Landscape Ecology **14:** 513–532, 1999.

Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado

Peter M. Brown[1]*, Merrill R. Kaufmann[2] and Wayne D. Shepperd[2]
[1]*Rocky Mountain Tree-Ring Research, Inc., 2901 Moore Ln., Ft. Collins, CO 80526 USA*
[2]*Rocky Mountain Research Station, 240 W. Prospect Rd. Ft. Collins, CO 80526 USA*
(**author for correspondence, e-mail: pmb@rmtrr.org)*

(Received 9 February 1998; Revised 2 November 1998; Accepted 27 February 1999)

Key words: crossdating, dendrochronology, fire chronology, fire extent, fire frequency, fire scars, fire regimes, fire seasonality, fire severity

Abstract

Parameters of fire regimes, including fire frequency, spatial extent of burned areas, fire severity, and season of fire occurrence, influence vegetation patterns over multiple scales. In this study, centuries-long patterns of fire events in a montane ponderosa pine – Douglas-fir forest landscape surrounding Cheesman Lake in central Colorado were reconstructed from fire-scarred trees and inferences from forest stand ages. We crossdated 153 fire-scarred trees from an approximately 4000 ha study area that recorded 77 total fire years from 1197 to the present. Spatial extent of burned areas during fire years varied from the scale of single trees or small clusters of trees to fires that burned across the entire landscape. Intervals between fire years varied from 1 to 29 years across the entire landscape to 3 to 58 years in one stand, to over 100 years in other stands. Large portions of the landscape did not record any fire for a 128 year-long period from 1723 to 1851. Fire severity varied from low-intensity surface fires to large-scale, stand-destroying fires, especially during the 1851 fire year but also possibly during other years. Fires occurred throughout tree growing seasons and both before and after growing seasons. These results suggest that the fire regime has varied considerably across the study area during the past several centuries. Since fires influence plant establishment and mortality on the landscape, these results further suggest that vegetation patterns changed at multiple scales during this period. The fire history from Cheesman Lake documents a greater range in fire behavior in ponderosa pine forests than generally has been found in previous studies.

Introduction

Vegetation patterns across landscapes are the result of often complex relationships and feedbacks between biotic processes and interactions, abiotic environmental constraints, and disturbance regimes (e.g., Urban 1994). Both spatial and temporal scales of observation are crucial to understanding whether such patterns are stable or unstable through time and across space (Sousa 1984; DeAngelis and Waterhouse 1987; Turner et al. 1993; Urban 1994). Stability in local plant assemblages subject to recurrent disturbances is increasingly understood by ecologists to be illusory, for the state of these assemblages is to be always in some stage of recovery from the last disturbance (Riece 1994). However, it has been proposed that by averaging patterns in plant succession found in local areas (patches) across a landscape, all phases of vegetation development will be represented such that a ‘unit pattern’ (Watt 1947) may be defined (Zarickson 1977; Bormann and Likens 1979; Smith and Urban 1988; Urban 1994). This view suggests that while local patterns in plant assemblages should be considered unstable and therefore unpredictable, broad-scale vegetation patterns across landscapes may be stable and hence predictable (e.g., the ‘shifting-mosaic steady state’; Bormann and Likens 1979).

Stability in a spatially-defined unit pattern will require that there be temporal stability not only in the underlying biotic processes and abiotic constraints that affect vegetation dynamics, but also in disturbance regimes that structure species composition and arrangement. Disturbance regimes are combinations of temporal and spatial elements (Pickett and White 1995), some of which may not change through time but including others that may be time-dependent (Romme 1982; Swetnam 1993; Turner et al. 1993). If components of disturbance regimes, such as frequency of occurrence or spatial patterning, change through time, resulting vegetation phases that comprise landscape patterns may not have enough time to equilibrate to these shifts and should be considered unstable at both patch and landscape scales.

Fire has been a ubiquitous disturbance of most temperate terrestrial ecosystems. Variability in the characteristics of fire regimes, such as fire timing or frequency, spatial extent, severity, and seasonality (sensu Pickett and White 1985), profoundly influences vegetation patterning primarily by alteration of habitats and resources available for colonization and growth. An understanding of the dynamics of the fire regime (the fire history) for a fire-prone landscape is therefore a first step to defining long-term patterning in plant communities. For example, in many ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests of the western United States, recent (twentieth century) cessation of historic fire regimes of frequent, episodic, low-intensity surface fires (Baisan and Swetnam 1990; Covington and Moore 1994; Swetnam and Baisan 1996a; Brown and Sieg 1996; Fulé et al. 1997) has resulted in shifts in forest structure and historically unprecedented increases in tree densities (Cooper 1960; White 1985; Covington and Moore 1992, 1994; Mutch et al. 1993; Arno et al. 1995; Fulé et al. 1997). These changes in vegetation patterns have resulted in feedbacks to fire regimes such that large-scale, stand-destroying crown fires are now more prevalent in these communities because of increases in fuel loadings and changes in fuel arrangement (Swetnam 1990; Covington and Moore 1994). As a result of these changes in landscape vegetation patterns and their constrained processes (Turner 1989), many ponderosa pine forests are considered to be outside their historical range of variability (Morgan et al. 1994) and possibly unsustainable in the long term (Covington et al. 1994).

In this study, we describe centuries-long patterns of fire events in a montane ponderosa pine (*P. ponderosa* var. *scopulorum* Dougl. ex Laws.) – Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco.) forest in the south-central Rocky Mountains surrounding Cheesman Lake in the Colorado Front Range. Fire events were reconstructed using proxy fire-scar records from dendrochronologically-crossdated tree-ring series. We used fire-scar records and inferences from forest stand ages to reconstruct spatial extent of burned areas, fire frequency, fire severity, and season of fire occurrence during the past 800 years across an approximately 4000 ha study area. The principle objectives of this study are: (1) to examine the potential role of historic fires as a cause of heterogeneity in forest structure and vegetation patterns in the montane ponderosa pine – Douglas-fir landscape of this area of the Rocky Mountains; and (2) to define reference data that can be used for ecosystem management of montane forests in central Colorado. Fire history data from the Cheesman landscape offer a different view of the historical variability of fire regimes in ponderosa pine forests in the western US than previously reported (e.g., Swetnam and Baisan 1996a; Fulé et al. 1997; Barrett et al. 1997). Site specific information, such as provided by fire history data from Cheesman Lake, is especially critical to provide guidelines and justification for efforts aimed at restoring or promoting historical processes in ponderosa pine and other montane ecosystems of the Front Range of Colorado.

Methods

Study area

The Cheesman Lake study area is located on the South Platte River approximately 60 km southwest of Denver in central Colorado (Figure 1). Chessman Lake and the 3000 ha area surrounding the reservoir (Figure 1) are owned and managed by the Denver Water Board. The montane forest surrounding Cheesman Lake is highly unique relative to much of the rest of the Colorado Front Range in that it has had few direct human impacts during the twentieth century. Cheesman Lake was created by the construction of a dam on the South Platte River in 1905. The area was never logged and livestock grazing was eliminated by a fence around the property at the time of dam construction. Recreational use of the area also has been restricted to protect the watershed immediately surrounding the reservoir. Although wildfires have been suppressed during this century, regeneration of trees has been generally low and ingrowth of younger trees does not appear to be excessive (Kaufmann et al. in revision) as has been the case in many ponderosa pine or montane forests in the

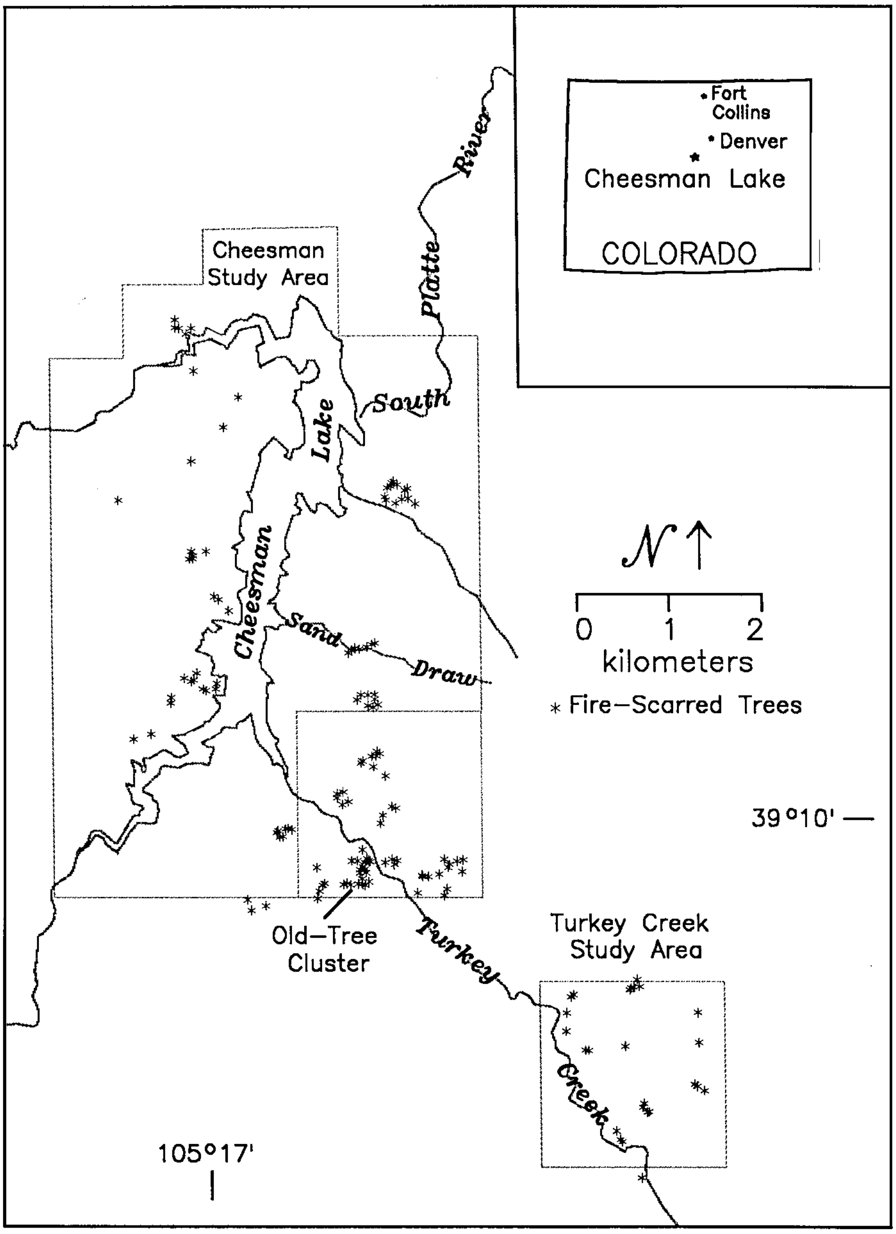

Figure 1. Locations of fire-scarred trees and areas mentioned in the text at Cheesman Lake.

southwestern US or Rocky Mountains (Mutch et al. 1993; Covington and Moore 1994; Arno et al. 1995; Covington et al. 1997; Fulé et al. 1997).

