	High	Inland	Forest	Wet	Lukens (2013)
Shadow Lake, WA, U.S.[a,b]	46.91°N, −121.66°W	1,891	10,180/0.03	High	Inland	Forest	Wet	Lukens (2013)

(*continued on next page*)

Table 1. Location, elevation, record length, and analysis categorization of the thirty-four study sites listed in order from highest to lowest latitude *(Continued)*

Site	Latitude, longitude	Elevation (m)	Record length (years)[d]; average sample resolution (cm/yr)	High/low elevation	Coastal/ inland	Forest/ woodland	Wet/ dry forest	Reference
Tipsoo Pond, WA, U.S.[a,b]	46.87°N, −121.52°W	1,630	7,630/0.04	High	Inland	Forest	Wet	Walsh (data collected 2012)
Taylor Lake, OR, U.S.[a,b,c]	46.10°N, −123.91°W	6	4,600/0.07	Low	Coastal	Forest	Wet	Long and Whitlock (2002)
Lost Lake, OR, U.S.[a,b,c]	45.82°N, −123.58°W	449	8,380/0.06	Low	Coastal	Forest	Wet	Long, Whitlock, and Bartlein (2007)
Battle Ground Lake, WA, U.S.[a,b,c]	45.80°N, −122.49°W	154	14,290/0.06	Low	Inland	Forest	Dry	Walsh, Whitlock, and Bartlein (2008)
Lake Oswego, OR, U.S.[a,b,c]	45.41°N, −122.66°W	30	3,320/0.17	Low	Inland	Woodland	—	Walsh, Whitlock, and Bartlein (2010)
Beaver Lake, OR, U.S.[a,b,c]	44.91°N, −123.31°W	69	11,190/0.20	Low	Inland	Woodland	—	Walsh, Pearl, et al. (2010)
Porter Lake, OR, U.S.[c]	44.45°N, −123.24°W	73	220/0.35	Low	Inland	Woodland	—	Walsh, Whitlock, and Bartlein (2010)
Warner Lake, OR, U.S.[c]	44.24°N, −122.96°W	590	880/0.25	High	Inland	Forest	Dry	Walsh, Whitlock, and Bartlein (2010)
Little Lake, OR, U.S.[a,b,c]	44.17°N, −123.58°W	703	41,320/0.13	High	Coastal	Forest	Dry	Long et al. (1998)

[a]Used in peak analysis.
[b]Used in functional principal components analysis.
[c]Records available in the Global Charcoal Database version 3 (Blarquez et al. 2014).
[d]Record lengths rounded to the nearest decade.

some combination of all three. Finally, regional patterns in biomass burning are considered in the context of a fire-history synthesis of the Western United States (Marlon et al. 2012).

Fire in the Pacific Northwest

Modern fire in the PNW is most common from May to October, with peak activity in August (van der Werf et al. 2006; Bartlein et al. 2008). On hourly to annual timescales, synoptic weather conditions determine many fire regime characteristics through controls on fire weather, including variability in temperature, precipitation, humidity, and lightning strike occurrence (Agee 1993; Whitlock et al. 2010). Vegetation and landscape characteristics interact with fire at fine spatial scales through their effects on fuel type, structure, composition, and distribution (Agee 1994; McKenzie et al. 2004). In the PNW and the Western United States more broadly, large areas generally burn during warm, dry summers when lightning strikes are abundant and fuels are driest (Rorig and Ferguson 1999; Littell and Gwozdz 2011). Fire occurrence and area burned in this region broadly responds most directly to current-year conditions that increase spring and summer drought and reduce fuel moisture (Hessl, McKenzie, and Schellhaas 2004; Wright and Agee 2004; Gedalof, Peterson, and Mantua 2005; Trouet et al. 2006; Heyerdahl, McKenzie, et al. 2008; Heyerdahl, Morgan, and Riser 2008), as opposed to antecedent wet or current-year dry conditions that increase fire activity in the fuel-limited systems of the U.S. Southwest (Swetnam and Betancourt 1998; Swetnam and Anderson 2008).

Two modes of interannual climate variability enhance current-year drought in the PNW, El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO; Mantua et al. 1997; Cayan, Redmond, and Riddle 1999; Mote et al. 2003). The influence of these modes on fire primarily manifests in reductions in winter and spring snowpacks during positive (El Niño) ENSO phases and positive (warm-dry) PDO phases, leading to longer fire seasons (Gershunov, Barnett, and Cayan 1999; Heyerdahl, Brubaker, and Agee 2002; Keeton, Mote, and Franklin 2007).

Strong linkages between fire occurrence and warm-phase PDO events have been demonstrated for the interior PNW (Heyerdahl, Brubaker, and Agee 2002; Hessl, McKenzie, and Schellhaas 2004) but remain unclear in other parts of the region. The relationship between ENSO and fire in the PNW is generally not well established (as it is in the U.S. Southwest), but some evidence suggests that positive ENSO phases are correlated with increased fire occurrence and size in the interior PNW (Heyerdahl, Brubaker, and Agee 2002; Wright and Agee 2004), especially when ENSO and PDO are in phase with one another (Heyerdahl, McKenzie, et al. 2008). Several studies, however, show no relationship (Gedalof, Peterson, and Mantua 2005; Trouet et al. 2010). Keeton, Mote, and Franklin (2007) hypothesized that stronger than observed linkages could exist between ENSO and fire activity in the PNW but that regional-level studies mask subregional variations in those relationships or that twentieth-century fire suppression has obscured them.

On millennial timescales, a higher order set of climatic controls affect the occurrence and seasonal distribution of fire in the PNW. Such climatic boundary controls include insolation, atmospheric greenhouse gas concentrations, and ice volume (Whitlock and Bartlein 2004). These in turn drive changes in atmospheric circulation that influence storm tracks, drought, and other longer term patterns of variability in temperature and precipitation (Morton et al. 2013). For example, in recent centuries large wildfire years in the PNW have been characterized by a strong trough over the North Pacific and a blocking ridge over the West Coast (Gedalof, Peterson, and Mantua 2005; Trouet et al. 2006). Numerous long-term fire records from the PNW show the influence of Holocene climatic changes on shifts in fire activity, namely, through changes in vegetation and associated fuel loads (Marlon, Bartlein, and Whitlock 2006; Long, Whitlock, and Bartlein 2007; Walsh, Whitlock, and Bartlein 2008; Gavin, Brubaker, and Greenwald 2013).

Although fires occur in a variety of ecological settings in the PNW, they are more common in forested landscapes as compared to low-elevation valleys such as the Puget Trough and Willamette Valley or the arid shrublands and grasslands of eastern Oregon and Washington (Agee 1993; Wimberly and Liu 2014). Roughly one third of all fires today in the PNW are caused by lightning, with the other two thirds related to human-caused ignitions (Bartlein et al. 2008). Lightning-caused fires are more common in forested regions of the Olympic, Cascade, and northern Rocky Mountains (excluding the very highest elevations; Rorig and Ferguson 1999), whereas human-set fires occur more evenly across all elevations and environments (Bartlein et al. 2008). Additionally, because the frequency of lightning strikes in the PNW is dependent on both climatic and synoptic weather conditions, interannual variability is higher for lightning-caused fires than human-caused fires, which tend to occur more consistently from year to year regardless of prevailing climatic conditions (Bartlein et al. 2008).

Decadal- to centennial-scale fire-history data in the PNW come from historical documents and dendrochronological (tree-ring) studies, which use annually resolved fire scars and stand replacement dates to reconstruct fire size and occurrence (Dieterich and Swetnam 1984). Studies from west of the crest of the Cascades indicate that prior to the twentieth century, fires in mesic forests were generally large, mixed- to high-severity, and relatively infrequent (>100 year fire return interval; Weisberg and Swanson 2001, 2003; Weisberg 2004, 2009). East of the Cascades, fires in more xeric forests were smaller, of lower severity, and more frequent than those on the west side, with fire return intervals typically ranging between about six and eighty years depending on individual site moisture characteristics (Everett et al. 2000; Heyerdahl, Brubaker, and Agee 2001; Wright and Agee 2004; Heyerdahl, Lertzman, and Karpuk 2007; Trouet et al. 2010). A reduction in fire is observed at many study sites both west and east of the Cascades as a result of twentieth-century fire suppression (e.g., Weisberg and Swanson 2003; Heyerdahl, McKenzie, et al. 2008).

