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FIRE AND VEGETATION HISTORY IN THE EASTERN CASCADE MOUNTAINS, WASHINGTON

CLINTON S. WRIGHT[1] AND JAMES K. AGEE

[1]*College of Forest Resources, Box 352100, University of Washington, Seattle, Washington 98195-2100 USA*

Abstract. Dendrochronological techniques were used to reconstruct a 433-yr fire history, and to characterize the historical fire regime (frequency, size, season, severity) of the Teanaway River drainage in the eastern Cascade Mountains of Washington, USA. General Land Office section corner data were used to reconstruct aspects of the late-19th-century structure and composition of the forests in the study area. Systematic fire-scar surveys (~30 000 ha; 92 sites; 257 fire-scarred cross-sections; 1569 individual fire scars) revealed that fire frequency was quite variable spatially; Weibull median probability intervals ranged from seven to 43 years. Fire extent also varied widely; most fires were relatively small (<1000 ha), although several large fires (>4000 ha) were detected. Mean and median fire sizes were 1795 ha and 988 ha, respectively. Large fires occurred every 27 years, on average (every 11 years, on average, between 1708 and 1889), and coincided with periods of annual and seasonal drought (Palmer Drought Severity Index and winter Southern Oscillation Index). Intervals from 1 to 37 years occurred between fires of >4000 ha. Over 80% of fires occurred late in the growing season, or after the onset of cambial dormancy. Sampling locations in dry forest types (dominated by ponderosa pine) yielded fire-scarred cross-sections with numerous fire scars leading us to infer that most historical fires were of low intensity, leaving the overstory structure intact. This inference is corroborated by the composition and structure of the historical forest, which was characterized by a preponderance of very large (>100-cm diameter) ponderosa pines. Mesic forest types (dominated by grand fir and Douglas-fir) likely exhibited a wider range of fire severities. Moderate and occasional high-severity understory fires or crown fires did occur within the study area, as indicated by the scarcity or lack of fire-scar evidence and the presence of relatively even-aged forests at several mesic forest sites. Historical section corner data indicate that small amounts of these forest types occurred in the study area. Fire frequency and size declined dramatically circa 1900, coincident with the advent of commercial timber harvesting, although most fires, despite their reduced number and size, continued to burn in the late summer or fall.

Key words: dendrochronology; Douglas-fir; ENSO; fire ecology; fire history; fire regime; grand fir; PDSI; ponderosa pine; Washington State (USA).

INTRODUCTION

Considerable attention has been focused on natural disturbance processes as a guide for forest management. Concepts such as the historic range of variability (Landres et al. 1999) and coarse filter conservation strategies (Hunter 1990, Haufler et al. 1996) suggest that successful management of ecosystems may best be achieved by mimicking natural disturbance patterns and processes. Ecological sustainability is being proposed as the foundation for sustainable forest management (Dale et al. 1999); understanding natural processes and their effects will be important in future ecosystem management plans. To ‘‘manage’’ natural processes for ecological and commercial benefit in fire-dependent ecosystems requires an awareness of the properties of the disturbance regime and a grasp of the linkages between disturbance process and landscape pattern.

Fire is the predominant disturbance type in many ecosystems in the western United States (Wright and Heinselman 1973). Disturbance processes (including fire), landform, climate, vegetation pattern, and individual species characteristics interact through time and over space to form the plant communities and disturbance regimes seen at specific times and locations on the landscape (Gara et al. 1985, Norris 1990, Johnson 1994, Veblen et al. 1994, Agee 1998, Lertzman et al. 1998, Miller and Urban 1999). In the eastern Cascade Mountains of Oregon and Washington, USA, a low-severity fire regime (Agee 1993) characterized and shaped dry forest types dominated by ponderosa pine (*Pinus ponderosa* P. & C. Lawson), Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), and western larch (*Larix occidentalis* Nutt.), while a variable severity (elements of low, moderate, and high severity) fire regime characterized more mesic forests dominated by grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) prior to European American settlement (Wischnofske

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[1] Present address: USDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, 400 North 34th, Suite 201, Seattle, Washington 98103 USA. E-mail: cwright@fs.fed.us

and Anderson 1983, Agee 1994, Everett et al. 1997, 2000). Land-use and land management changes throughout the dry and mesic forest types of the eastern Cascades starting in the late 1800s and early 1900s (e.g., settlement, grazing, timber cutting, fire suppression, road building) coincided with a notable decline in fire frequency and fire size (Agee 1994).

Ponderosa pine, Douglas-fir, and western larch develop thick bark and high crowns providing protection from surface fires, whereas grand fir is a thin-barked species that retains its low branches making it susceptible to virtually all fires. The historical fire regime of frequent, low-intensity surface fires in forests dominated by ponderosa pine maintained a pattern of large, widely-spaced, predominantly fire-tolerant trees (Cooper 1960, Weaver 1961, White 1985). Significant reductions in fire occurrence have allowed seedlings and saplings, particularly of fire-sensitive species such as grand fir, to persist on the landscape where most would have previously been eliminated by frequent low-intensity surface fires. Less frequent and smaller fires have resulted in a larger proportion of the landscape in denser forests with relatively more shade-tolerant, fire-sensitive species, and greater vertical and horizontal fuel continuity. Such structural and compositional changes support moderate-intensity and high-intensity fires in areas that historically did not experience them (Agee 1994, Everett et al. 2000).

Links between fire regimes and regional and global climate phenomenon have been discovered for various regions in the United States, but have not been examined for dry forest types in the eastern Cascades of Washington. The relation of increased fire occurrence and size to current year drought conditions is obvious, particularly in light of large fire years in 2000 and 2002 most recently. However, it is unclear if other conditions such as multiyear droughts, alternating wet and dry years, or the phase of the El Niño/Southern Oscillation (ENSO: a semiperiodic climate–ocean phenomenon occurring every 2–7 years that influences global weather and circulation patterns) are related to fire regime characteristics in the eastern Cascades (primarily fire frequency and fire size). For example, the Southwest tends to experience larger fires in years where the ENSO is in its positive phase (La Niña; Swetnam and Betancourt 1990), and also where very dry years follow wetter than average years (Swetnam and Betancourt 1998); whereas a lagged ENSO relationship exists in Florida (i.e., larger and more frequent fires in the year following a La Niña or negative ENSO event; Harrison and Meindl 2001). In the Northwest, large fire years were correlated with years when the ENSO was in its negative phase (El Niño) in some locations in the Blue Mountains of eastern Oregon but not in others (Heyerdahl et al. 2002). Hessl et al. (2004) found direct associations only between fire extent and current year drought in the eastern Washington Cascades, and Gedalof (2002) observed links between regional area burned in the Pacific Northwest and the Pacific Decadal Oscillation, an interdecadal climatic oscillation (Mantua et al. 1997).

Documentation of historical fire regimes in areas where fire is the major disturbance type is necessary to provide the framework within which to raise questions and devise strategies for ecosystem management. Such documentation simultaneously improves our understanding of the processes that govern fire-influenced landscapes. In this paper, we attempt to define the characteristics of the fire regime (sensu Agee 1993) of the lower Teanaway River valley, Washington, using spatially explicit fire scar data with intra-annual resolution and historical vegetation data. Our objectives were: (1) to document the frequency and variability with which fire occurred in the study area; (2) to evaluate temporal, spatial, and seasonal aspects of the fire regime; (3) to investigate potential relationships between climate and fire history; and (4) to relate the fire history to historical vegetation structure and composition.

Study Area

The Teanaway River, a tributary of the Yakima River that flows into the Columbia River, is located in the eastern Cascades in Kittitas County, central Washington (47°16′ N, 120°54′ W). The study area, in the lower ~30 000 ha of the Teanaway River valley (Fig. 1), is divided into 15 smaller drainages, with elevations ranging from 600 m to 1450 m. Because of its location in the rain shadow of the Cascade Mountains, the area is characterized by hot, dry summers (mean July temperature of 28°C, April–September precipitation of 10 cm) and cold winters (mean January temperature of −7°C). Over 80% of the 54 cm of annual precipitation falls during the winter, mostly as snow (Franklin and Dyrness 1987, World WeatherDisc 1994). Thunderstorms occur regularly (three to six storms annually) in July and August, the driest months of the year (Morris 1934).