On-going studies in the Cheesman Lake area are examining species diversity, forest stand and age structures, landscape patterning, and historical forest processes to provide reference data for Front Range montane ecosystems (Kaufmann et al. 1997; Kaufmann et al. in revision; Kaufmann and Stohlgren unpublished data). Two 400 ha study areas have been established at Cheesman Lake and an adjacent landscape in Turkey Creek (Figure 1) to examine vegetation patterning at a stand level. The Turkey Creek study area is on the Pike-San Isabel National Forest where trees have been harvested since the 1870s and livestock grazing occurred from the 1880s up to the 1940s. The Turkey Creek area is a managed landscape that is being used for comparison to the un-managed, reference forest at Cheesman Lake (Kaufmann et al. 1997; Kaufmann et al. in revision). The Turkey Creek study area contains topographic units and vegetative communities similar to those of the Cheesman landscape and is considered to be a useful analog to the reference forest (see further discussion in Kaufmann et al. in revision).

Forests on the Cheesman Lake and Turkey Creek study areas are typical of xeric, open, ponderosa pine – Douglas-fir forests of the lower montane zone of the Front Range (Peet 1981). Ponderosa pine is the dominant species and generally forms open, pure stands on south-facing slopes and ridge tops with bunch grass, herbaceous, and occasional sparse shrub understories (Kaufmann et al. in revision). North-facing slopes support denser stands of ponderosa pine and less commonly Douglas-fir, also with less understory development except in local canopy openings where bunch grasses or shrubs may be abundant. Aspen (*Populus tremuloides* Michx.), narrow-leaf cottonwood (*P. augustifolia* James), and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) are occasionally present. Hardwood riparian communities of aspen, willow (*Salix* spp.), and other shrubs are found on the larger stream channels, especially along Turkey Creek (Figure 1). In addition to the forested areas, large areas of mostly south-facing slopes or ridgetops, especially between Sand Draw and Turkey Creek (Figure 1), are open with grass and shrub cover and occasional young ponderosa pine trees. These open areas usually have abundant, often heavily decayed, coarse woody debris (logs and more rarely snags). Coarse woody debris is locally abundant in other locations of the study area.

Soils in the study area are generally poorly developed from granite parent material. The Cheesman landscape is dissected by several steep, rocky drainages, the largest of which is Turkey Creek. Slopes are commonly moderate to steep and granite rock outcrops are common across the area. Elevations at the Cheesman property range from 2100 to 2400 m. Elevations at the Turkey Creek study area are slightly higher and range from 2250 to 2520 m.

Development of the fire chronology

Fire-scarred ponderosa pine trees were collected in both clusters and singly at multiple locations to examine spatial and temporal patterns of past fire events (Figure 1). The general locations and relative sizes of burned areas can be assessed from the locations of trees that either recorded or did not record fire scars during any fire year. Fire scars result when surface fire kills cambial tissue along a portion of the tree's growing circumference, forming a characteristic lesion visible in the tree rings. Fire-scarred trees were collected from the Cheesman Lake and Turkey Creek study areas to provide reference data from both the un-managed and managed landscapes. The total area at Cheesman Lake and Turkey Creek from which we collected fire-scarred trees was estimated to be approximately 4000 ha.

Fire-scarred trees were generally selected for multiple fire scars visible in fire-created 'cat-faces'. This collection strategy was designed to maximize the record of fire from any one location (tree) and to extend the fire chronology as far back in time as possible (sensu Baisan and Swetnam 1990; Brown and Sieg 1996; Swetnam and Baisan 1996a). Trees were collected during hikes through the forest and thus are not evenly distributed across the study area. In addition, in several large areas we were not able to find trees with fire-scar records owing to the relative young ages of trees, especially in the area between Sand Draw and Turkey Creek (Figure 1). Many of the trees collected for this study were remnant logs or snags.

Once suitable fire-scarred trees were located, cross sections were cut using a chainsaw. Full circumference cross sections were generally removed from downed logs while partial sections were cut from the vicinity of the scarred surface on living or standing dead trees. Cross sections were surfaced using hand planers, belt sanders, and hand sanding to distinguish cell structure within the tree ring series.

All cross sections were dendrochronologically crossdated (Stokes and Smiley 1968). We developed a ring-width chronology for Cheesman Lake that extends from AD 991 to 1996 that aided in crossdating of remnant material (Brown and Kaufmann unpublished data). The ring-width chronology was developed from both living and remnant trees, almost all of which were not fire-scarred. After crossdating of ring series was complete for fire-scarred trees, dates were assigned to fire scars seen within the ring series. Positions of fire scars within the rings also were assigned to assess possible seasonality of past fires (Dieterich and Swetnam 1984; Baisan and Swetnam 1990; Brown and Sieg 1996). Scar positions assigned were: early-earlywood, within the first third of earlywood band; middle-earlywood, in the second third of earlywood; late-earlywood, in the last third of earlywood; latewood, within the latewood band; dormant season, between two rings; or unknown position owing to narrowness of ring, scar damage or erosion, or other factors. Dormant season scars were assigned to either the earlier or later year (i.e., to have been early spring fires occurring before the growing season began or late summer or early fall fires occurring after the growing season ended) depending on the presence of early or late season fire scars on other trees for the same time period. Years in which only dormant season scars were recorded were arbitrarily assigned to the earlier year (i.e., to have been fall fires) owing to the greater number of late season fire scars noted in preliminary crossdating efforts. After crossdating of tree rings and fire scars was complete for all trees, a final check was made of all crossdating for verification of fire-scar dates and fire-scar ring positions. Dates of fire scars were complied into a composite fire chronology (sensu Dieterich 1980).

Measures of fire frequency

A critical variable in evaluating fire frequency is the area over which frequency is assessed. Changes in fire frequency through time in the entire fire chronology and a spatially distinct subset of trees called the old-tree cluster (Figure 1) were examined using combinations of three measures. Two of these measures were derived statistically: mean fire interval (MFI) and Weibull median probability interval (WMPI; Grissino-Mayer 1995; Swetnam and Baisan 1996a). MFI is the average number of years between fire dates in a composite fire chronology and has been widely used to describe fire frequency (e.g., Arno and Sneck 1977; Romme 1980; Grissino-Mayer 1995; Swetnam and Baisan 1996a; Brown and Sieg 1996). Variance in fire intervals is described by the first standard deviation and range of intervals. However, statistical inferences derived from the use of MFI require that fire intervals be distributed normally, while, in general, fire interval data are positively skewed since there is no upper bound on intervals while 1 year is the lowest possible interval (Baker 1992; Grissino-Mayer 1995). WMPI is the fire interval associated with the 50% exceedance probability of a modeled Weibull distribution of all fire intervals from a fire chronology and is considered to be a less-biased estimator of central tendencies in fire interval distribution (Grissino-Mayer 1995; Swetnam and Baisan 1996a). MFI and WMPI will be the same if fire intervals are distributed normally. Variance with the Weibull model is described by the 5% and 95% exceedance intervals (Grissino-Mayer 1995). Program FHX2 (Grissino-Mayer 1995) was used to calculate MFI and WMPI for each site.

The third measure for fire frequency is a regression-derived statistic that is considered here as an alternative, robust descriptor for comparisons of fire frequency within fire chronologies. This descriptor is simply the number of fires per year (the definition of frequency) and was determined by a regression slope fit through a cumulative sequence of fire dates (Brown and Sieg in press; Brown et al. unpublished manuscript). Piecewise linear regression procedures (Neter et al. 1989) were used to estimate the number of segments and break points in cumulative fire frequency through time. Analysis of variance procedures were used to estimate when there were significant differences in regression slopes between periods.

Results and Discussion

A total of 486 fire scars representing 77 fire years were crossdated from 153 fire-scarred trees collected from the study area (Figure 2). The first fire year recorded at Cheesman Lake was in AD 1197 while the last was in 1963, making this one of the longest absolutely-dated fire chronologies yet developed from a ponderosa pine forest. In the first four sections below, we examine parameters of the fire regime at Cheesman Lake using data derived from the fire chronology. The last section below will compare the fire regime at Cheesman Lake to historical patterns in other ponderosa pine forests and discuss implications for vegetation patterning in this area.

Spatial patterns of past fires

Spatial extent of areas burned at Cheesman Lake varied from small fires that burned around the bases of single trees (<0.1 ha) to fires that burned across the entire study area ($>$ approximately 4000 ha; Figure 2). Forty-seven of the 77 total fire years in the fire chronology were recorded on only one tree or on two trees that were less than 50 m apart. In most cases, these scar records most likely represent small fires that burned over very limited areas. Low grass or herbaceous (fine) fuel loadings during dry periods, poor fuel conditions (i.e., high moisture content), and/or poor fuel continuities owing to rocky outcrops or bare ground probably restricted fire spread after ignition during these years. However, at least 20 of the 47 years with only one or two scarred trees were