Ethnographic and historical records such as fur trade documents, missionary diaries, and military, government, and private papers are the primary source for information about past human use of fire. Such data indicate that Native Americans in the PNW used fire for thousands of years for various domestic, cultural, and sustenance purposes (Boyd 1999). Fire use was likely greatest in interior valleys, subalpine environments, and the dry forests and woodlands east of the Cascades (Robbins 1993; Turner 1999; Whitlock and Knox 2002; Lepofsky, Hallett, et al. 2005; Walsh, Whitlock, and Bartlein 2010). At low elevations, Native Americans used fire to encourage the growth of food sources (e.g., camas and acorns), fertilize tobacco plants, gather grasshoppers and wild honey, and promote browse and drive deer for hunting (Boyd 1986; Leopold and Boyd 1999; Knox 2000). At higher elevations, Native Americans typically used fire to encourage huckleberry yields (Mack 2003) and clear trails

Table 2. State/province, ecoregions, vegetation description, and dominant vegetation for the thirty-four study sites

Site	State/province and country	Ecoregion	Vegetation description	Dominant vegetation[a]
Frozen Lake	British Columbia, Canada	Pacific and Nass Ranges	*Tsuga mertensiana* forest[b]	*Tsuga mertensiana*, *Abies amabilis*, *Chamaecyparis nootkatensis*
Rockslide Lake	British Columbia, Canada	Columbia Mountains/ Northern Rockies	*Picea englemannii–Abies lasiocarpa* forest[b]	*Abies lasiocarpa*, *Picea engelmannii*
Cooley Lake	British Columbia, Canada	Columbia Mountains/ Northern Rockies	Interior *Thuja plicata* forest[b]	*Abies lasiocarpa*, *Picea engelmannii*, *Tsuga heterophylla*, *Thuja plicata*, *Pinus contorta*, *Pinus monticola*, *Pseudotsuga menziesii*, *Larix occidentalis*
Turtle Lake	British Columbia, Canada	Strait of Georgia/Puget Lowland	*Tsuga heterophylla* forest[b]	*Tsuga heterophylla*, *Pseudotsuga menziesii*
Enos Lake	British Columbia, Canada	Strait of Georgia/Puget Lowland	*Pseudotsuga menziesii* forest[b]	*Pseudotsuga menziesii*, *Abies grandis*
Mount Barr Cirque	British Columbia, Canada	North Cascades	*Tsuga mertensiana* forest[b]	*Tsuga mertensiana*, *Abies amabilis*, *Chamaecyparis nootkatensis*
Boomerang Lake	British Columbia, Canada	Strait of Georgia/Puget Lowland	*Tsuga heterophylla* forest[b]	*Pseudotsuga menziesii*, *Alnus rubra*
Porphyry Lake	British Columbia, Canada	Strait of Georgia/Puget Lowland	*Tsuga mertensiana* forest[b]	*Tsuga mertensiana*, *Abies amabilis*, *Pinus monticola*
Whyac Lake	British Columbia, Canada	Coastal Western Hemlock-Sitka Spruce Forests	*Tsuga heterophylla* forest[b]	*Thuja plicata*, *Tsuga heterophylla*, *Picea sitchensis*, *Malus fusca*, *Myrica gale*
Panther Potholes	Washington, U.S.	North Cascades	*Tsuga heterophylla/Abies amabilis* subalpine forest[c]	*Pseudotsuga menziesii*, *Thuja plicata*, *Tsuga heterophylla*, *Abies amabilis*, *Abies lasiocarpa*
Fish Lake	Washington, U.S.	North Cascades	*Pinus ponderosa* forest[c]	*Pinus ponderosa*, *Pseudotsuga menziesii*, *Salix*, *Betula*, *Cornus*, *Artemisia*
Pixie Lake	British Columbia, Canada	Coastal Western Hemlock-Sitka Spruce Forests	*Tsuga heterophylla* forest[b]	*Tsuga heterophylla*, *Thuja plicata*, *Abies amabilis*
Walker Lake	British Columbia, Canada	Coastal Western Hemlock-Sitka Spruce Forests	*Tsuga mertensiana* forest[b]	*Tsuga mertensiana*, *Abies amabilis*, *Chamaecyparis nootkatensis*
Mt Constitution C32	Washington, U.S.	Strait of Georgia/Puget Lowland	*Tsuga heterophylla* forest[c]	*Pseudotsuga menziesii*, *Tsuga heterophylla*, *Pinus contorta*
Mt Constitution C38	Washington, U.S.	Strait of Georgia/Puget Lowland	*Tsuga heterophylla* forest[c]	*Pseudotsuga menziesii*, *Tsuga heterophylla*, *Pinus contorta*
Mt Constitution C11	Washington, U.S.	Strait of Georgia/Puget Lowland	*Tsuga heterophylla* forest[c]	*Pseudotsuga menziesii*, *Tsuga heterophylla*, *Pinus contorta*
East Sooke Fen	British Columbia, Canada	Strait of Georgia/Puget Lowland	*Tsuga heterophylla* forest[b]	*Pseudotsuga menziesii*, *Tsuga heterophylla*, *Thuja plicata*, *Pinus contorta* var. contorta, *Alnus rubra*
Five Lakes	Washington, U.S.	Columbia Plateau	Shrub-steppe[c]	*Artemisia*, *Pinus ponderosa*
Wentworth	Washington, U.S.	Coast Range	*Picea sitchensis* forest[c]	*Thuja plicata*, *Tsuga heterophylla*, *Picea sitchensis*
Moose Lake	Washington, U.S.	North Cascades	*Abies lasiocarpa* subalpine forest[c]	*Abies lasiocarpa*, *Picea angelmannii*
Martins Lake	Washington, U.S.	North Cascades	*Tsuga mertensiana* forest[c]	*Tsuga mertensiana*, *Abies amabilis*, *Pinus monticola*, *Chamaecyparis nootkatensis*

(*continued on next page*)

Table 2. State/province, ecoregions, vegetation description, and dominant vegetation for the thirty-four study sites *(Continued)*

