DISSERTATION

FIRE, CLIMATE, AND FOREST STRUCTURE IN PONDEROSA PINE FORESTS OF THE BLACK HILLS

Submitted by

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In partial fulfillment of the requirements

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY PETER MARK BROWN ENTITLED FIRE, CLIMATE, AND FOREST STRUCTURE IN PONDEROSA PINE FORESTS OF THE BLACK HILLS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

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A prevailing model for historical conditions in ponderosa pine forests is that frequent surface fires maintained open, low-density forest stands composted primarily of old, large trees. However, this model may not apply uniformly to ponderosa pine forests in the Black Hills of southwestern South Dakota and northeastern Wyoming. Infrequent, extensive stand-replacing fires also may have occurred and apparently resulted in large landscapes of dense, even-aged forest. I examined this alternative model for the Black Hills using fire-scar and tree-age data. Fire chronologies from over 1000 trees collected at over 50 locations span the past four to six centuries. Compared to other ponderosa pine forests in the southwest US or southern Rocky Mountains, these communities burned less frequently. Surface fire frequency varied from an average of every 10 to 13 years at lower elevation sites on the ponderosa pine - northern Great Plains prairie ecotone to as much as 30 to 33 years at higher elevations. Mid-elevation interior sites at Jewel Cave National Monument burned on average every 20 to 26 years. Fires largely ceased in all areas shortly after Euro-American settlement began in the 1870s. Pre-settlement age structure documents very pulsed patterns of tree establishment, with the most abundant cohort occurring from 1770 to 1805. Cohorts established during wet periods in the northern Great Plains. Extended wet conditions likely promoted abundant tree regeneration, fast growth, and longer periods between surface fires that would have permitted more trees to reach canopy status, therefore becoming more "fireproof" during later surface fires. The absence of fire was likely more critical to structuring the current forest than any potential variation in fire behavior. The late 1700s cohort also followed an extended drought from1756 to 1761, and tree mortality caused by moisture stress may have contributed to stand opening. Patchy crown mortality from fire coupled with other disturbances undoubtedly contributed to stand opening before pulses of climatically driven seedling establishment. Mortality and regeneration were likely completely uncoupled processes and even-aged structure is not definitive evidence of stand-replacing fires in ponderosa pine forests. However, abundant fire scars indicate that surface fires were ubiquitous across the Black Hills landscape. Thus, the prevailing historical model of frequent surface fires promoting and maintaining mostly open forest stands is largely supported by the tree-ring evidence, although the Black Hills had a greater range of variability in fire behavior than ponderosa pine forests of other regions as documented by historic descriptions of the forest at settlement.

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I. INTRODUCTION

Recent, intensive research efforts have focused on two major properties of ponderosa pine forests of the western US: 1) over the long term, variability in the type, timing, extent, and severity of fires has structured and regulated ponderosa pine ecosystems as much or more so than site (e.g., soils, physiography) or biotic (e.g., competition) factors (e.g., White 1979); and 2) longer-term (centennial- to millennial-scale) patterns in fire regimes have been severely disrupted as a result of land use that accompanied Euro-American settlement in the 19th century (Allen et al. 2002). A highly useful concept that has been applied to the study of these properties is that of historical range of variability (HRV; Morgan et al. 1994). Ecologists and managers increasingly rely on historical data to assess forest conditions over longer time scales than are available from direct observations (Morgan et al. 1994, Landres et al. 1999, Swetnam et al. 1999, Allen et al. 2002). Historical data serve two primary purposes: 1) they provide what Aldo Leopold (1941) termed a "base datum" against which contemporary forest and ecosystem conditions can be contrasted; and 2) they provide a longer time frame for understanding the spatiotemporal drivers of ecosystem processes, including stochastic and transient events such as climate change, that often have lasting impacts on forest structure and function.

However, recovering the past is also problematic. Paleoecological data of all types (e.g., pollen sequences, fossil assemblages, fire-scar records) are proxy records of past events or conditions; i.e., they are an expression of the event or condition recorded in a natural archive. Ecological and physiological filtering processes strongly affect both the original formation of a record, its subsequent preservation through time, and our ability to recover the information contained in the record. Furthermore, both spatial and temporal scales over which historical data are reconstructed and, thus, may be applied, must be defined. Certainly all ecological studies suffer from these same constraints. Ecological data have both a “grain” (the smallest or shortest unit of resolution of the data) and an “extent” (the largest or longest unit), which limit spatiotemporal inferences that can be drawn from such data. Obviously, one of the greatest strengths of paleoecological studies is the ability to extend temporal scales of information to periods longer than those recoverable through contemporary analyses.

In this dissertation, I applied tree-ring methods to reconstruct past fire and forest histories and to explore the spatiotemporal drivers of fire regimes in ponderosa pine forests of the Black Hills in southwestern South Dakota and northeastern Wyoming. In chapters II and III (published as Brown and Sieg 1996, 1999), I described and compared surface fire histories at seven sites in two geographic areas in relation to landscape attributes and local climatic regimes. The first of these chapters examined spatiotemporal patterns of the fire regime in four sites at Jewel Cave National Monument in the interior of the Black Hills. Basic parameters of the fire regime, including fire frequency, spatial patterning of burning, and fire seasonality, were explored in this chapter. Chapter III reconstructed fire frequency, seasonality, and relative spatial scales in three sites at Wind Cave National Park on the southeastern margin of the ponderosa pine forest on the edge of the Great Plains grassland. Fire frequency was much greater in the this area than any others I found in the Black Hills, and was likely related to the fire regime that was present on the grasslands rather than that in the majority of the ponderosa pine forest of the interior Hills.

Chapter IV expanded the site-level comparisons of the previous two chapters to the rest of the Black Hills. I applied a novel methodology by examining stand-age data in relation to the fire-scar data to infer possible variations in past fire severity. Shinneman and Baker (1997) proposed that even-aged forest structure found in many areas across the Black Hills is an indication of extensive pre-settlement stand-replacing fires. In data presented here, I found abundant evidence of even-aged structure across the Black Hills, but cohorts also corresponded temporally to wet periods in a reconstruction of northern Plains rainfall. Extended wet conditions likely promoted abundant tree regeneration, faster growth, and longer periods between surface fires that would have permitted more trees to reach canopy status, therefore becoming more "fireproof" during later surface fires. A question posed by these data: if even-aged structure resulted from wet conditions in the northern Plains, how likely is it that trees established in openings created by stand-replacing fires? I found the tree-ring data to be equivocal on this point. Stand opening likely resulted from many factors, including less severe fire behavior, other disturbances, and drought. Mortality and regeneration were apparently uncoupled processes and even-aged structure may never be definitive evidence of stand-replacing fires in Black Hills ponderosa pine forests. However, abundant fire scars found in all stands indicate that surface fires were ubiquitous across the Black Hills landscape. The prevailing historical model - based mainly on data from Southwestern ponderosa pine forests - of frequent surface fires promoting and maintaining mostly open forest stands is largely supported by the tree-ring evidence from the Black Hills.

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II. FIRE HISTORY IN INTERIOR PONDEROSA PINE COMMUNITIES OF THE BLACK HILLS, SOUTH DAKOTA, USA

ABSTRACT

Chronologies of fire events were reconstructed from crossdated fire-scarred ponderosa pine trees for four sites in the south-central Black Hills. Compared to other ponderosa pine forests in the southwest US or southern Rocky Mountains, these communities burned less frequently. For all sites combined, and using all fires detected, the mean fire interval (MFI), or number of years between fire years, was 16 years (± 14 SD) for the period 1388 to 1900. When a yearly minimum percentage of trees recording scars of ≥ 25% is imposed, the MFI was 20 years (± 14 SD). The length of the most recent fire-free period (104 years, from 1890 to 1994) exceeds the longest intervals in the pre-settlement era (before ca. 1874), and is likely the result of human-induced land use changes. Based on fire scar position within annual rings, most past fires occurred late in the growing season or after growth had ceased for the year. These findings have important implications for management of ponderosa pine forests in the Black Hills and for understanding the role of fire in pre-settlement ecosystem function.

INTRODUCTION

Fire was a keystone ecological process that shaped the composition and structure of many plant communities in western North America before widespread settlement by non-Native Americans in the mid- to late-19th century. Since that settlement, livestock grazing and fire suppression have reduced or completely excluded fire in many ecosystems (e.g., Savage and Swetnam 1990, Swetnam and Baisan in press). A historical perspective on pre-settlement fire regimes is therefore needed to understand the role that fires may have had in shaping plant community patterns and its relations with other ecosystem processes.

Relatively little is known about pre-settlement fire regimes in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests of the Black Hills of western South Dakota and eastern Wyoming. Paired comparisons of photographs from 1874 with recent photographs demonstrate dramatic increases in ponderosa pine densities and invasion into meadows in the Black Hills over the past 100 years (Progulske 1974). McAdams (1995) quantified increases in ponderosa pine tree densities and basal areas in Black Hills forests for the period 1874 to 1995, with up to five-fold increases in 1-20 cm diameter-class trees over this time period. These community structural changes are similar to those in ponderosa pine forests of the southwest US and southern Rocky Mountains that are argued to be the result of fire exclusion over the past century (e.g. Covington and Moore 1992, 1994). Fire history studies in these areas (Cooper 1960, Swetnam and Dieterich 1985, Baisan and Swetnam 1990, Savage 1991, Swetnam and Baisan in press) have shown that relatively low-intensity surface fires were frequent and widespread in ponderosa pine forests prior to land use changes. Pre-settlement fires in the southwest US occurred an average of every 3 to 20 years and synchronous, climate-related, fire years resulted in burning over very large areas (Swetnam and Betancourt 1990, Swetnam and Baisan in press). This high fire frequency maintained open ponderosa pine stands by killing seedlings and saplings.

Fisher et al. (1987) found average pre-settlement fire intervals of 14 to 27 years at a ponderosa pine savanna site near the western edge of the Black Hills at Devil's Tower National Monument in eastern Wyoming. This study suggests that frequent fire was present in ponderosa pine forests of the Black Hills and that its exclusion may be at least partially responsible for historic changes seen in community structure and density. However, fire histories are needed from other areas of the Black Hills to better understand and document the range of variability in fire regimes before and since widespread settlement that took place in the late 1800s.

The objectives of our study were to reconstruct past fire frequencies, timing, season of burning, and spatial patterning at Jewel Cave National Monument in the south-central Black Hills using fire scars recorded in dendrochronologically-crossdated tree-ring series. In addition, we used pith dates of these ponderosa pine trees to provide preliminary data on stand establishment dates. This type of information is needed to both understand the historical role of fire in this region and to provide land managers with guidelines and justification for prescribed burning.

METHODS

Study area

The Black Hills are an isolated mountain range in the Northern Great Plains physiographic province, covered primarily by ponderosa pine forest and surrounded by mixed-grass prairies. Jewel Cave National Monument is in the south-central Black Hills in the interior of the ponderosa pine forest. The Monument is underlain by limestone substrate and dissected by several deeply incised canyons; elevations range from 1585 to 1768m (National Park Service 1991). An average of 432mm of precipitation falls annually, most of which occurs as rain between April and September. The Monument was established in 1908 and administered by the U.S. Forest Service until 1933 (National Park Service 1991). The Monument is now managed by the National Park Service with only 11% of the original Monument included within the current boundaries, the rest in the Black Hills National Forest. Although bison *(Bison bison)* were once common in adjacent prairies and wandered into the foothills (Turner 1972) and even upper elevations (Fryxell 1926) of the Black Hills, by 1874, they had been eliminated from this region (Dodge 1965). Since that time, the area encompassed by the original monument has not been grazed by bison. Most of the Monument area has been accesible to livestock grazing at some time over the past 100 years, although steep topography has generally limited grazing to lowlands.