The geology of the study area is described primarily as sandstone overlying basalt (Tabor et al. 1982) with well-drained loam soils (Washington State Soil Survey 1983). The climate and geology support forests indicative of four vegetation series (potential vegetation; Daubenmire 1968): *Abies grandis* (grand fir, 85% of land area), *Pseudotsuga menziesii* (Douglas-fir, 14%), *Tsuga heterophylla* (Raf.) Sarg. (western hemlock, <1%), and *Pinus ponderosa* (ponderosa pine, <1%). Despite the prevalence of the *Abies grandis* series, ponderosa pine and Douglas-fir are the dominant overstory species throughout much of the study area.

The lower watershed is primarily owned by forest industry (Boise Cascade Corporation during the study, and U.S. Timberlands since 2001). Most of the large ponderosa pines were cut during a period of active horse and railroad logging between 1903 and 1930 (Henderson 1990). Livestock grazed in the Teanaway in the 1920s (passing references in Henderson 1990), and Oliver et al. (1994) documented cattle and sheep

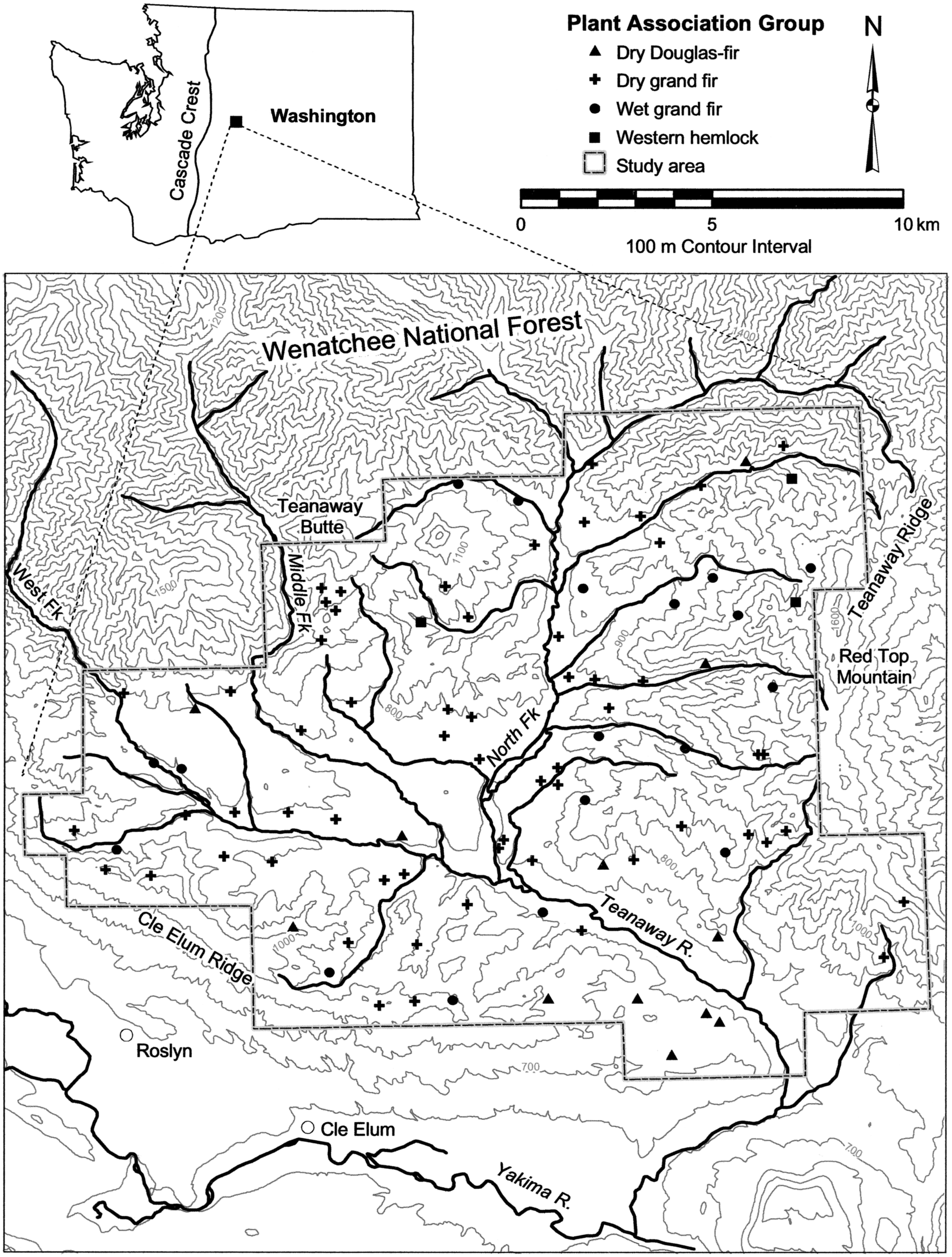

FIG. 1. Study area location in the lower Teanaway River drainage. The study area includes a contiguous block of private forest industry lands and USDA Forest Service lands for ~1.6 km around the perimeter.

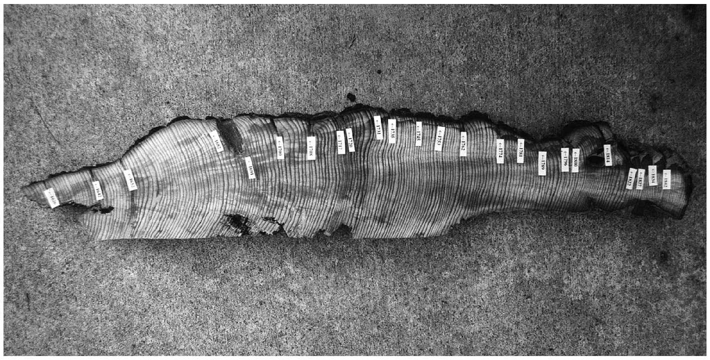

PLATE. 1. Fire-scarred ponderosa pine cross section removed from a railroad-logging-era stump. This tree was scarred by at least 24 fires between the early 1600s and mid-1800s.

grazing in Kittitas County (though not specifically in the Teanaway) as early as 1885. The upper watershed and surrounding watersheds are managed by the USDA Forest Service as part of the Wenatchee National Forest and the Alpine Lakes Wilderness Area.

Fire was apparently common in the region prior to the logging era in the early 20th century. Early visitors such as surveyor (later General) George McClellan in September 1853 noted from his camp adjacent to the western limit of the study area, ‘‘The air is so smoky that we can see nothing of the lake . . . ’’ (Glauert and Kunz 1976:99). Native tribes had settlements in the vicinity, and reportedly used the area for fishing and gathering (Glauert and Kunz 1972). Historical fire ignitions probably came from a combination of lightning and human sources (Boyd 1999).

METHODS

Fire history sampling

Field sampling was designed to collect fire history data over the entire study area. A total of 92 sites were established at a density of ~1/260 ha; sites ranged in size from 0.5 ha to 2.5 ha and were represented by the best two to four (up to six) fire-scarred trees or stumps encountered. We restricted the sampled area at each site so that fire intervals would represent an area small enough to be interpreted as a point (Agee 1993). More samples could have been collected at each site by expanding the area, but the resulting fire interval statistic then represents occurrence of fire within an area, rather than at a point. Trees and stumps with the greatest number of visible fire scars and the least decay were chosen preferentially. Where fire-scarred specimens were absent, stand ages in the form of increment cores from dominant trees were collected.

Sampling sites were located systematically using the township, range, and section grid, not randomly (e.g., Johnson and Gutsell 1994), as the goal of this study was to characterize the fire history of all forest types in the study area, and to efficiently compile the longest, most complete inventory of past fires possible while also achieving complete geographic coverage (Swetnam and Baisan 1996). The approximate center of each land survey section served as the starting point when searching for fire-scarred specimens; however, reconnaissance of a larger area often identified higher quality samples at some distance from the starting point. Coupled with a lack of access in some areas, this led to a lack of uniformity in the grid arrangement of fire history sites (Fig. 1). A total of 257 fire-scarred specimens (1569 crossdated fire scars) were collected by removing cross sections from stumps, logs, and live trees with a chainsaw (Arno and Sneck 1977). Eighty-seven percent of the samples were from stumps, most created by logging in the early part of the 20th century (see Plate 1).