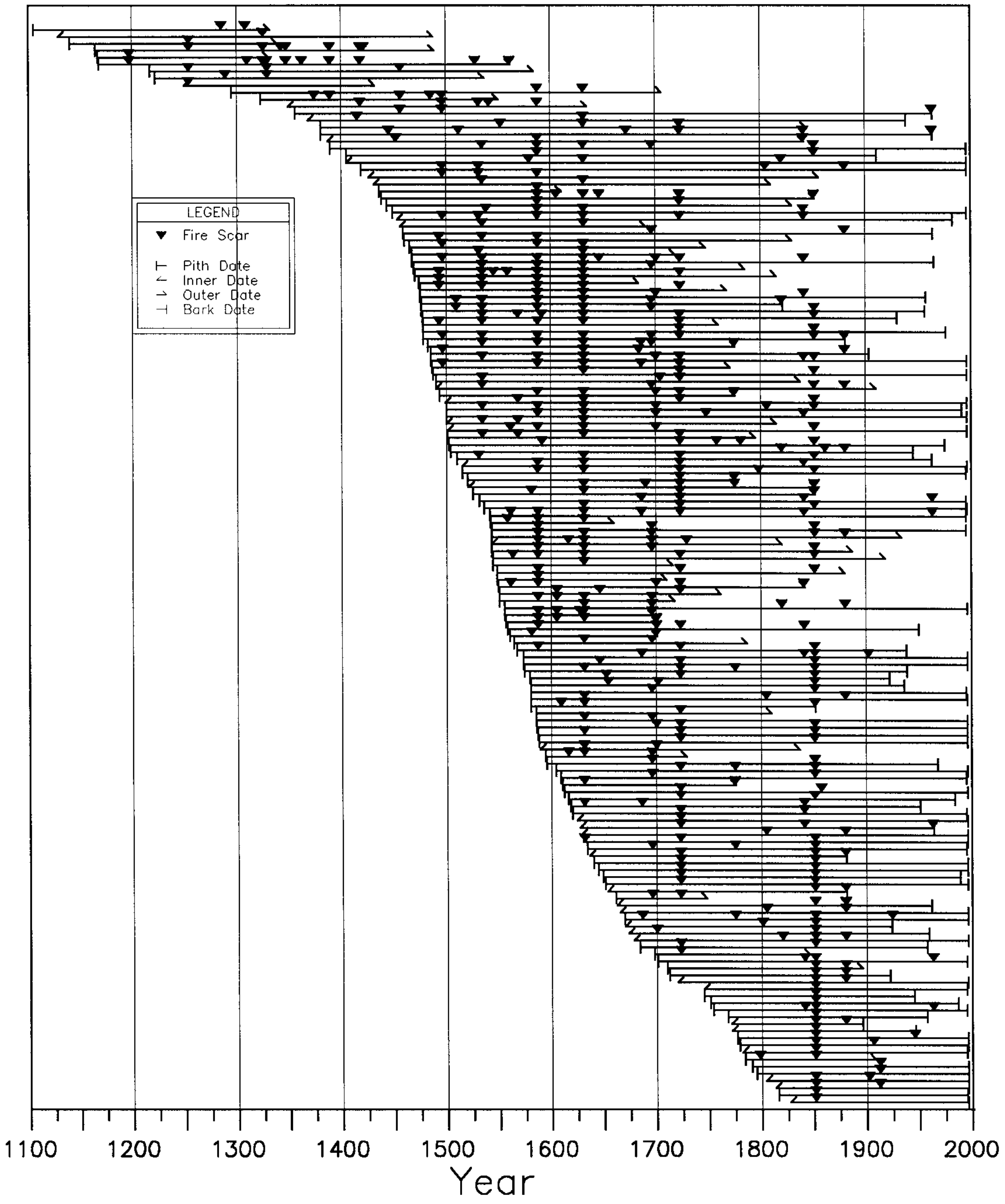

Figure 2. Fire chronology for Cheesman Lake and Turkey Creek study areas. Time spans of individual trees are represented by horizontal lines with inverted triangles at dates of fire scars recorded within ring series. Vertical bars at the ends of tree time spans record pith or bark (death) dates while slanted lines represent inside or outside dates on cross sections.

recorded on trees growing on or near the periphery of where we collected fire-scarred trees. Some of these fire-scar records may represent the edge of larger fires that burned more extensively outside our study area.

Fire-scar records from the other 30 fire years are mapped in Figure 3. Several of these fire years were apparently also relatively small fires, reflected by local patches of three or more fire-scarred trees (1418, 1456, 1493, 1509, 1561, 1568, 1616, 1686, 1805, and 1963), although, again, some of these fire-scar records may represent the edge of more extensive fires that burned outside our collection area. During other years, groups of fire-scarred trees were widely separated by intervening areas of unscarred trees (1496, 1531, 1558, 1605, 1646, 1686, 1700, 1775, 1798, 1820, and 1841). Fire-scar records for these years may reflect multiple ignitions on the landscape, such as can happen during ‘dry’ lightening storms. During such storms, lightening from a thunderstorm cell that is not accompanied by rain can start multiple fires across relatively local areas (e.g., Pyne 1984). Multiple ignitions may coalesce into a larger fire, or they may be extinguished by precipitation from subsequent thunderstorms. Some of these years also may reflect multiple periods of burning during a single fire season, with relatively small areas of trees scarred during any one fire event.

Fire scars were recorded on large numbers of trees across the study area for only a few years, in 1496, 1534, 1587, 1631, 1696, 1723, possibly 1775, 1851, and possibly 1880 (Figure 3). However, even during most of these years there were apparently areas of the landscape that did not burn, especially in the northwest portion of the study area during otherwise extensively recorded fires in 1587, 1723, and 1851 (Figure 3). The only year when scars were recorded on trees across all of the study area was during 1631 (Figure 3). While the lack of fire scars is not evidence that fires did not occur, it is likely that portions of the Cheesman landscape did not burn during many of these otherwise extensively-recorded fire years. How far beyond the bounds of our study area fire may have burned during any year is impossible to answer with data at hand. However, a majority of the fire years recorded at Cheesman Lake were recorded at other fire history sites in central Colorado (Brown et al. unpublished data, manuscript in preparation; Goldblum and Veblen 1992; Veblen et al. 1996). For example, 1587, 1631, and 1851 (Figure 2) were widely recorded at sites both north and south of our study area. While it is unlikely that single fires burned across vast areas during these years, it is probable that multiple ignitions during summers when fuel conditions were right resulted in large areas burned during regional fire years (Swetnam 1993; Swetnam and Baisan 1996a).

Fire frequency

The length of time between fire events varied from very short (1 to 10 years) to very long (>100 years) intervals, both at landscape and stand scales. At the landscape scale, using fire years recorded on all trees from the study area, more frequent fire was apparent in the early and middle part of the record, especially fire years that scarred more trees across the landscape (i.e., in 1496, 1534, 1587, 1631, 1696, and 1723; Figure 4). During the 1500s, numerous small fires were recorded across the landscape, and fire frequency during this century was significantly greater than either the periods before or after based on results from piecewise linear regression (Neter et al. 1989) of cumulative fire dates (Table 1; Figure 5). However, there were fewer trees that date back to the 1200s to 1400s (Figure 3) and we are undoubtedly missing some smaller fires in this earlier period of the fire-scar record. After 1723, there was a 128 year-long period without a widespread fire until 1851 (Figures 2 and 4), although fires in 1775, 1798, 1805, 1820, and 1841 did burn small patches during this otherwise fire-free period (Figure 3). Fire scars were recorded in 1775 at several locations on the east side of the current reservoir (Figure 3). This fire year may have been more extensive in this area since it followed a pattern noted by Kaufmann et al. (in revision) in which large fires occurred during periods that were also favorable for tree recruitment in the Cheesman area.

No extensive fires have been recorded on the Cheesman landscape since 1851 (Figure 4), although fires in 1880 and 1963 scarred multiple trees in two different areas (Figure 3). Cessation of spreading fires during the twentieth century was likely primarily the result of modern fire suppression efforts, both on the Cheesman property and in the surrounding landscape where some of the past spreading fires undoubtedly originated. The fire in 1963 was suppressed at the time, and probably would have burned more extensively across the landscape if it had been left unchecked. Workers at Cheesman Lake report that an average of 10 to 12 lightening-caused fires per year have been suppressed on the Cheesman property in recent years. Livestock grazing in the early settlement period before the fence was established around the Cheesman property also may have contributed to

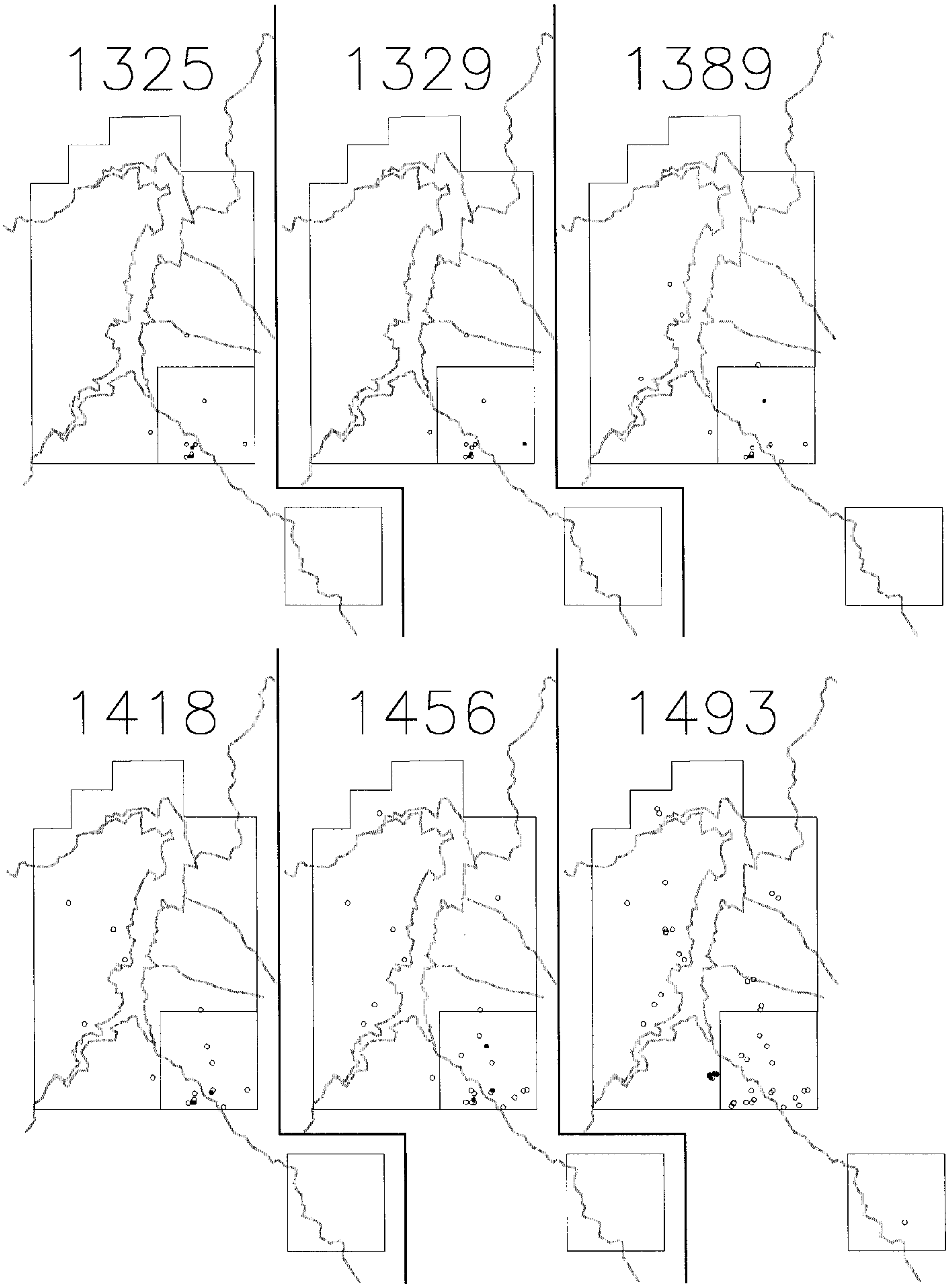

Figure 3. Locations of fire-scarred trees (closed circles) and non-fire-scarred trees (open circles) for 30 fire years at Cheesman Lake and Turkey Creek study areas. Fire years shown are those when 3 or more fire-scarred trees were recorded. See Figure 1 for place names and scale.