Ponderosa pine forest occurs on over 90% of the Monument. A large portion of the original Monument was harvested for timber beginning in the late 1800s and continuing into the early part of this century (National Park Service 1991). Much of the second-growth forest that arose after harvest is dense, with a sparse understory of mostly white corralberry *(Symphoricarpos albus* L.) under a nearly continuous canopy of ponderosa pine trees. Mountain ninebark *(Physocarpus monogynus* ([Torr.] Coult.) is a conspicuous component of the pine understory on north-facing slopes. South-facing slopes support a more open pine canopy with an understory of little bluestem *(Andropogon scoparius* Michx.) and western wheatgrass *(Agropyron smithii* Rydb.). Small areas of original old-growth forest are relatively open with grass understory, although gap-filling by younger ponderosa pine trees is occurring in these areas.

Fire history

Fire scars have been used to examine temporal and spatial patterning of past fires in many forest ecosystems (e.g. McBride and Laven 1976, Arno and Sneck 1977, Dieterich and Swetnam 1984, McClaran 1988, Baisan and Swetnam 1990, Swetnam 1993, Brown and Swetnam 1994). Fire scars result when surface fire kills cambial tissue along a portion of a tree's growing circumference, forming a characteristic lesion visible in the tree rings. Long-term sequences of fire scars are often recorded on individual trees owing to repeated fire events during the life of a tree.

Fire-scarred ponderosa pine trees were collected from four sites in the Jewel Cave National Monument area (Figure 2.1). Collection sites were chosen to encompass a range in aspects, slopes, and area of the Monument. The purpose of collection was to obtain comprehensive, long-term inventories of fire events for each stand-level site through the use of proxy fire-scar records. We attempted to maximize both the comprehensiveness and length of the record of fire events at each site by collecting several fire-scarred trees and then compiling a fire chronology from fire dates recorded on all trees (*sensu* Dieterich 1980). Compilation of fire chronologies minimized any potential incompleteness in fire scar records found on individual trees (Brown and Swetnam 1994). Not all fires that burned around the base of a tree may have been recorded as scars and scars may have been lost by subsequent burning or weathering (Brown and Swetnam 1994, Swetnam and Baisan in press). Further, numbers of fire scars were usually directly related to the age of a tree. By collecting trees exhibiting greater numbers of scars, we were able to compile fire chronologies covering longer time periods.

At each of our four sites, we removed cross sections from fire-scarred stumps, logs (dead and down trees), snags (standing dead trees), and living trees using a chainsaw. Because of past harvesting in the area, the majority of our collected trees were stumps. Full-circumference cross sections were generally removed from stumps or logs, while only partial cross sections were removed from the vicinity of the fire-scarred area of living trees and snags. Cross sections were taken to the laboratory and surfaced to 400 grit (very fine) sandpaper using a hand planer, belt sander, and hand sanding. Fine sanding was necessary to observe tracheid cell structure within the rings and at fire scar boundaries (Dieterich and Swetnam 1984).

We crossdated all tree-ring series using standard dendrochronological procedures (Stokes and Smiley 1968, Swetnam et al. 1985). To provide dating control for the remnant (dead) material, we developed a master chronology for the Jewel Cave area from increment cores collected from 10 living ponderosa pine trees growing on the slopes of Hell Canyon (Figure 2.1). These cores were surfaced in the lab, crossdated, and compiled into a master skeleton plot chronology (Swetnam et al. 1985). Crossdating of fire-scarred cross sections was also verified using two ponderosa pine ring-width index chronologies from the central Black Hills: Pilger Mountain Lookout (collected by H.C. Fritts, archived at the International Tree-Ring Data Bank, National Geophysical Data Center, Boulder, Colorado), and Reno Gulch (D.M. Meko, Laboratory of Tree-Ring Research, University of Arizona, personal communication). Crossdating provided absolute dates for fire events and enabled us to use remnant material to reconstruct fire history. Use of remnant material minimized removal of cross sections from living trees within the National Monument and maximized the period of fire history reconstruction (Baisan and Swetnam 1990).

After crossdating of tree-ring series on all cross sections from a site was verified, dates were then assigned for fire scars. Positions of fire scars within annual rings (Dieterich and Swetnam 1984, Baisan and Swetnam 1990) were recorded when possible (see descriptions for scar positions in Table 2.3). It was difficult to tell if dormant season scars (formed between two rings) occurred in the earlier or later year (i.e., to have been fall fires occurring after growth had ended for a year or spring fires occurring before the growing season began for the next). Assignment of dormant season scar dates was based on the presence of either latewood or earlywood scars on other trees. If latewood or late-earlywood scars were present on other trees in the earlier year, dormant season scars were assigned to that year. Fire scars for which we were not able to assign a position within an annual ring (unknown position owing to the narrowness of the ring or damage in the scar area) were dated to either the earlier or later year based upon positions of fire scars on other trees for that period.

After all samples were crossdated, dates of fire scars were complied into a fire chronology for each site. Mean fire-free intervals (MFIs), or number of years between fire years, and standard deviations were calculated for each site.

RESULTS

A total of 448 fire scars were crossdated from 59 trees collected at the four sites (Figure 2.2). Fire dates showed agreement both within and between sites. Regular fire events were recorded on all trees from the beginning of the fire chronologies up until 1890. Only one fire scar was recorded on any tree after 1890, this in 1900. Widespread fire dates that were recorded on most trees at all four sites included 1697, 1706, 1785, 1822, and 1890.

Although the mean fire intervals (MFIs) were relatively similar among sites, they were also highly variable with large standard deviations and ranges. When all fires were considered, MFIs were 20 to 23 years at individual sites; the MFI for all fire dates at all sites combined was 16 years (Table 2.1a). We also calculated MFIs for time periods encompassing a minimum number of 2 trees and for those years when at least 25% of trees were scarred (dates in middle portions of Figure 2.2). MFIs for these more widespread fire years ranged from 20 to 32 years, and was 20 years for fire dates at all four sites combined (Table 2.1b).

There was also general agreement in timing of intervals between sites. All four sites recorded the longest intervals between widespread fire years (recorded on ≥ 25% of the trees for that year; dates in middle of graphs in Figure 2.2) in the early 1700s (Table 2.2). At site JCS, there were no widespread fire years for the period 1706 to 1785, although two trees did record fire scars in two different years within this period (Figure 2.2d). The fire-free period after the end of the 19th century has not been used in calculations of MFI. However, the length of this most recent fire-free period (104 years, from 1890 to 1994) exceeded the longest intervals recorded in the pre-settlement era of the fire chronologies at three sites by more than 2 times (Table 2.2). At the fourth site (JCS), the length of the longest pre-settlement interval has been exceeded by 25 years during the post-settlement period.

Spatial patterning of selected fire years is shown in Figure 2.3. While historic patterns of fire in these and other ponderosa pine communities suggest that single fires often burned over large areas, it is also possible that scars recorded on scattered trees or sites were from different fire ignitions in the same year. In addition, it is impossible to know the true spatial extent of fire in any of these years beyond the bounds covered by collected trees. While fire scars were recorded on most of the trees at all four sites in some years (Figure 2.3), there is still no means to know how extensive burning may have been without further data.

Based on fire scar position within annual rings, the majority of those scars that could be assigned to a season occurred late in the growing season (i.e., scar recorded in the last third of the earlywood or in the latewood) or after growth had ceased for the year (Table 2.3). Only two years, 1863 and 1785, were classified as early season fires. Slightly over 30% of the scars could not be assigned a seasonal position primarily because of the narrowness of the annual ring.

In addition to the fire history data, we found clusters of pith dates on collected trees that suggest patterns of establishment in the Jewel Cave area. There was a clustering of pith dates in the 1540s to 1560s at site JCN (Figure 2.2a) while the remaining sites had a majority of pith dates from 1610 to 1650 (Figures 2.2b, c, and d). Two trees at JCC recorded their earliest dates in the early 1300s (Figure 2.2b). One of these trees, JCC 14, extended from 1320 to 1993 and was a minimum of 674 years old at the time of collection. The second tree, JCC 13, extended from 1355 to 1993 and was a minimum of 639 years old.

DISCUSSION

Development of fire chronologies

Fire regimes are combinations of spatial and temporal elements that influence the responses of communities, populations, and individual organisms to fire as an ecosystem disturbance process. These elements include frequency, intensity, spatial extent, and seasonality (Pickett and White 1985). Recent debates about sampling strategies (Johnson and Gutsell 1994, Swetnam and Baisan in press) relate to attempts to provide a more rigorous statistical foundation for describing and interpreting these elements as reconstructed from fire history studies. Johnson and Gutsell (1994) suggest that the only statistically valid reconstructions of fire frequency are through the use of "time-since-fire" maps. Such maps contain both temporal and spatial elements in which boundaries of dated fire events are drawn over a study area (*sensu* Heinselman 1981). Johnson and Gutsell (1994) describe the use of such maps in low frequency, high intensity fire regimes where stand-destroying fire events were common and the possible spatial extent of such events may be determined today from changes in stand age structure or density or by remote sensing methods.

However, for high frequency, low intensity, episodic fire regimes in which stand-destroying events were rare, time-since-fire maps are impossible to construct. Extant stand structures or other external stand features are of little use as surface fires most often had little or no impact on overstory forest structure. Further, dramatic changes in stand structure and density in many forest ecosystems resulting from human impacts such as fire exclusion (e.g. Covington and Moore 1994) or logging during the post-settlement period may make any post-fire forest structure from before this period even more difficult to detect. This latter point will also make time-since-fire maps in areas of stand-destroying fire regimes that have been logged potentially suspect.

The fire chronologies developed by this study are inventories of fire events that are as comprehensive and as long as possible to obtain for specific locations on the landscape. These are essentially temporal and spatial maps of fire occurrences at the scale of a forest stand (Swetnam and Baisan in press). Because of the need to include a comprehensive selection of fire-scarred trees, the sizes of collection units vary. However, this should not invalidate statistical analyses of the data since they are considered to be a complete census of fire events within the bounds covered by selected trees both in space and time, and not a sample of a fire scar population (as per Johnson and Gutsell 1994). While a fire history analysis such as this could focus on single-tree fire scar records and thereby eliminate the problem of non-uniform sizes of collection sites, there is still the possibility of lost fire records owing to potential incomplete original recordation of fire scars and subsequent preservation of those records (see Methods section).

By collecting multiple sites in an area such as Jewel Cave National Monument, generality of fire regime parameters is possible because of replication of patterns seen in those parameters between sites. Although there were differences in fire dates and fire frequency between sites, these were slight and overall patterns of fire timing were similar (Tables 2.1 and 2.2). Furthermore, all sites recorded similar fire scar seasonal positions during individual fire years (Table 2.3). Eventually, fire chronologies will be developed in other areas of the Black Hills to assess regional-scale patterns of fire regimes. Patterns of synchrony or asynchrony between regional fire records through time may be relatable to patterns of vegetative community structure, climate variation, land use history, or landscape-scale ecosystem processes (Swetnam and Baisan in press).