Site	State/province and country	Ecoregion	Vegetation description	Dominant vegetation[a]
Yahoo Lake	Washington, U.S.	Coast Range	*Abies amabilis* subalpine forest[c]	*Abies amabilis*, *Tsuga heterophylla*, *Thuja plicata*, *Pseudotsuga menziesii*, *Picea sitchensis*
Little Sunrise Lake	Washington, U.S.	Cascades	*Tsuga mertensiana* forest[d]	*Abies lasiocarpa*, *Abies procera*, *Picea engelmannii*, *Pinus albicaulis*
Sunrise Lake	Washington, U.S.	Cascades	*Tsuga mertensiana* forest[d]	*Abies lasiocarpa*, *Abies procera*, *Tsuga mertensiana*, *Abies amabilis*, *Pinus albicaulis*
Shadow Lake	Washington, U.S.	Cascades	*Tsuga mertensiana* forest/ subalpine parkland[d]	*Abies lasiocarpa*, *Pinus albicaulis*, *Abies procera*, *Chamaecyparis nootkatensis*, *Tsuga mertensiana*
Tipsoo Pond	Washington, U.S.	Cascades	*Tsuga mertensiana* forest/ subalpine parkland[d]	*Abies lasiocarpa*, *Tsuga mertensiana*, *Chamaecyparis nootkatensis*, *Thuja plicata*
Taylor Lake	Oregon, U.S.	Coast Range	*Picea sitchensis* forest[c]	*Tsuga heterophylla*, *Picea sitchensis*, *Thuja plicata*, *Pseudotsuga menziesii*, *Alnus rubra*
Lost Lake	Oregon, U.S.	Coast Range	*Tsuga heterophylla* forest[c]	*Tsuga heterophylla*, *Thuja plicata*, *Pseudotsuga menziesii*, *Alnus rubra*, *Picea sitchensis*, *Abies grandis*
Battle Ground Lake	Washington, U.S.	Willamette Valley	*Tsuga heterophylla* forest[c]	*Pseudotsuga menziesii*, *Thuja plicata*, *Tsuga heterophylla*, *Abies grandis*, *Picea sitchensis*
Lake Oswego	Oregon, U.S.	Willamette Valley	Willamette Valley woodland[c,e]	*Pseudotsuga menziesii*, *Thuja plicata*, *Quercus garryana*, *Alnus rubra*, *Fraxinus latifolia*
Beaver Lake	Oregon, U.S.	Willamette Valley	Willamette Valley riparian woodland[c,e]	*Salix*, *Populus trichocarpa*, *Fraxinus latifolia*, *Quercus garryana*
Porter Lake	Oregon, U.S.	Willamette Valley	Willamette Valley riparian woodland[c,e]	*Salix*, *Populus trichocarpa*, *Fraxinus latifolia*, *Quercus garryana*
Warner Lake	Oregon, U.S.	Willamette Valley/ Cascades	*Tsuga heterophylla* forest[c]	*Pseudotsuga menziesii*, *Pinus ponderosa*, *Thuja plicata*, *Tsuga heterophylla*, *Alnus rubra*, *Acer macrophyllum*, *Calocedrus decurrens*
Little Lake	Oregon, U.S.	Coast Range	*Tsuga heterophylla* forest[c]	*Pseudotsuga menziesii*, *Tsuga heterophylla*, *Thuja plicata*, *Pinus monticola*, *Alnus rubra*, *Acer macrophyllum*

[a]See references listed in Table 1.
[b]Meidinger and Pojar (1991).
[c]Franklin and Dyrness (1988).
[d]Franklin et al. (1988).
[e]Hulse, Gregory, and Baker (2002).

through mountain passes (Norton, Boyd, and Hunn 1999). Human use of fire certainly varied in both space and time during the Holocene in the PNW but likely was highest when populations were largest and in areas most frequently used for either travel or resource extraction, a relationship that still exists today (Bartlein et al. 2008).

Data and Methods

Study Area

Our study sites ($n = 34$) range from 44.15° to 49.67°N and 118.90° to 124.97°W (Figure 1; Table 1); thirty of the sites exist west of the crest of the Cascade Mountains, whereas only four exist to the east. Generally, sites west of the Cascades Mountains experience a temperate West Coast climate. Summers are warm and dry due to the dominance of high-pressure systems, which suppress precipitation and lead to summer drought (Mock 1996). Winters are typically cool and wet because of a strong Aleutian low-pressure system offshore and frequent storms (Mitchell 1976). Temperatures decrease and precipitation increases with increasing elevation, and rain shadows exist on the leeward sides of the Coast and Cascade ranges (Figure 1). East of the Cascades, summer and winter temperature extremes are greater, and sites generally experience hot summers and cold winters, with precipitation spread more evenly throughout the year. Study site vegetation varies considerably in relation to local differences in average annual temperature and precipitation, as well as topography and soil type (Table 2).

Methods

Of the thirty-four charcoal records, twenty-three are archived in the Global Charcoal Database (GCD) version 3 (Blarquez et al. 2014), five are from additional published sources (Sugimura et al. 2008; Prichard et al. 2009; Gavin, Brubaker, and Greenwald 2013; Gavin and Brubaker 2015), and two are unpublished records contributed by the authors (see Table 1). Synthesis of the charcoal records can only be used to indicate relative changes in biomass burning over time because the absolute amount of charcoal that enters a given lake is a function of lake size, watershed slope, vegetation type, and other non-fire-related factors (Marlon, Bartlein, and Whitlock 2006). Consequently, standardization is required to analyze charcoal data across sites. We used previously developed methods described in Power et al. (2010), which include several steps. First, charcoal concentrations (particles cm^{-3}) are converted to flux values (particles cm^{-2} $year^{-1}$) and then rescaled using a minimax transformation to values between 0 and 1 for convenience. The variance of each series is then homogenized using a power transformation (Box–Cox) and values are converted to Z scores using the mean and standard deviation from the interval 3,000 to 200 calendar years before present (cal yr BP). The 3,000- to 200-year base period is used because it excludes the years after AD 1750 when charcoal values are often unusual relative to pre-European American settlement values. The resulting standardized influx data were smoothed using a lowess method based on a 500-year smoothing window. This window width provides information about centennial- to millennial-scale changes in burning, which is our focus here. Confidence intervals were calculated by bootstrap resampling the charcoal series by site (with replacement, 1,000 replications).

A subset of seventeen high-resolution records was decomposed into low-frequency trends and discrete charcoal peaks using CharAnalysis (see Table 1; Higuera et al. 2010). All records were interpolated to their median temporal resolution (year/sample). Low-frequency (background) charcoal accumulation rates (CHAR) were estimated using a lowess method robust to outliers. The smoothing window widths were determined through a sensitivity analysis. Smoothing window widths that produced a high signal-to-noise index and a high goodness-of-fit index for the noise distribution were selected individually for each record. High-frequency CHAR was calculated using the residuals of interpolated minus background CHAR. Threshold values for peak identification were locally defined and based on a percentile cutoff of a noise distribution determined by a Gaussian mixture model. The final peak selections were based on those samples that exceeded the 99th percentile of the noise distribution. To identify shared trends in peak frequency across the sites, we summarized them using a kernel density estimator (Venables and Ripley 2002) with a bandwidth of 100 years. Bootstrap confidence intervals were calculated by resampling by site 1,000 times.

The regional peak density and biomass burning curves from the PNW were compared to a reconstruction of ENSO event frequency for the Holocene (Moy et al. 2002) as a means of assessing the influence of climate variability on fire history. Although modern studies suggest a stronger connection between PDO events and fire relative to ESNO, no long-term records of PDO activity are available (Keeton, Mote, and Franklin 2007). The regional fire curves were also compared to a fire-history reconstruction of the Western United States as a whole (Marlon et al. 2012), which is based on sixty-nine charcoal influx records primarily from the northern part (both PNW and inland areas) of the Western United States (above 40° N). There is a thirteen-site overlap between this study and the Marlon et al. (2012) study. Also included is a reconstruction of changes in the percentages of arboreal pollen from fifteen sites in the Northwestern United States (Marlon, Bartlein, and Whitlock 2006), to provide information about variations in vegetation composition that can be used to infer biomass levels during the Holocene.

For the spatial analysis, we developed a classification system that subdivides the study sites into categories based on their location as either high or low elevation (above or below 550 m; roughly divides the number of sites in half), coastal or inland (coastal sites exist within the Strait of Georgia/Puget Lowland and Coast Range ecoregions), and forest or woodland (presettlement vegetation at forested sites indicates a closed canopy forest immediately surrounding the site; riparian forest was classified as woodland). If forested, the site was further classified as wet or dry forest (Table 1). Forested sites designated as wet forest generally receive $\geq$1,500 mm of mean annual precipitation and are dominated by mesophytic taxa such as western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and Pacific silver fir (*Abies amabilis*). Sites designated as dry forest generally receive $\leq$1,500 mm precipitation annually and are dominated by drier forest taxa such as Douglas fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), or ponderosa pine (*Pinus ponderosa*). PNW population estimates were obtained from the HYDE data set (Klein-Goldewijk, Beusen, and Janssen 2010) and were summarized for inland and coastal grid cells separately.

