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CLIMATIC AND HUMAN INFLUENCES ON FIRE REGIMES IN PONDEROSA PINE FORESTS IN THE COLORADO FRONT RANGE

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Abstract. In the northern Colorado Front Range, fire suppression during the 20th century is believed to have created a high hazard of catastrophic fire in ponderosa pine (*Pinus ponderosa*) forests. Since the early 1990s, resource managers have increased the use of prescribed fires to re-create fire regimes and forest structures similar to those of the pre-Euro-American settlement period in order both to reduce fire hazard and to improve forest health. To improve understanding of historical fire regimes, we conducted a study of fire history along an elevational gradient from ~1830 to 2800 m in ponderosa pine forests in the northern Front Range. Fire-scar dates were determined from 525 partial cross sections from living and dead trees at 41 sample sites. Fire frequencies and fire intervals were analyzed in relation to changes in human activities and interannual climatic variability as recorded in instrumental climatic records and tree-ring proxy records.

Prior to modern fire suppression, the low elevation, open ponderosa pine forests of the northern Front Range were characterized by frequent surface fires, similar in frequency to many other ponderosa pine ecosystems in the West. In contrast, in higher elevation forests (above ~2400 m) where ponderosa pine is mixed with Douglas-fir (*Pseudotsuga menziesii*) and lodgepole pine (*Pinus contorta*), the fire regime was characterized by a much lower fire frequency and included extensive stand-replacing fires as well as surface fires. In the mid-1800s there was a marked increase in fire occurrence that can be related both to Euro-American settlement and increased climatic variability. This episode of increased fire left a legacy of dense, even-aged stands in higher elevation ponderosa pine forests, whereas increased stand densities in low elevation forests are attributed mainly to fire exclusion during the 20th century.

Warmer and drier spring–summers, indicated in instrumental climatic records (1873–1995) and in tree-ring proxy records of climate (1600–1983), are strongly associated with years of widespread fire. Years of widespread fire also tend to be preceded two to four years by wetter than average springs that increase the production of fine fuels. Alternation of wet and dry periods over time periods of 2–5 years is conducive to fire spread and is strongly linked to El Niño–Southern Oscillation (ENSO) events. The warm (El Niño) phase of ENSO is associated with greater moisture availability during spring that results in a peak of fire occurrence several years following El Niño events. Conversely, dry springs associated with La Niña events were followed by more widespread fire during the same year.

The 1600–1920 fire-scar record indicates that individual years during which high percentages of the 41 sample sites synchronously recorded fire have occurred at least several times per century. The association of these years of widespread fire with very strong ENSO events demonstrates the importance of ENSO-related climatic variabililty in creating extreme fire hazard at a landscape scale.

Key words: climatic variation; Colorado; El Niño–Southern Oscillation; fire regime; forest dynamics; forest health; Pinus ponderosa.

INTRODUCTION

In the western United States fire exclusion in many forest ecosystems during most of the 20th century is believed to have caused changes in forest structure that make forests more susceptible to widespread crown fires and to outbreaks of pests and disease (Sampson et al. 1994, Little 1995, Illg and Illg 1997). For example, in many ponderosa pine (*Pinus ponderosa*) forests during the 20th century, decreased occurrence of formerly frequent surface fires is associated with historically unprecedented increases in stand densities and fuel accumulations (Cooper 1960, Mutch et al. 1993, Covington and Moore 1994, Arno et al. 1995, Covington et al. 1997, Fulé et al. 1997). These changes in forest structure are believed to have increased the susceptibility of ponderosa pine forests to outbreaks of disease and insect pests and to occurrence of extensive stand-replacing fires. Resource managers are trying to restore such ecosystems to their pre-20th century struc-

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ture and composition by reintroducing fire in the form of prescribed burns (Covington et al. 1997, Fulé et al. 1997).

Resource managers increasingly rely on knowledge of pre-20th century fire history to refine management goals and to demonstrate to the general public that fire frequencies during the present century are outside the range of historical variability characteristic of a particular landscape (Morgan et al. 1994, Cissel et al. 1998). The most abundant historical information, both photographic and documentary, on forest conditions and disturbance patterns during the period prior to fire exclusion is from the late 1800s to early 1900s (Kaufmann et al. 1998). In developing knowledge of reference conditions for guiding ecological restoration, it is sometimes assumed that forest conditions documented photographically in the 1870s to 1890s are consistent with patterns over the previous several centuries (Dahms and Geils 1997). However, several studies in ponderosa pine forests in Colorado have shown that fire frequencies were atypically high during the latter half of the 19th century in comparison with the previous 150 to 250 years (Rowdabaugh 1978, Laven et al. 1980, Skinner and Laven 1983, Goldblum and Veblen 1992, Alington 1998). Thus, longer term historical studies of fire occurrence are important for evaluating possible changes in fire frequencies that may have influenced forest conditions by the time of their photographic documentation in the late 1800s. Historical studies of fire regimes and forest conditions are also important in developing public support for fire hazard mitigation practices such as forest thinning and prescribed burning. Given the short-term period of observations by humans, it is particularly important to document extreme fire hazard associated with weather conditions that may occur at frequencies of only a few events per century.

Both for predicting fire hazard and for evaluating effects of suppression activities on fire regimes, resource managers need better information on the sensitivity of specific ecosystem types to interannual climatic variation. For example, in ponderosa pine forests of the southwestern United States fire regimes are highly sensitive to interannual and multidecadal climatic variability related to the changes in tropical Pacific sea-surface temperature and pressure known as the Southern Oscillation (Swetnam and Betancourt 1992, 1998). Large-scale warming of sea-surface temperatures in the eastern and central equatorial Pacific is known as the El Niño phase of the Southern Oscillation, and the reverse phase is termed La Niña. El Niño/Southern Oscillation (ENSO) refers to the coupled ocean–atmosphere system in which El Niño and La Niña are extreme phases (Enfield 1989). In the Southwest, winter–spring precipitation tends to be above average in the year after the onset of El Niño and below average after the onset of La Niña (Andrade and Sellers 1988). Both tree-ring studies and documentary records of fire history in the Southwest show that fires are more widespread during La Niña events (Swetnam and Betancourt 1998). Although the climatic response of the Colorado Front Range to ENSO events is not as consistent as in the Southwest, there is a similar but weaker association of ENSO events and spring precipitation (Kiladis and Diaz 1989). Furthermore, two tree-ring chronologies at subalpine sites (∼3400 m) in the northern Colorado Front Range show a detectable ENSO signal over the past several 100 years (Woodhouse 1992). Consequently, we hypothesized that ENSO events significantly influence fire occurrence in the northern Colorado Front Range.

In the northern Front Range forest managers are currently using prescribed fire to reduce fuels and restore ponderosa pine forests to their presettlement structure (Colorado State Forest Service 1998, City of Boulder 1999). The management goals include the improvement of forest health and the reduction of the hazard from wildfires that would endanger human lives and property. To evaluate the appropriateness of management goals and prescriptions, as well as to garner public support for increased prescribed burning, resource managers need to address the following questions: (1) How significantly has modern fire exclusion reduced fire frequency during the present century? (2) After initiation of large-scale Euro-American settlement in the 1850s did fire occurrence change relative to the previous century? (3) What was the variability in pre-20th century fire behavior and frequency over the elevational range of ponderosa pine forests from ∼1800–2800 m? (4) How is the hazard of wildfire related to interannual climatic variability affecting quantities and desiccation of fine fuels as opposed to long-term fuel accumulations related to forest management? To help address these questions we developed an extensive fire history data set covering the entire elevational range of ponderosa pine in the northern Front Range, which we used to examine long-term trends in fire occurrence and to evaluate the sensitivity of fire occurrence to interannual climatic variation.

Study Area and Methods

We sampled fire history in the montane zone (∼1830–2790 m) of the eastern slope of the northern Colorado Front Range at 41 sites over an ∼45 km north–south distance from near Estes Park to Pinecliff (Fig. 1). The bulk of the Front Range in this area is composed of a core of acidic Precambrian intrusive rocks, which in turn have been intruded by acidic Tertiary plutons (Madole 1973). Toward the east at elevations below ∼2200 m, outside of the mineralized belt are a series of narrow sedimentary formations forming cuestas and hogbacks. Soils are highly variable but are usually coarsely textured and shallow. In the study area, mean annual temperature ranges from 10.9°C at an elevation of 1646 m to 4.7°C at 2590 m for 1944–1997 (Colorado Climate Center, Colorado State University,