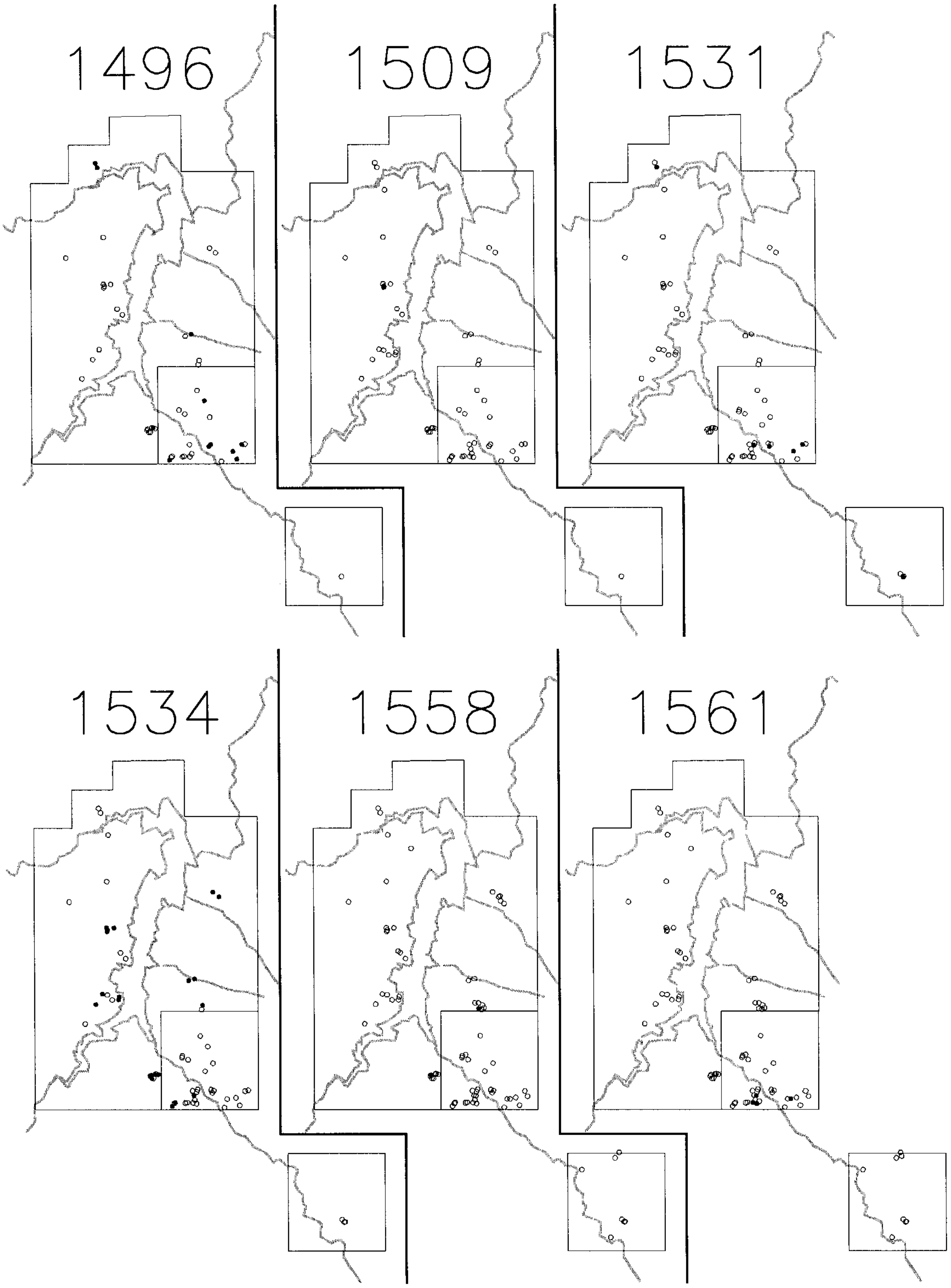

Figure 3. Continued.

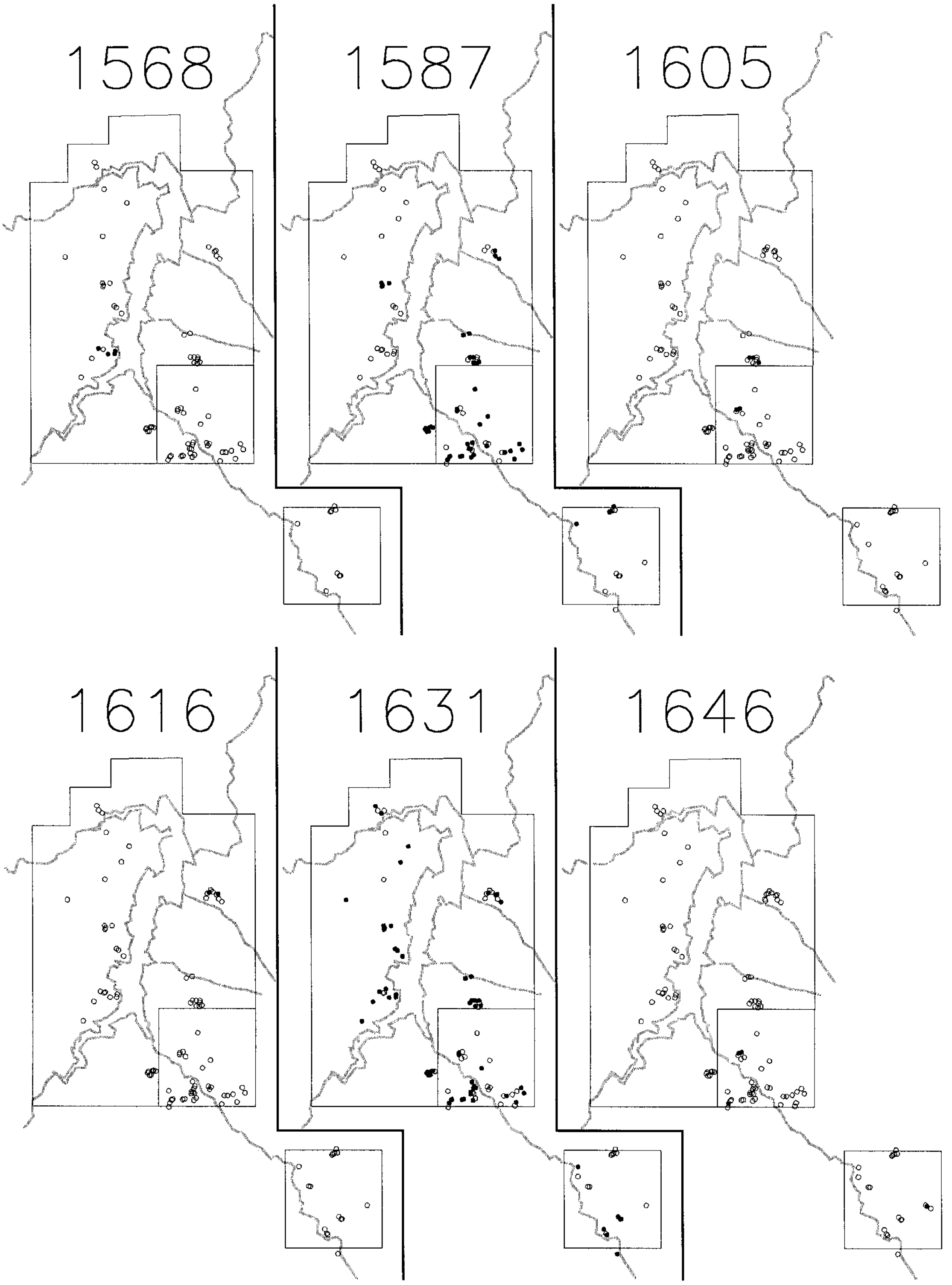

Figure 3. Continued.

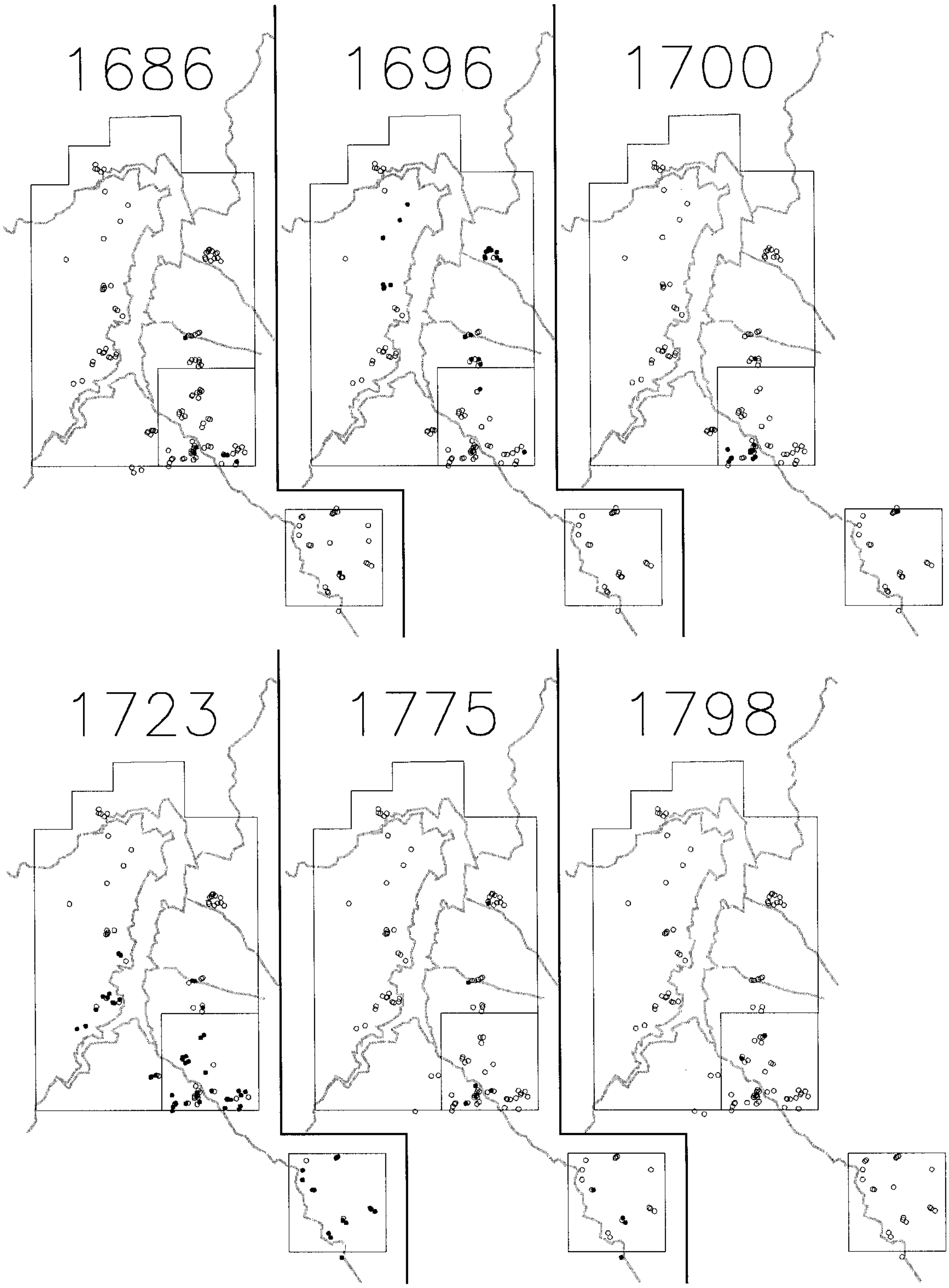

Figure 3. Continued.