Finally, we used the twenty charcoal records that spanned the past 3,000 years with a resolution higher than 100 year/sample to perform a functional principal components analysis (fPCA; fda package in R; Ramsay et al. 2012) to identify temporal trends in the data (see Table 1). The fPCA output is similar to a standard PCA, which includes major eigenvectors, axis scores for individual sites, and the amount of variance loading on the axis. The primary difference between fPCA and PCA is that the unit of analysis in fPCA is a function, here a b-spline fit to the CHAR data for each site. The b-spline enables preservation of the temporal structure of the data. The charcoal data for the twenty sites were first smoothed using a flexible spline (*smooth.spline* in R package stats; R Development Core Team 2014) with degrees of freedom equal to the data set size, interpolated at 100-year intervals) so that the data were sampled at equal intervals. The fPCA algorithm used a b-spline with thirty basis functions, a period of approximately 100 years (all raw data and R code used to run the fPCA analysis are available at http://dx.doi.org/10.5281/zenodo.14635). The first and second fPCA axis scores were calculated for each site. We compared fPCA scores for sites at high and low elevations, coastal and inland sites, woodland and forest cover, and across higher level ecozones (Commission for Environmental Cooperation [CEC] 1997) using an analysis of variance (ANOVA) test.

Results

Holocene Trends in Fire Activity

The peak density and biomass burning curves (hereafter fire activity) both show a long-term increase during the Holocene (Figure 2). Fire frequency in this analysis is measured as peak density (hereafter fire frequency), which is calculated as a probability. As a result, the area under the curve is equal to 1.0. To express the peak densities as relative frequencies, the kernel bin width (200 in this case) is multiplied by the number of sites ($n = 17$), which yields a peaks per site-year dimension. In the peak density analysis, the seventeen sites contained 606 peaks over the 12,000-year period, or an average of 0.003 peaks per site per year (606/12,000/17) or 2.97 fires per 1,000 years per site.

Biomass burning for the PNW was low at the beginning of the Holocene (ca. 12,000 cal yr BP), with a large increase over the next 2,000 years (Figure 2). It remained high ca. 10,000–8,000 cal yr BP but decreased thereafter, reaching the lowest level of disturbance at ca. 5,500 cal yr BP. It then increased throughout most of the late Holocene, peaking ca. 900 cal yr BP. During the last millennium, biomass burning decreased sharply until ca. 150 cal yr BP, after which it subtly increased. The fire frequency curve generally mimics the biomass burning curve, except during the intervals of ca. 8,200 to 7,300, 3,800 to 3,500, and 1,600 to 1,200 cal yr BP (Figure 2A).

The reconstruction of past ENSO activity (hereafter interannual climate variability) suggests that its strength and frequency generally increased after ca. 7,000 cal yr BP until ca. 900 cal yr BP, after which time it decreased toward the present (Figure 2C; Moy et al. 2002). Several periods of high ENSO activity generally coincide with local peaks or increasing trends in the biomass burning and fire frequency curves; for example, ca. 5,000, 3,500 to 2,500, and 1,100 to 800 cal yr BP. There are also several periods of reduced variability that coincide with lower fire activity at ca. 7,600 to 7,200, 5,400 to 5,000, 4,500 to 4,200, and 600 to 200 cal yr BP.

Biomass burning trends in the PNW indicate regional variability that is distinct from the broader Western United States trend (Figure 2E). The early

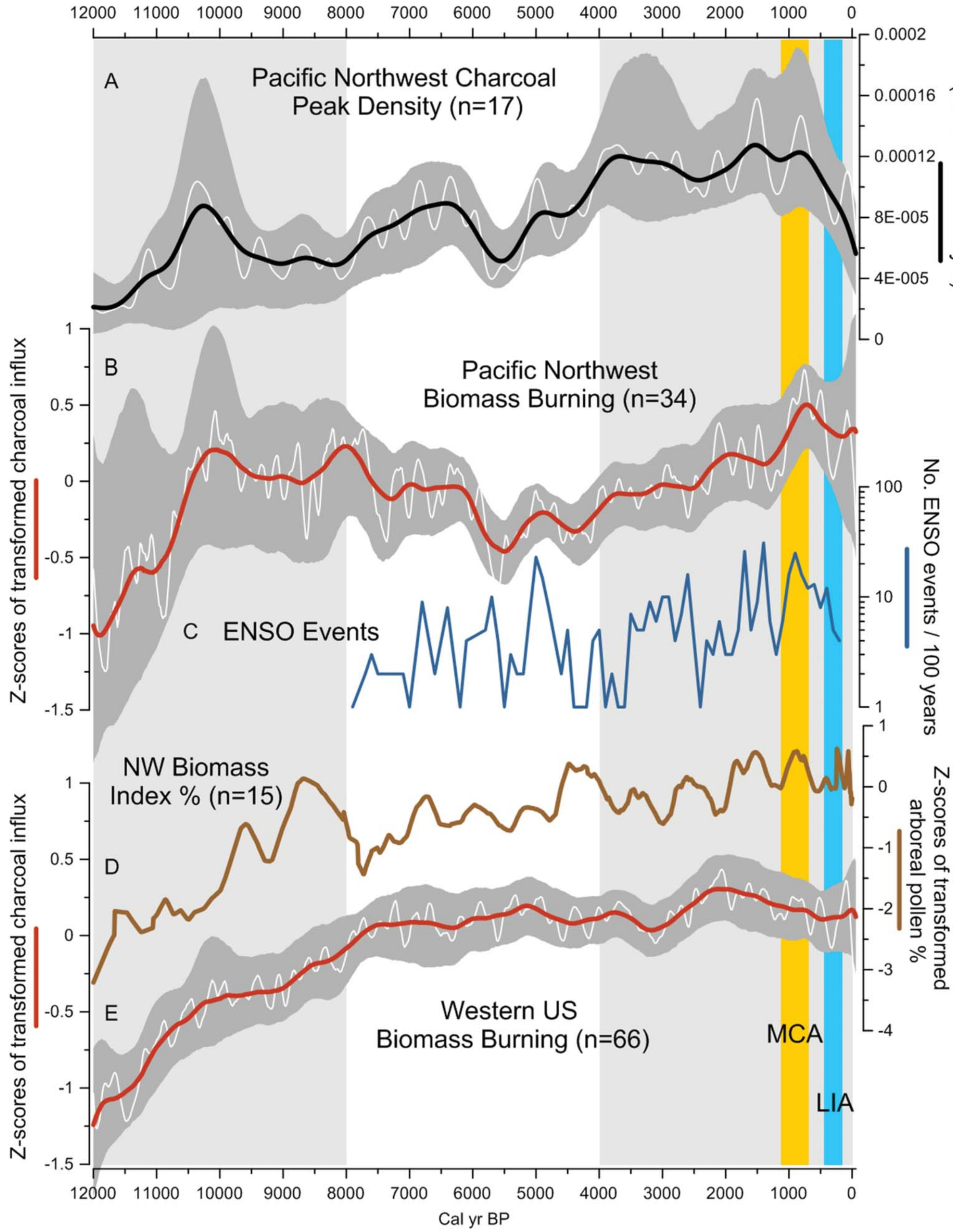

Figure 2. Holocene trends in fire, vegetation, and El Niño/Southern Oscillation (ENSO) events: (A) smoothed peak density (inferred fire frequency) from charcoal records ($n = 17$); (B) biomass burning for the Pacific Northwest inferred from thiry-four charcoal records; (C) inferred event frequency of El Niño/Southern Oscillation (ENSO events/100 years; Moy et al. 2002); (D) biomass index (percentage arboreal pollen taxa) constructed from fossil pollen data from fifteen sites in the Northwest United States (Marlon, Bartlein, and Whitlock 2006); (E) biomass burning inferred from sixty-nine charcoal records for the western United States (Marlon et al. 2012). All smoothed curves are plotted with 95 percent bootstrap confidence intervals. Units of the peak-density curve are number of peaks per year per record. The orange and blue shaded vertical bars represent the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) in the Pacific Northwest, respectively. (Color figure available online.)