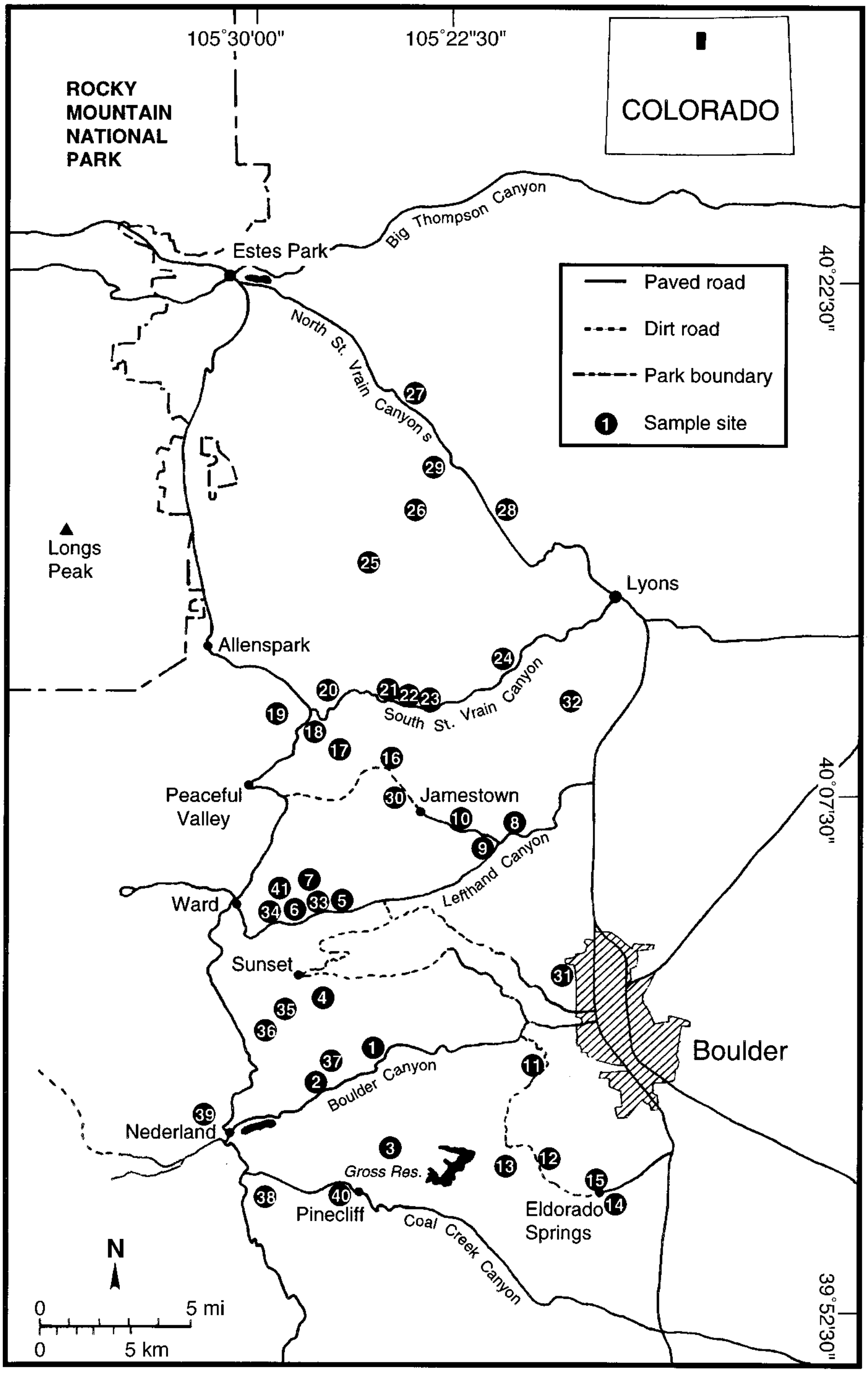


FIG. 1. Map showing the locations of the 41 sites sampled for fire scars in the northern Colorado Front Range.

Ft. Collins, Colorado, *unpublished data*). Precipitation is less variable with elevation, ranging from 482 mm at 1646 m to 536 mm at 2590 m over the same period (Colorado Climate Center, Colorado State University, Ft. Collins, Colorado *unpublished data*). Precipitation peaks in April and May. Low precipitation and high temperatures during June through September coincide with a peak in fire occurrence based on records from adjacent Rocky Mountain National Park.

On the eastern slope of the Colorado Front Range, the structure of ponderosa pine-dominated ecosystems varies with elevation, ranging from open forests at the

TABLE 1. Summary information on elevational groups of sample sites and on fire scars over the full record for each group.

Group	Range of site median elevations (m)	Sites included	Total search area (ha)	No. of samples (trees)	No. of fire years	Earliest fire (year)	Year of ≥3 scarred trees	Latest fire
F	2630–2670	4, 7, 35, 36, 37, 39, 41	335	99	57	1552	1581	1983
E	2500–2624	6, 16, 17, 19, 33, 34, 40	346	91	46	1474	1564	1986
D	2440–2488	2, 3, 5, 18, 20, 25, 37	624	94	29	1584	1624	1977
C	2189–2432	1, 13, 21, 22, 26, 27, 30	438	72	31	1597	1624	1976
B	2048–2177	10, 11, 12, 23, 28, 29, 32	320	72	36	1595	1624	1930
A	1884–2015	8, 9, 14, 15, 24, 31	261	97	58	1513	1567	1951

Note: For site locations see Fig. 1.

ecotone with Plains grasslands (∼1800 m) to dense mixed stands with Douglas-fir (*Pseudotsuga menziesii*) and lodgepole pine (*Pinus contorta*) at >2500 m (Marr 1961, Peet 1981). With increasing elevation there is also an increase in the importance of aspen (*Populus tremuloides*) and limber pine (*Pinus flexilis*). Throughout the elevational range of ponderosa pine, north-facing, moister slopes tend to be more densely forested and characterized by greater relative abundances of Douglas-fir (Marr 1961).

Native Americans settled and hunted in the Front Range for at least several thousand years prior to the first permanent settlement by Euro-American settlers in the late 1850s (Buccholtz 1983). There are 19th century reports of Native Americans intentionally setting fires in the Front Range and in northwestern Colorado for driving game animals and occasionally in warfare (Jack 1899, Sudworth 1899). However, it is not known how abundant anthropogenic ignitions were in comparison to lightning ignitions. Mineral prospecting in the 1850s yielded a major gold strike in 1858 and subsequent rush of miners and other settlers (Pettem 1980, Smith 1981). There are numerous reports of early settlers intentionally setting fires during the second half of the 19th century (Tice 1872, Fossett 1880, Jack 1899, Clements 1910, Fritz 1933). Livestock numbers are believed to have peaked in the 1890s to early 1900s (Marr 1961), and most of the area has not been grazed since the 1960s. Selective logging of ponderosa pine and Douglas-fir was widespread from the late 1850s to the early 1900s, but subsequent logging has been minor (Veblen and Lorenz 1991). Most of the northern Front Range (including present-day Arapaho-Roosevelt National Forest) was included in the Medicine Bow Forest Reserve in 1905 and subsequently would have been subjected to a fire suppression policy (Veblen and Lorenz 1991). However, lack of personnel and infrastructure probably reduced the effectiveness of fire suppression during the first two decades of the present century.

Field sampling

Forty-one sites were sampled for fire scars during the summers of 1993–1995 on lands belonging to Arapaho-Roosevelt National Forest, City of Boulder Open Space, City of Boulder Mountain Parks, and Boulder County Open Space (Fig. 1). Given the history of extensive 19th century logging and the loss of old trees to recent insect outbreaks, trees older than ∼200 years are relatively rare in the Front Range. Consequently, sampling had to focus on subjectively located stands of older trees on properties to which researchers could gain access. The sample sites were widely dispersed to fully sample the elevational range of ponderosa pine from ∼1830 to 2800 m.

Vegetation types sampled range from open forests of ponderosa pine below ∼1900 m to dense forests of ponderosa pine with Douglas-fir and/or lodgepole pine, especially above 2500 m. Each sample site was systematically searched for fire-scarred trees. Fire scars were sampled nondestructively by cutting partial cross sections following the techniques of McBride and Laven (1976). Wherever possible, samples were collected in clusters because it is unlikely that individual trees record every scar that burns in the vicinity (Arno and Sneck 1977). The goal was to collect at least 10 fire scars per site without exceeding a search area of 200 ha. However, the number of scars sampled per site ranged from 6 to 37 scars depending on the availability of fire-scarred trees. Locations of sampled trees were recorded on 1:24 000 topographic maps to permit estimation of the area sampled, which ranged from 10 to 190 ha (median of 50 ha). A total of >700 fire-scarred trees (live and dead) was sampled from which 525 sections yielded annually precise fire dates. On the other samples, precise dating was not possible due to decay or crossdating problems. Ninety percent of the 525 wedges used were from ponderosa pine, including 60 samples from snags and cut stumps. Douglas-fir, limber pine, and lodgepole pine accounted for the other 10% of the samples.

To examine possible variations in fire regime associated with elevation, the 41 sample sites were arranged by their median site elevations and divided into six groups of six to seven sites each of similar elevation (Table 1). Since only a few sample sites recorded more than 10 fires, grouping of sites was also necessary to obtain enough fire dates for detection of temporal trends and statistical analyses.

Sample processing

Standard methods were used to prepare cross sections for dating of fire scars (Arno and Sneck 1977, McBride 1983). On sanded samples from live trees, dates of rings containing fire scars were determined by counting backwards from the outermost ring and were verified by graphically crossdating against marker rings from master tree-ring chronologies from nearby sites (McBride 1983). Fire scars from dead trees and from trees with severely suppressed growth were crossdated by measuring ring widths and using the program COFECHA (Cook and Holmes 1984), which compares the ring-width series with a master tree-ring chronology from the nearby site. COFECHA was used to correlate 50-year segments (overlapped by 25 years) of the undated series against a master chronology derived from several nearby ponderosa pine ring-width chronologies. Samples that could not be conclusively dated to an annual resolution were not included in the analyses. Dormant season (September through April) scars were assigned to the calendar year corresponding to autumn because modern fire records for the Front Range indicate fires are >5 times more common during the autumn (September through December) than during winter or early spring (January through May; Rocky Mountain National Park, *unpublished data*).