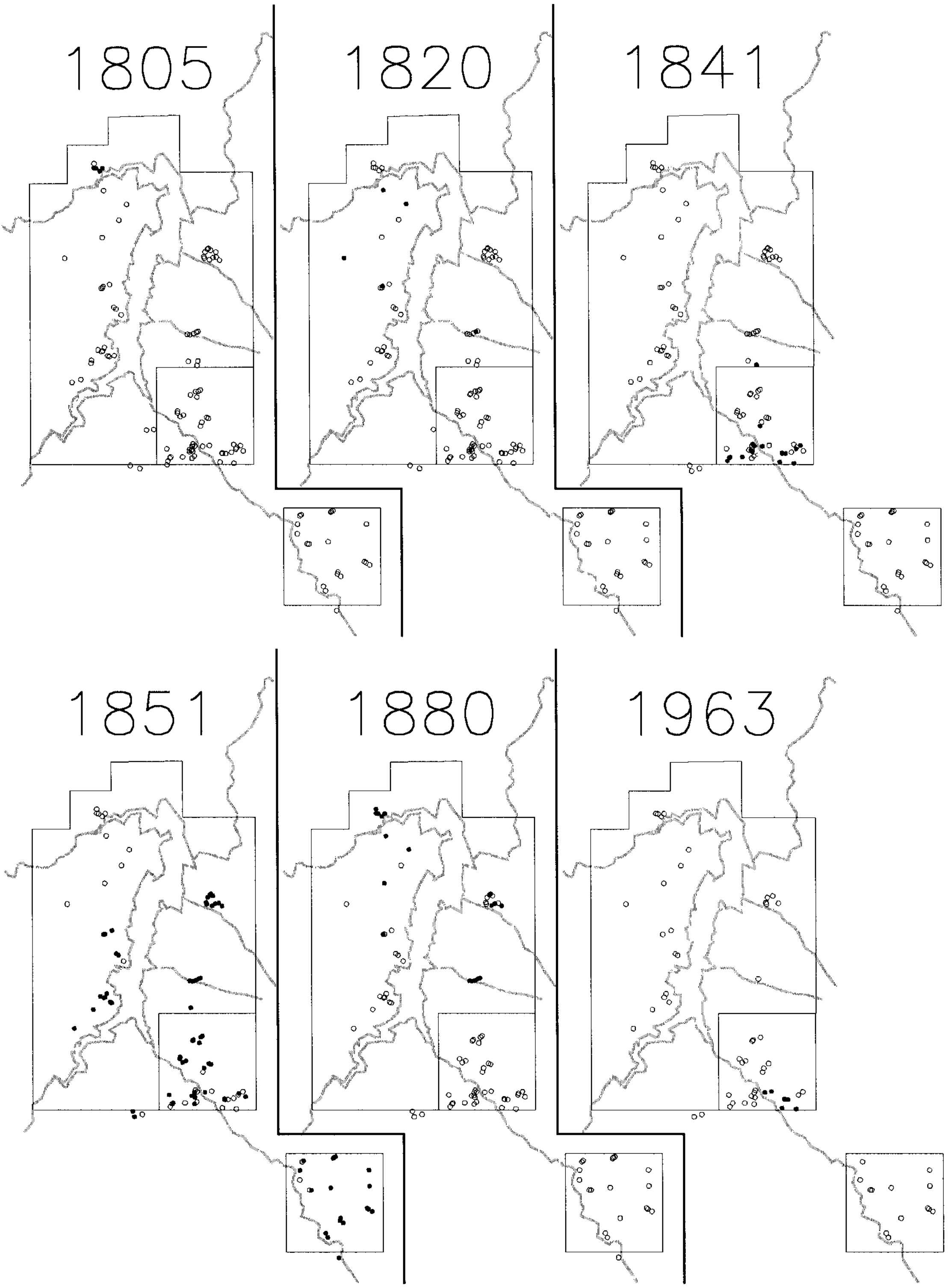

Figure 3. Continued.

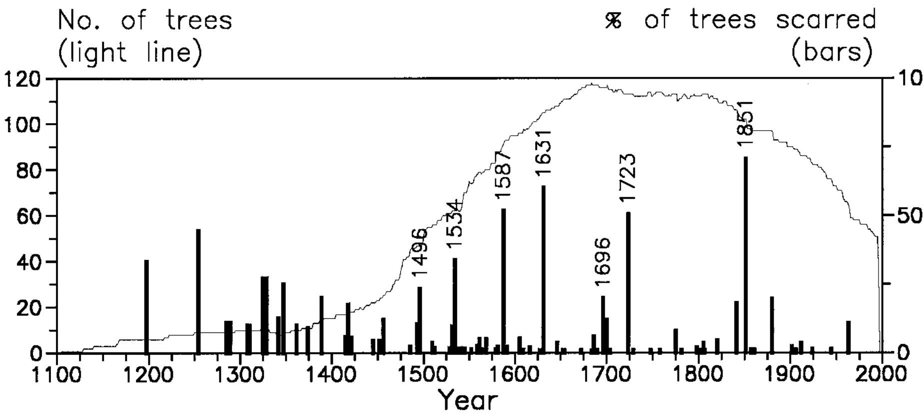

Figure 4. Composite fire chronology for Cheesman Lake and Turkey Creek study areas. Light line is sample depth (number of trees) through the time period of the chronology while histograms are the number of trees scarred during each fire year.

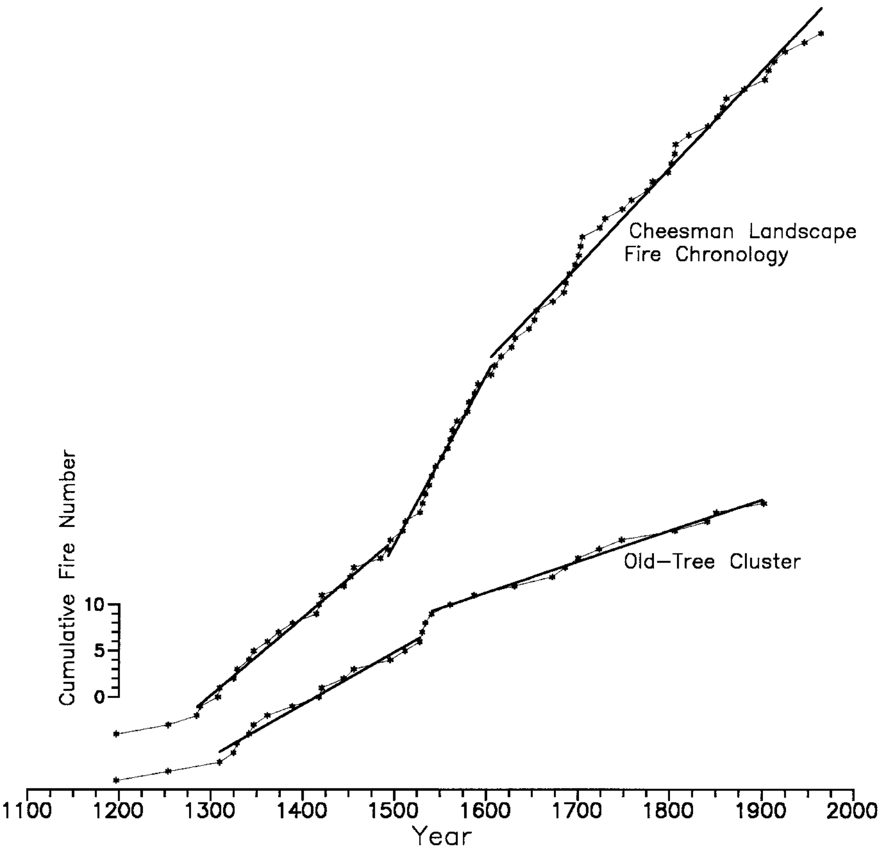

Figure 5. Fire frequencies determined as linear regressions through cumulative fire dates from the Cheesman landscape and old-tree cluster fire chronologies.

Table 1. Measures of fire frequency for the Cheesman landscape (Figure 2) and old-tree cluster (Figure 6) fire chronologies. Areas for which fire intervals are determined are over the entire Cheesman landscape (an area of approximately 4000 ha) and for the old-tree cluster (an area of approximately 30 ha). Fire intervals used in calculations are for all fire dates recorded at site for period of analysis except for the Cheesman landscape, widespread fires, which are fire intervals between fire years marked in Figure 4 (i.e., those years when large areas of the Cheesman landscape recorded fire scars).

Scale and time period	Period of analysis	No. of intervals	MFI (±SD)[a]	Range of intervals[b]	WMPI[c]	5% to 95% prob. inter.[d]	Fire freq. (from Figure 5)[e]
CHS landscape, full period	1285 to 1963	74	9.2 ± 7.0	1 to 29	7.7	1.5 to 19.5	
CHS landscape, 1300s & 1400s	1285 to 1493	18	11.6 ± 8.6	2 to 29	9.8	1.8 to 25.6	0.084a
CHS landscape, 1500s	1493 to 1605	19	5.9 ± 4.3	2 to 16	5.3	1.4 to 11.0	0.185b
CHS landscape, 1600s to 1900s	1605 to 1963	37	9.7 ± 6.8	1 to 22	8.3	1.5 to 21.5	0.106a
CHS landscape, widespread fires	1496 to 1851	6	59.2 ± 36.1	27 to 128	50.1	28.3 to 108.0	
Old-tree cluster, full period	1310 to 1902	28	21.1 ± 15.1	3 to 58	18.0	3.1 to 48.8	
Old-tree cluster, 1300s to early 1500s	1310 to 1528	13	16.8 ± 10.8	3 to 40	15.0	3.0 to 36.9	0.056a
Old-tree cluster, mid-1500s to 1800s	1541 to 1902	12	30.1 ± 15.6	10 to 58	28.8	9.3 to 54.5	0.034a

[a] Mean fire interval and standard deviation of all intervals in composite fire chronology in years.
[b] In years.
[c] Weibull median (50% exceedance) probability interval in years.
[d] Weibull 5% and 95% exceedance probability intervals in years.
[e] Piecewise regression slopes calculated from cumulative fire dates (number of fires year^{-1}). Subscript letters refer to significant differences in regression slopes between periods based on analysis of variance.

a reduction in grass and herbaceous fuels that carry surface fires during that time.