Holocene rise in burning from ca. 12,000 to 10,000 cal yr BP in the PNW is one of the few features shared with the broader biomass burning trend. Subsequent trends in burning across the Western United States as a whole appear muted as compared with those of the PNW. Biomass burning increased during the early Holocene until ca. 7,500 cal yr BP before leveling off for the Western United States, with the exception of the increase at ca. 3,000 to 2,000 cal yr BP and a general decline at ca. 2,000 to 500 cal yr BP. Biomass burning in the Western United States then increased slightly at ca. 500 to 200 cal yr BP and decreased slightly in the past century. The composite pollen curve (Figure 2D) suggests that forest area or density increased rapidly during the early Holocene (ca. 12,000–9,000 cal yr BP) and then more gradually during the middle and late Holocene.

6,000-Year-Long Biomass Burning Trends

Coastal versus Inland Sites

Eighteen of the paleofire sites were categorized as coastal and sixteen as inland (Table 1). In general, biomass burning increased during the past 6,000 years at both coastal and inland sites (Figure 3A). At inland sites, maximum biomass burning occurred at ca. 1,000 years ago during the Medieval Climate Anomaly (MCA, 1,100–700 cal yr BP; Mann et al. 2009), whereas at coastal sites it occurred during the past two centuries. Fire at both coastal and inland sites, however, declined from a peak during the MCA to a local minimum at ca. 300 cal yr BP during the Little Ice Age (LIA; 500–100 cal yr BP; Grove 2001) and after Native American population collapse (Boyd 1999). The major difference in biomass burning between inland and coastal sites occurred during the past 300 years, when fire activity at coastal sites increased sharply, whereas fire at inland sites continued to decrease. Yet, at centennial scales, the direction of change as well as local minima and maxima in fire activity at coastal and inland sites was largely synchronous after ca. 4,500 cal yr BP.

High- versus Low-Elevation Sites

Nineteen sites were categorized as high elevation and fifteen as low elevation (Table 1). In general, biomass burning at high-elevation sites increased from ca. 6,000 to 1500 cal yr BP and then declined toward the present (Figure 3B). In contrast, biomass burning at low-elevation sites was variable with no long-term trend. Similar to the coastal and inland groups, both

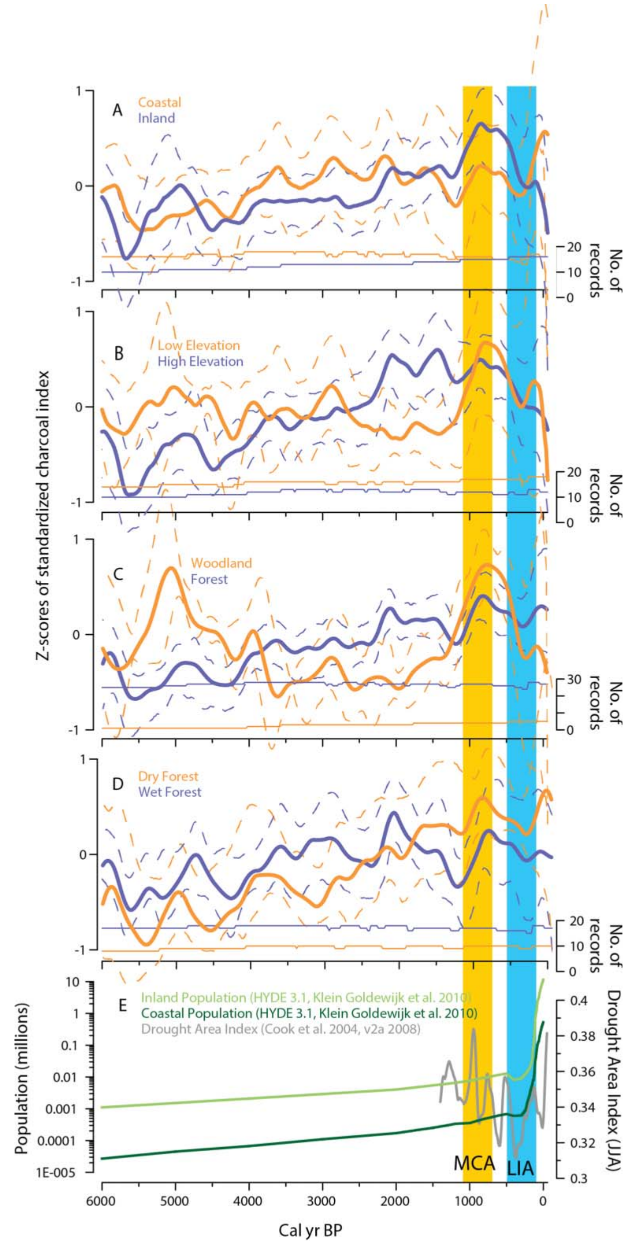

Figure 3. Biomass burning curves for the past 6,000 cal yr BP for (A) coastal–inland; (B) low–high elevation; (C) woodland–forest; and (D) dry–wet forest sites. (E) Population estimates for the Pacific Northwest (inland–coastal areas) in millions (HYDE 3.1 data set; Klein-Goldewijk, Beusen, and Janssen 2010). The number of records curve indicates the number of records (or sites) contributing to the composite biomass burning reconstructions at any given point along the curve. Bootstrap confidence intervals are shown with dotted lines. None of the differences between the curves are statistically significant except between the woodland ($n = 5$) and forest sites ($n = 29$) from 1,500 to 2,000 and 4,500 to 5,500 years ago and between the low-elevation ($n = 14$) and high-elevation sites ($n = 20$) for the same intervals. The orange and blue shaded vertical bars represent the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) in the Pacific Northwest, respectively. (Color figure available online.)

groups showed generally high burning during the MCA followed by a sharp decrease during the LIA. Since the LIA, fire at low-elevation sites increased and then decreased sharply, whereas fire simply decreased at high-elevation sites. In contrast to coastal–inland sites, the direction of change and the timing of peaks and troughs in the high–low-elevation composite curves are not similar.

Forest versus Woodland Sites

Twenty-nine sites were categorized as forest and five were designated woodland (Table 1). Given the number of forested sites, the trends in the biomass burning curve generally follow that of the composite curve for the past 6,000 years (Figures 2B and 3C). A steep increase in biomass burning occurred at woodland sites at ca. 2,000 to 600 cal yr BP, similar to the increases observed in the inland and low-elevation groups (which overlap with the woodland group). Fire was high at woodland sites during the MCA and then dramatically decreased into the LIA, ca. 300 cal yr BP. A small rise occurred subsequent to the LIA, followed by a sharp decline toward the present. Although the large magnitude of the variations in biomass burning at the woodland sites is partly due to the shortage of records, the dramatic shifts in the past few centuries indicate strongly coherent, synchronous signals among the few sites. This trend, however, might also be due in part to the common ecological conditions at these sites. All of the woodland sites are located in an inland setting and only one is high elevation. Forested sites, in contrast, are more varied in elevation and geographic location.

Wet versus Dry Forest Sites

Seventeen forest sites were designated wet and twelve were designated dry (Table 1). Millennial-scale trajectories of biomass burning are different between the groups; however, the direction of change and the inflection points on centennial scales is often the same (Figure 3D). Fire gradually increased during the past ca. 6,000 years at dry sites. At wet sites it generally increased from ca. 6,000 to 2,000 cal yr BP, decreased until ca. 1,100 cal yr BP, increased until ca. 700 cal yr BP, and generally decreased toward the present. Both groups show increased burning during the MCA and decreased burning during the LIA, although the overall level of burning is consistently higher at dry forest sites. As with the coastal and inland groups, trends between the groups differ substantially during the past approximately 200 years; burning increased and then decreased at dry forest sites and remained generally consistent at wet forest sites.