Characteristics of the fire regime

The mean fire intervals in the Jewel Cave area were generally longer than those found in southwestern or southern Rocky Mountain ponderosa pine forests (Wright and Bailey 1982, Dieterich and Swetnam 1984, Baisan and Swetnam 1990, Savage 1991). Many of those forests recorded fire up to four or five times as frequently as interior forests of the southern Black Hills. The MFIs in our study are consistent with those Fisher et al. (1987) reported in ponderosa pine savanna in the Devil's Tower area on the western edge of the Black Hills. Fisher et al. (1987) reported average fire intervals for the period from 1632 to 1770 to be 27 years. From 1770 to 1900, fire frequency increased to once every 14 years, which Fisher et al. (1987) attributed to increased use of the area by the Sioux and other aboriginal groups. Fire frequency at Jewel Cave was also consistent with that reported for ponderosa pine stands in the northern Rocky Mountains (e.g. Arno 1976, Barrett and Arno 1982, Wright and Bailey 1982). MFIs in these areas have been reported to range from 5 to 20 years (Arno 1976) for areas in the Bitterroot Valley of Montana to 18.2 years for remote stands in eastern Idaho (Barrett and Arno 1982).

However, because of the high variance in fire intervals, it is difficult to estimate what an "average" fire interval was at Jewel Cave. All four sites recorded fairly frequent fire for a short period from the late 1600s to 1706 (Figure 2.2). After the 1706 fire year, however, there was a long period without fire, especially at site JCS where widespread fire was not recorded again until 1785. There was another relatively long gap in scar dates at all four sites from 1785 to 1822, with no tree in any of the sites recording fire during this period. In the latter half of the 1800s, especially at 2 sites (Figures 2.2c and d), there was an increase in fire frequency that may have been related to non-Native American settlement activities that began at that time. Intensive non-Native settlement in this area of the Black Hills started after the discovery of gold near the town of Custer (approximately 20km east of Jewel Cave) in 1874, with the population of Custer possibly as high as 6000 people by 1876 (Progulske 1974). Increased use of this area by miners and later, ranchers, probably resulted in increased fire ignitions, some of which may have burned into the Jewel Cave area. It is impossible to say whether any of the fire history recorded before this was the result of aboriginal activities on the landscape.

However, in contrast to central tendencies in fire frequency, heterogeneity in the timing of fire occurrences may be a more important component of a fire regime when assessing fire's effects on ecosystem and community function. There is increasing recognition that heterogeneity in spatial components of an ecosystem, such as habitat availability and resource distribution, contribute to community structure and species diversity as much or more so than community-level processes such as competition and predation (e.g. Ricklefs 1987, Reice 1994). If spatial variability in fire regime parameters - such as large versus small fires or variation in intensities within the same fire - is a major contributor to such ecosystem heterogeneity, then temporal variability should be as well. Large variability in the length of fire-free intervals may mean that fire had greater impacts on community dynamics through distribution of habitats and resources through time similar to that through space. For example, fire causes immediate volatilization and mineralization of forest floor biomass. Greater variability in the length of fire-free intervals would lead to greater dynamics in ecosystem nutrient pulses related to fire events. Perhaps it is appropriate to focus as much attention on variance of fire interval distributions as central tendencies when assessing impacts of disturbance dynamics in ecosystem and community function.

The cessation of scar dates at the end of the 19th century follows patterns seen in other fire history studies that are also argued to be the result of non-Native American settlement activities (Fisher et al. 1987, Swetnam et al. 1989, Baisan and Swetnam 1990, Savage 1991, Swetnam 1993, Brown and Swetnam 1994). Pre-settlement fires in ponderosa pine forests were most likely primarily grass fires, and the introduction of livestock grazing reduced fine fuels necessary to carry fire for any distance beyond a point of ignition (Zimmerman and Neuenschwander 1984, Savage and Swetnam 1990, Covington and Moore 1994, Touchan et al. 1995). Furthermore, the establishment of the Black Hills Forest Preserve in 1897 and National Park Service areas in the Black Hills in the early 1900s led to active fire suppression by land managers, especially after 1910 (Progulske 1974). In addition to livestock grazing after settlement, bison grazing before settlement may have played a role in both the temporal and spatial patterning of fire during individual fire years. However, we could find no data for historic levels of bison population dynamics or migration patterns to compare to patterns seen in the fire chronologies.

Differences in spatial patterning in the Jewel Cave area in selected fire years were apparently due to natural fire breaks, although during most fire years, fire scars were recorded on trees at all four sites (Figure 2.3). Hell Canyon, especially north of the highway crossing in the Monument (Figure 2.1), is a very steep walled canyon with rocky slopes. Lithograph Canyon south of the Monument headquarters (Figure 2.1) is also a relatively steep-sloped canyon, although not as steep or deep as Hell Canyon. Both of these canyons apparently acted as fire breaks during some fire years. For example, fire burned only on the northeast sides of Hell and Lithograph Canyons in 1668, while only on the south and west sides 16 years later in 1684 (Figure 2.3). Another example was in 1845 when fire burned on only the west and south sides at sites JCS and JCN but not on the northeast side at JCE or JCC. A single year difference in fire dates was also recorded between sites in 1863 and 1864. Fire was recorded on trees at JCS and most of the trees at JCE in 1863 while trees at JCN and JCC recorded fire in 1864. Two trees at JCE (JCE 10 and JCE 11; figures 1 and 2c) recorded the 1864 fire date but not the 1863 date. These two trees were growing on the north-facing side of a ridge (figure 1) which apparently was enough of a fire break that the 1863 fire did not cross over.

The presence of late season scars fits with patterns of historic fire occurrence in the Black Hills and Northern Great Plains. Higgins (1984) found a majority (73%) of 294 historic lightning-ignited fires in the Northern Great Plains grasslands and pine savannas occurred in July and August, with the peak (40%) in August. Although data on radial (ring) growth phenology for ponderosa pine in the Black Hills are not available, Fritts (1976) indicates that radial growth in Arizona ponderosa pine is generally complete by mid-July to mid-August. Assuming a similar or slightly shorter growing season for ponderosa pine in the more northerly Black Hills, scars recorded as either late-earlywood, latewood, or dormant season (Table 2.3) would cover the July-August window when the majority of historic fires occurred.

Given the limited number of trees we collected, the distribution of pith dates tentatively suggests that stand-establishing events occurred in the Jewel Cave area in the mid-1500s and again in the early 1600s. High intensity, stand-destroying fires could have initiated post-fire stands. Many trees that predate the early 1600s period recorded a widespread fire year in 1591. Climate variability is another possible explanation for the patterns of pith dates seen, as is the possible case in southwestern US ponderosa pine stands (Swetnam and Brown 1992). Possible temporal patterns of establishment in Black Hills forests will be explored with further climate and stand establishment data in the future.

CONCLUSION

Data from interior ponderosa pine forests in the south-central Black Hills suggest that fire frequency was not as high as in other ponderosa pine forests of the southwest or southern Rocky Mountains. However, even with these longer pre-settlement fire intervals, interior Black Hills ponderosa pine forests are not burning today nearly as often as they did in the past. The longest pre-settlement fire interval recorded at any the four Jewel Cave sites (79 years, from 1706 to 1785) has been exceeded by the absence of fire events during the twentieth century post-settlement period. This finding has important implications both for management of ponderosa pine forests at Jewel Cave National Monument and for understanding of ecosystem processes in the absence of human disturbance and changes in land use.

Covington and Moore (1994), reviewing their own and many other studies, list post-settlement changes in ponderosa pine community structure and function can be directly or indirectly attributed to fire exclusion. These changes include: 1) overstocked patches of saplings and pole-sized trees; 2) reduced tree growth and increased mortality, especially of the older trees in a stand; 3) stagnated nutrient cycling; 4) increased irruptions of insects and diseases; 5) higher fuel loads, including increased vertical fuel continuity ("ladder fuels"); 6) decreased stream flows; and 7) less wildlife habitat for species dependent upon herbaceous vegetation. All of these changes are or may be present in ponderosa pine forests at Jewel Cave today and are most likely contributing to the loss of species and habitat diversity in these forests (Reice 1994). Furthermore, definition of reference conditions in pre-settlement forests are needed since such conditions are often our only viable template for long-term sustainability of forest ecosystems (Kaufmann et al. 1994). Meaningful reintroduction of fire as a ecosystem process should be a prime component of any management strategy to restore natural conditions in interior ponderosa pine forests of the Black Hills. Data such as presented here should offer both guidelines and justification for on-going prescribed burn programs at both Jewel Cave National Monument and nearby Wind Cave National Park in the south central Black Hills.

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Table 2.1. a. Number of fire intervals, mean fire intervals (MFIs) (± SD) and ranges of fire intervals at four sites and all sites combined, using all detected fire dates. All sites combined are intervals between fire years recorded at any of the four sites. b. Number of fire intervals, MFIs (± SD) and ranges of fire intervals at four sites and all sites combined, using fire dates recorded when sample depth ≥ 2 trees and fire index (or percentage of trees recording a fire in that year) ≥ 25% (i.e. using dates in middle portions of Figure 2.2).

a.	Site	Period	No. fire intervals	MFI (yrs.)	Range (yrs.)
	JCS	1591 to 1900	13	23 ± 23	7 - 93
	JCE	1591 to 1890	13	23 ± 22	1 - 77
	JCN	1576 to 1890	17	20± 13	4 - 45
	JCC	1388 to 1890	22	22 ± 18	1 - 63
	ALL SITES	1388 to 1900	34	16 ± 14	1 - 45

b.	Site	Period	No. fire intervals	MFI (yrs.)	Range (yrs.)
	JCS	1684 to 1890	9	23 ± 23	7 - 79
	JCE	1668 to 1890	11	20 ± 15	5 - 47
	JCN	1663 to 1890	11	21 ± 13	6 - 45
	JCC	1668 to 1890	7	32 ± 12	9 - 47
	ALL SITES	1576 to 1890	16	20 ± 14	1 - 45

Table 2.2. Longest fire-free intervals for the period 1663 to 1890. Fire dates used are those when sample depth ≥ 2 trees and fire index ≥ 25% (dates in middle portions of Figure 2.2).

Site	Longest fire-free period	No. of years
JCN	1706 to 1751	45
JCC	1706 to 1753	47
JCE	1706 to 1753	47
JCS	1706 to 1785	79

Table 2.3. Number of fire scars by position within annual rings. Scar positions are: **Unknown earlywood**: position within the earlywood cannot be defined more precisely; **Early-earlywood**: within first 1/3 of earlywood band; **Middle-earlywood**: second 1/3 of earlywood; **Late-earlywood**: last 1/3 of earlywood; **Latewood**: within the latewood band; **Dormant**: between 2 rings; **Unknown**: due to narrowness of ring or quality of scar (Baisan and Swetnam 1990).