Fires that burned over larger portions of the landscape (> approximately 1000 ha) in at least seven years (1496, 1534, 1587, 1631, 1696, 1723, and 1851; Figures 2 and 3) ranged from 38 to 128 years apart (Table 1). However, fires in 1496 and 1534 largely burned in different areas (Figure 3) and the time between extensive fires more appropriately ranged from 44 (1587 to 1631) to 128 years. In addition, the area burned in the 1696 fire year largely did not burn in the otherwise widespread fire year of 1723 (Figure 3), further suggesting that spatial and temporal patterns of fire events were confounded across the landscape of Cheesman Lake. Much of the area recorded by the 1696 fire did not record fire again until 1820 (Figure 3), a span of 125 years. In contrast, overlapping portions of areas of scarred trees in 1587 and 1605, 1686 and 1700, and 1841 and 1851 (Figure 3) are evidence that short intervals between fires also have been part of the historical variability in fire frequency across this landscape.

The length of fire-free intervals is inversely proportional to the size of area over which the intervals are assessed; i.e., larger areas will have shorter intervals. To look at variability in fire intervals at one stand of trees, we compiled a fire chronology for a subset of trees that we collected near the bottom of Turkey Creek (Figure 6, Table 1). This subset of trees, which we designated the old-tree cluster (Figure 1), came from an area of less than 30 ha in size and had the largest number of older remnant trees of any location at Cheesman Lake. These trees were growing on a rocky spur ridge just above the bottom of Turkey Creek in an area that we believe may have been more protected from or less susceptible to crown fire events or rapid decomposition of remnant trees and therefore had a longer, more complete record of past fire at this one site. The oldest remnant log (not fire-scarred) from the old-tree cluster yielded a pith date of 991 and 8 other logs extended back to the 1100s. Two of these logs recorded the earliest fire scars at Cheesman Lake in 1197.

Temporal changes in fire frequency in both the landscape and old-tree cluster fire chronologies are evident as deviations from piecewise linear regressions fit through cumulative fire dates (Figure 5). Fires recorded before about 1300 in both the full set of fire years from the Cheesman landscape and in the subset from the old-tree cluster do not fit longer-term trends in fire frequency from the early 1300s to the 1500s. Fire dates before 1300 were not used to determine regression slopes because of low numbers of fire-scarred trees during this time (Figures 4 and 6). Centuries-long shifts in fire frequency that began later in the sixteenth century in both sets of data (Table 1) are evident as changes in the long-term trend lines

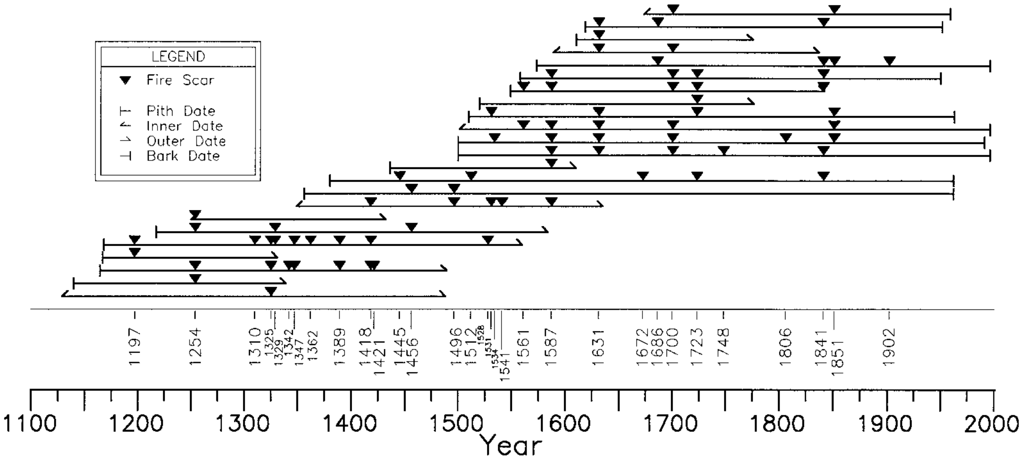

Figure 6. Fire chronology for the old-tree cluster near Turkey Creek (see Figure 1 for location). Time spans of individual trees are represented by horizontal lines with inverted triangles at dates of fire scars recorded within ring series. Dates at bottom of chronology are all fire dates recorded on trees in the cluster.

in cumulative fire dates in Figure 5. Shorter shifts in fire frequency are also evident in the cumulative fire data. For example, both the landscape and old-tree cluster data show increased frequency during a short period around 1700 (see also Figures 4 and 6). Shorter, decadal-scale, shifts in frequency in figure 5 may be related to multi-year changes in climate, such as annual precipitation or the El Niño/Southern Oscillation (sensu Swetnam and Betancourt 1990). The last fire recorded in the old-tree cluster was in 1902, hence no estimate of twentieth century patterns can be made. However, that stand of trees has not recorded any fire for a 95 year-long period from 1902 to 1996 when the trees were collected, in contrast to the longest historical fire-free interval at this site of 58 years (Table 1; see also Figure 6). This recent long period without fire in the old-tree cluster is, again, most likely due to human-caused fire exclusion during the twentieth century.

Fire severity

Large fires with significant areas of complete overstory tree mortality were a component of the fire regime in ponderosa pine forests at Cheesman Lake. Fire severity may be assessed by the incidence and extent of complete overstory mortality. Complete mortality likely occurred during crown fires, but intense surface fires may cause overstory mortality. While seedlings and saplings are often killed in low-intensity surface fires, mature ponderosa pine trees are considered to be well-adapted to surface fires with thick basal bark that generally protects vascular cambium from lethal heating and high crowns that lessen leaf scorch (e.g., Mutch 1970). Overstory mortality by crown or severe surface fire may be highly localized (i.e., individual trees to small groups of trees) or it may occur over large portions of a landscape under extreme weather and fuel conditions.

Twelve remnant trees were collected from open, south-facing slopes or ridgetops between Sand Draw and the north side of the 400 ha study area at Cheesman Lake (Figure 1). Each of these trees had 1850 or 1851 as the last ring recorded, and were undoubtedly killed in the 1851 fire year. (The 1851 ring was very narrow in the ring-width chronology and not always present before fire scars recorded on other trees that were not killed during 1851. Hence, 1850 was the last ring recorded on some trees killed in the 1851 fire event.) Open slopes and ridges are prominent features over much of the landscape between Turkey Creek and Sand Draw and usually contain often heavily decayed remnant logs and occasional snags, most of which we believe dates to 1851. In addition to tree death dates from these open areas, germination dates for trees in stands in the north end of the 400 ha study area at Cheesman Lake (Figure 1) postdate 1851, further suggesting a stand-destroying event at that time (Kaufmann et al. in revision). From these data, we infer that the 1851 fire was a mixed crown and surface fire event across at least this portion of the landscape, with large areas of forest on primarily south-facing slopes and ridgetops killed by fire during a year that otherwise was recorded as surface fire over large areas (Figure 3). In addition, the 1723 fire, again recorded as surface fire over much of the landscape (Figure 3), may have had a crown fire component to it, although we do not have remnants of any trees killed in that fire because of decomposition of woody material that may have resulted from such an event. However, ages of many trees from the 400 ha study area at Cheesman Lake have earliest pith dates in the mid to late 1700s, suggesting there may have been a stand-destroying event before that time (Kaufmann et al. in revision).

The 1851 fire year followed a 128 year-long period (from 1723) when there were no large spreading surface fires, although smaller fires were recorded in several locations during this time (Figures 2, 3, and 4). Possible fuel buildups over the landscape during this long fire-free period may have contributed to more extreme fire conditions during the 1851 fire year. Furthermore, many trees from outside the areas where we suspect complete overstory mortality to have occurred in 1851 were established in the period from the late 1830s to the early 1850s (Kaufmann et al. in revision). Age structures in ponderosa pine forests from the southwest tend to have evidence of pulsed, climatically-driven regeneration events that can structure a forest for centuries afterwards (e.g., Pearson 1933; Swetnam and Brown 1992; Savage et al. 1996; Swetnam and Betancourt 1998). A number of regeneration pulses have been detected for the Chessman Lake landscape (Kaufmann et al. in revision). We have tentative evidence that the 1830s to 1850s pulse in the Cheesman area was also present in other areas of the Front Range and corresponded to a cooler, wetter period that may have led to optimal conditions for ponderosa pine regeneration (Brown and Kaufmann unpublished data). The 1830s to 1850s pulse of tree establishment may have resulted in fuel ladder conditions that contributed to increased fire severity in 1851.

Fire seasonality

There was large variability in the position of fire scars in annual growth rings both within and among fire years (Figure 7). Fire scar positions in rings, coupled with knowledge of ring growth phenology, can be used to infer when fires burned in relation to an average tree growing season (Baisan and Swetnam 1990; Ortloff 1996). Although data on timing of ponderosa pine radial growth are not available for the southern Rocky Mountains, data from southern Arizona ponderosa pine indicate that radial growth commonly begins in middle to late May and ends by mid-July to mid-August depending on climatic variability in different years (Fritts 1976). The growing season for ponderosa pine trees in the more northerly Cheesman Lake area is likely shorter, with growth initiation in early June (unpublished data). Fire-scar positions recorded during fire years at Cheesman Lake suggest that fire may have burned throughout the growing season during many of the widespread fire years and was highly variable during other, less widespread fire years (Figure 7). Figure 7 does not include years during which only dormant season fire scars (occurring between two rings) were recorded. Fire scars during these years were arbitrarily assigned to the earlier year (i.e., to have been fall fires that occurred after the growing season ended). However, given the range of variability in fire-scar positions in the Cheesman Lake data, fire dates reported here for years with only dormant season fire scars recorded may be one year earlier than the true date (they may have been spring fires that occurred before the growing season began for the following year).