Data analyses

Fire interval analyses.—A fire interval is the time period between two consecutive fires affecting the same area (composite interval) or the same tree (point interval). The computer program FHX2 (Grissino-Mayer 1995), an integrated software package for analysis of fire history information from tree-rings, was used to analyze fire-interval data. Composite fire intervals (sensu Dieterich 1980) refer to fires affecting a group of trees or occurring within a specified area (i.e., either a single sample site or group of sample sites). Since trees that have been initially fire scarred are more likely to record subsequent fires due to the loss of some protective bark, trees are considered recorder trees only from the date of their initial scarring until the date of their death or date of field sampling (Romme 1980). Fire intervals were analyzed for: (1) years in which a minimum of two recorder trees was scarred in at least one site; and (2) years in which scars were recorded in at least two of the 41 sample sites and on ≥10% of all trees in an elevational group of sites. The second type of fire year implies that a much larger percentage of the landscape burned, either in single or multiple events, during a single year.

Two measures of fire frequency were derived from fire interval distributions: mean fire intervals (MFI) and the Weibull Median Probability Interval (WMPI). MFI is the average number of years between consecutive fire dates in a composite chronology (Dieterich 1980, Romme 1980). However, because fire intervals are typically positively skewed (Baker 1992), fire intervals are often fit to a Weibull distribution in which case the central tendency is described as the fire interval associated with the 50% exceedance probability of the modeled distribution (Johnson and Van Wagner 1985, Grissino-Mayer 1995). Half the fire intervals in the modeled frequency distribution will be longer or shorter than WMPI.

Temporal trends in fire occurrence were examined by comparing mean fire intervals in different time periods and by plotting annual time series of the percentages of sites and recorder trees that recorded fires. Due to the mortality and decay of old trees, evidence of old fires gradually disappears. Consequently, only the most recent 70 years of the Native American period (1781–1850) was used for statistical comparison of fire intervals with the subsequent period of Euro-American settlement (1851–1920). Similarly, in constructing two composite indices of changes in fire occurrence over time, we used percentages of recorder trees and of recorder sites instead of absolute numbers of either. Thus, the bias expected from larger numbers of younger recorder trees is eliminated.

Relationships of fire to climatic variation.—Mean climatic parameters were compared for fire years and nonfire years based on both an instrumental climatic record and a climatically sensitive tree-ring record. Superposed epoch analysis (SEA; Baisan and Swetnam 1990) was used to test the null hypothesis that there is no relationship between occurrence of fire years and climatic conditions in the years preceding and during fire years. Mean values of climatic parameters from instrumental records or tree-ring proxy records (described below) were calculated for five to nine-year windows including the year of the fire event. Mean values of climatic parameters preceding, during, and following fire years were compared to variation in the complete record by performing Monte Carlo simulations that randomly pick years, calculate expected means, and provide 95% bootstrap confidence intervals (Mooney and Duval 1993, Grissino-Mayer 1995). In each case, the number of randomly selected years equals the number of actual fire years. Results are described as percentage departures from the mean values determined by the random selection of nonfire years.

The instrumental climate record used was the Denver record (Colorado Climate Center, Colorado State University, Ft. Collins, Colorado, *unpublished data*), which is the longest and most complete record in the Front Range. The Denver record includes data collected in the City of Denver from 1873 through 1934 and from the airport 6 km to the northeast from 1935 through 1995. For the recording period common to both locations (1935–1972) mean annual temperature and precipitation at the two stations had common variances (F ratio; $P < 0.05$) and were highly correlated ($r > 0.90$). Thus, a single record was created by normalizing the two records and using monthly standard deviations as the independent variables in analyses of climatic relationships of fire and radial tree growth.

To permit analyses of fire–climate relationships over a multi-century period, a regional tree-ring record of

TABLE 2. Characteristics of ponderosa pine chronologies used in creating a climatically sensitive regional tree-ring chronology.

Site	Latitude N	Longitude W	Elevation (m)	Number of trees	Number of cores	First order auto-correlation	Mean series inter-correla-tion	Record period (year)
Waterdale (H. C. Fritts)	40°25′	105°12′	1707	10	20	−0.04	0.77	1680–1964
Deer Ridge (this study)	40°22′	105°34′	2580	15	27	−0.02	0.73	1715–1996
Deer Mountain (D. A. Graybill)	40°22′	105°35′	2610	11	26	−0.03	0.76	1640–1987
Lykins Gulch (D. A. Graybill)	40°10′	105°17′	1840	11	22	0.16	0.71	1690–1987
Eldora (F. Kienast)	39°57′	105°33′	2650	11	21	0.13	0.59	1716–1982
Eldorado Canyon (D. A. Graybill)	39°56′	105°16′	1890	17	32	0.00	0.74	1677–1988
Van Bibber Creek (D. A. Graybill)	39°57′	105°14′	1930	13	26	0.07	0.77	1690–1987
Jefferson County Open Space (D. A. Graybill)	39°41′	105°12′	1970	12	25	−0.03	0.75	1550–1987

Notes: The first-order autocorrelation is the serial correlation coefficient for the residual chronology at a lag of one year. The mean first-order autocorrelation for all eight sites is 0.03, and the mean series intercorrelation (i.e., mean of all comparisons of pairs of sites) is 0.62. Contributors of the tree-ring collections to the International Tree-Ring Data Bank of NOAA are listed in parentheses after the name of each site.

climatic variability was developed from eight ponderosa pine ring-width chronologies. Seven were developed from data in the International Tree-Ring Data Bank of the National Oceanic and Atmospheric Administration (NOAA) for the time span 1550–1988, and an eighth chronology was developed from a site sampled in 1996 (Table 2). The eight tree-ring data sets were combined into an average tree-ring chronology based on the following procedures. First, possible measurement or dating errors were identified with the computer program COFECHA (Holmes 1983), which compares each tree-ring series against all other series within each site. Any tree-ring series with potential errors was removed from the data set. Second, mean chronologies for each of the eight data sets were produced with the computer program ARSTAN (Cook and Holmes 1984). This involved fitting the individual tree-ring series to a negative exponential or a straight line to initially detrend the series. The tree-ring indices resulting from this first detrending were then detrended a second time using a cubic-smoothing spline. Finally, autoregressive modeling (Cook 1985) was performed on the detrended tree-ring indices to produce the residual chronology in which first-order serial autocorrelation (i.e., autocorrelation at a time lag of one year) was reduced to near zero. Residual chronologies are used in dendroclimatic studies because removal of the serial autocorrelation is required for some statistical analyses. The mean serial autocorrelation for the eight ponderosa pine chronologies is 0.03 (Table 2).

To test the climatic sensitivity of radial tree growth, the residual chronology for each of the eight sites was compared to monthly temperature and precipitation records from the Denver station using correlation function analysis (Blasing et al. 1984). Correlation coefficients were computed between ring indices and climate variables for a sequence of average values for three-month seasons starting with the fall of the calendar year before the growing season and ending with the summer of the growing season. Since all eight chronologies showed highly similar correlations to climatic variation, they were averaged into a single regional record of climatic variation. During decades-long periods of distinct climate, the influence of a climatic parameter on tree growth may differ. For example, high spring–summer temperatures may shift from a neutral or positive influence during wet periods to a negative influence on tree growth during drought periods. Because a previous study had detected some instability of climate–tree growth relationships associated with warmer and drier conditions during the 1930s and 1940s in the Front Range (Graybill 1992), climate–tree growth relationships were examined and compared for a cool–wet period (1873–1929), a warm–dry period (1930–1959), and a period of intermediate climatic conditions (1960–1995). Correlation coefficients between tree-growth and seasonalized climatic parameters maintained the same signs and statistical significance for the same seasons for all three periods. Consequently, the entire 1873–1995 period was used.

Three types of records of ENSO activity were used to examine possible influences of ENSO on regional climate, tree growth, and fire occurrence. The use of all three types of ENSO records is required both for verification of proxy records against modern instrumental records and for extending the analysis backwards in time. The first record is the Southern Oscillation Index (SOI) based on differences in standardized sea-level pressure between Tahiti and Darwin, Australia (Ropelewski and Jones 1987). Positive values of SOI generally indicate La Niña (cold) events and negative values indicate El Niño (warm) events. The average winter (December through February) SOI was used to relate fire years to ENSO activity from 1883 to 1995 and to examine relationships between ENSO and climatic parameters from the Denver instrumental record. The second record is a tree-ring reconstruction of winter SOI (Stahle and Cleaveland 1993), which was

TABLE 3. Fire interval statistics (in years) over the period 1650–1920 for fire event years defined as years in which two or more trees recorded fire scars or in which ≥10% of recorder trees in an elevational zone (and in two different sample sites) recorded fire scars.