	Fire Scar Position						
	Earlywood						
Site	Unknown	Early	Middle	Late	Latewood	Dormant	Unknown
JCN	7	3	3	12	22	29	37
JCC	6	5	6	10	27	28	33
JCE	7	3	2	14	31	16	23
JCS	6	11	3	8	20	33	43
Total(%)	26(5.8%)	22(4.9%)	14(3.1%)	44(9.8 %)	100(22.3%)	106(23.7%)	136(30.4%)

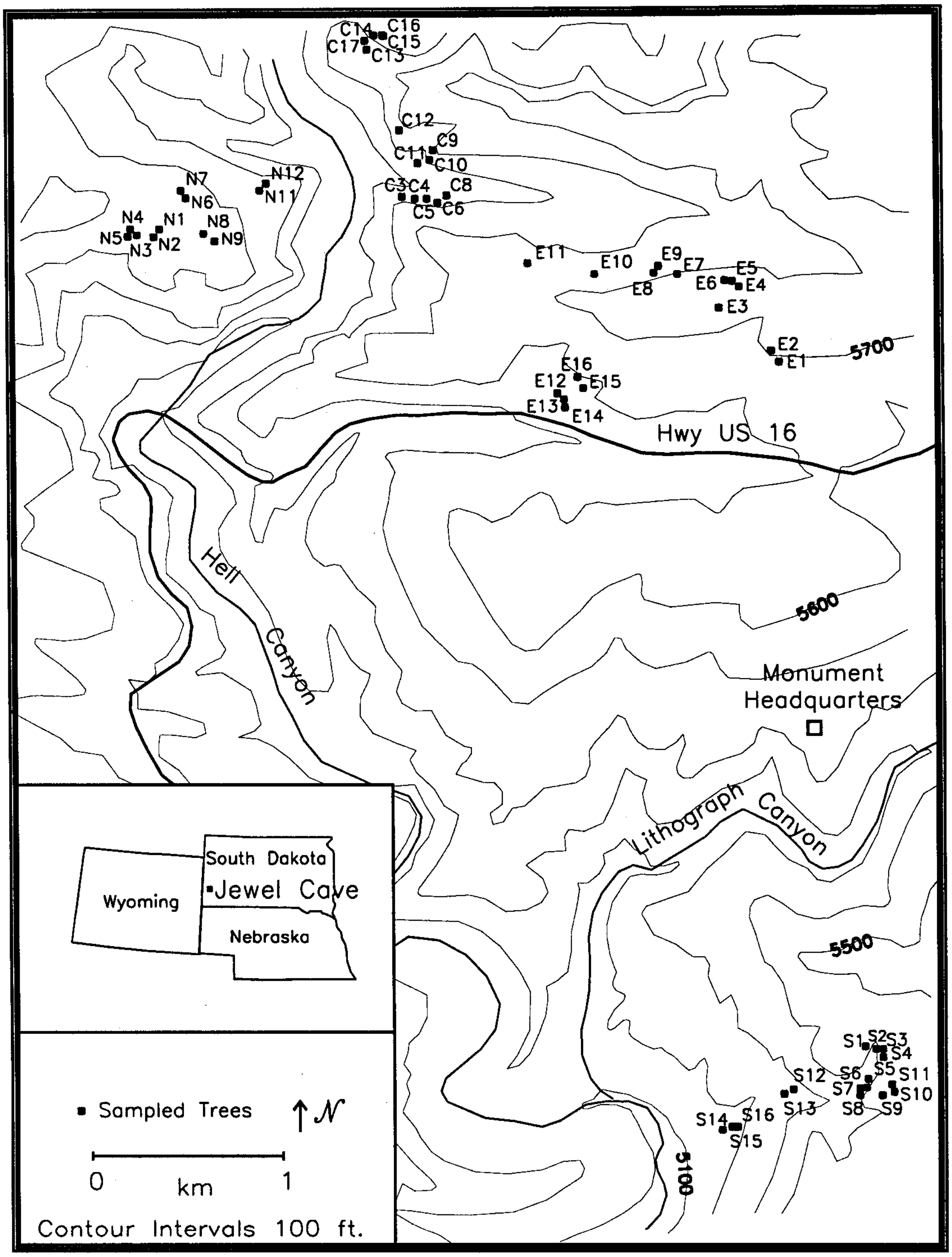

Figure 2.1. Locations of fire-scarred trees collected at Jewel Cave National Monument. Site designations are: Jewel Cave East (E numbers), Jewel Cave South (S), Jewel Cave Central (C), and Jewel Cave North (N). All sites are within the current or original boundaries of Jewel Cave National Monument.

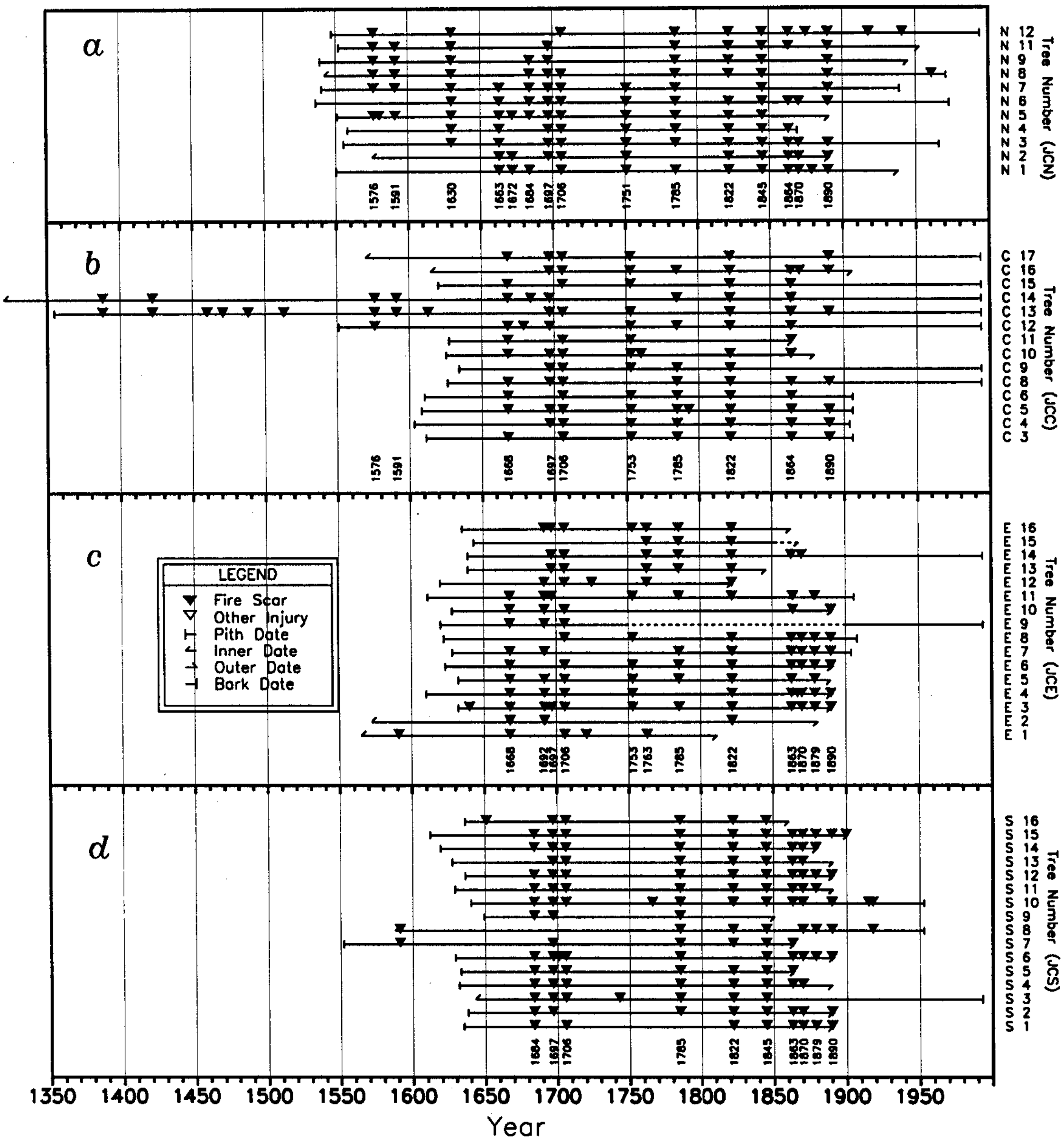

Figure 2.2. Fire chronologies for Jewel Cave National Monument sites. Time spans of individual trees are represented by horizonal lines, with fire scars noted by triangles at the dates they were recorded. Open triangles are other injuries or questionable fire scars recorded within the ring series. (Questionable scars or other injuries are not used in calculations of mean fire intervals.) Dates in the lower part of each site were those years when sample depth was ≥ 2 trees and fire index ≥ 25% (defined as widespread fire years at a site).

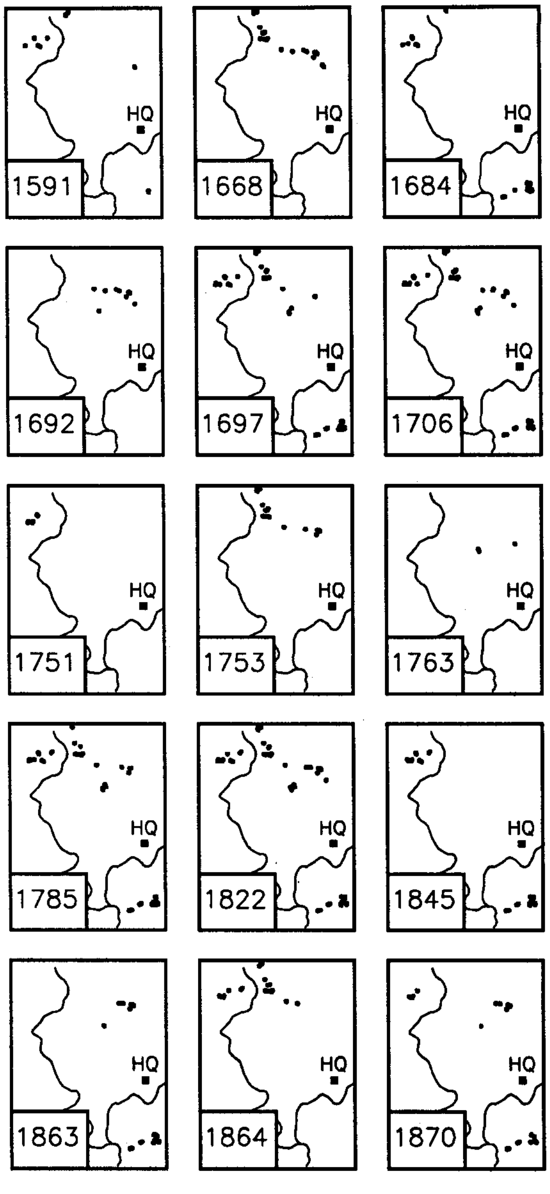

Figure 2.3. Maps of fire occurrence for selected fire years at Jewel Cave National Monument sites. Black stars represent trees recording a fire scar for each fire year. HQ in each map is location of Monument headquarters and light lines are locations of Hell and Lithograph Canyons. See Figure 2.1 for more detailed map for reference of locations of collected trees.

III. HISTORICAL VARIABILITY IN FIRE AT THE PONDEROSA PINE - NORTHERN GREAT PLAINS PRAIRIE ECOTONE, SOUTHEASTERN BLACK HILLS, SOUTH DAKOTA

ABSTRACT

Ecotones are boundaries between plant assemblages that can represent a physiological or competitive limit of species' local distributions, usually through one or more biotic or abiotic constraints on species' resource requirements. However, ecotones also result from the effects of chronic or episodic disturbances, and changes in disturbance regimes may have profound effects on vegetation patterns in transitional areas. In this study, centuries-long chronologies of surface fire events were reconstructed from fire-scarred ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) trees in three sites at the ecotone between ponderosa pine forest and Northern Great Plains mixed-grass prairie in the southeastern Black Hills of South Dakota. The fire chronologies provide baseline data to assess the possible role of fire in this transitional area and to document historical variability in fire regimes in this region of the Northern Great Plains.