Vegetation composition and stand structure were surveyed in a 0.04-ha plot at each site; plant associations were assigned using a local vegetation classification (Lillybridge et al. 1995) and a field-checked vegetation map of the area developed by the landowner. Increment cores from the bases of one to six dominant early seral trees were collected at each site, and were used to reconstruct the most recent stand-replacing fire at sites where fire scar data were absent. Small (<10 yr) adjustments were made to account for inaccuracies associated with estimating stand-replacing fire dates from stand ages (i.e., missing rings to pith for off-center cores, number of years to core height, regeneration lag) and to synchronize initial stand age estimates with known fire-scar-derived fire dates from adjacent sites.

All wood samples (fire-scarred cross sections and increment cores) were returned to the laboratory, sanded until the cell structure was visible under magnification, and crossdated (Stokes and Smiley 1968) to identify missing and false rings (Madany et al. 1982, McBride 1983, Dieterich and Swetnam 1984). A master tree-ring width chronology (Fritts 1976) was developed from the oldest cores of Douglas-fir and ponderosa pine collected at each site in the study area for the period from 1566 to 1994. Both species were used in the chronology because of similar radial growth patterns at this site; incorporation of Douglas-fir extended the chronology back an additional 60 years.

Only crossdated samples were used in this analysis. To check the visual crossdating of fire-scarred cross sections, individual annual ring widths were measured with a sliding stage micrometer (Robinson and Evans 1980), input into program COFECHA (Holmes et al.

1986), and checked for ring width pattern correlation against the master tree-ring width chronology (Holmes et al. 1986). Five percent of fire-scarred specimens were undateable either because they showed complacent annual ring width patterns or because they were in poor condition (i.e., excessive decay, insect galleries).

The position of fire scars within growth rings, coupled with information about tree-ring phenology can be used to interpret the season of fire occurrence. To better assess the seasonality of fire occurrence in the study area, the phenology of cambial growth (i.e., the timing of changes in cambial vessel size, shape, and color) was measured in 1995 (a relatively wet summer in central Washington; Agee et al. 2002) by removing increment cores from 24 trees approximately every two weeks from June through September (see Wright 1996).

Fire history data analysis

Fire scars were assigned to the year of the annual ring in which they occurred. The position of the scar in the early, middle, or late wood, or at the ring boundary was used to establish season of fire occurrence. Fire scars that formed during the season of cambial dormancy (i.e., on the boundary between two rings) were assigned to the year of the preceding ring (as elsewhere in this region) because modern fires in the area burn in the late summer or fall, following the cessation of annual ring growth for the earlier year. All samples from each site were combined to create a master fire chronology from which composite fire intervals were calculated (Dieterich 1980).

Master fire chronologies were compiled and descriptive statistics were calculated (Grissino-Mayer 1995) over the period for which we have reliable fire history information in the Teanaway (i.e., from 1562 to 1995 we had at least one living sample capable of recording a fire at 25% of the sites). Only sites with four or more fire intervals (five or more fires) were used to calculate descriptive statistics (73% of sites); years preceding the earliest fire and following the most recent fire were not included in any of the calculations. Of the excluded sites, roughly equal numbers occurred in ‘‘wet’’ and ‘‘dry’’ vegetation types.

Three measures of fire frequency (central tendency) were calculated from master fire chronologies for each site where fire history data were collected: the mean fire interval (MFI), the median fire interval (MedFI), and the Weibull median probability interval (WMPI). The first two measure central tendencies of symmetric distributions, while the Weibull is a flexible distribution that often fits skewed fire history data better than a normal distribution (Grissino-Mayer 1995). The WMPI represents the median value of a Weibull distribution (i.e., half of all fire intervals are expected to be larger, and half smaller than the WMPI).

Variability of fire intervals was measured using several techniques: the range, represented by the maximum and minimum fire-free interval in each master fire chronology; the variability of fire frequency (VFF), equal to the standard deviation of the MFI for each site; the Weibull confidence interval (WCI), the difference between the 33% and 67% exceedance probability levels for a given Weibull distribution (roughly equivalent to the width of one standard deviation for a normal distribution [Zar 1984]); and the coefficient of variation (CV), calculated as VFF divided by MFI.

For individual sites, goodness-of-fit between the fire interval data and the normal and Weibull distributions was evaluated with the one-sample Kolmogorov-Smirnov test (Zar 1984, Grissino-Mayer 1995). The measures of central tendency and variability were also compiled for groups of closely allied plant associations (dry Douglas-fir, dry grand fir, wet grand fir). Analysis of variance was used to test the null hypothesis of no difference in fire frequency among groups (Zar 1984). To compensate for possible dependence among sites, we incorporated the effects of spatial autocorrelation in the analysis of variance by means of a generalized least squares procedure (e.g., Pinheiro and Bates 2000) with a variety of different spatial correlation structures (exponential, spherical, and linear) and ranges (2 km and 20 km).

We reconstructed fire extent from maps of sampling sites with evidence of fire for each year with such evidence. Fire boundaries were determined by drawing polygons around all sites showing evidence of a fire in a given calendar year. Streams and ridges were assumed to be firebreaks, unless there was evidence of fire on both sides. Boundaries were assumed to fall halfway between sites with and without evidence of fire unless topographic conditions dictated otherwise. A site without fire evidence was included within a fire boundary if it was surrounded by sites with such evidence. A complete set of fire year maps is included in Wright (1996).

Fire–climate relationships were explored by comparing reconstructed fire date and size data with tree-ring reconstructions of the Palmer Drought Severity Index (PDSI; Cook et al. 1999) and the winter Southern Oscillation Index (SOI; Stahle et al. 1998*a*). The PDSI is a widely used meteorologic and hydrologic index that incorporates precipitation, temperature, evapotranspiration, and soil moisture conditions to indicate relative levels of drought (Palmer 1965, Alley 1984). The winter SOI is an indicator of El Niño/La Niña conditions. Relatively dry, warm winter conditions occur in the northwestern United States during El Niño periods (negative SOI). Conversely, conditions tend to be wetter and cooler during La Niña periods (positive SOI; Cayan et al. 1999). Using superposed epoch analysis (SEA; Baisan and Swetnam 1990, Grissino-Mayer 1995), we explored whether climate during large fire years (>4000 ha) differed from climate during years that preceded and followed large fire years (±5 yr).

Significance of the SEA was determined by bootstrapping (2000 trials; Grissino-Mayer 1995).

Historical vegetation

We estimated historical forest composition and structure from General Land Office records (General Land Office 1872–1900). A substantial amount of forest information was recorded when section corners were established in the first land surveys. A section corner was typically described by a wooden stake or rock monument, surrounded by four bearing trees, one in each of the four quadrants surrounding the corner point (Bourdo 1956, Habeck 1994). Surveyors noted the species and size (i.e., diameter) of these bearing trees in addition to their distance and direction from the section corner. Cottam and Curtis (1956) outlined a method from which historical tree density and basal area has been calculated in many regions (e.g., Grimm 1984, Leitner et al. 1991, Habeck 1994, Abrams and McCay 1996, McCracken et al. 1996). The average of the four distance measurements to bearing trees surrounding each section corner is assumed to be equal to the square root of the mean area occupied by each tree. Density per unit area is calculated as the unit area divided by the mean area occupied by each tree. Data are collated over multiple sample points and averaged for the data set, rather than calculated as the mean distance for each section corner (Cottam and Curtis 1956). Mean basal area per tree by species is calculated from diameter data; basal area is converted to an area basis by multiplying the mean basal area per tree by the average density per species. Mean spacing is calculated as the square root of the quantity: 10 000/tree density (in stems/ha).

In this analysis, historical vegetation data were analyzed for surveys between 1872 and 1900 and segregated into groups of closely allied plant associations (dry Douglas-fir, dry grand fir, wet grand fir) based on their locations with respect to a vegetation map of the area developed by the landowner. There were a total of 115 section corners for which survey data were collected and available in the study area. Plummer (1902) mapped logged areas in the Yakima River valley and showed little substantial impact relative to the potential bearing trees in the study area, suggesting that logging impacts were negligible during the time of the General Land Office surveys (1872–1900) and should not affect the results of analyses based on those surveys. A total of 17 mapped corners were in dry Douglas-fir associations, 72 were in dry grand fir associations, 25 were in wet grand fir associations, and one was in a western hemlock association. Tree density and basal area/ha by species were calculated for each of the three major plant association groups in the survey area.