Elevation (m)	No. fire intervals	WMPI	MFI	SD	Minimum fire interval	Maximum fire interval
Fire years of ≥2 trees scarred						
2630–2670	14	10.4	18.6	24.6	1	88
2500–2624	15	8.1	17.2	25.0	1	92
2440–2488	11	11.6	22.4	36.3	1	125
2189–2432	14	14.4	17.7	15.4	1	63
2048–2177	17	9.0	13.4	13.7	1	47
1884–2015	28	6.4	8.3	7.6	1	29
Fire years of ≥10% of trees scarred						
2630–2670	6	21.8	34.3	32.0	1	88
2500–2624	6	30.8	40.3	29.8	1	92
2440–2488	5	31.2	43.4	48.1	7	125
2189–2432	11	15.7	19.3	16.8	1	63
2048–2177	8	23.0	23.6	11.3	14	47
1884–2015	16	12.0	14.4	11.7	2	46

Notes: WMPI is the Weibull median probability interval. MFI is the mean fire interval, and SD is the standard deviation of the MFI.

used to extend the analysis of ENSO influences on fire and tree-growth patterns backwards to 1699. The tree-ring reconstruction was based on regionally averaged tree-ring data from Mexico and Oklahoma, which accounts for 41% of the variance in winter SOI from 1900 to 1971 (Stahle and Cleaveland 1993). The third record is Quinn's (1992) documentary compilation of El Niño events from 1525 to 1987, which was used to further extend the analysis back in time. Fire occurrence during years identified in Quinn's (1992) qualitative record as El Niño years are compared to non-El Niño years.

RESULTS

Fire intervals: spatial and temporal trends

The total of 525 sections yielded 909 crossdated fire-scar dates with the earliest fire dated in 1474 and the most recent in 1986 (Table 1). By the year 1650 there were at least five trees and three older fire scars in each elevational data set. Thus, to compare the long-term fire regimes of the different elevational zones, fire intervals were computed from 1650 until the beginning of fire suppression in 1920 (Tables 3 and 4). Over this period and at the spatial scale of the total search areas for each elevational zone (i.e., 261–624 ha), the minimum interval between fires that scarred ≥2 trees was one year in all zones (Table 3). At the scale of individual trees, five of the six zones had minimum point return intervals of <10 years (Table 4). Despite the potential for such frequent fire occurrence, maximum composite fire intervals were 29–125 years and 46–125 years for years of ≥2% and ≥10% trees scarred, respectively (Table 3). Similarly, the high standard deviations of the mean fire intervals indicate a high degree of variation in the occurrence of fire from 1650 to 1920.

All measures of fire occurrence indicate that between 1650 and 1920 the lowest elevational zone was characterized by the highest fire frequency (Tables 3 and 4). Composite fire intervals indicate that years of widespread fire (years with ≥10% trees scarred) are more than twice as frequent in the zone below 2015 m as above 2440 m. Elevational difference in intervals between years with ≥2 trees scarred is much less striking (Table 3; Fig. 2). Larger search areas should yield more fire-scarred trees, and, consequently, higher fire frequencies are expected for larger search areas. Given that the 1884–2015 m zone has the smallest search area (261 ha vs. an average of 413 ha for the other five zones), smaller intervals between years of widespread fire clearly indicate a higher fire frequency in the lowest elevational zone. Similarly, more than twice as many point return fire intervals are recorded for the lowest zone than any other zone (Table 4). At individual sites in the low elevation zone, fires often recur to the same tree in fewer than 10 years (Fig. 3b) whereas at high elevation sites few trees record two fires in fewer than 30 years (Fig. 3a).

Percentages of recorder trees and recorder sites with

TABLE 4. Point fire intervals (in years) over the period 1650–1920.

Range of site median elevations (m)	No. fire intervals	WMPI	MFI	SD	Minimum	Maximum
2630–2670	28	61.0	67.6	40.1	4	140
2500–2624	40	59.0	67.0	45.7	7	205
2440–2488	38	62.8	69.3	44.8	6	205
2189–2432	38	63.0	68.4	40.7	9	192
2048–2177	54	60.0	63.3	33.3	14	158
1884–2015	124	30.2	35.7	27.5	3	177

Notes: WMPI is the Weibull median probability interval. MFI and SD are defined as in Table 3.

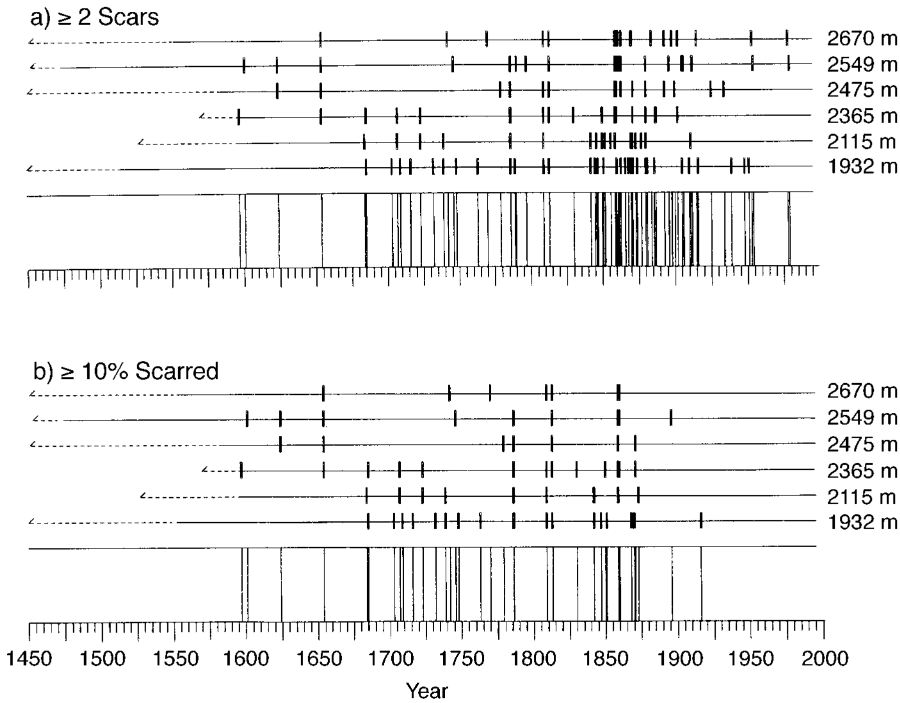


FIG. 2. Composite fire-scar records indicating years in which (a) a minimum of two recorder trees were scarred in at least one site and (b) at least two of the 41 sample sites and ≥10% of all trees in an elevational group of sites recorded fire. Each horizontal line represents a different elevational zone of sites (Table 1) including the information from 72–99 fire-scarred trees. Dates of fire scars are indicated by short vertical lines. Dashed horizontal lines indicate years prior to the occurrence of the first scar in that group; diagonal lines indicate the date of the earliest innermost ring in that group. Vertical lines drawn to the *x*-axis indicate dates of all fires of each respective type (≥2 scars, ≥10% scarred) in all elevational groups. Elevations are given as the midpoint of the elevational range for each group of sites (Table 1).

fire-scarred trees are used for describing temporal trends in fire occurrence over the entire study area. Both of these fire indices indicate an increase in fire occurrence from the 1600s to the 1700s, but sample sizes are relatively small until the late 1600s (Fig. 4). Fire years are frequent during the 1700s, but decline in frequency after 1780 even though high percentages of trees were scarred in some single years (e.g., 1786; Fig. 4b). Both fire indices indicate relatively long fire intervals for the entire study area from ~1780 to 1840, followed by a peak in fire in the latter half of the 1800s. Percentage of sites recording fire, which better indicates spatial extent of fires, shows that fires were widespread during the latter half of the 1800s (Fig. 4a). Mean fire intervals for years with >2 fire scars for the entire study area decline from 2.4 years in 1780–1850 to 1.31 years in 1851–1920 ($P < 0.03$; Kolmogorov-Smirnov test for significantly different distributions).

All elevational zones show a decline in fire frequency after ~1920 that is particularly marked for years of widespread (≥10% trees scarred) fire (Fig. 2). For both years of ≥2 trees scarred and ≥10% trees scarred, each zone records relatively long fire-free intervals during the late 1700s to early 1800s. For years of ≥2 trees scarred there is an increase in fire frequency from the late 1850s to early 1900s for the upper three elevational zones (Fig. 2a). For the lower two elevational zones this increase in fire frequency begins in the 1840s (Fig. 2a).

Climatic influences

Mean monthly temperature and precipitation for all single months and consecutive two-month combinations were compared for years with ≥2 trees scarred and nonfire years for 1873–1995 using the Denver instrumental climatic record. Only the months of May through August yielded statistically significant results and are presented here (Fig. 5). Since 1873, years in which ≥2 trees were scarred are associated with below average precipitation during May through August (Fig. 5). Summer temperatures during the year preceding fire years tend to be below average, and spring or summer precipitation two to four years preceding fire years tends to be above average (Fig. 5). Thus, the overall pattern associated with fire years is greater moisture availability (due either to cooler temperatures or more precipitation) one to four years prior to a fire year coinciding with spring or summer drought during the year of the fire.