Regular fire events were recorded at all three sites from the beginning of the fire chronologies in the 1500s up to the late 1800s or early 1900s, at which time spreading fires ceased. Fire frequencies derived from the fire chronologies were compared to each other and to four sites from interior ponderosa pine forest in the south-central Black Hills. Mean fire intervals at the savanna sites were between 10 to 12 years while Weibull median probability intervals were 1 year shorter. Fire frequency at the savanna sites was

twice as high as at the interior forest sites, and most likely was due to spatial extent of fires on the mixed-grass prairie coupled with warmer and dryer climate regime. Post-settlement shifts in the ponderosa pine savanna during the twentieth century in this area may be largely attributed to lack of fire occurrences, although grazing and other factors also likely contributed to observed changes in forest and grassland margins.

INTRODUCTION

Ecotones are boundaries between plant assemblages where presumably environmental conditions change enough to provide species with competitive advantages or disadvantages over others. Much of the research on ecotones has focused on quantifying present-day abiotic (e.g., climatic or edaphic) or biotic (e.g., competition for light or soil moisture) environmental gradients to understand spatial dynamics of vegetative patterning across transitional areas (Peet, 1981; Hansen & Di Castri, 1992; Gosz; 1993; Risser, 1995). This approach has often succeeded in explaining transitions between plant assemblages at a biome or regional scale, but may not fully explain patterning at smaller landscape or patch scales (Gosz, 1993; Risser, 1995).

At smaller scales, vegetation patterns at ecotones are often the result of more complex interactions between environmental factors that control plant reproduction, establishment, growth, and mortality. The position of an ecotone can be the result of historic events or processes that may not be related to any measurable environmental factor. Abrupt climate change, such as a major drought or an anomalous cold period that causes widespread mortality of a species at its environmental limit, can be a cause of major shifts in ecotones (Risser, 1995; Allen & Breshears, 1998). Conversely, climate conditions favorable for plant regeneration may occur more slowly or episodically and lead to lags in re-establishment of an ecotone to some former position (Taylor, 1995). For example, drought in the early 1950s in the southwestern US caused large uphill elevational shifts in woodland - grassland ecotones (Betancourt et al., 1993; Swetnam & Betancourt, 1998) and woodland - forest ecotones (Allen & Breshears, 1998) that have not yet returned to previous positions even after wet periods in the 1970s and 1980s (Gosz, 1991; Swetnam & Betancourt, 1998).

Ecotones also shift in response to changes in either natural or human-induced disturbance regimes (McPherson, 1997). Tree invasion into grasslands has been noted world-wide in response to changes in disturbance frequency or severity (Richardson et al., 1994; McPherson, 1997; Mast et al., 1998). A review of possible explanations for recent woody plant encroachment in southwestern US grasslands by Archer (1994) concluded that widespread and intensive grazing practices that began after non-Native American settlement has been largely responsible for invasion of woodlands into what were formerly pure grassland communities. Archer (1994) also suggested that cessation of surface fire regimes has contributed to observed shifts in woodland ecotones during recent decades.

The Black Hills of southwestern South Dakota and northeastern Wyoming are often described as an island of predominately ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forest surrounded by seas of mixed grasslands of the Northern Great Plains prairie (e.g., Raventon, 1994). The often broad transition zone between forest and grassland on the periphery of the Black Hills - hereafter referred to as the ponderosa pine savanna (McPherson, 1997) - is usually considered to be controlled mostly by climate, with tree establishment and growth on the prairie margins precluded by lower precipitation and warmer temperatures that lead to reduced soil moisture regimes (*sensu* Daubenmire, 1943; Peet, 1981). However, there is evidence that the ecotonal mosaic of ponderosa pine forest, savanna, and grasslands on the periphery of the Black Hills has shifted over the past century in response to changes in land use that began in the late 1800s. Ponderosa pine trees have established in what were formerly grassland communities (Progulske, 1974; Bock & Bock, 1984; Fisher et al., 1987). Sequences of aerial photographs from the southeastern Black Hills (Figure 3.1) document often dramatic changes in ponderosa pine stand density and landscape coverage during very short time periods in recent decades (34 years between scenes in Figure 3.1). Changes in the pine - grassland ecotone in the Black Hills are similar to tree and shrub encroachment seen in many areas of the Northern and Central Great Plains region (Steinauer & Bragg, 1987; Archer, 1994; McPherson, 1997; Mast et al., 1997; 1998).

In this study, we used dendrochronologically-crossdated fire-scarred ponderosa pine trees to document timing and frequency of historical fire occurrences at three sites in the ponderosa pine savanna at Wind Cave National Park in the southeastern Black Hills. We have two objectives with data described here. First, fire chronologies from Wind Cave provide baseline information on the possible role of fire as a control of forest - grassland ecotones in this area. Shifts in forest and grassland patterns in the Black Hills have been attributed at least in part to the disruption of pre-settlement fire regimes of frequent, generally low intensity surface fires (Gartner & Thompson, 1972; Progulske, 1974; Bock & Bock, 1984; Fisher et al., 1987). Frequent surface fires would have tended to maintain the ecotone by killing ponderosa pine seedlings and saplings before they could become established on the prairie margins.

Our second objective with this study was to document historical variability in the fire regime of the Northern Great Plains mixed-grass prairie. Although fire has long been recognized as a pervasive factor influencing the structure and function of prairie ecosystems of North America (Sauer 1950), there are few studies that have quantified pre-settlement fire regimes in these areas (but see Bragg, 1985; Fisher et al., 1987; Umbanhower, 1996). We contrast fire data from Wind Cave National Park with similar data from four interior ponderosa pine forest sites at Jewel Cave National Monument in the south central Black Hills, approximately 35 km northwest of Wind Cave (Brown & Sieg, 1996). Fire data from Wind Cave National Park offer a larger regional view of the historical range of variability (Morgan et al., 1994) in pre-settlement fire regimes in the Black Hills, and provide some of the most detailed fire history information yet available for this area of the Northern Great Plains grasslands.

METHODS

Study area

The Black Hills are an isolated dome of often rugged mountains that rise over 1000 m above the surrounding relatively flat Great Plains of southwestern South Dakota and northeastern Wyoming. Elevations in the Black Hills range from around 1050 to

1350 m on the margins of the Great Plains to Harney Peak, the highest point, at 2207 m. The Black Hills cover an elliptical area roughly 200 km north to south and 100 km east to west. Often considered as the easternmost extension of the Rocky Mountains, the Black Hills were originally formed from an intrusive granitic pluton (Froiland, 1990). The Black Hills are both wetter and cooler than the surrounding Great Plains, and support extensive coniferous forests in contrast to the adjacent mixed-grass prairies (Hoffman & Alexander, 1987; Froiland, 1990). There is a strong decreasing moisture gradient from northwest to southeast across the Black Hills (Bunkers et al., 1996). Lead, in the northern part of the range, received an average of 673 mm precipitation between 1931 and 1990. In contrast, Hot Springs, in the southeastern Black Hills, received an average of 440 mm during the same period. The surrounding Great Plains area receives an average 350 to 430 mm. Approximately 65% to 75% of the precipitation in the Black Hills falls from April to September (Froiland, 1990).

Extensive ponderosa pine forest dominates up to 95% of the forested areas of the Black Hills (Thilenius, 1971; Boldt et al., 1983), with white spruce (*Picea glauca* [Moench] Voss) the other major coniferous species of the higher and wetter forests of the northern Hills (Hoffman & Alexander, 1987). Limber pine (*Pinus flexilis* James), lodgepole pine (*Pinus contorta* [Dougl.]), and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) are minor components of the coniferous forest. There is also a considerable deciduous tree component from eastern forests, many species of which reach their westernmost extent in the Black Hills.

Wind Cave National Park is in the southeastern foothills of the Black Hills at the ponderosa pine forest - Northern Great Plains prairie ecotone (Figure 3.2). Elevations at the Park range from 1100 to 1530 m and slopes are commonly moderate to flat. Ponderosa pine forests and savannas and prairie grasslands form a complex landscape mosaic across the Park (Figures 3.1 and 3.2). Contiguous ponderosa pine forest is primarily concentrated in the northwest and west. Forests grade irregularly into scattered savanna stands, with clusters of trees found on isolated scarps or steeper drainages in the south and east (Shilts et al., 1980). Ponderosa pine stands are occasionally dense with little understory vegetation, especially in areas with continuous canopy, although more often stands are open with abundant grassy or herbaceous understories. Prairie grasslands are most continuous at lower elevations in the south and east (Gartner & Thompson, 1972; Shilts et al., 1980; Bock & Bock, 1984).

Reconstruction of fire history

Fire-scarred ponderosa pine trees were collected from three sites near the present day limit of ponderosa pine forest in and near Wind Cave National Park (Figure 3.2). Wind Cave North (WCN) is in Black Hills National Forest just to the north of the Park boundary in relatively continuous ponderosa pine forest. Pigtail Bridge (PIG) also is in more continuous ponderosa pine forest closer to the Black Hills proper. The third site, Gobbler Ridge (GOB), is located as far out on the savanna as we could find old (i.e., pre-settlement) ponderosa pine trees.

The overall methodology of fire history reconstruction at these three sites follows that described by Brown & Sieg (1996). The goal of collection at each site was to obtain comprehensive, long-term inventories of fire events using annually-resolved proxy fire scar records from individual trees (Swetnam & Baisan, 1996; Brown & Sieg, 1996). Fire scars result when surface fire kills cambial tissue along a portion of a tree's growing circumference, forming a characteristic lesion visible in the tree rings. Long-term sequences of fire scars are often recorded on individual trees owing to repeated fire events during the life of a tree. Sites ranged from 20 to 25 ha in size, the scale of forest stands. Sites were selected in old-growth ponderosa pine stands in order that we could find long fire scar records on individual trees. Visual inspection and increment core sampling of living trees in many areas of the Park suggested that much of the present-day ponderosa pine forest at Wind Cave consists of relatively young trees (< ca. 100 years) that are not old enough for reconstruction of long-term fire history.

At each site, cross sections were collected from fire-scarred trees using a chainsaw. We selected individual trees at each site based upon the numbers of fire scars visible in either fire-created "cat-faces" or on stump tops. Generally full circumference cross sections were removed from stumps or logs while partial cross sections were removed from the vicinity of scarred areas on living or standing dead trees. Once returned to the lab, cross sections were surfaced using hand planer, belt sander, and hand sanding to 320 or 400 grit sandpaper. Fine sanding was crucial for observation of cell structure within tree rings and at fire scar boundaries.

Cross sections were crossdated using standard dendrochronological procedures such as skeleton plotting (Stokes & Smiley, 1968). After crossdating was assured on all cross sections at a site, dates were then assigned to fire scars seen within the dated ring series. Intra-annual positions of fire scars were also noted when possible (Dieterich & Swetnam, 1984; Brown & Sieg, 1996). Dormant season scars were those that occurred between two rings and were assigned to either the earlier or later year (i.e., fall fires occurring after annual growth had ceased for a year or spring fires occurring before growth began for the next) based upon positions of scars for the same years on other trees (Brown & Sieg, 1996). If only dormant season scars were recorded on all trees for a specific fire date, the fire date was assigned to the previous year (i.e., a fall fire) based upon the almost ubiquitous presence of late season scars on other trees in the Black Hills (Brown & Sieg, 1996). Once crossdating was verified on all trees at a site, fire chronologies were compiled from all fire dates recorded (*sensu* Deiterich, 1980). Compilation of fire chronologies minimized any potential incompleteness of scar records on individual trees. Fire events may not be recorded on every tree at the time of occurrence or fire scars may be lost by erosion or burning in subsequent fire events (Swetnam & Baisan, 1996; Brown & Sieg, 1996).