RESULTS

Fire history

A total of 136 fire dates were identified over the 433-yr record in the lower Teanaway River valley. The earliest fire in the record (1562–1995) occurred in 1567, and the most recent was in 1994. The number of fire dates per site ranged from zero at two sites to 33 at a site near the southeastern corner of the study area (Fig. 2). The most common fire interval was eight years, with a range from two years to $>$50 years across all sites (Fig. 3). For the 67 sites with five or more fires, the mean fire interval (MFI), the measure of central tendency most commonly reported in the fire history literature, ranged from 7.7 yr to 48.4 yr, while the median fire interval (MedFI) ranged from 7.5 yr to 46.5 yr, and the Weibull median probability interval (WMPI) ranged from 7.1 yr to 43.2 yr.

The three measures of central tendency produced slightly different values for fire frequency (Fig. 4). The MFI was longer than the MedFI and the WMPI for 91% and 96% of the sites, respectively, while the MedFI was longer than the WMPI for 72% of the sites. For sites with more than four fire dates, the Weibull distribution fit better than a normal distribution on 67 of 69 sites. In addition, the Weibull distribution was found to adequately model fire interval data in all cases (Kolmogorov-Smirnov *d* statistic, $P = 0.05$), whereas the normal distribution did not adequately model fire interval data for 19% of the sites (Grissino-Mayer 1995).

The variability of fire frequency (VFF) ranged from 3.1 yr to 37.7 yr, while the Weibull confidence interval (WCI), the Weibull analog to the VFF, ranged from 2.4 yr to 25.7 yr for the 67 sites with five or more fires. The WCI was generally shorter than the VFF; the presence of longer fire intervals at some sites affected the VFF more than the WCI. The coefficient of variation (CV), a standardized measure of dispersion that allows direct comparisons of variability among sites with means of different magnitude, ranged from 0.190 to 1.077. Fire interval lengths ranged from 2 yr to 107 yr, with an average minimum of 10.1 yr and an average maximum of 45.9 yr. None of the sites recorded fires in successive years.

When data were combined into plant association groups, fires were most frequent for the dry Douglas-fir associations and least frequent for the wet grand fir associations (Table 1); differences in fire frequency (MFI) were not statistically significant ($P > 0.37$ for all correlation structures and ranges). While the dry Douglas-fir group had the shortest average fire intervals, the dry grand fir group showed the least variability, as measured by the VFF and the WCI. The CV values were similar across all three plant association groups.

Fire extent has been quite variable since the mid-16th century (Figs. 5, 6). Estimates of area burned ranged from ~30 ha to $>$10 760 ha, with mean and median areas of 1795 ha and 988 ha, respectively. Large fires ($>$4000 ha) ceased early in the 20th century, although fires in 1902 and 1909 burned 1700 ha and 1650 ha, respectively, before railroad logging and fire

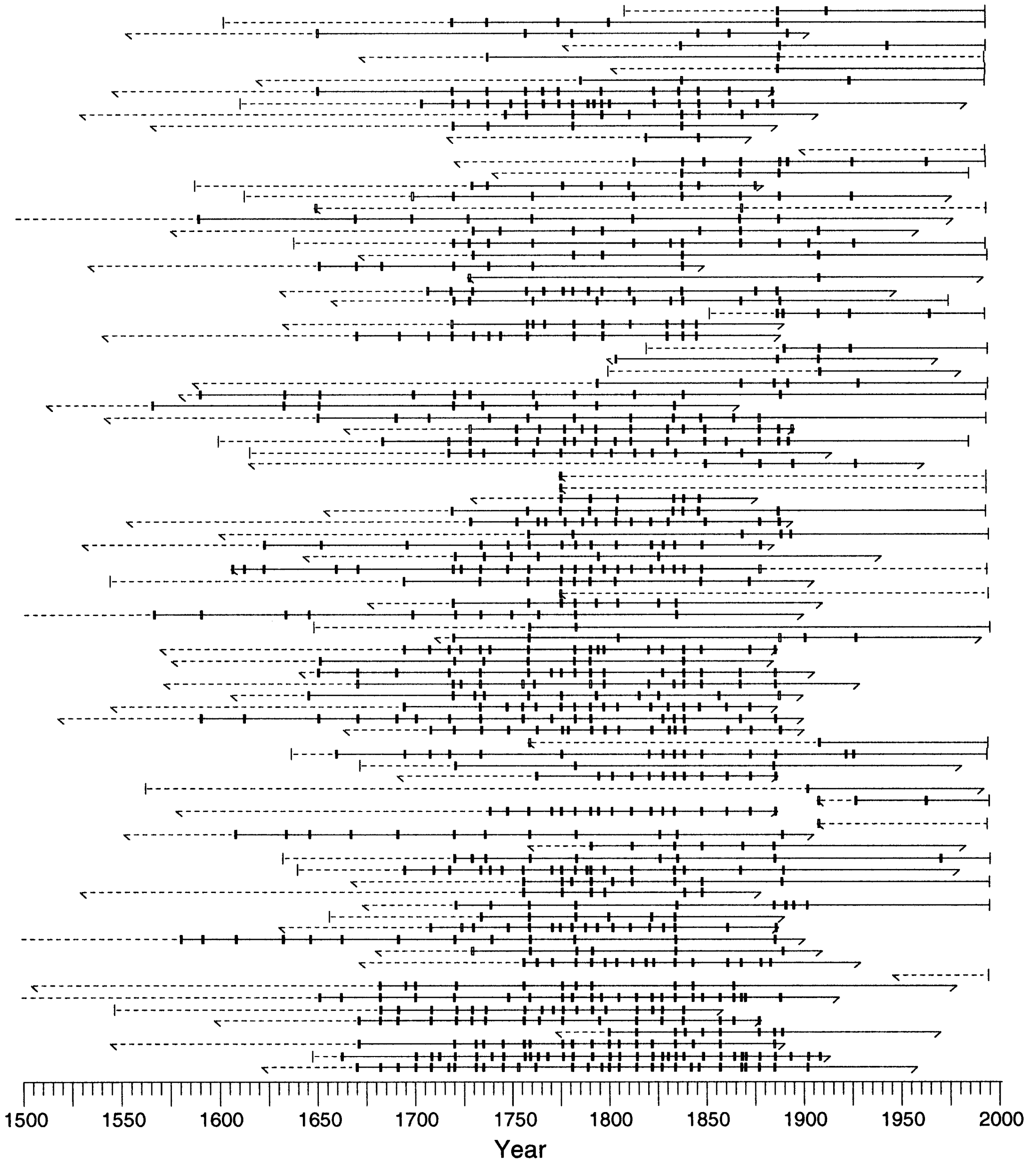

FIG. 2. Fire history of the lower Teanaway River drainage, central Washington. Individual horizontal lines represent the master fire chronology of each fire history site. The lines are arranged north (top) to south (bottom). Solid vertical bars mark definite fire years; open vertical bars mark probable fire years. Fine vertical lines at the beginning and end of each chronology represent pith or bark dates; fine diagonal lines represent earliest or latest ring dates in the absence of pith or bark.

suppression began. While fires occurred frequently (a fire approximately every 3 yr, on average, somewhere in the study area) most were relatively small. However, for the period from 1708 to 1889 a fire >4000 ha occurred somewhere in the study area approximately every 11 years, on average, although intervals as long as 37 years and as short as one year occurred between fires of >4000 ha.

The location of the fire scar within the annual ring is an indicator of the season of fire occurrence. Of the 1569 fire scars where scar position in the annual ring could be identified, most occurred in the latewood (32%) or at the ring boundary (49%) after annual growth had ceased for the year. In 1995, latewood formation occurred in late August (Wright 1996). No change in the season of fire scar formation occurred over the analysis period (1562–1995).