By establishing that tree-ring widths of ponderosa pine can be used as a proxy for moisture availability, the analysis of climatic influences on fire years can be

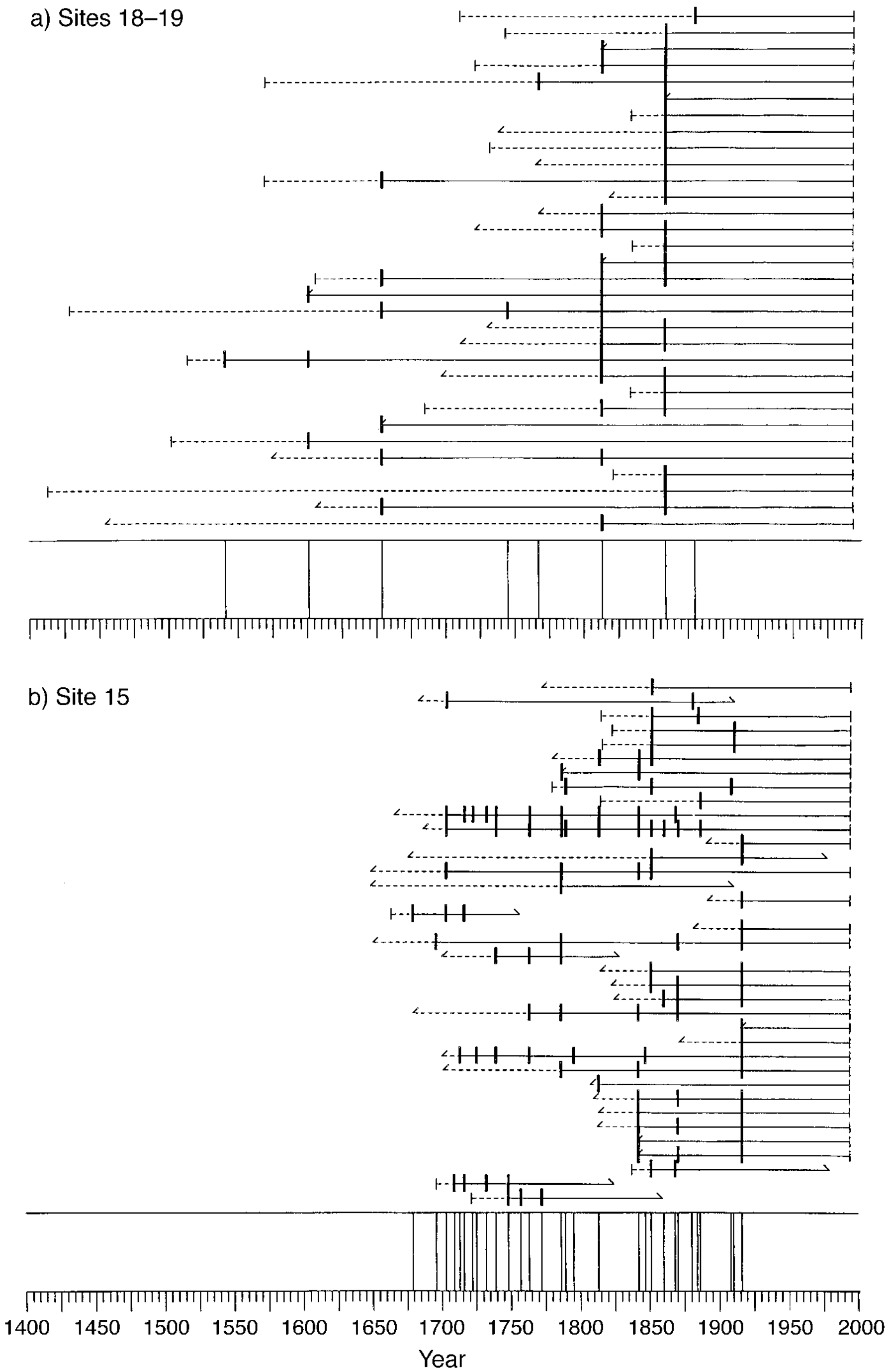


FIG. 3. Composite master fire charts for (a) sites 18–19 (274 ha) at 2414–2682 m elevation and (b) site 15 (72 ha) at 1853–1914 m elevation. Each horizontal line represents a fire-scarred tree on which bold vertical lines indicate fire-scar dates. Innermost rings are indicated by diagonal lines, pith dates by thin vertical lines, and recorder vs. nonrecorder years by dashed vs. solid horizontal lines. Vertical lines drawn to the *x*-axis indicate dates of any fire occurrence at each site.

extended over several centuries. Growth of ponderosa pine is positively correlated with spring–summer (March–August) precipitation and negatively correlated with spring–summer temperature during the current growing season (Fig. 6). Fall (September–November) temperature and precipitation of the year preceding the year of tree-ring formation have a similar influence on growth. Thus, the ponderosa pine chronology is an indicator of variation in moisture availability, especially during the spring of the year of ring growth. Over the

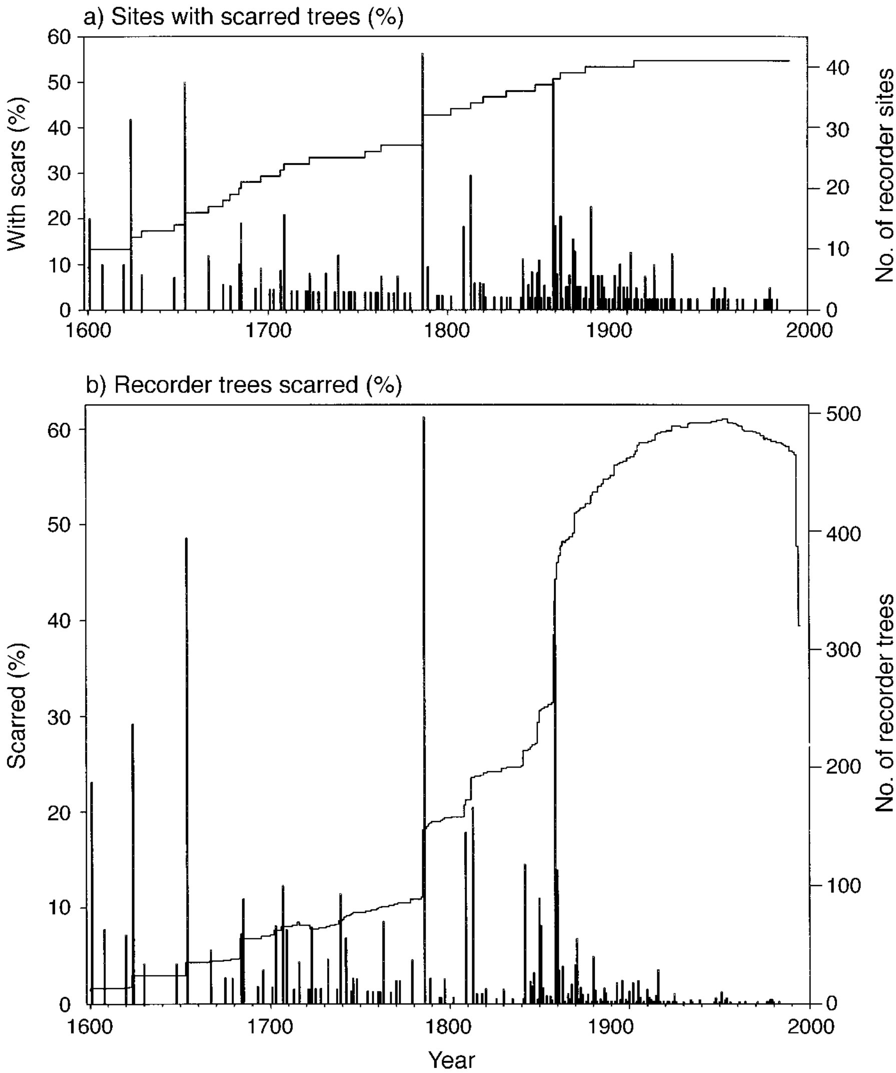


FIG. 4. Fig. 4. Percentage of sites with (a) scarred trees per year and (b) percentage of samples (recorder trees) scarred per year based on all 41 sites. Sample depth lines give the number of sites with (a) recorder trees alive and (b) the total number of recorder trees alive in each year.

period 1600–1983, fire years are associated with narrow tree-rings in ponderosa pine indicating the association of fire and drought (Fig. 7a). Analogous to the findings with the Denver instrumental record, tree-rings tend to be wider (i.e., indicating greater moisture availability) two years prior to fire occurrence.

Winter SOI from the instrumental record (1883–1995) as well as reconstructed winter SOI (1699–1971) are strongly correlated with warmer and drier springs of the same year in the Denver instrumental record (Fig. 8). Thus, the tree-ring reconstruction of winter SOI can be used to extend the fire-climate analysis backward in time. Over the period 1600–1971, fire years show positive departures from the mean of reconstructed winter (December through February) SOI (i.e., Niña conditions) during the fire year (Fig. 7b). The negative departure of SOI four years prior to fire years suggests that fire years tend to follow El Niño events by four years but is not statistically significant. A strong coupling of fire to the ENSO cycle is indicated by marked peaks in percentages of both recorder sites and recorder trees with fire scars four years following strong or very strong Niño events as listed in Quinn's (1992) record (Fig. 9). Since most of Quinn's El Niño events span two (and sometimes three) calendar years, these results suggest an increase in fire occurrence one to three years following increased spring precipitation during the year after the onset of an El Niño event. This timing is consistent with increased fire occurrence two to four years following above-average precipitation seen in the instrumental climatic record (Fig. 5).