Fire frequency

Fire frequency in each fire chronology was described using three measures: mean fire interval (MFI), Weibull median probability interval (WMPI) (Grissino-Mayer, 1995; Swetnam & Baisan, 1996), and a regression-derived measure from cumulative fire dates (Brown et al., 1999). 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., Heyerdahl et al., 1995). Variance in fire intervals is described by the first standard deviation and range of intervals. WMPI is the fire interval associated with the 50% exceedance probability of a modeled Weibull distribution of all fire intervals in a fire chronology and is considered to be a less-biased estimator of central tendencies in fire interval data (Grissino-Mayer, 1995; Swetnam & Baisan, 1996). If fire interval data are distributed normally, MFI and WMPI will be the same. 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 descriptor for fire frequency is a regression-derived measure determined by piecewise regression procedures (Neter et al., 1989) fit through a cumulative sequence of fire dates. The use of piecewise regression for describing fire frequency permits both statistical and visual assessments of changes in frequency through time (Brown et al., 1999).

We compared fire frequency in the three sites at Wind Cave National Park to four sites at Jewel Cave National Monument that were collected using similar methodology (Brown & Sieg, 1996). Sites at Jewel Cave are located in the interior of the ponderosa pine forest of the Black Hills northwest of Wind Cave. The Jewel Cave sites are higher (1580 to 1750 m elevation) than those at Wind Cave (1220 to 1510 m), with correspondingly cooler and wetter climate regimes. Significant differences between MFIs and WMPIs at the three Wind Cave sites and between them and the Jewel Cave sites were assessed using a generalized F-test with a Bonferroni adjustment (Weerahandi, 1995).

RESULTS

Fire chronologies

Fire chronologies from three sites at Wind Cave National Park are shown in Figure 3.3. Frequent, episodic surface fires were recorded on trees from beginning dates in the 1500s or 1600s until the late 1800s or early 1900s. Fire dates recorded on trees at all three sites included 1591, 1652, 1706, 1724, 1739, 1768, 1822, 1845, 1853, 1863, 1870, 1875, and 1881. Trees at both Wind Cave North (WCN) and Pigtail Bridge (PIG) showed generally synchronous fire scars recorded on most trees during fire years, while Gobbler Ridge (GOB) trees showed generally less synchrony in scars recorded, especially before 1822. Synchronous fire events stopped at all three sites in the late 1800s, although we found fewer trees that extend into the 1900s, especially at WCN. Trees at sites PIG and GOB recorded two widespread fire dates (recorded on most trees) in the early 1900s. After these two fire dates, there were occasional fire scars recorded on one or two trees, but fire scars were much less common at all three sites during the twentieth century.

Most fire scars recorded on trees at Wind Cave occurred later in the growing season or as dormant season scars between two rings (Table 3.1). In general, years when only dormant season or unknown position scars were recorded were dated to the prior year. However, 9 out of 13 trees at GOB recorded dormant season scars between the 1909 and 1910 rings that were dated to 1910. This date was determined from a reference in the Wind Cave National Park's annual Superintendent's records of a fire that burned in March, 1910, on the south side of the Park where the GOB trees were collected. It is possible that other fire dates prior to the 20th century that were recorded only as dormant or unknown position scars could have been spring fires and are therefore recorded in the fire chronologies as one year earlier than the actual calendrical date.

Fire frequency

Mean fire intervals (MFIs) and Weibull median probability intervals (WMPIs) were not significantly different ($P < 0.01$) between the three sites at Wind Cave National Park in a generalized F-test (Table 3.2). WMPIs were generally 1 year less than MFIs reflecting the positive skew in fire intervals distributions. The three Wind Cave sites also recorded similar variances in fire intervals as reflected by the standard deviations, ranges of intervals, and Weibull 5% and 95% exceedance probability intervals. MFIs and WMPIs for the Wind Cave sites were approximately half as long as the four ponderosa pine forest interior sites at Jewel Cave National Monument (Table 3.2), which also tended to record greater variability in lengths of fire intervals (Brown & Sieg, 1996). There were significant differences in fire frequency between sites from the two areas. The measures of fire frequency for all sites were calculated for the period of record up the late 1800s or early 1900s as there were few fire events recorded at any site after that time.

Fire frequency determined by regression slopes fit through sequential fire dates also show similarity in the three Wind Cave sites and differences with the four Jewel Cave sites (Figure 3.4, Table 3.2). Piecewise regression (Neter et al., 1989) through fire dates recorded before 1652 at GOB is significantly different than the longer-term trend in fire frequency after 1652 and this earlier period was not used for calculations of measures of fire frequency. The fire scar record at GOB before the 1652 fire date was determined to be too sparse (see also Figure 3.3) to reflect a true record of past fire events (Brown et al., 1999). Visual assessment of patterns through time also suggests shorter term shifts in fire frequency, although none of these shifts were significant in piecewise regression. However, sites at both Wind Cave and Jewel Cave recorded slightly increased fire frequency from the middle to the end of the 19th century (Figure 3.4; see also Figure 3.3). Slightly reduced fire frequency was also evident in both the Wind Cave and Jewel Cave sites in the early 1700s (Brown & Sieg, 1996).

DISCUSSION

Fire at the margin of the northern Great Plains grassland

Fire intervals found at Wind Cave National Park are among the shortest documented for northern ponderosa pine forests. Fire frequencies at Wind Cave sites are comparable to those found in southwestern US ponderosa pine forests and some lower elevation ponderosa pine sites in the northern Rocky Mountains (Arno, 1976; Wright & Bailey, 1982; Heyerdahl et al. 1995; Swetnam & Baisan, 1996; Barrett et al., 1997). In the southwest, stands often recorded fire once every 3 to 15 years, depending upon climate regimes and fuel conditions. Northern Rocky Mountain ponderosa pine forests generally had longer intervals between fires, but some stands burned as often as every 7 to 15 years (Arno, 1976; Barrett & Arno, 1982).

Fire was twice as frequent in ponderosa pine savanna at Wind Cave National Park as in the forest interior ponderosa pine stands at Jewel Cave National Monument in the central Black Hills (Table 3.2, Figure 3.4). Higher fire frequency in the Wind Cave area may have been due to differences in climate regimes and/or fuel dynamics at the ponderosa pine forest - grassland ecotone. Wind Cave ponderosa pine forests are lower in elevation and both warmer and dryer than those at Jewel Cave. Warmer and dryer conditions would have led to more years when fuels were able to carry fire. Also, the fire history recorded on ponderosa pine trees at Wind Cave should be considered more reflective of the fire regime that was present in the mixed-grassland prairies surrounding the Black Hills rather than that of the ponderosa pine forest of the interior of the Hills. Grasslands have, in general, greater spatial continuity and uniform loadings of fine fuels which result in larger potential "firesheds" over which fire can potentially burn from any ignition point. If ignition and not fuels was a limiting factor in fire occurrences, then more extensive fires should result in more frequent fires at any one location. Early accounts from the Northern Great Plains often described single fires burning over vast areas of grassland (possibly >100, 000 ha; e.g., Higgins, 1986). In contrast, spatial patterns of fire at Jewel Cave suggested that there were topographic breaks present in the interior area that limited fire spread between sites (Brown & Sieg, 1996). Vegetative and topographic discontinuities in the more mountainous and rocky interior of the Black Hills would have limited fire spread from an ignition location, resulting in smaller potential burn areas in any one year.

Although fire frequency was different between the Wind Cave and Jewel Cave sites, there was synchrony in fire timing in the two areas over the past several centuries. Many of the same fire years, including 1591, 1706, 1785, 1822, 1845, 1863, and 1870, were recorded at sites in the two areas. Both areas recorded slightly decreased fire frequency in the 1700s and slightly higher fire frequency in the late 1800s (Figure 3.4).

Lower fire frequency in the early 1700s appears to have been a regional pattern across the Black Hills (Brown, unpublished data). Higher fire frequency in the late 1800s may have been the result of either increased use of this area by Native Americans at the time of widespread non-Native American settlement of this area beginning in 1875 (Progulske, 1974) or early settlement activities such as mining and land clearing for farming. Fisher et al. (1987) attributed an increase in fire frequency from the 1700s to late 1800s in the western Black Hills at Devil's Tower National Monument to an increase in aboriginal activity in this area.

The presence of late season scars for most fire years at Wind Cave National Park (Table 3.1) corresponds to seasonal patterns seen in both recent fire records for the Northern Great Plains (Higgins, 1984) and in the fire scar data from Jewel Cave National Monument (Brown & Sieg, 1996). Most historic lightening-caused fires in the Northern Great Plains occurred in July and August (Higgins, 1984) and fire scars in trees at Jewel Cave occurred almost exclusively later in the growing season. Tree growth in the Black Hills area probably is complete by early to late August (Brown & Sieg, 1996). An exception to the pattern of late season scars at Wind Cave was the March, 1910, fire at Gobbler Ridge. The fire season of 1910 was the most widespread fire year for which written records exist in the northern Rocky Mountains, including the Black Hills (Plummer, 1912), and was largely responsible for the US Forest Service's "10 AM" policy (all fires suppressed by 10 AM of the following day; Pyne, 1992) that contributed to fire exclusion in forests throughout the western US.

Fire, grazing, and ecotonal dynamics

Cessation of fires at Wind Cave beginning in the early twentieth century (Figure 3.3) corresponds to patterns seen in other ponderosa pine ecosystems of the western US (Cooper, 1960; Savage, 1991; Grissino-Mayer, 1995; Touchan et al., 1995; Swetnam & Baisan, 1996; Brown & Sieg, 1996; Fulé et al., 1997). Fire cessation was usually coincident with the beginning of widespread, intensive livestock grazing, and often preceded, occasionally by several decades (Savage, 1991; Touchan et al., 1995), direct fire suppression efforts by land management agencies.

Intensive livestock grazing and loss of surface fire regimes also were contemporaneous with the beginnings of shifts in plant community structure and composition at ecotones between forests and grasslands, with woody plant encroachment into what were formerly prairie areas (Archer, 1994; McPherson, 1997; Mast et al., 1997, 1998). However, it is difficult to disentangle cause-and-effect relationships between changes in vegetation and possible driving factors because of the presence of both positive and negative feedbacks between environmental components. In savannas, a positive feedback exists between fuels and fire. Fires promote grasses and herbaceous plants by killing woody plants before they can establish and exclude understory individuals through shading or allelopathic mechanisms. Grazing contributed indirectly to a reduction in fires by removing grasses and other fine fuels that were necessary for fire spread (Zimmerman & Neuenschwander, 1984; Archer, 1994; Touchan et al., 1995). However, herbivory by livestock also directly changed the competitive relationships between grasses and woody plants by selectively removing grasses to favor unpalatable woody species in a community (Archer, 1994). Archer (1994) concluded that although herbivory, fire exclusion, minor climate changes, and possibly atmospheric CO_2 enrichment have interacted to produce recent changes in woodland - grassland patterns and species associations, the proximal cause for change in most cases has been grazing by large numbers of livestock.