Fires in the study area occurred during wet, normal, and dry years. Large fires (>4000 ha) in the study area appear to be related to annual dry periods, aligning with negative values of the winter Southern Oscillation Index (SOI) and the Palmer Drought Severity Index (PDSI; Fig. 7). In the few instances where large fire years align with positive values of the winter SOI, the PDSI is negative, and vice versa. Superposed epoch analysis did not indicate significant lagged relation-

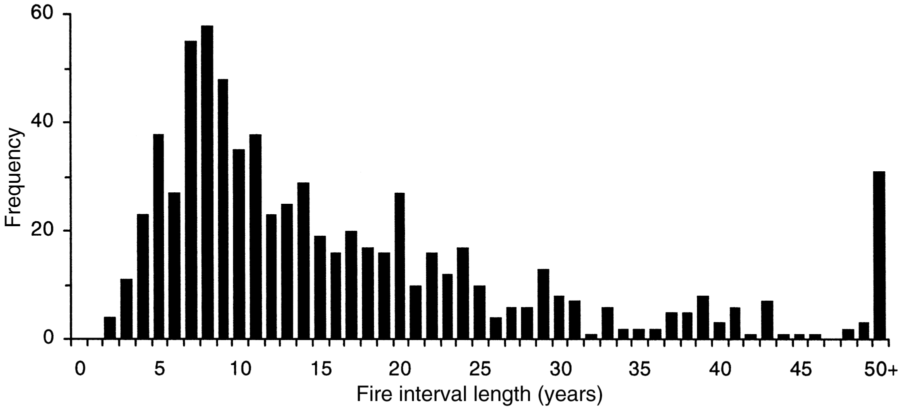

FIG. 3. Distribution of fire interval lengths combined for all fire history sites in the lower Teanaway River drainage. Note the absence of 1-yr intervals and the scarcity of 2-yr and 3-yr intervals.

ships (±5 yr) between climate indicators (PDSI and winter SOI) and large fire occurrence for this study. That is, PDSI and winter SOI values one or more (up to five) years prior to and following large fire years were not consistently positive or negative, although PDSI was significantly lower ($P < 0.001$) than average conditions during large fire years (Fig. 8).

Historical vegetation

Historically, tree density and basal area were relatively low across the study area (Table 2). Estimates of mean density ranged from about 50–80 trees/ha (excluding, most likely, some but not all trees less than ~15 cm in diameter, as larger trees were chosen preferentially to be bearing trees). This is equivalent to a spacing of 11–14 m between trees of all sizes except the very smallest in the stand, and suggests an open stand similar to the historical descriptions in comparable types (Agee 1993, 1994). Estimates of basal area ranged from ~13 m^2/ha to 15 m^2/ha. Basal area was concentrated on a few stems per hectare, however, so that average tree sizes were quite large (>100 cm). The most common species used for bearing trees in these General Land Office surveys were ponderosa pine and Douglas-fir. Western larch, lodgepole pine (*Pinus contorta* Dougl. ex Loud.), western red cedar (*Thuja plicata* Donn ex D. Don), grand fir, and miscellaneous hardwoods (vine maple [*Acer circinatum* Pursh], alder [*Alnus* spp. P. Mill], quaking aspen [*Populus tremuloides* Michx.], black cottonwood [*Populus trichocarpa* T. & G. ex Hook.], and cherry [*Prunus* spp. L.]) were occasionally used as bearing trees for section corners within the study area.

The dry Douglas-fir associations are the driest and warmest in the study area, covering 15% of the studied section corners. Ponderosa pine was the dominant species in the dry Douglas-fir associations, followed by Douglas-fir (Table 3). The largest tree diameter recorded was 122 cm, and both ponderosa pine and Douglas-fir reached this size. Over 75% of the total stem density was comprised of ponderosa pine. The dry grand fir associations were the most widespread in the study area, covering 63% of the studied section corners. Ponderosa pine was the most common species in the dry grand fir associations, followed by Douglas-fir. The largest tree diameter recorded was 127 cm, and both ponderosa pine and Douglas-fir reached this size. About 60% of the density was comprised of ponderosa pine, less than the dry Douglas-fir group, although the relative basal area of ponderosa pine was very similar. The wet grand fir associations, like the dry Douglas-fir associations, cover a small proportion of the studied section corners (22%). Douglas-fir was the most common species in the wet grand fir associations, followed by ponderosa pine. Tree species diversity was slightly higher in the wet grand fir group. The largest tree diameter recorded was 102 cm, and both ponderosa pine and Douglas-fir grew this large. About 60% of the density was comprised of Douglas-fir. Western larch was present in small amounts in the dry and wet grand fir plant association groups, while lodgepole pine and western red cedar were only recorded in small numbers in the wet grand fir group, and grand fir was only recorded in small amounts in the dry Douglas-fir group.

DISCUSSION

Fire history

Fire was a frequent visitor to the lower Teanaway River valley. Reports like those of surveyor McClellan were not isolated incidents but probably common to the summer and fall months. More than one in four years the Teanaway had a fire, and if all the other drainages in the region are considered, fires must have occurred most years somewhere in the upper Yakima River basin. The frequent fires recorded for the Teanaway are consistent with other studies in the eastern Cascades (Wischnofske and Anderson 1983, Bork 1984, Everett et al. 2000) and studies in similar forest types in the Blue Mountains of eastern Oregon and Washington (Maruoka 1994, Heyerdahl et al. 2001).

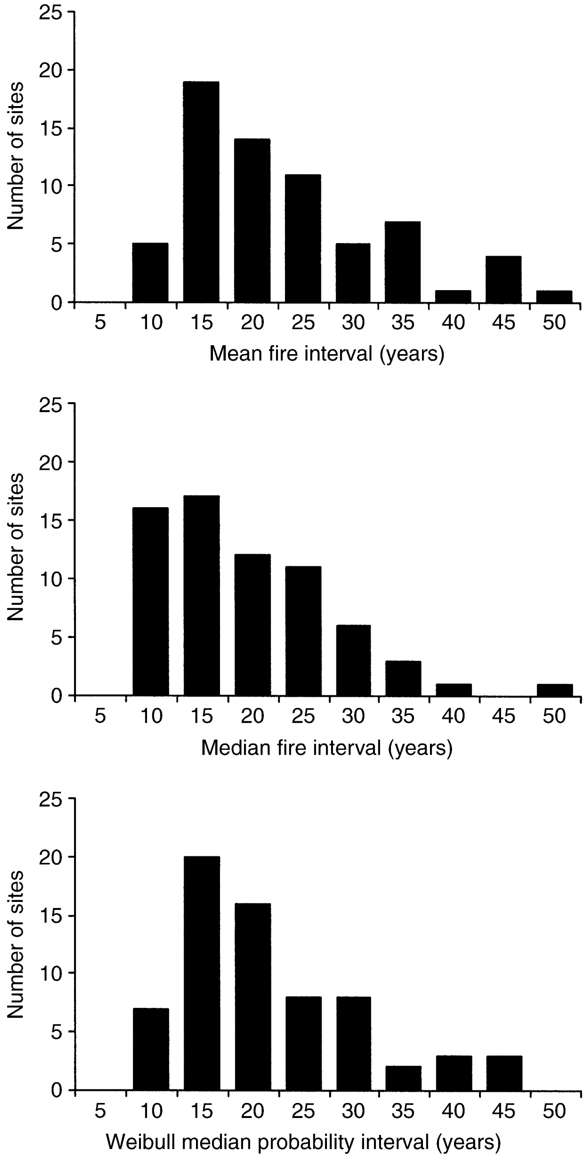

FIG. 4. Distribution of measures of central tendency for fire history sites with five or more fire dates in the lower Teanaway River drainage. The *x*-axis scale numbers are the upper limits for each category.

Fires became less frequent and smaller in the early 1900s in the Teanaway, consistent with the decline in fire activity that has been observed for several other fire histories in the ponderosa pine-dominated forests of Washington and Oregon (e.g., Maruoka 1994, Everett et al. 2000, Heyerdahl et al. 2001). Forest management (commercial timber harvesting operations) and fire suppression activities were initiated in and around the forests of the Teanaway during the early 20th century, coinciding with wetter than average climatic conditions in the area (as indicated by primarily positive values of the PDSI; Fig. 7). The typically wetter than average ~20-yr time period at the turn of the century likely contributed to the success of what would be considered limited fire suppression actions by today's standards. Despite apparently annually wetter than average climatic conditions, six small fires did occur between 1900 and 1920. This early 20th century time period was characterized by similar fire frequency when compared to the overall record, although fires were smaller than typical for the overall record.

Variability can be a key ecological factor in local vegetation dynamics (Agee 1994). Individuals of some species, such as grand fir and Douglas-fir, are fire sensitive when small. These species will persist only on sites where there is a fair probability that they will avoid fire for several decades until they develop thicker bark and higher crowns. Where the average interval between fires is short, sites with greater interval length variation are likely to contain more of these species than sites with more uniformly short intervals. The ability of species killed by fire that rely on seed to persist can be limited where very short fire return intervals occur. For example, where two fires occur in quick succession (for example, 2–3 years in this data set), shrubs such as those in the genus *Ceanothus* that rely on seed for regeneration are killed by the first fire, and the next generation is killed by the second fire before new seed can be produced (Kauffman 1990, Agee 1996). This can result in local extirpation of some species, and has been suggested as a means of reducing shrub competition by depleting the seed bank with two

TABLE 1. Mean and range of fire frequency and variability for fire history sites in the lower Teanaway River drainage, by plant association group.