Comparisons with fire regimes in other ponderosa pine forests and implications for vegetation patterns

The fire regime at Cheesman Lake comprised a greater range of fire behavior than has been documented from other ponderosa pine stands in the western US. The definition of a fire regime distills the temporal and spatial complexity of multiple, individual fires into an evolutionary perspective for how plant communities responded to fire as a disturbance process (Heinselman 1981). For example, an often postulated pattern in forest or shrub ecosystems is that fire severity is inversely correlated with the time between fires, especially when compared to lifespans of dominant or co-dominant species in a plant community (Heinselman 1981; Sousa 1984). High intensity stand-destroying fires (e.g., crown fires) tend to have longer intervals between events while lower-intensity surface fires are more frequent. Crown fires also tend to be more extensive than surface fires owing to often extreme fuel and weather conditions that are necessary for such catastrophic events to occur. Even-aged forests usually result from catastrophic fires because of synchronous tree regeneration after the event. Recent, stochastic models of fire history that make use of ‘time-since-fire’ maps (summarized in Johnson and Gutsell 1994), while suggested to apply to all types of fire regimes, are best fit to forests that experienced low frequency, stand-destroying fires where spatial extent may be inferred from present-day stand structures (Finney 1995;

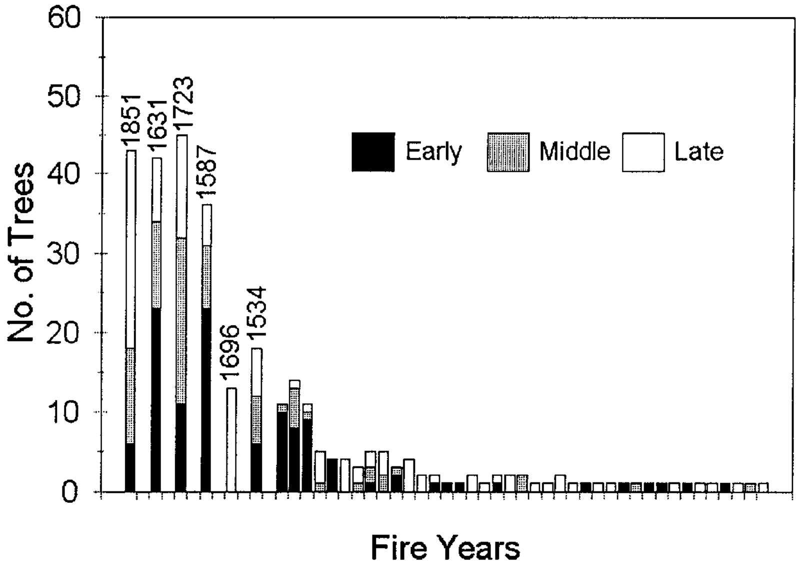

Figure 7. Fire seasonality based upon fire-scar positions within ring series. Early category includes early dormant season and early earlywood fire scars, middle category is middle earlywood fire scars, and late category includes late earlywood, latewood, and late dormant season fire scars. Fire-scar positions shown are those for which position could be assigned (i.e., not including unknown position scars) and for those years when scars were recorded within ring series (i.e., not those years when only dormant season scars were recorded).

Swetnam and Baisan 1996a; Brown and Sieg 1996). In these models, spatial extent is the variable of the fire regime of primary interest, and has been suggested to be the most ‘ecologically meaningful variable’ (Bessie and Johnson 1995; see also Heinselman 1981) when assessing the role of fire in community and ecosystem dynamics.

However, in communities that have a history of surface fires it is potentially more difficult to disentangle one variable of a fire regime that had a greater ecological impact than another. While spatial extent is necessary for understanding fire’s effects on landscape patterns in vegetation structure, it is the indirect consequences of fire frequency that are more crucial to understanding fire’s effects on individual trees and forest stands. Frequent surface fires result in killing of seedlings and saplings before they are able to reach competitive advantage in the overstory, maintaining what is often referred to as ‘park-like’ conditions with widely spaced mature trees and well-developed grassy or herbaceous understories (Cooper 1960; White 1985; Covington and Moore 1994). Overstory trees are rarely killed in surface fires except when local fuel loads are high or wind and/or dry conditions result in fire burning into localized canopy patches. Subsequent tree establishment in canopy gaps, whether caused by fire or other disturbances, results in multiaged forests.

The prevailing view of historical fire regimes in ponderosa pine forests is of frequent, low-severity surface fires that tended to maintain open, multiaged, forests. This view is based principally on data from forests in the southwestern US (Swetnam and Baisan 1996a; Fulé et al. 1997; Covington et al 1997). Fire history data from ponderosa pine forests of the northern Rocky Mountains (e.g., Barrett et al. 1997), Front Range of Colorado (Goldblum and Veblen 1992; Veblen et al. 1996; Brown et al., unpublished data), and Black Hills of South Dakota (Brown and Sieg 1996; Brown and Sieg in press) tend to support these dominant patterns, only with often longer intervals between fires than in the usually warmer and dryer forests of the southwest. Longer intervals in these other locations are likely related to differences in elevation or microclimates, ignition sources (i.e., anthropogenic vs. natural ignitions; Swetnam and Baisan 1996b; Veblen et al. 1999), lower quality soils or associated nutrient status, or to some other physical or historical factor or combination of factors that resulted in fewer years when fires were able to ignite and burn.

While frequent surface fires were a major component of the fire regime at Cheesman Lake, our data also document that extensive stand-destroying fires occurred across the landscape. Variability in the fire regime is furthermore reflected in forest structure. For example, the old tree cluster recorded numerous surface fires going back to 1197 that occurred an average of every 21 years (Table 1). This type of fire regime appears to have promoted and maintained an open, multiaged stand that has persisted at this site for at least the past 800+ years. Other areas at Cheesman Lake also appear to have had historical fire regimes and resultant age structures that are similar to those reported from the southwest. However, extensive crown-destroying fires, especially during 1851 but perhaps also during 1723 and some other fire years, contributed to the formation of different patterns in forest structure (Kaufmann et al. in revision). Evidence indicates that tree establishment into openings that we suspect were the result of large-scale crown fires was uneven through time, yielding generally multiaged stands, but that these areas have a maximum age structure over fairly extensive areas (Kaufmann et al. in revision). While the age structure of forest patches may be inadequate for determining when major disturbances occurred (Lorimer 1985), age structure can be used to establish the spatial extent of stand-destroying fires since all trees in such areas will postdate certain years. Mapping of patch structure is being completed for the Cheesman landscape and, when combined with ages of oldest trees in patches, the spatial extent of the stand-replacing component of past fires may be inferred.

During the past five centuries, more than two-thirds of all trees established in specific periods that amounted to only one-third of the time. These establishment periods had a periodicity similar to the average intervals between larger fires (about 50 years; Table 1), and all of the larger fires except 1696 fell in periods of tree recruitment (Kaufmann et al. in revision). Indeed, the occurrence of crown fires at Cheesman Lake may have been compounded by feedbacks from vegetation structure to fire behavior. Crown fire in the 1851 fire year may have been promoted by an increase in tree density during a period of heavy tree establishment in the 1830s and 1840s. Fine fuel (grasses and herbaceous plants) loadings also may have been greater owing to probable cooler and wetter climatic conditions that led to tree establishment in the early 1800s (Brown and Kaufmann unpublished data). The 1851 fire was followed by a period with little tree establishment until the 1880s, a period of establishment that is evident in many Front Range ponderosa pine stands (Veblen and Lorenz 1986; Mast 1993; Brown unpublished data).

Finally, fire history data from the Cheesman landscape show probable effects of recent non-Native American settlement in the Front Range area. These patterns are similar to those seen in virtually every fire history reconstructed from ponderosa pine forests in the western US. While intervals between fires at Cheesman Lake tended to be longer than in most areas of ponderosa pine forest, there has not been a widespread, landscape fire at Cheesman Lake since 1851, a period of 148 years to the present time (1998). This surpasses the longest period between landscape fires in the historical record of 128 years from 1723 to 1851 (Table 1). Individual stands on the landscape also have not experienced fire for similarly long periods during the recent century. The longest pre-settlement period without fire in the old tree cluster was 58 years (Table 1) compared to the recent fire-free period in this stand of 97 years (1902 to 1998). Cessation of surface fires in the western US was usually coincident with settlement and subsequent changes in land use (see summaries of fire history data in Swetnam and Baisan 1996a; Barrett et al. 1997). Livestock grazing, logging, fragmentation of forest stands caused by road and fence construction, and active fire suppression by land management agencies are often-cited reasons for loss of or changes in surface fire regimes.

Summary and management implications

Fire scars are point data from which we can infer general patterns in parameters of a fire regime through the time covered by a fire chronology and across a study area where fire-scarred trees were collected. From the record we developed at Cheesman Lake, we infer that the area burned during fire years, the length of time between fires, the severity of individual fire events, and the season of occurrence of fires varied considerably. Fire sizes ranged from the scale of individual trees or small groups of trees to the entire landscape, an area of approximately 4000 ha (Figure 3). Intervals between fire years ranged from 1 to 29 years across the entire landscape, to 3 to 58 years at one stand (the old-tree cluster; Table 1), to more than 100 years at other locations. Fire severity varied, with both surface fires and widespread stand-destroying fires in the ponderosa pine forest. Finally, season of fire occurrence varied, with fires recorded at all times during growing seasons and both before and after growing seasons during individual fire years (Figure 7).

Disturbances are temporally and spatially discreet events that remove existing biomass and create both spaces for plant colonization and resources for surviving individuals (Pickett and White 1985). Greater variability in spatial and temporal components of a disturbance regime should therefore result in greater heterogeneity of habitats and resources across multiple scales. Ecologists and managers are increasingly recognizing that the loss of historical rates of and variability in natural processes from landscapes is leading to unexpected and usually undesirable consequences for biodiversity and sustainable ecosystems (e.g., Covington et al. 1994; Holling and Meffe 1996). Historical studies provide crucial data to describe long-term patterns that resulted from natural variability in ecosystem processes, and to provide guidelines with which to maintain or restore integrated ecological components across landscapes and ecosystems (Kaufmann et al. 1994; Kaufmann et al. 1998). Our results document that the historical range of variability in fire regimes for at least this area of ponderosa pine ecosystems must be expanded to include greater complexity in fire behavior than has been previously recognized in ponderosa pine forests. However, how far beyond the montane forest landscape of Cheesman Lake these results should be extrapolated will require more quantitative data on fire history and stand structure in ponderosa pine forests from this and other regions. The results from this study provide landscape restoration targets for ponderosa pine forests analogous to Cheesman Lake where management goals are to return ecosystem processes and patterns to a semblance of historical variability.

Acknowledgements

We thank L. Huckaby for help with field sampling. W.W. Covington, M.M. Moore, P.Z. Fulé, and an anonymous reviewer provided invaluable comments that helped to focus the results of this research. We especially thank the Denver Water Department for access to Cheesman Lake and their logistical support during the course of this work. This research was supported by the USDA Forest Service, Rocky Mountain Research Station, through Cooperative Agreement 28-C5-883 and Research Joint Venture 28-JV6-921.

References

Arno, S.F., Harrington, M.G., Fiedler, C.E. and Carlson, C.E. 1995. Restoring fire-dependent ponderosa pine forests in western Montana. Rest. Manag. Notes 13: 32–36.

Arno, S.F. and Sneck, K.M. 1977. A method of determining fire history in coniferous forests in the Mountain West. USDA Forest Service, Gen. Tech. Rep. INT-42. 28 p.

Baisan, C.H. and Swetnam, T.W. 1990. Fire history on a desert mountain range, Rincon Mountain Wilderness, Arizona, USA. Can. J. For. Res. 20: 1559–1569.

Baker, W.L. 1992. The landscape ecology of large disturbances in the design and management of nature reserves. Landscape Ecol. 7: 181–194.

Barrett, S.W., Arno, S.F. and Menakis, J.P. 1997. Fire episodes in the inland northwest (1540–1940) based on fire history data. USDA Forest Service, Gen. Tech. Rep. INT-GTR-370. 17 p.

Bessie, W.C. and Johnson, E.A. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology 76: 747–762.

Bormann, F.H. and Likens, G.E. 1979. *Pattern and Process in a Forested Ecosystem*. Springer-Verlag, New York.