In the Wind Cave savanna, as in other areas of tree invasion in the western US, it is difficult to determine the timing and magnitude of driving factors and ecosystem responses. It is likely that extensive ponderosa pine forest expansion in this area began in the early 1900s (e.g., Progulske, 1974). There does not appear to have been any major changes in either precipitation or temperature regimes at that time that could explain movement of trees into lower elevation grasslands (e.g., Meko, 1992; Cook et al., 1996). Conversely, herbivory by livestock may only partially explain observed shifts in ponderosa pine forest savanna. Wind Cave National Park was established in 1906 and the area has not been grazed by livestock since that time. After extensive non-Native American settlement of this area starting around 1875 up to the time the Park was established, this area most likely was grazed by livestock, although we have not been able to find records of numbers of animals or specific locations grazed during this period. The last extensive fire (recorded at all three sites) at Wind Cave was in 1881 (Figure 3.3). Fire cessation may have been precipitated by livestock grazing in this area that started around 1875 and continued until the Park was established in 1906. Geographical fragmentation caused by road and fence construction and cattle grazing in areas adjacent to the Park also would have stopped the spread of what would have been formerly landscape fire events. Active fire suppression after the Park's establishment would have further contributed to fire exclusion from the landscape during recent decades.

A further complicating factor to understanding the driving factors of ecotonal change in the Black Hills savanna is that extensive bison (*B. bison*) herds are native to this area. Bison were extirpated from virtually the entire Northern Plains about the time of the introduction of livestock and later reintroduced to the Park in 1913 (Turner, 1974). The Park supports a large bison herd at the present time. The impacts of bison on dynamics of fire regimes in the Great Plains are not well understood. Herbivory by bison during the pre-settlement period may not be ecologically equivalent to herbivory by cattle since temporal and spatial patterns of disturbance tend to be different between the two species (Laurenroth & Milchunas, 1989). Bison traveled in large herds that likely moved on when resources were depleted. Laurenroth & Milchunas (1989) suggest that bison grazing was likely of heavy intensity but low frequency for a given area, while later cattle grazing is high frequency but low intensity. Under a pre-settlement bison grazing regime, it is probable that grass fuels would have had time to recover between periods of herbivory, a pattern that could have led to frequent surface fires as found by this study (Figure 3.3).

By assuming that bison grazing in Wind Cave National Park over this past century is not ecologically equivalent to livestock grazing, this would exclude grazing as a significant control on the encroachment of ponderosa pine into grassland communities. It is likely that recent encroachment has been more the result of fire exclusion than possible shifts in competitive relationships between grasses and woody plants that resulted from grazing alone. The Park has begun to re-introduce prescribed fires in recent decades and these often kill ponderosa pine trees that established in what were formerly grassland areas (Bock & Bock, 1984). These results suggest that a return to historical patterns of fire regimes should restore the ecotonal mosaic to more of a pre-settlement configuration in the Wind Cave area.

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Table 3.1. Numbers of fire scars by season of occurrence from trees at Wind Cave National Park. Numbers in parentheses are percentages of the total number of fire scars with an assigned season of occurrence (excluding unknown position fire scars).

Site	early season[1]	middle season[2]	late season[3]	unknown dormant[4]	unknown position	total fire scars
WCN	12 (10.4)	2 (1.7)	71(61.7)	30 (26.1)	22	137
PIG	14 (8.8)	3 (1.9)	106 (66.3)	37 (23.1)	39	199
GOB	9 (15.3)	0	19 (32.2)	31 (52.5)	20	79

[1] Includes fire scars recorded as early dormant or in first third of the earlywood.

[2] Includes fire scars recorded in middle third of earlywood.

[3] Includes fire scars recorded in last third of earlywood band, in the latewood band, or as late dormant.

[4] Includes years when only dormant season position fire scars were recorded (i.e., not associated with earlywood or latewood scars on other trees for that period).

Table 3.2. Measures of fire frequency for three ponderosa pine savanna sites at Wind Cave National Park (GOB, PIG, and WCN) and four forest interior sites at Jewel Cave National Monument (JC site designations) (Brown & Sieg, 1996). Fire intervals used in calculations are for all dates recorded on any tree at each site for the period of analysis.

Site	Period of analysis	No. of intervals	MFI (± SD)[1]	Range of intervals[2]	WMPI[3]	5% to 95% prob. inter.[4]	Fire frequency (from fig. 4)[5]
Wind Cave National Park:							
WCN	1564 to 1896	27	12.3 ± 6.9	3 to 32	11.6	3.5 to 22.7	0.077
PIG	1528 to 1912	38	10.1 ± 5.8	2 to 23	9.3	2.3 to 20.3	0.100
GOB	1652 to 1910	21	12.3 ± 7.2	3 to 34	11.5	3.5 to 22.6	0.078
Jewel Cave National Monument:							
JCN	1576 to 1890	16	19.6 ± 13.5	4 to 45	17.4	3.9 to 40.3	0.045
JCC	1388 to 1890	22	22.8 ± 17.6	1 to 63	18.8	2.6 to 57.0	0.042
JCE	1591 to 1890	13	23.0 ± 22.0	1 to 77	16.9	1.6 to 63.9	0.043
JCS	1591 to 1900	13	23.8 ± 23.1	7 to 93	20.1	4.6 to 46.3	0.043

[1] Mean and first standard deviation of all intervals in composite fire chronology in years

[2] In years

[3] Weibull median (50% exceedance) probability interval in years

[4] Weibull 5% and 95% exceedance probability intervals in years

[5] Slope of line of cumulative fire dates (number of fires year^{-1})

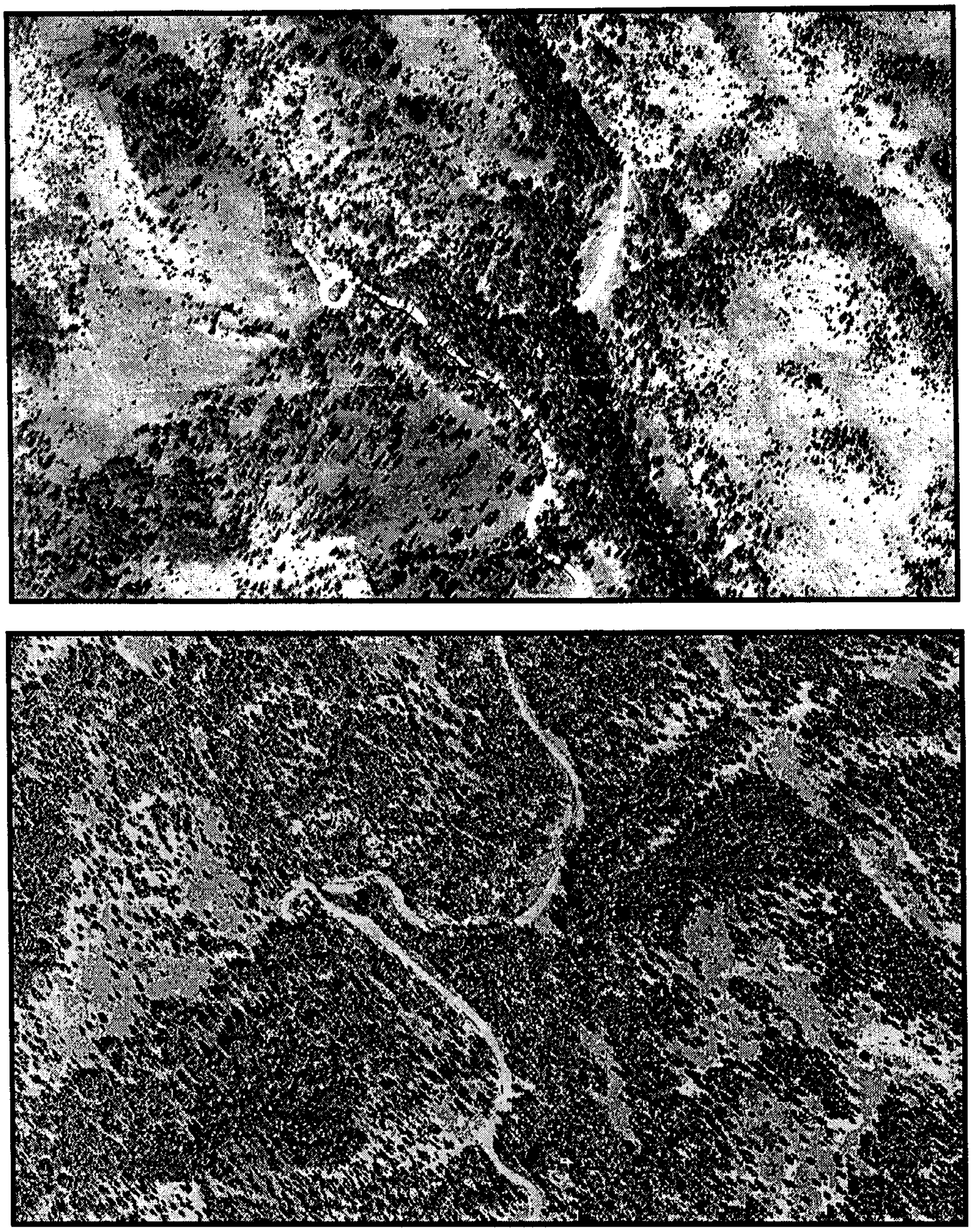

Figure 3.1. Aerial photographs from September 19, 1938 (top photograph), and September 17, 1972 (bottom photograph), from the vicinity of the Pigtail Bridge (PIG) site. Dark areas in the photographs are ponderosa pine trees and light areas are grasslands. Fire-scarred trees at PIG were collected from the area between the roads in the center of the photographs.

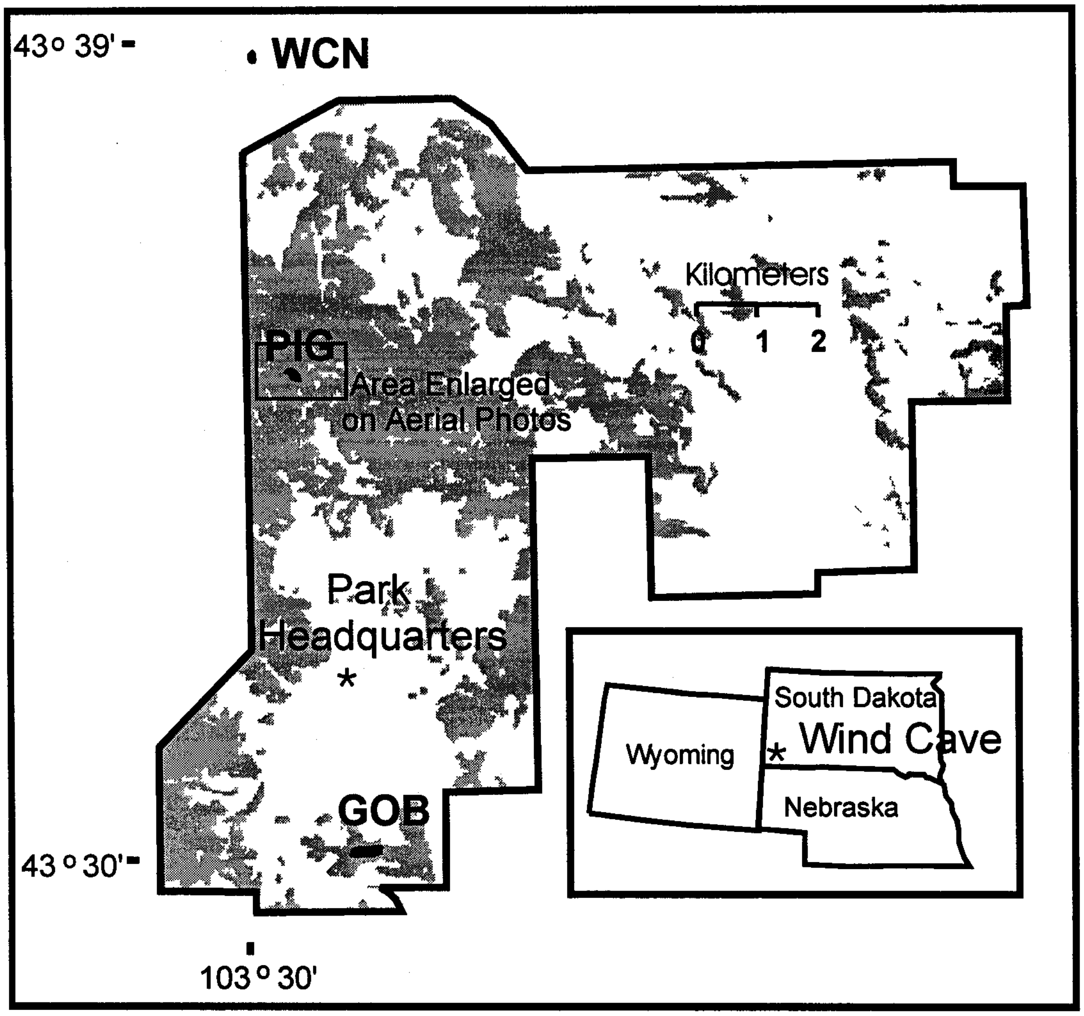

Figure 3.2. Locations of three sites (WCN, PIG, and GOB) collected for fire chronologies at Wind Cave National Park. Light grey areas on map are locations of ponderosa pine forest and savannas, white areas are grasslands. Area enlarged on aerial photographs is that shown in Figure 3.1. Data on the landscape patterning of ponderosa pine forest were not available for the vicinity of site WCN.