3,000-Year-Long Biomass Burning Trends

To explore the potential influences on fire in the PNW during the past 3,000 years, the interval in which pre-European American populations in the PNW were the highest (Figure 3E), we examined the major temporal patterns of variation in the highest resolution records ($n = 20$) using fPCA (Figure 4) and spatially assessed the statistical differences based on the divisions described earlier. Axis one of the fPCA distinguishes between two groups of sites. The first group shows increased biomass burning from ca. 3,000 to 1,500 cal yr BP, followed by declining burning to ca. 750 cal yr BP and subsequent stabilization (red line, Figure 4A, 4C, 4G). The second group shows sites where burning decreased gradually from ca. 3,000 cal yr BP to 1,250 cal yr BP, with a rapid increase to ca. 750 yr BP, and a subsequent decline to present day (blue line, Figure 4A, 4D, 4G). The fPCA assigns 36 percent of total variability among the sites to this pattern. Sites showing high axis one scores, which include Yahoo, Taylor, and Little lakes, tend to be more coastal and from the Marine West Coast Forest ecozone, whereas sites with low axis one scores (e.g., Battle Ground and Fish Lake) are farther inland and from the Western Cordillera ecozone. The relationship between fPCA axis one scores and geographic location and ecozone is not significant, however: ANOVA, $F(1, 18) = 0.58$, $p = 0.46$. Elevation, as a discrete class (high vs. low), is significant: ANOVA, $F(1, 18) = 6.81$, $p = 0.01$; however, this trend is driven entirely by two lower elevation sites, Lost Lake and Fish Lake, both very close to the 550 m cutoff. Elevation as a continuous variable shows no trend in fPCA values: ANOVA, $F(1, 18) = 0.29$, $p = 0.58$, and, as such, we feel that the significant result for elevation as a class (uncorrected for multiple comparisons) is unsupported by the data.

Axis two of the fPCA accounts for 25 percent of the variability. It represents the difference between sites that show a decline in burning to ca. 1,200 cal yr BP and then an increase to ca. 700 cal yr BP versus sites that increase to ca. 500 cal yr BP followed by a decline (Figure 4B, 4E, 4F, and 4H). Sites with a high axis two fPCA score (red line, Figure 4B, 4E, 4H) include Lost Lake and Taylor Lake, whereas Fish Lake, Lake Oswego, the Mt

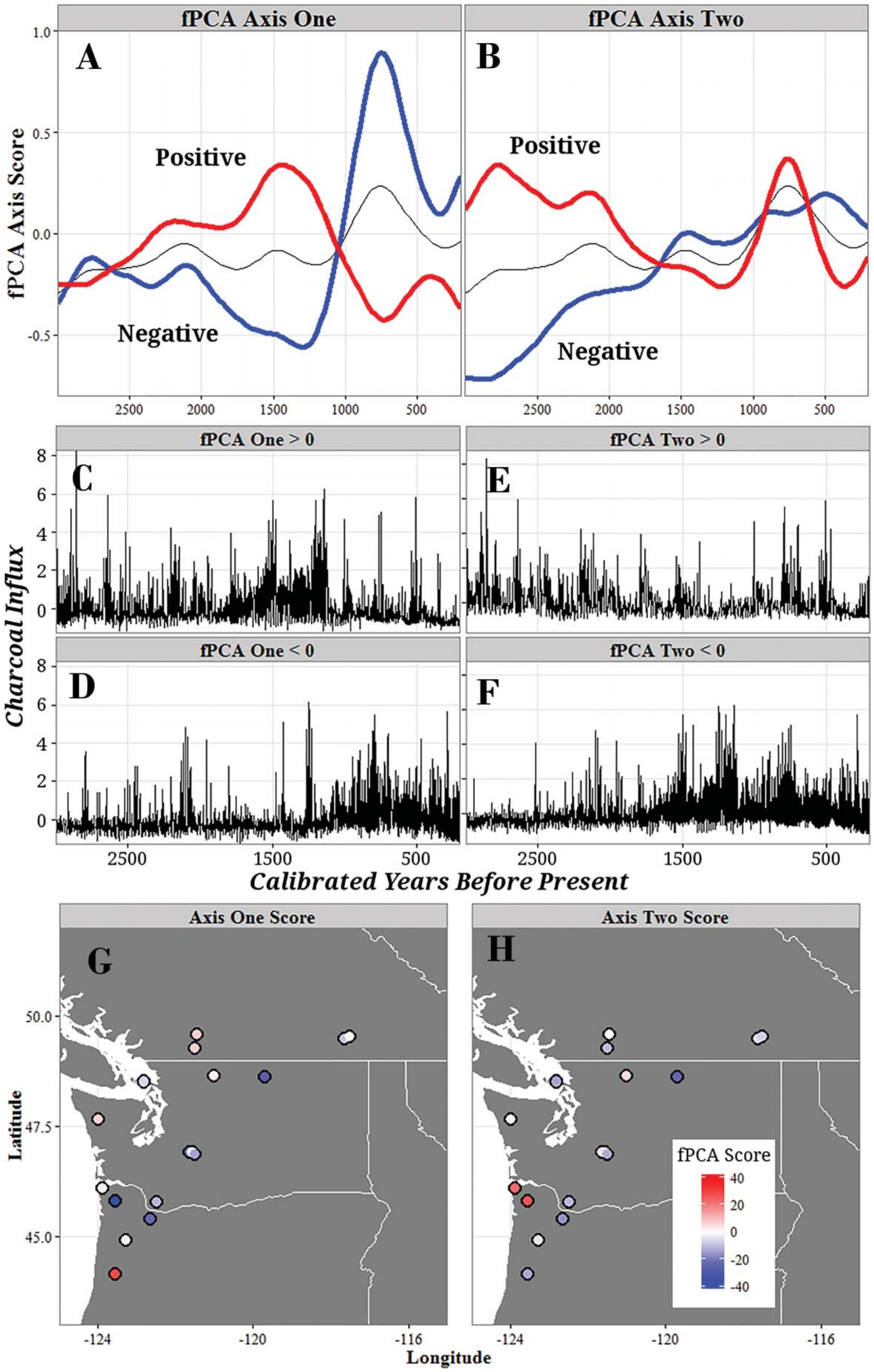

Figure 4. Functional principal components analysis (fPCA) results from twenty Pacific Northwest biomass burning records spanning the past 3,000 years. Major axes of variation include (A) an opposing trend of increasing influx to ca. 1,500 cal yr BP and then rapid decline to present (positive fPCA axis one, opposite trend for negative fPCA axis one) and (B) trends of declining charcoal influx to ca. 1,200 cal yr BP with a peak at ca. 750 cal yr BP (positive fPCA axis two) versus gradually increasing influx (negative fPCA axis two). Raw influx values from (C) records with positive and (D) negative axis one scores and (E) positive and (F) negative axis two scores. The spatial distribution of records with positive scores are shown by red dots and with negative scores by blue dots for (G) axis one and (H) axis two. Results from an analysis of variance (not shown) indicate no well-defined geographic patterns when records are separated by ecozone (CEC 1997; Western Cordillera–Marine West Coast Forest), elevation (high–low), land cover type (woodland–forest), or geography (coastal–inland). (Color figure available online.)

Constitution sites, and Little Lake show low axis two scores (blue line, Figure 4B, 4F, 4H). No single factor explains significant differences in the second axis score; however, ANOVA indicates that interaction between geographic location (inland vs. coastal) and elevation (high vs. low) explains 70 percent of variance in the model, $F(3, 16) = 16.4$, $p < 0.001$. This means that low-elevation sites have both the highest (coastal, low-elevation sites; Lost Lake and Taylor Lake) and lowest (inland, low-elevation sites; Fish Lake and Lake Oswego) fPCA axis two scores, whereas high-elevation sites have curves closer to the mean (black line, Figure 4B). This model largely isolates the two low-elevation coastal sites with high charcoal influx from ca. 3,000 to 2,000 cal yr BP.