	Plant association group		
Statistic	Dry Douglas-fir	Dry grand fir	Wet grand fir
Mean fire interval (MFI)			
Mean	18.8	20.6	23.9
Range	34.3	39.9	34.7
Median fire interval (MedFI)			
Mean	15.5	17.4	20.6
Range	24.0	31.0	38.5
Weibull median probability interval (WMPI)			
Mean	17.1	19.3	21.9
Range	32.0	34.8	33.6
Variability of fire frequency (VFF)			
Mean	13.1	12.3	15.6
Range	18.8	34.3	31.9
Weibull confidence interval (WCI)			
Mean	9.2	8.9	11.7
Range	17.7	23.3	20.2
Coefficient of variation (CV)			
Mean	0.678	0.588	0.639
Range	0.534	0.709	0.642

Notes: Eleven sites were dry Douglas-fir, 47 were dry grand fir, and nine were wet grand fir. Of the 25 sites that were not included in this analysis, 12 were dry grand fir, 10 were wet grand fir, and three were western hemlock. Differences between groups were not statistically significant.

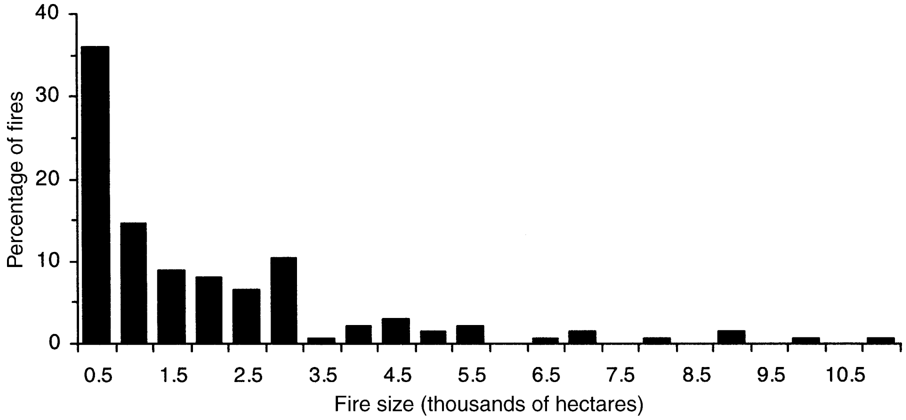

FIG. 5. Distribution of estimated fire sizes for fires that occurred since 1562 in the lower Teanaway River drainage. The *x*-axis scale numbers are the upper limits for each category.

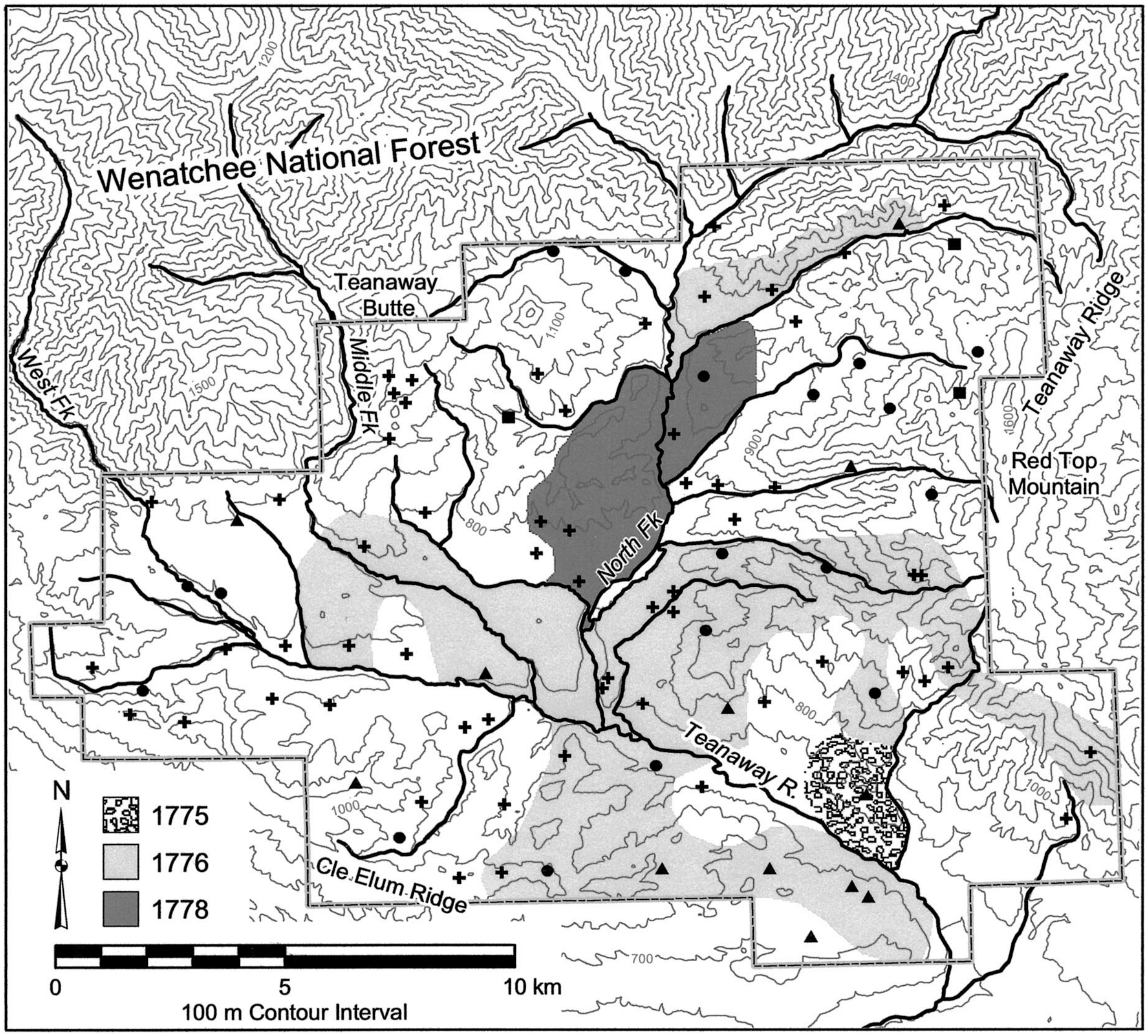

FIG. 6. Example of lack of spatial overlap among fires occurring at very short intervals in the lower Teanaway River drainage. See Fig. 1 for symbol legend. Fire boundaries are based on rules outlined in Wright (1996).

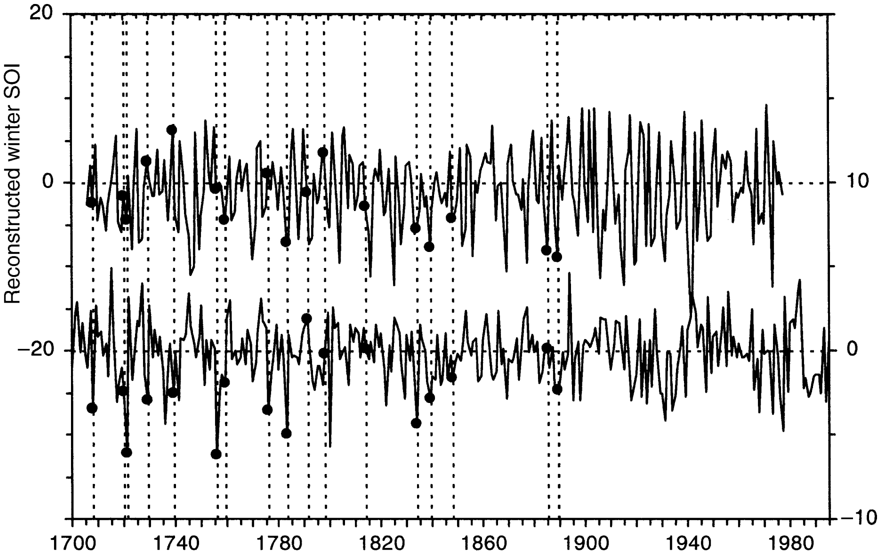

FIG. 7. Tree-ring reconstructions of the winter Southern Oscillation Index (SOI, upper time series; Stahle et al. 1998*b*), and the Palmer Drought Severity Index (PDSI, lower time series) for central eastern Washington (grid point 9; Cook 2000). All fires >4000 ha are indicated by dashed lines and dots. Note that large fire years typically align with years of negative winter SOI and PDSI (i.e., El Niño, lower snow pack, earlier snow melt, less precipitation, drought).

closely timed fires (Biswell 1989, McCandliss 2002). Temporal irregularity can result in quite variable local vegetation patterns, not because the average interval between fires is different, but because variability is different.