Brown, P.M. and Sieg, C.H. 1996. Fire history in interior ponderosa pine forests of the Black Hills, South Dakota, USA. Int J Wildland Fire 6: 97–105.

Brown, P.M. and Sieg, C.H. In press. Fire history at the ponderosa pine forest – savanna ecotone in the southeastern Black Hills, South Dakota. Écoscience.

Cooper, C.F. 1960. Changes in vegetation, structure, and growth of southwestern pine forest since white settlement. Ecol Monog 30: 129–164.

Covington, W.W., Everett, R.L., Steele, R., Irwin, L.L., Daer, T.A. and Auclair, A.N.D. 1994. Historical and anticipated changes in forest ecosystems in the inland west of the United States. J Sustainable For 2: 13–63.

Covington, W.W., Fulé, P.Z., Moore, M.M., Hart, S.C., Kolb, T.E., Mast, J.N., Sackett, S.S. and Wagner, M.R. 1997. Restoring ecosystem health in ponderosa pine forests of the southwest. J For 95: 23–29.

Covington, W.W. and Moore, M.M. 1992. Postsettlement changes in natural fire regimes: implications for restoration of old-growth *P. ponderosa* forests. *In*: Old-Growth Forests in the Southwest and Rocky Mountain Regions, Proceedings of a Workshop, Portal, Arizona, March 9–13, 1992. pp. 81–99. Edited by Kaufmann, M.R., Moir, W.H. and Bassett R.L. USDA Forest Service, Gen. Tech. Rep. RM-213.

Covington, W.W. and Moore, M.M. 1994. Southwestern ponderosa forest structure: changes since Euro-American settlement. J. For. 92: 39–47.

DeAngelis, D.L. and Waterhouse, J.C. 1987. Equilibrium and non-equilibrium concepts of ecological models. Ecol. Monog. 57: 1–21.

Dieterich, J.H. 1980. The composite fire interval – a tool for more accurate interpretations of fire history. *In* M.A. Stokes and J.H. Dieterich Proceedings of the fire history workshop, October 20–24, 1980, Tucson, Arizona. pp. 8–14. Edited by Stokes, M.A. and Dieterich, J.H. USDA Forest Service, Gen. Tech. Rep. RM-81.

Dieterich, J.H. and Swetnam, T.W. 1984. Dendrochronology of a fire-scarred ponderosa pine. For. Sci. 30: 238–247.

Finney, M.A. 1995. The missing tail and other considerations for the use of fire history models. Int J Wildland Fire 5: 197–202.

Fritts, H.C. 1976. *Tree-rings and climate.* Academic Press, New York.

Fulé, P.Z., Covington, W.W. and Moore, M.M. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecol. Appl. 7: 895–908.

Goldblum, D. and Veblen, T.T. 1992. Fire history of a ponderosa pine/Douglas-fir forest in the Colorado Front Range. Phys. Geog. 13: 133–148.

Grissino-Mayer, H.D. 1995. Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. PhD. Diss., University of Arizona, Tucson, 407 pp.

Heinselman, M.L. 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. *In* Fire

Regimes and Ecosystem Properties. pp. 7–57. Edited by Mooney, H.A. et al. USDA Forest Service, Gen. Tech. Rep. WO-26.

Holling, C.S. and Meffe, G.K. 1996. Command and control and the pathology of natural resource management. Cons. Biol. 10: 328–337.

Johnson, E.A. and Gutsell, S.L. 1994. Fire frequency models, methods, and interpretations. Adv Ecol Res 25: 239–287.

Kaufmann, M.R., Graham, R.T., Boyce, D.A., Jr., Moir, W.H., Perry, L., Reynolds, R.T., Bassett, R.L., Mehlhop, P., Edminster, C.B., Block, W.M. and Corn, P.S. 1994. An Ecological Basis for Ecosystem Management. USDA Forest Service, Gen. Tech. Rep. RM-246, 22 p.

Kaufmann, M.R., Huckaby, L.S., Regan, C.M. and Popp, J. 1998. Forest reference conditions for ecosystem management in the Sacramento Mountains, New Mexico. USDA Forest Service, Gen. Tech. Rep. RMRS-GTR-19.

Kaufmann, M.R., Regan, C.M. and Brown, P.M. In revision. Heterogeneity in ponderosa pine/Douglas-fir forests: Age and size structure in unlogged and logged landscapes of central Colorado. Can. J. For. Res.

Kaufmann, M.R., Stohlgren, T.R., Brown, P.M. and Regan, C.M. 1997. Maintaining heterogeneity in montane forests of the southern Rocky Mountains: a multi-scaled analysis of forest diversity in an unmanaged landscape. Bull Ecol Soc Amer, Program and Abstracts 78: 120.

Lorimer, C.G. 1985. Methodological considerations in the analysis of forest disturbance history. Can. J. For. Res. 15: 200–213.

Mast, J.N. 1993. Climatic and disturbance factors influencing *Pinus ponderosa* stand structure near the forest/grassland ecotone in the Colorado Front Range. PhD. Diss., University of Colorado-Boulder. 215 p.

Morgan, P., Aplet, G.H., Haufler, J.B., Humphries, H.C., Moore, M.M. and Wilson, W.D. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. J. Sustainable For 2: 87–111.

Mutch, R.W. 1970. Wildland fires and ecosystems – a hypothesis. Ecology 51: 1046–1051.

Mutch, R.W., Arno, S., Brown, J., Carlson, C., Ottmar, R. and Peterson, J. 1993. Forest health in the Blue Mountains: A management strategy for fire-adapted ecosystems. USDA Forest Service, Gen. Tech. Rep. PNW-310.

Neter, J., Wasserman, W. and Kutner, M.H. 1989. *Applied linear regression models.* 2nd ed. Irwin, Homewood, IL, 667 pp.

Ortloff, W. 1996. Wood-anatomical evidence of fire seasonality. *In* Tree rings, environment, and humanity: proceedings of the International Conference, Tucson, Arizona, 17–21 May, 1994. pp. 89–93. Edited by Dean, J.S., Meko, D.M. and Swetnam, T.W. Radiocarbon 1996.

Pearson, G.A. 1933. A twenty-year record of changes in an Arizona pine forest. Ecology 17: 270–276.

Peet, R.K. 1981. Forest vegetation of the Colorado Front Range. Vegetatio 45: 3–75.

Pickett, S.T.A. and P.S. White (eds). 1985. *The ecology of natural disturbance and patch dynamics*. Academic Press, New York, 472 pp.

Pyne, S.J. 1984. *Introduction to wildland fire*. John Wiley, New York, 455 pp.

Riece, S.R. 1994. Nonequilibrium determinants of biological community structure. Amer Sci 82: 424–435.

Romme, W.R. 1980. Fire history terminology – report of the ad-hoc committee. *In* (Technical Coordinators), Proceedings of the fire history workshop, October 20–24, 1980, Tucson, Arizona. pp. 8–14. Edited by Stokes M.A. and Dieterich, J.H. USDA Forest Service, Gen. Tech. Rep. RM-81.

Romme, W.H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecol Monog 52: 199–221.

Savage, M.A., Brown, P.M. and Feddema, J. 1996. The role of climate in a pine forest regeneration pulse in the southwestern United States. Écoscience 3: 310–318.

Smith, T.M. and Urban, D.L. 1988. Scale and resolution of forest structural pattern. Vegetatio 74: 143–150.

Sousa, W.P. 1984. The role of natural disturbance in natural communities. Ann Rev Ecol Syst 15: 353–391.

Stokes, M.A. and Smiley, T.L. 1968. *An introduction to Tree-Ring Dating.* University of Chicago Press, Chicago, 68 p.

Swetnam, T.W. 1990. Fire history and climate in the southwestern United States. *In* Effects of Fire Management of Southwestern Natural Resources, Proceedings of the Symposium. pp. 6–17. Edited by Krammes, J.S. UDSA Forest Service, Gen. Tech. Rep. RM-191.

Swetnam, T.W. 1993. Fire history and climate change in giant sequoia groves. Science 262: 885–889.

Swetnam, T.W. and Baisan, C.H. 1996a. Historical fire regime patterns in the southwestern United States since 1700. *In* Fire Effects in Southwestern Forests, Proceedings of the 2nd La Mesa Fire Symposium, March 29–31, 1994, Los Alamos, New Mexico. pp. 11–32. Edited by Allen, C.D. USDA Forest Service, Gen. Tech. Rep. RM-GTR-286.

Swetnam, T.W. and Baisan, C.H. 1996b. Fire histories of montane forests in the Madrean Borderlands. *In* Proceedings of the Symposium on effects of fire on Madrean Province Ecosystems, March 11–14, 1996, Tucson, AZ. pp. 15–36. Edited by Ffolliott, P.F. et al. USDA Forest Service, Gen. Tech. Rep. RM-GTR-289.

Swetnam, T.W. and Betancourt, J.L. 1990. Fire-southern oscillation relations in the southwestern United States. Science 249: 1017–1020.

Swetnam, T.W. and Betancourt, J.L. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American southwest. J. Climate 11: 3128–3147.

Swetnam, T.W. and Brown, P.M. 1992. Oldest known conifers in the southwestern United States: temporal and spatial patterns of maximum age. *In* Old-Growth Forests in the Southwest and Rocky Mountain Regions: the Status of Our Knowledge. Proceedings of a Workshop pp. 24–38. Edited by Kaufmann, M.R., Moir, W.H. and Bassett, R.L. USDA Forest Service, Gen. Tech. Rep. RM-213.

Turner, M.G. 1989. Landscape ecology: The effect of pattern on process. Ann Rev Ecol Syst 20: 171–197.

Turner, M. G., Romme, W.H., Gardner, R.H., O'Neill, R.V. and Kratz, T.K. 1993. A revised concept of landscape equilibrium: Disturbance and stability on scaled landscapes. Landscape Ecol 8: 213–227.

Urban, D.L. 1994. Landscape ecology and ecosystem management. *In* Sustainable ecological systems: Implementing an ecological approach to land management. pp. 127–136. Edited by Covington, W.W. and DeBano, L.F. USDA Forest Service, Gen. Tech. Rep. RM-247.

Veblen, T.T., Kitzberger, T. and Donnegan, J. 1996. Fire ecology in the wildland/urban interface of Boulder County. Unpublished research report to City of Boulder, Colorado, Open Space.

Veblen, T.T., Kitzberger, T., Villalba, R. and Donnegan, J. 1999. Fire history in northern Patagonia: The roles of humans and climatic variation. Ecol Monog.

Veblen, T.T. and Lorenz, D.C. 1986. Anthropogenic disturbance and recovery patterns in montane forests, Colorado Front Range. Phys Geog 7: 1–24.

Watt, A.S. 1947. Pattern and process in the plant community. J. Ecol 35: 1–22.

White, A.S. 1985. Presettlement regeneration patterns in a southwestern ponderosa pine stand. Ecology 66: 589–594.

Zaricksson, O. 1977. Influence of forest fires on the northern Swedish boreal forest. Oikos 29: 22–32.