Discussion

Holocene Fire Controls in the Pacific Northwest

Human impacts are often assumed to produce heterogeneous trends in biomass burning across space and time, as demographic, cultural, and land-use shifts would be expected to alter fire regimes depending on changes in local conditions, resources, and lifeways (Coughlan and Petty 2012). Yet, regional charcoal syntheses have shown that rapid increases or decreases in population numbers have created widespread changes in fire history; for example, across the Western United States in the 1800s (Marlon et al. 2012). As a result, it remains unknown whether shifts in human population in the PNW and their associated use of fire prior to European American settlement (ca. AD 1850) could have influenced spatiotemporal variations in fire activity at broad spatial and long temporal scales in the same way climate has in the past (Marlon et al. 2008; Vannière et al. 2011), given that individual fires were likely small. Despite these complexities, fire activity in the PNW shows trends and features that are more easily explained by either known climate changes or major population shifts, whereas some variations remain difficult to assign to either factor, as addressed later.

Early- to Middle-Holocene Fire Activity

Fire activity trends in the PNW during the early Holocene are well explained by regional changes in climate and vegetation. Most notable is the influence that the retreating ice sheet and increased Northern Hemisphere summer insolation anomaly had on biomass burning at ca. 12,000 to 10,000 cal yr BP. By ca. 10,000 cal yr BP the Cordilleran Ice Sheet had collapsed (Ryder, Fulton, and Clague 1991) and summer insolation had peaked (ca. 10,000 cal yr BP; Kutzbach et al. 1993). These changes led to warmer summers and a subsequent increase in biomass burning and fire frequency, both in the PNW (Figure 2A, 2B) and in the broader Western United States (Figure 2E). These climatic changes triggered shifts in fire activity in large part through changes in local vegetation (i.e., fuels).

During the transition from the late Pleistocene to the early Holocene (ca. 12,000–11,000 cal yr BP), nonarboreal communities and open woodlands were eventually replaced by forested landscapes (Tsukada, Sugita, and Hibbert 1981; Cwynar 1987; Whitlock 1992; Brown and Hebda 2002a, 2003; Walsh, Whitlock, and Bartlein 2008), evidenced by a rise in the NW Biomass Index (percent; Figure 2D). For example, at East Sooke Fen and Pixie Lake on Vancouver Island, open late-glacial pine (*Pinus* spp.) woodlands and mixed conifer forest yielded to Douglas fir, alder (*Alnus* spp.), and bracken (*Pteridium* spp.) during the early Holocene (Brown and Hebda 2002a). Subalpine fir–dominated forest rapidly replaced herbaceous tundra at Moose Lake at ca. 11,000 to 10,000 cal yr (Gavin et al. 2001). At Little Lake, forests of pine and spruce (*Picea* spp.) were replaced by Douglas fir, red alder (*Alnus rubra*), and bracken at ca. 11,000 to 10,200 cal yr BP, with similar shifts occurring at sites in the Cascades of Oregon (Sea and Whitlock 1995; Grigg and Whitlock 1998). All of these shifts indicate conditions that were warmer and drier than modern conditions, which would have been more conducive to increased fire activity than the cooler conditions of the late glacial.

Fire frequency declined regionally following ca. 10,000 cal yr BP, although biomass burning remained higher than earlier until ca. 8,000 cal yr BP (Figure 2A, 2B). Strong summer drought throughout this interval is evidenced by increasing proportions of xerophytic taxa, especially at many low-elevation sites. Forests in the Puget Trough and the Fraser Lowland experienced greater abundance of Douglas fir, red alder, and bracken fern during the early Holocene, and prairies expanded, both locally within the Lowland and northward from the Willamette Valley (Whitlock 1992). Such changes are consistent with continued summer warming (Thompson et al. 1993), which in forested areas might have produced larger and perhaps more frequent fires.

Declines in summer insolation and cooler, wetter conditions during the middle Holocene (ca. 8,000–4,000 cal yr BP; Bartlein et al. 1998; Bartlein, Hostetler, and Alder 2014) led to moderate fire frequencies and lower levels of biomass burning (Figure 2A, 2B). This was likely caused by region-wide vegetation shifts; modern assemblages were established at many of the study sites during this interval (Whitlock 1992). For example, at Panther Potholes in the northern Cascades of Washington, western hemlock– and western red cedar–dominated wet forest gradually replaced lodgepole pine (*Pinus contorta*)-dominated dry forest at ca. 7,000 to 5,000 cal yr BP (Prichard et al. 2009). Similar changes occurred on Vancouver Island at Porphyry Lake and Walker Lake, where western hemlock, Pacific silver fir, and spruce expanded as climate moistened (Brown and Hebda 2003; Brown et al. 2006).

Overall, changes in PNW fire activity during the early to middle Holocene, at least until ca. 5,500 cal yr BP, are consistent with known climatic and vegetation changes. Increasing summer temperatures and dryness during the beginning part of this interval triggered widespread shifts in the distribution and composition of forests and woodlands, leading to higher fire activity. Thereafter, a decrease in insolation and wetter conditions are consistent with less fire. Human activity might have augmented fire activity at some locations during this interval, but the observed changes appear far beyond the scope of human agency.

Middle- to Late-Holocene Fire Activity

Fire-history reconstructions for the past 5,500 years show that increasing fire activity was characteristic of most sites, except for those at low elevations, which show no trend (Figure 3B). The one woodland site with a record older than 4,000 years, Beaver Lake, shows high biomass burning at ca. 5,500 cal yr BP, followed by a decrease and eventual increase in burning after ca. 2,000 cal yr BP. This is in contrast to the majority of sites, which show increasing biomass burning after ca. 5,500 cal yr BP. The fact that fire activity increases at most sites during this interval is seemingly contradictory to the moist conditions and cooler temperatures that characterized the middle to late Holocene, respectively (Bartlein et al. 1998; Bartlein, Hostetler, and Alder 2014), particularly given that it is doubtful that any of the forested sites were fuel limited during this period. Furthermore, the increase in fire activity cannot be attributed to larger but less frequent fires because fire frequency remained relatively high compared to earlier in the Holocene (Figure 2A).

Relatively frequent fires and a steady increase in biomass burning during the middle to late Holocene, particularly between ca. 4,000 and 1,000 cal yr BP (Figure 2A, 2B), are difficult to explain given current paleoclimate data and known vegetation changes in the PNW during this interval. It is hypothesized that intensified seasonal precipitation regimes during the early Holocene led to drier conditions and higher than modern fire rates in areas that are characterized by dry summers today, which includes the PNW (Whitlock and Bartlein 1993; Brunelle et al. 2005). The steady increase in PNW biomass burning during the latter half of the Holocene contradicts this hypothesis, however. Vegetation assemblages inferred from pollen data suggest that forest composition has changed little during the past 4,000 to 5,000 years in the PNW (Whitlock 1992; Walsh, Whitlock, and Bartlein 2008). It is possible, though, that spatiotemporal variability in forest openness, structure, understory vegetation, and other aspects that are not well recorded by pollen data could have facilitated increased burning during that period, or that fire activity responded directly to climate variability (Whitlock, Shafer, and Marlon 2003; Carcaillet et al. 2010). The middle Holocene vegetation changes that indicate a shift to moister conditions are consistent with the observed reduction in fire at that time but not with increased fire activity after ca. 5,500 cal yr BP.

We explore two plausible hypotheses that could explain the overall increase in biomass burning after ca. 5,500 to 900 cal yr BP. The first involves greater interannual climate variability (Figures 2C, 3E) estimated using ENSO event frequency (Moy et al. 2002) and the Palmer Drought Severity Index (Cook et al. 2004). The second is that the increase is related to an increasing human population within the PNW and their associated use of fire.

Climate Variability and Increased Burning

The relatively high levels of biomass burning in the PNW during the late Holocene might be related to greater interannual climate variability, even though climate was generally moist and cool (Lynch, Hollis, and Hu 2004; Reyes and Clague 2004; Koch and Clague 2006). Although fire-history studies from the PNW have yet to show a strong region-wide connection between ENSO variability and fire activity, some linkages have been found between positive (El Niño) phase ENSO events and fire activity, especially in the interior PNW (Heyerdahl, Brubaker, and Agee 2002; Wright and Agee 2004; Keeton, Mote, and Franklin 2007). The ENSO reconstruction indicates a large increase in climate variability during the late Holocene, culminating at ca. 900 cal yr BP, which is accompanied by increasing PNW fire activity during the same interval (Figure 2C). It is possible that during periods of greater than present ENSO event frequency and intensity (i.e., much of the past 4,000 years), the impact of El Niño events could have been amplified and experienced region-wide. Such climate variability would have reduced winter and spring precipitation, and thus snowpack and soil moisture, enhancing summer fire activity and lengthening the fire season (Gedalof, Peterson, and Mantua 2005; Littell et al. 2009). During the past 6,000 years, several periods of frequent ENSO events coincide with local peaks in biomass burning, whereas reduced ENSO variability often coincides with lower fire activity (Figure 2B, 2C).