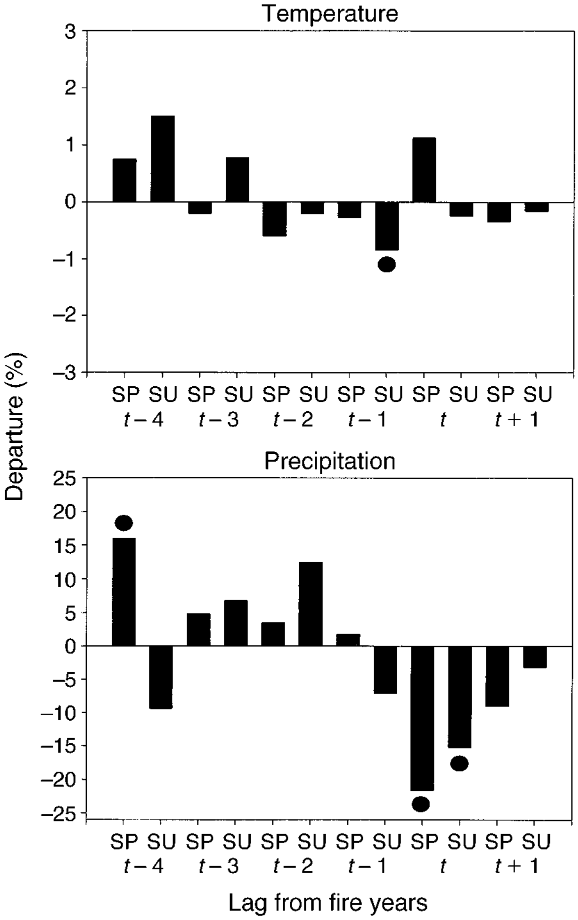


FIG. 5. Spring and summer temperature and precipitation departures for the Denver climate station (1873–1995) for lag years (t = time) −4 through +1 for years during which ≥2 trees were scarred (n = 29). Departures are percentage differences from means derived from a random selection of the same number of years as fire years. SP (spring) is May–June, and SU (summer) is July–August. Dots indicate statistical significance determined from bootstrap 95% confidence intervals based on 1000 Monte Carlo simulations of the same number of years as fire years (Mooney and Duval 1993).

Discussion and Conclusions

Spatial variation in the fire regime

Prior to the beginning of fire exclusion in ~1920 in the northern Front Range, low elevation ponderosa pine forests experienced substantially higher fire frequencies than high elevation ponderosa pine forests (Tables 3 and 4). Both fuel desiccation and rate of herbaceous fuel recovery probably contributed to this higher fire frequency. At low elevation the greater importance of grass fuels allowed quicker regrowth of fine fuels following a fire, and these fine fuels are more easily desiccated by the higher temperatures and lower precipitation of low elevations. This elevational trend in fire frequency is consistent with patterns reported for ponderosa pine forests in the Southwest (Swetnam and Baisan 1996, Touchan et al. 1996) and also with the much lower fire frequencies reported for subalpine (i.e., above ~2800 m) forests in the Colorado–Wyoming Rocky Mountain region (Clagg 1975, Romme and Knight 1981, Romme and Despain 1989, Kipfmueller 1997, Alington 1998; Veblen *in press*).

Prior to Euro-American settlement the higher elevation ponderosa pine forests appear to have been characterized by a mixed fire regime that included both surface fires and common stand-replacing fires. Forest age structures and historical photographs from the late 1800s indicate that stand-replacing fires were common in the 19th century in the higher elevation ponderosa pine forests of the northern Front Range (Veblen and Lorenz 1986, 1991). The occurrence of relatively long, fire-free intervals at higher elevations documented in the present study indicates ample time for sufficient woody fuel accumulation to support intense stand-replacing fires. This contrasts with the greater relative

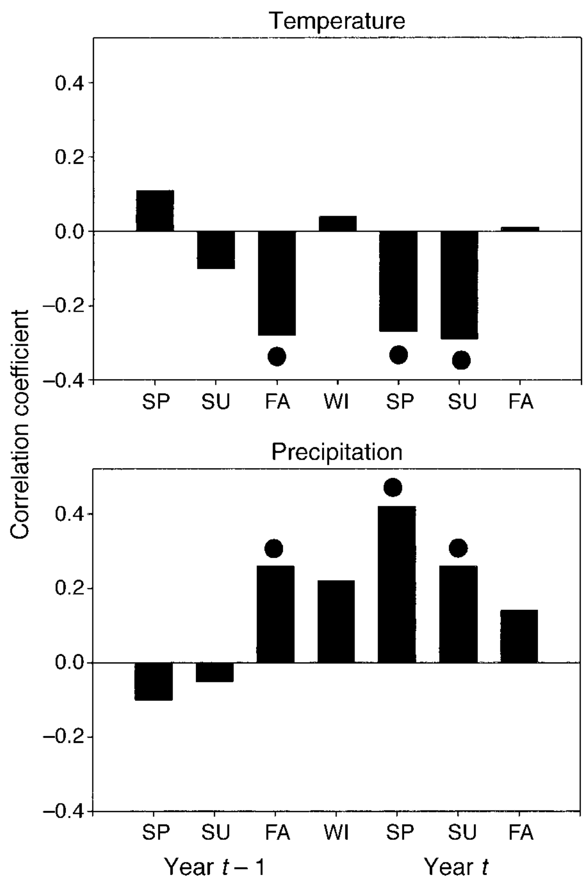


FIG. 6. Correlation functions relating variation in the radial growth of ponderosa pine in the northern Front Range to mean seasonal temperatures and precipitation from the Denver climatic record for 1873–1995. Bars capped with dots indicate statistically significant correlations ($P < 0.05$). Ponderosa pine tree-ring chronologies used for the composite chronology are given in Table 2. Seasons are: WI (winter) = December–February; SP (spring) = March–May; SU (summer) = June–August; and FA (fall) = September–November.

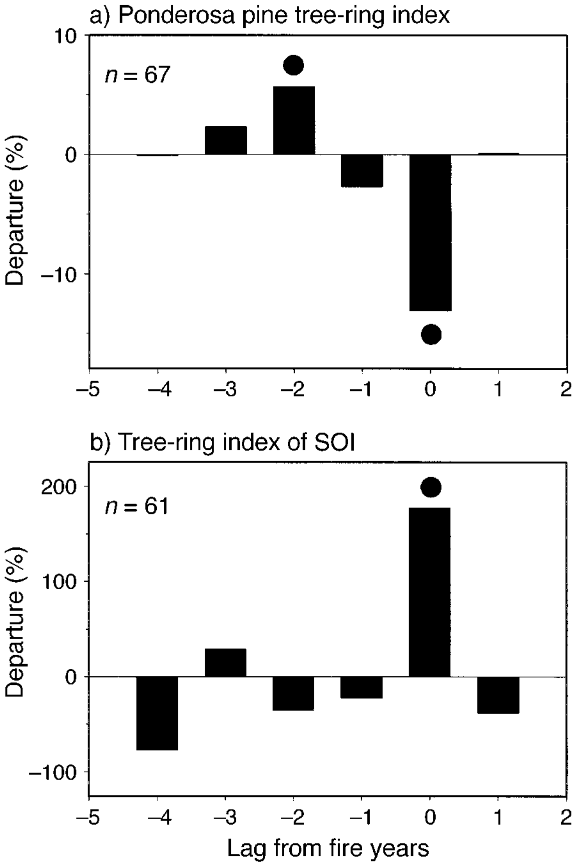


FIG. 7. (a) Departure (%) from the mean ponderosa pine composite tree-ring index for lag years from −4 through +1 for fire years with ≥2 fire-scarred trees in at least one site for 1600–1983; and (b) departure of the tree-ring proxy record of winter Southern Oscillation Index (SOI) for lag years from −4 through +1 for fire years with ≥2 fire-scarred trees in at least one site for 1699–1971. Positive departures in (a) indicate above-average moisture availability in the northern Colorado Front Range, and positive departures in (b) indicate the positive phase (La Niña) of the Southern Oscillation. The tree-ring index used in (a) is from the ponderosa pine sites listed in Table 2, and the one used in (b) is from Stahle and Cleaveland (1993). Bars capped with dots are statistically different ($P < 0.05$) from means determined from 1000 Monte Carlo simulations based on the same number of years as the fire years (Mooney and Duval 1993). The number of fire years is given by *n*.

abundance of less intense fires at lower elevations indicated by survival of large percentages of fire recorder trees through many fire episodes (Fig. 3b). Occurrence of stand-replacing fires prior to the 20th century also has been documented in other ponderosa pine ecosystems (Arno et al. 1995, Brown and Sieg 1996, Swetnam and Baisan 1996, Shinneman and Baker 1997, Brown et al. 1999).