The Weibull distribution appears to better describe these fire history data than a normal distribution. This will generally be true when a skewed distribution exists, as is common for fire interval data sets in low-severity fire regimes. Fire intervals are short but cannot be less than one, while long fire intervals almost always occur, skewing the distribution to the right. Few studies in the region have reported quantitative measures of fire frequency variability. For Maruoka (1994) and Heyerdahl's (1997) data from the Blue Mountains, variability of fire frequency (VFF) and CV values compared well with values for the Teanaway. These studies were conducted in vegetation types very similar to those found in the Teanaway, indicating that the distribution of fire intervals that we observed can serve as a starting point for restoration and forest management planning over the range of the ponderosa pine- and Douglas-fir-dominated *Abies grandis* forest series.

Spatial variability appears to be enhanced in short-return-interval systems because of natural barriers to fire. Natural barriers, such as those provided by moist conditions (north aspects, riparian zones) or fuel limitations, likely played a role in limiting fire extent. Fires spreading toward adjacent areas that had burned 1–3 years prior either stopped spreading in previously burned areas or burned with such low intensity that no trees were scarred. Fuel limitations may be associated with this phenomenon. The lack of very short fire intervals (Fig. 3), and the apparent barrier to fire spread across recently (1–3 years) burned areas (Fig. 6) suggests that once a fire occurred, several years of fuel buildup were required to enable the same area to burn again. Spatial reconstructions of fire activity in similar forest types of the eastern Cascades (Everett et al. 1997, 2000) and Blue Mountains of northeastern Oregon (Heyerdahl 1997) show similar patterns of fires closely spaced in time abutting one another. The red fir forests of California also show a similar ''jigsaw puzzle'' type of fire activity over time (van Wagtendonk 1995).

While large fires occurred regularly in the Teanaway, the majority of reconstructed fires were <1000 ha. Small fires are important not so much because of their individual effects, but as a result of their cumulative effects; small fires create a mosaic of forest conditions on the landscape (i.e., age classes, stand structures, fuel beds, wildlife habitat, plant communities) that influence the behavior and spread of subsequent fires (Kilgore and Taylor 1979, Swetnam and Baisan 1996, Agee 1997).

The season of fire occurrence varies regionally in North America so it is important to understand site- and region-specific fire season patterns because they can influence ecological processes (see, for example, Swezy and Agee 1991, Whelan 1995). Over 80% of the fires identified in this study were late season fires. Although cambial phenology varies on an annual basis, Wright's (1996) observation of latewood formation occurring in late August suggests that most fires spread after that time (although they may have been ignited earlier). The consistency of late season fire scar formation since the mid-1500s indicates little change in the overall processes governing intra-annual timing of

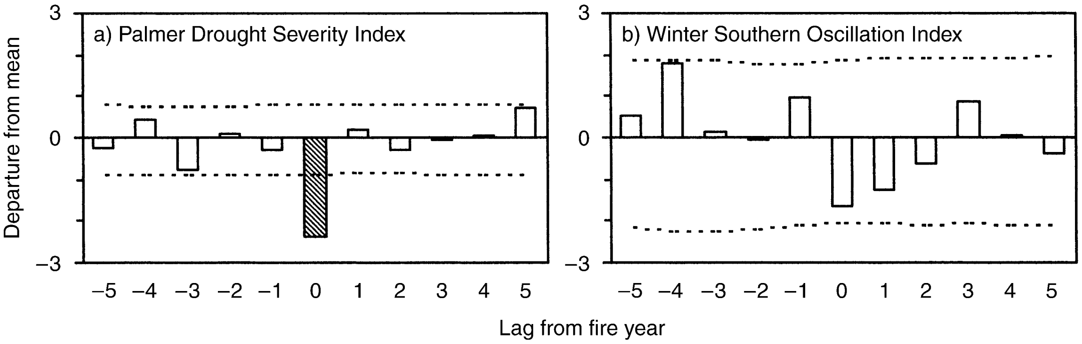

FIG. 8. Relationship between (a) reconstructed Palmer Drought Severity Index (grid point 9, 1703–1894; Cook 2000) or (b) reconstructed winter Southern Oscillation Index (1706–1894; Stahle et al. 1998*b*) and major fire years in the lower Teanaway River drainage for all fires >4000 ha ($N = 17$). Year zero is the fire year, $t - 1$ is the year preceding the fire, $t + 1$ is the year following the fire, and so forth. Departures from the mean that fall outside of the 95% confidence interval (dashed lines) are hatched. Results are the same if the 20th-century portion of the two climate time series (i.e., 1895 and later) are included in the analysis.

forest fires in the Teanaway over the last half millennium.

At higher elevations in an adjacent drainage in the Wenatchee National Forest, Camp et al. (1997) evaluated fire refugia, defined as places where fire was less likely to burn. Fire refugia were generally found in areas above 1200 m and either on north aspects or near the confluences of larger streams. Conversely, Olson (2000) found fire occurrence in riparian zones to be only slightly less frequent than on adjacent uplands in similar forest types in the Blue Mountains in Oregon. In the Teanaway study, the scale of analysis was too coarse to evaluate the effect of riparian areas on fire activity. In our reconstructions, we assumed that riparian zones would be fire boundaries if fire activity was recorded on only one side. Our reconstructed fires (see Wright 1996, and Fig. 6) show fires stopping at creeks and rivers, when in fact the fires could have crossed them (but not been recorded at the next sample location), or could have stopped before reaching the riparian area. Greater sampling intensity is required to more precisely map historical fire boundaries and address more specific spatially explicit questions relating to past fires.

Fire–climate relations

Interactions between climate and fire have been investigated at a wide range of spatial and temporal scales (Swetnam and Betancourt 1992, Grissino-Mayer and Swetnam 2000, Donnegan et al. 2001, Heyerdahl et al. 2002). An understanding of these interactions is necessary if ecosystem management strategies that aim to reintroduce or mimic the effects of fire are to be effective. Applying spatial and temporal patterns of fire occurrence and size to landscapes that currently exist under different climatic regimes could lead to unexpected and undesired changes in ecosystem properties and processes (Donnegan et al. 2001), including, for example, a shift from a surface to a crown fire regime, and the attendant forest structure and composition changes such a shift would cause.

TABLE 2. Historical tree density and basal area of the major plant association groups of the forests of the lower Teanaway River drainage, based on General Land Office survey records.

Plant association group	Number of section corners	Density (trees/ha)	Basal area (m^2/ha)
Dry Douglas-fir	17	73.3	15.3
Dry grand fir	72	49.3	13.4
Wet grand fir	25	80.1	15.4

This study examined potential relationships between regional climatic conditions and fire frequency and size. Annual and short-term drought conditions appear to be associated with larger fires in the study area as indicated by negative values of the winter SOI and the PDSI during large fire years (Fig. 8). Warmer and drier conditions prevail during the negative phase of the winter SOI (El Niño) in the Pacific Northwest (Cayan et al. 1999). Warm, dry winters lead to lower than average mountain snow pack, and consequently earlier snow-free conditions. Early spring snowmelt lengthens the drying period for forest fuels making them flammable for longer time periods. While fire occurrence was relatively common throughout the historical record in the study area (a fire every three years regardless of historical weather conditions), early spring/drought episodes during some years apparently increased the probability that a fire could start during, or persist until, conditions occurred that caused it to spread widely (e.g., strong winds, very dry fuels, low relative humidity). Large fires occurred in most instances when warm, dry winters (El Niño years) and persistent drought conditions occurred sequentially (synchronous highly negative spikes in Fig. 7). Teleconnections with ENSO have also been observed in mixed-conifer and ponderosa pine forests in the southwestern United States and in various ecosystems in Florida. Wetter than

TABLE 3. Historical species composition and structure of the major plant association groups of the forests of the lower Teanaway River drainage, based on General Land Office survey records.