The fPCA results indicate that trends in biomass burning were similar for many sites from 3,000 to 1,500 years ago. Differences among the four paired subgroups of records (i.e., coastal–inland, low–high elevation, woodland–forest, and dry–wet forest sites) were not statistically significant. There are tendencies, though, toward increased biomass burning during the past 1,000 years at inland sites (Figure 4A, 4E), contrasted with a decline over that time period at more coastal sites (e.g., at Yahoo, Taylor, and Little lakes). Increased biomass burning, especially at Little Lake, in the past 1,500 years and decreased biomass burning at Taylor Lake around this same time (Figure 4B, 4H) drives the primary differences in the fPCA results for the late Holocene. The fPCA results highlight the strong increase in biomass burning around 1,000 years ago (Figure 4A, 4C); this feature occurs in wet and dry inland forests (Figure 3A–3D) and corresponds to the MCA in the PNW. The MCA is documented by independent climate records as a period of unusual warmth (Mann et al. 2009), elevated summer aridity (Cook et al. 2004; Steinman et al. 2012), and reduced glacier activity (Wanner et al. 2008). Tree ring–based records of fire activity also show increased burning at this time in dry, low-elevation forests that historically experienced low-severity ground fires (Trouet et al. 2010). Additionally, this is a period of persistently high ENSO event frequency.

Following the MCA, fire frequency decreased to its late Holocene minimum (Figure 3A) and biomass burning declined at most sites as well (Figures 3B, 4A–4D). British Columbia glaciers had begun advancing ca. 900 to 800 cal yr BP (Luckman and Villalba 2001), and the continued drop in biomass burning that followed at ca. 900 to 150 cal yr BP is consistent with the cool, dry conditions of the LIA (Figure 3E; Cook et al. 2004). The drop in fire activity is also consistent with decreased ENSO event frequency after ca. 900 cal yr BP (Figure 2C). Analyses of fire scar and climate data over the past 500 years indicate that the PNW exhibited its largest declines in fire activity during the LIA (Trouet et al. 2010); such declines are likewise observed across the Western United States in charcoal records (Marlon et al. 2012).

Collectively, the long-term trends in fire frequency and biomass burning in the PNW since the middle Holocene are not consistent with the known decrease in summer temperatures and increased effective moisture over the past approximately 5,500 years. Climatic changes are complex, though, and it is conceivable that other climatic changes not related to summer temperatures, such as increased autumn and winter temperatures (Bartlein, Hostetler, and Alder 2014), forced an increase in fire activity over the past five and a half millennia in the region. An alternative climate-related explanation is that storms increasingly penetrated farther inland, and associated convection and lightning therefore increased both biomass burning and fire frequency, despite general climatic patterns that increased available moisture (Lynch, Hollis, and Hu 2004). Modeling experiments could potentially be used to test this hypothesis. Regardless, the increase in burning during the MCA and the decline in burning during the LIA remain highly consistent with known climatic changes.

Human–Environment Interactions

As with many regions of the Americas, numerous attempts have been made to estimate presettlement populations in the PNW (see Boyd 1990; Ames 2004). The HYDE population data set (Figure 4E) indicates a rise in coastal and inland populations until the arrival of Europeans about 500 years ago (Klein-Goldewijk, Beusen, and Janssen 2010). Archaeological evidence from the Northwest coast (Campbell and Butler 2010) and the Canadian and Columbia plateaus (Miss 1985; Prentiss et al. 2005) suggests that Native American populations reached a maximum somewhere between 1,300 and

500 years ago, before being dramatically reduced in the eighteenth century due to the introduction of European diseases (Boyd 1990; Prentiss et al. 2005). The question, then, is how increasingly large populations in the PNW influenced late Holocene fire regimes.

A common assumption in fire models is that below a relatively high population threshold, fire use increases with population densities, whereas fires are increasingly suppressed as that threshold is exceeded (e.g., Pechony and Shindell 2009). Generally increasing anthropogenic fire use during the past 5,500 years might reflect growing PNW populations and their increasing reliance on fire, which would have been particularly helpful in maintaining open forest or woodland, particularly in resource-rich ecotones (Ames 2004). Some of the highest levels of biomass burning for the past 5,500 years occurred simultaneously with estimated peaks in populations, ca. 1,100 to 500 cal yr BP. Higher levels of biomass burning are observed particularly at inland, low-elevation, forest (particularly dry forest), and woodland sites (Figures 3 and 4A–4D), which are all environments that would have responded positively to burning in terms of fire's effects on ecologically important resources (i.e., camas, acorns, beargrass, game forage; Boyd 1999; Mack 2003; Ames 2004; Peter and Shebitz 2006).

The peak in biomass burning at ca. 900 cal yr BP and subsequent decline are consistent with known climatic shifts as well as estimated changes in PNW populations (Prentiss et al. 2005; Campbell and Butler 2010). The region-wide Holocene maximum in biomass burning occurred during the MCA, with warm, dry conditions that likely facilitated an increase in human-set fires as well as natural ignitions. Similarly, the colder conditions of the LIA likely caused a reduction in both lightning- and human-set fires, leading to the decline in biomass burning (Figures 2B and 3A–3E) and fire frequency (Figure 2A). Only the very large decline in recent fire frequency evident in the regional summary is clearly of anthropogenic origin, the result of a broad-scale reduction in fire activity associated with nineteenth- and twentieth-century grazing and eventually twentieth-century fire suppression, which is recorded in diverse fire proxies from across the Western United States (Marlon et al. 2012).

Despite the undoubtedly complex spatiotemporal patterns of human fire use that must have occurred on finer spatial scales in the PNW as cultures, climate, and ecosystems changed, the broad similarity in increased biomass burned and fire frequency during the late Holocene seems consistent both with increasing population densities and associated human-set fires, as well as interannual- to centennial-scale climate variability. Coastal sites do show different patterns of burning from inland sites during the late Holocene, but it is difficult to know whether the changes are associated with differences in human activity, climate, or vegetation changes without additional data; many of the observed differences in the coastal region are explained by only two sites (Lost Lake and Taylor Lake). Additionally, with the majority of sites analyzed in this study located west of the crest of the Cascades and in forested settings, east side and woodland fire activity trends remain highly uncertain.

Conclusions

Holocene trends in biomass burning in the PNW differ substantially from broader trends in the Western United States as a whole. A long-term trend toward increased fire activity in the late Holocene does not conform to the prevailing theory that fire decreased in response to decreasing summer insolation and increased effective moisture. Instead, even though climate cooled and moistened during this interval, biomass burning largely increased from ca. 5,500 to 900 cal yr BP. It is possible that region-wide hydrologic shifts associated with more frequent and intense ENSO activity caused more frequent and intense drought during much of the late Holocene, allowing naturally-ignited fires to burn more frequently. Increasing human populations and their associated use of fire likely contributed to this rise in fire activity, however. During this interval, Native Americans were using fire to maintain open forests and prairies (Turner 1999; Peter and Shebitz 2006; Weiser and Lepofsky 2009), even as the regional climate became cooler and wetter. Without a more thorough comparison of individual fire histories to site-specific archaeological records, however, it is impossible to know the scale of the burning. Finally, shorter term changes in fire activity (i.e., the MCA and LIA) closely match widespread shifts in both climate and population and thus both factors likely influenced fire regimes during those periods.

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