Human and climatic influences on fire history

For the Native American period, distinction of human-set from lightning-caused fires in the fire-scar record is not possible. Native Americans certainly increased the total number of fires over the number of fires ignited by lightning, but without data on fire spread according to ignition source it is impossible to quantitatively assess Native American impact on the fire regime. The 20th century decrease in fire years that included relatively small fires (Figs. 2a and 4) coincides with the onset of active fire suppression in the 1920s. This is consistent with fire history studies conducted in nearby ponderosa pine ecosystems in the Front Range (Rowdabaugh 1978, Laven et al. 1980, Skinner and Laven 1983, Goldblum and Veblen 1992, Brown et al. 1999). This decrease in fire frequency also follows the cessation of intentional burning by early settlers and by Native Americans who were expelled from the region in the 1870s (Buccholtz 1983, Wyckoff 1999). Fuel reduction by livestock grazing may also have contributed to this decrease, but the sharp decline in numbers of trees and sites recording fire after 1920 suggests that fire spread was significantly curtailed by suppression activities.

The increased fire frequency during the latter half of the 19th century found in the present study is supported by other fire history studies conducted in ponderosa pine forests in the northern Front Range (Rowdabaugh 1978, Laven et al. 1980, Skinner and Laven 1983, Goldblum and Veblen 1992). This increase in fire occurrence coincides with permanent Euro-American settlement as well as with a period of increased climatic variability. For example, in the three elevational zones above 2400 m, the sharp increase in years with ≥2 trees scarred in 1859–1860 (Fig. 2) immediately follows the gold discoveries of 1858 and 1859 that triggered a major gold rush in the Front Range (Pettem 1980, Smith 1981, Buccholtz 1983). Furthermore there are numerous historical observations of widespread fires in the northern Front Range during the mid-1800s period of exploration and early settlement that were allegedly set by Euro-American settlers (Tice 1872, Fossett 1880, Jack 1899, Clements 1910, Fritz 1933). However, in the lowest elevational zones, the trend toward increased burning starts in the 1840s (Fig. 2), at least a decade before the founding of mining towns in 1859–1860. Although the 1840s was a period of active prospecting and exploration by Euro-Americans (Hafen and Hafen 1956, Smith 1981, Buccholtz 1983), it was also the beginning of an ~50-year period of climatic conditions more favorable to greater fire spread.

The latter half of the 19th century was a time of increased ENSO activity (Michaelson and Thompson 1992, Quinn 1992, Dunbar et al. 1994, Villalba 1994), which, based on the relationship of fire and ENSO events documented in the current study, probably contributed to the mid-19th century increase in burning in the northern Colorado Front Range. Analogously, in the Southwest, a decline in fire frequency between ~1780 and 1830 coincided with reduced ENSO activity

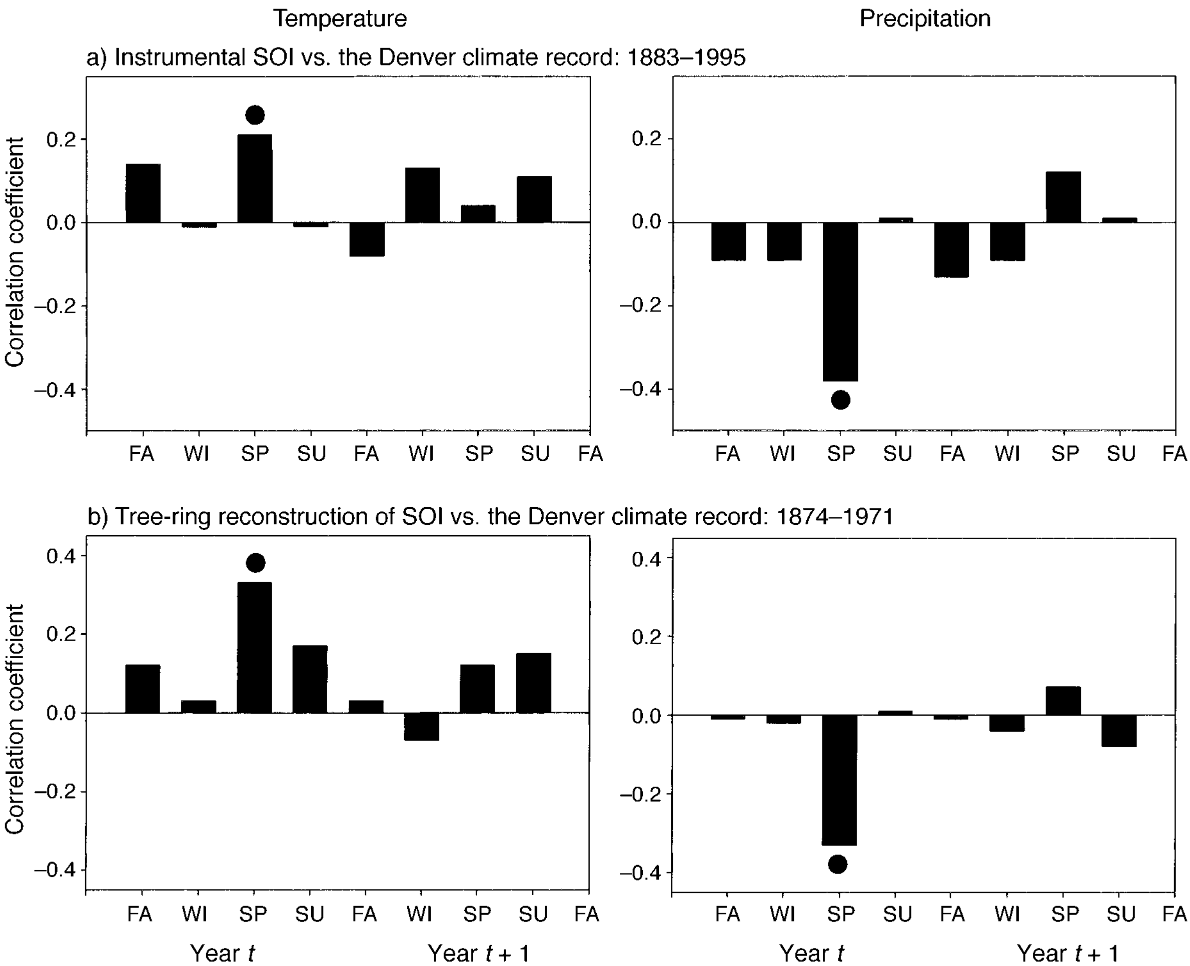


FIG. 8. Correlation functions relating variation in Denver's mean seasonal temperatures and precipitation to (a) the instrumental record of the winter (December–February) mean Southern Oscillation Index (SOI, 1883–1995), and (b) to Stahle and Cleaveland's (1993) tree-ring reconstruction of the winter mean Southern Oscillation Index (1874–1971). Bars capped with dots indicate statistically significant correlations ($P < 0.05$). The SOI is based on pressure differences between Tahiti and Darwin, Australia (Ropelewski and Jones 1987). Seasons are: WI (winter) = December–February; SP (spring) = March–May; SU (summer) = June–August; and FA (fall) = September–November.

(Swetnam and Betancourt 1998). Similarly, in the Front Range, all indices of fire show a decline in the late 1700s followed by an increase in the mid-1800s. There were no widespread fires (≥10% trees scarred) in the composite fire record between 1786 and 1809, and between 1813 and the early 1840s there was only a single year of widespread or smaller fires (Fig. 2). Analogous to the pattern in the Southwest, a period of low interannual variability of ponderosa pine growth during 1780 to the1830s is followed by a marked increase in variability during the mid- and late-1800s (T. T. Veblen, *unpublished data*). This increased interannual variability in tree rings reflects a higher frequency of alternatively wet and dry periods, which would be favorable to fire occurrence.

Both instrumental and tree-ring proxy records of climate indicate that interannual variability in moisture availability rather than drought alone is conducive to years of widespread fire in the northern Front Range. For example, these records indicate that fire occurrence, especially years of more widespread fire, tends to increase one to four years following above-average moisture availability during the spring or summer. Above-average precipitation promotes fire by enhancing the growth of herbaceous plants, which increases the quantity of fine fuels during the fire season a few years later. A similar pattern of increased fire occurrence two to three years after wetter than average winter–springs (vs. spring–summers in the Front Range) also has been reported for ponderosa pine forests in the Southwest (Baisan and Swetnam 1990, Swetnam and Baisan 1996). In the Front Range, instrumental as well as tree-ring proxy records of climatic variation show that the warm (El Niño) phase of ENSO is associated with greater moisture availability during the spring. Thus, enhanced production of fine fuels asso-

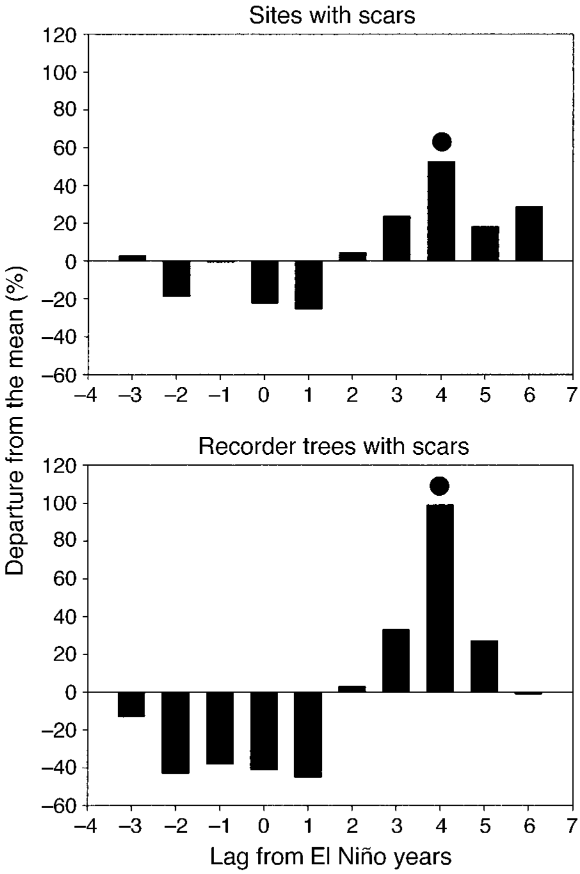


FIG. 9. Departures (%) from mean numbers of sites with fire-scarred trees and of recorder trees with scars for lag years from −3 through +6 for years listed by Quinn (1992) as ''strong'' or ''very strong'' El Niño events for the period 1600–1983 (n = 89).