	Plant association group					
	Relative density (%)			Relative basal area (%)		
Species	Dry Douglas-fir	Dry grand fir	Wet grand fir	Dry Douglas-fir	Dry grand fir	Wet grand fir
Ponderosa pine	76.5	61.4	32.3	72.9	70.5	38.8
Douglas-fir	22.1	35.4	58.1	26.4	28.2	53.9
Western larch	···	2.5	2.1	···	1.2	4.7
Lodgepole pine	···	···	4.3	···	···	1.3
Grand fir	1.4	···	···	0.7	···	···
Western red cedar	···	···	1.1	···	···	1.2
Hardwoods	···	0.7	2.1	···	0.1	0.1

average climatic conditions during the preceding one to three years apparently influenced fire occurrence by promoting the growth and accumulation of understory fuels, primarily grasses and pine needles in ponderosa pine forests in the Southwest (Swetnam and Baisan 1996, Swetnam and Betancourt 1998), and understory vegetation in Florida (Harrison and Meindl 2001). As with other watersheds in the eastern Cascades (Hessl et al. 2004), no such lagged relationships were observed in the Teanaway.

Historical vegetation

Historical vegetation data indicate that the forests through which past fires burned were composed primarily of large, widely spaced ponderosa pines suggesting that a single-canopy, old-growth forest structure was the typical dry forest structure that existed prior to European American settlement of the area. Whether it was a result of Native American burning, lightning ignitions, or both, can never be quantitatively determined. What appears to be certain is that the ponderosa pine-dominated forest was relatively stable as many trees achieved large size and old age in the presence of frequently occurring fires. Fire acted as a negative feedback, preventing its recurrence for several years and lowering potential fire intensity for a number of subsequent years. By frequently thinning the understory trees, fire maintained low tree density and limited insect outbreaks (Agee 1994, Hessburg et al. 1994). When weather was severe (i.e., dry and windy), fire sizes were often larger, but fire severity remained low. Today, fire severity has increased in all of the lower elevation forest types of the eastern Cascades (Agee 1993), due to fuel buildup, species composition shifts, smaller average tree size, and multi-layered canopies that act as fuel ladders.

General Land Office record reconstructions of historical vegetation are subject to several potential sources of bias (Manies et al. 2001, Whitney and DeCant 2001). Where trees are clumped rather than randomly distributed spatially, basal area and density are underestimated (Bourdo 1956), but the degree of bias is not known. Most studies of ponderosa pine-dominated forests show that clumped distributions are typical (Cooper 1961) so our estimates of basal area and density are likely low (Table 2). More surprising in our data, and one other study using General Land Office data in similar stands in the Washington Cascade Range (J. Dickinson, *unpublished data*), is the near absence of grand fir as a bearing tree. It appears as an outlier in the dry Douglas-fir type and is absent in both the wet and the dry grand fir plant association groups. Grand fir was not a common dominant in the dry grand fir plant associations until the advent of fire exclusion (Agee 1994), but we expected it to be more common historically in the wet grand fir plant associations. While grand fir appears but once in the section corner notes and not at all in the section line narratives of the Teanaway surveyors, it was recorded more commonly as a bearing tree in the adjacent Blewett watershed (northeast of the study area), another tributary of the Yakima River (McCracken et al. 1996). Plummer (1902) estimated that grand fir comprised only 2% of the timber volume of the Yakima watershed, so a surveyor tree selection bias against grand fir as a bearing tree does not appear to be the case. Grand fir was simply uncommon in the area. Of the major tree species, grand fir is the least fire tolerant, so the frequent fire typical of the lower Teanaway watershed apparently selected quite heavily against it.

High-severity fires have been documented in historical ponderosa pine forests of the Black Hills of South Dakota (Shinneman and Baker 1997). These, however, are forests transitional to boreal forest, and white spruce (*Picea glauca* (Moench) Voss) is an understory species. In the Teanaway River valley, high-severity fire was inferred at a few locations where fire-scarred stumps and trees were absent and single cohort age class stands existed, but these were in the wetter forest types (wet grand fir) and not the most common type of fire even in those forests. Stand-replacing fire events historically occurred at the stand scale (10–100 ha), not the landscape scale (>1000 ha), and served the purpose of creating scattered small to medium-sized patches on the larger landscape.

Both western larch and lodgepole pine are typical early seral species after high-severity fires in the *Abies grandis* forest series (Agee 1994). The very limited historical presence of western larch and lodgepole pine in the General Land Office records for the study area (Table 3) despite the widespread occurrence of *Abies grandis* series forests (Table 2) suggests that high-severity fire was not predominant. At higher elevations in the watershed, where the *Abies lasiocarpa* (Hook.) Nutt. (subalpine fir) forest series occurs, a high-severity fire regime predominates (Camp et al. 1997).

Management implications

Our reconstruction of a frequent surface fire regime across much of the study area suggests that the accumulation and longevity of coarse woody debris on the forest floor would have been limited. Similarly, snags likely were retained only for short time periods, but were also being created on a regular basis as a result of fire-caused mortality, particularly in small size classes. Coarse woody debris amounts would have been rather uniformly low in the dry Douglas-fir and dry grand fir plant association groups, and would have been more variable but generally higher in the wet grand fir associations, based on generalized patterns for low- and mixed-severity fire regimes (Agee 2002*a*).

The lower Teanaway has been managed as industrial forest land for the last century. Initial extraction of large-diameter ponderosa pines and subsequent management of the residual and second-growth forest has provided timber, wildlife habitat, and recreational opportunities. Given recent high-severity, stand-replacing wildland fires in regional forests of similar structure, composition, and environment, we feel the forests in the vicinity of the Teanaway valley, in their current state, comprise a nonsustainable ecological condition.

We would advocate management activities designed to mimic the historic range of variability using plant association group as a reasonable meso-scale planning unit in order to best tailor activities to the local site. To bring basal area into the historic range, management should emphasize producing fewer, but larger trees. It is not uncommon for dry grand fir sites that historically carried perhaps 50 trees/ha and 15 m^2 of basal area to have 10–15 times the density and 3–4 times the basal area today. Under severe fire weather, contemporary stand structures commonly support torching of trees, although conditions for independent crown fire appear to be marginal (Williamson 1999). Despite overstocking and altered composition, mixed-conifer forests in the Teanaway valley specifically, and the eastern Cascades in general, can be restored to more sustainable conditions with less hazardous fuels. Considerable economic and ecological challenges exist to restoring these forest structures, even if there were social consensus that this was desirable (Tiedemann et al. 2000). Thinning and prescribed fire can be used for restoration, but the smaller trees should be the focus of thinning, with the residual stand composed of larger, more fire-tolerant trees (Agee et al. 2000). This makes some operations economically marginal in the short term, but could produce valuable outputs over longer time periods when the added value of larger, higher quality trees, ecological stability and landscape resistance to severe fires and insect outbreaks is considered.

Some have suggested a conservative approach to restoration using prescribed fire, until the effects are better understood (Tiedemann et al. 2000). Their idea is that in the face of scientific uncertainty, we need to understand much more about the effects of fire on forest productivity and wildlife before applying it widely. Adopting too conservative an approach, though, is not a choice of no action. It inherently accepts the risks of high-severity wildfires, which are much greater now in the historically low-severity fire regimes of the eastern Cascades, as well as much of the West (Agee 2002*b*). Such high-severity wildfire will likely have much more severe consequences than the negative impacts of restoration activities, although wildfire occurrence is less deterministic in occurrence than restoration actions. The approach of Allen et al. (2002) seems more appropriate. With recognition that the risks of no action are unacceptable, they urge that restoration to more natural conditions is critical. Treatments must be flexible, and recognize not only the concerns addressed by Tiedemann et al. (2000) but the high levels of natural heterogeneity in these forest types. In some cases, staged restoration treatments will be preferable to attempted ''full'' restoration (see the example of experimental treatment levels of ''partial'' and ''full'' restoration in Fulé et al. 2002). Regardless of the operational mechanism, we agree with the recommendation to move ''toward an envelope of conditions encompassing 'natural variability' (Allen et al. 2002),'' while learning about effects and scale of treatment using monitoring and adaptive management.

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