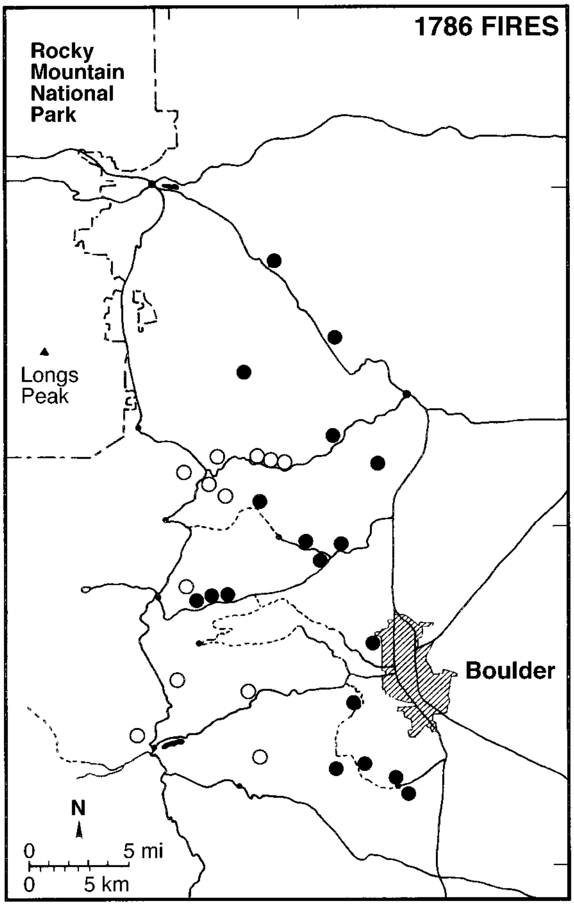
ciated with El Niño events appears to explain the peak in fire occurrence several years following El Niño events (Fig. 9). Conversely, the peak in fire occurrence during years that coincide with La Niña events reflects dry springs during the same year as the fire event (Fig. 7b).

Regardless of cause of the mid-19th century increase in fire, the importance of widespread, stand-replacing fires in the upper montane zone during that period is consistent with the abundance in today's Front Range landscape of extensive, postfire stands of ponderosa pine, Douglas-fir, and/or lodgepole pine that originated mostly between 1850 and 1910 (Clements 1910, Moir 1969, Veblen and Lorenz 1986, Peet 1988, Hadley and Veblen 1993, Hadley 1994, Mast et al. 1998). In the present study, the occurrence of years of extremely widespread fire such as 1859, 1860, 1863, 1871, and 1880 over a relatively short time span means that a large percentage of the montane forests consist of postfire cohorts of roughly similar age. This homogeneity of stand age and structure over such large areas may have increased the current hazard of more catastrophic fire as well as the extent and severity of forest insect outbreaks in the northern Front Range (Swetnam and Lynch 1989, Veblen and Lorenz 1991, Hadley and Veblen 1993, Hadley 1994; Veblen, *in press*). This pattern of altered forest structure due to an episode of increased burning in the upper montane forests, complements the better known pattern for the lower montane forests where historical photographs and tree ages indicate a dramatic shift from grasslands and sparse woodlands to dense stands of ponderosa pine during the past ~80 years of fire exclusion (Veblen and Lorenz 1991, Mast et al. 1997).

Management implications

Given the dramatic reduction of years of widespread fire during the 20th century in comparison with previous centuries (Fig. 2b), fire occurrence over the past century has been well outside the historical range of variability in ponderosa pine forests in the northern Front Range. The magnitude of fire decline is greater at lower than at higher elevations, and this needs to be considered in determining where management actions to reduce fuels or restore more natural fire regimes might be of highest priority. Although the lowest elevation ponderosa pine stands historically were characterized by high fire frequencies that maintained an open park-like forest structure, at higher elevation, the lower fire frequencies documented here are consistent with the evidence of stand-replacing fires in dense stands seen in historical photographs from the late 1800s (Veblen and Lorenz 1991). Even in the lowest elevational zone, more mesic sites in ravines and on north-facing slopes probably supported denser forest patches capable of supporting stand-replacing fires. Thus, for the montane zone of ponderosa pine forests in general, the prior existence of a mixed fire regime of surface and stand-replacing fires means that managers cannot follow a single prescription over the entire range of this forest type. Instead, relatively small areas (e.g., 10–200 ha) need to be characterized in terms of their past fire history when determining appropriate management prescription. Consequently, for the northern Front Range, fire history data have been provided to resource managers at the spatial scale of 10–200 ha (i.e., the scale of the 41 sample sites; Veblen et al. 1996).

The increase in fire frequency in the mid-1800s needs to be considered in evaluating the hazard of both insect outbreaks and extensive wildfire. Management actions that create a mosaic of stand ages may return the upper montane landscape to a structure more similar to its pre-1850 condition, and may reduce hazards of both insect outbreak and fire spread. However, there are socioeconomic limitations on the type of management prescriptions (e.g., intensive thinning and stand-replacing prescribed burns may not be acceptable) practical in a landscape of substantial residential development. Furthermore, there are uncertainties over the



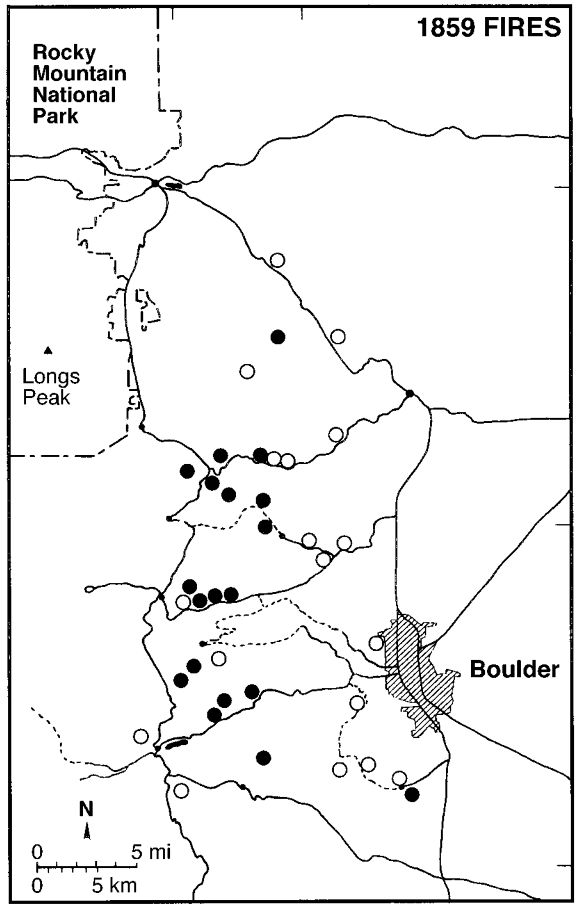


FIG. 10. Maps showing sites (filled symbols) that recorded fire in 1786 (left) and in 1859 (right). Open symbols are sites that had recorder trees at the date of the respective fires but did not record fire.

degree of forest management required to significantly reduce hazard from catastrophic wildfire, which is also highly sensitive to interannual climatic variability. Although fuels reduction through thinning and prescribed burning clearly reduces the probability of small fires becoming more widespread in most years, it is uncertain that moderate levels of fuels management can prevent wildfires during years in which the weather is exceptionally conducive to fire spread. The occurrence of prehistoric fires at large percentages of the sample sites scattered throughout the study area in a single year (Fig. 10) demonstrates the potential for a large part of the montane zone to burn during a single year. Evidence of such widespread fire occurrence lacking any 20th century analogue, needs to be emphasized in public education programs on fire hazard.

Given the lagging by several months to a few years of the effects of ENSO on weather and fire hazard in the Front Range, the ENSO-fire relationships documented in this study can be used in planning fire hazard mitigation. For example, the occurrence of the strong 1997 El Niño event followed by the 1998–1999 La Niña event may be creating fuel conditions similar to those which in the past have resulted in very widespread fire. Such knowledge should be incorporated into both public education and planning of fire management programs.

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