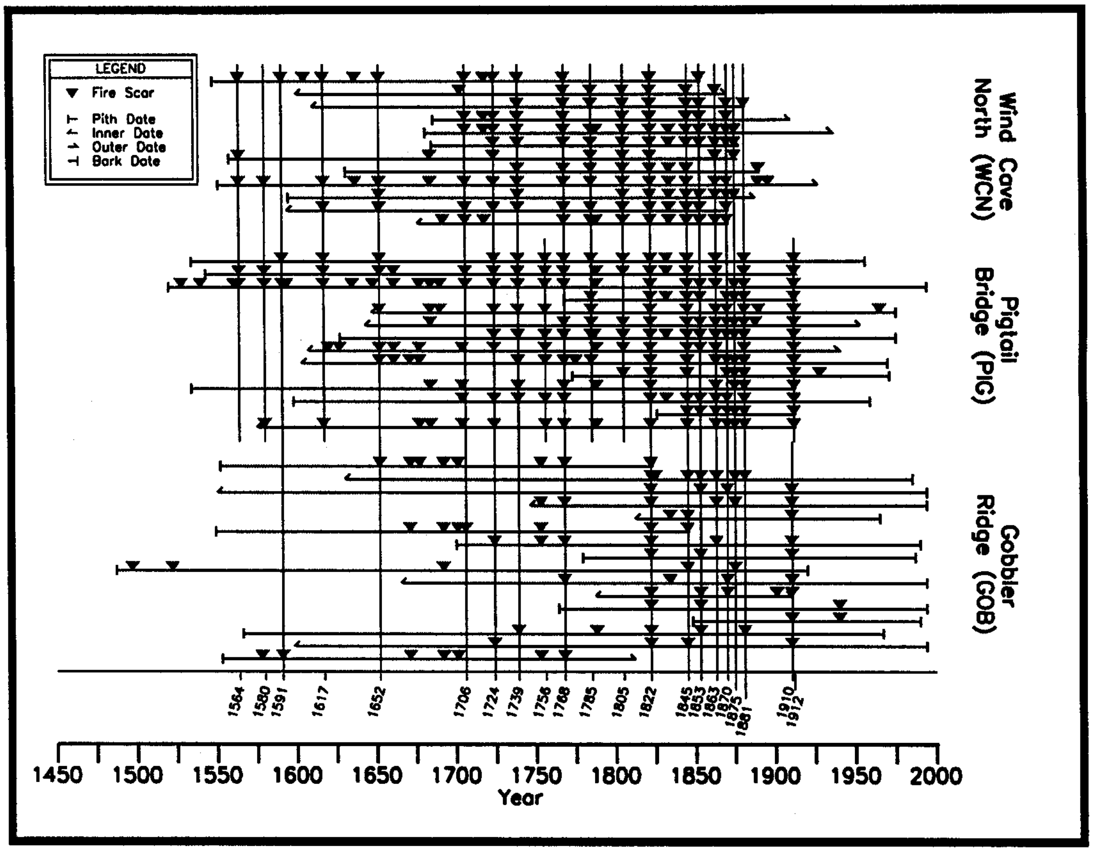

Figure 3.3. Fire chronologies for Wind Cave National Park sites. Time spans of individual trees are represented by horizontal lines, with fire scars noted by triangles at the dates they were recorded. Dates at the bottom of the fire chronologies are those years when fire scars were recorded at more than one site, except for 1910 and 1912 which were recorded only at sites GOB and PIG, respectively.

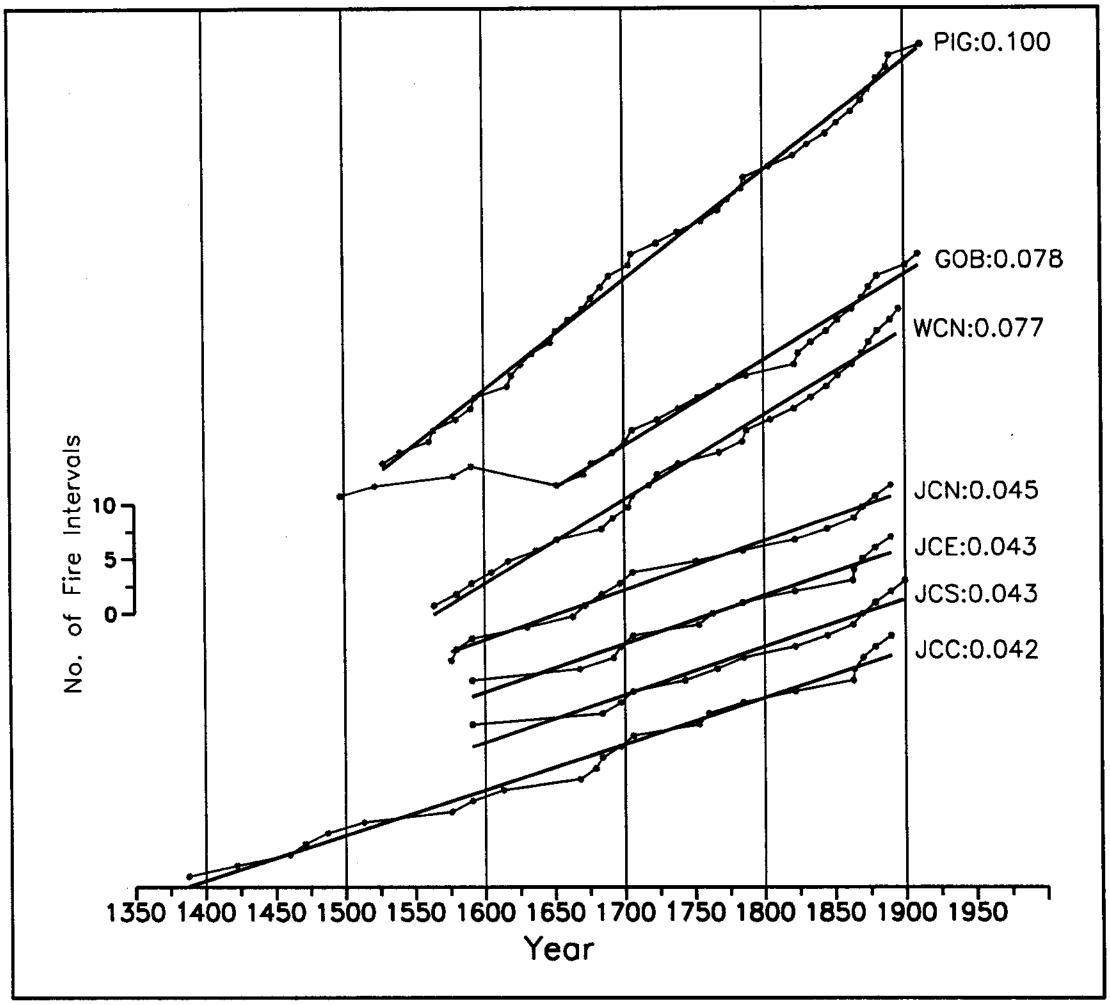

Figure 3.4. Fire frequencies determined by slopes of line fit through cumulative fire dates for Wind Cave National Park (top three lines) and Jewel Cave National Monument (bottom four lines) sites. Numbers after site designations are slope of best-fit regression line (number of fires per year).

IV. FIRE, CLIMATE, AND FOREST STRUCTURE IN BLACK HILLS PONDEROSA PINE FORESTS

ABSTRACT

A prevailing model for historical conditions in ponderosa pine forests is that frequent, episodic surface fires maintained open, low-density, uneven-aged forests. However, this model does not apply uniformly to ponderosa pine forests in the Black Hills of southwestern South Dakota and northeastern Wyoming. Infrequent stand-replacing fires also occurred and apparently resulted in large landscapes of even-aged trees. I examined this alternative model for the Black Hills using fire-scar and tree-age data. Fire chronologies complied from over 1000 trees collected at over 50 locations span the past four to six centuries. Surface fire frequency reconstructed from fire scars varied from an average of every 10 to 13 years at lower elevation sites to 30 to 33 years at higher elevations. Fires largely ceased after Euro-American settlement in the latter 1800s. Pre-settlement tree ages document highly synchronous tree establishment at plot, landscape, and regional scales, with the most abundant cohort established from 1770 to 1805. However, timing of cohort establishment largely corresponded to wet periods in the northern Great Plains. Extended wet conditions likely promoted abundant tree regeneration, fast growth, and, in some cases, longer periods between surface fires that would have permitted more trees to reach canopy status. The late 1700s cohort also followed a severe drought from1756 to 1761, and tree mortality caused by moisture stress during this and other periods probably also contributed to stand opening. A combination

of seedling mortality from surface fires, patchy crown mortality from moderate-severity fires, and tree mortality from other disturbances and drought, likely resulted in naturally open stands that were taken advantage of by climatically driven seedling recruitment. Mortality and regeneration were apparently uncoupled processes and even-aged structure is equivocal evidence for assessing the potential scale and timing of stand-replacing fires. However, abundant fire scars found in all stands indicate that surface fires were common disturbances across the Black Hills landscape. Thus, the prevailing historical model of frequent surface fires is largely supported by the tree-ring evidence, although the Black Hills had a greater range of fire behavior and resulting forest structure than ponderosa pine forests of the southwestern US that burned more often.

INTRODUCTION

A fire regime for a vegetation type or landscape is often defined based on typical fire behavior over a period of time. Fire severity and the cumulative effects from multiple individual fires are factors of a fire regime that strongly affect vegetation composition, structure, and successional dynamics (Keane et al. 1990). In ponderosa pine (*Pinus ponderosa* Laws.) and closely related forests of the western US, a remarkably consistent historical model has emerged in which frequent, low-severity surface fires maintained mostly low-density, often park-like, uneven-aged forest stands dominated by large, old trees (Weaver 1943, 1951, Cooper 1960, White 1985, Arno 1988, Savage 1991, Mutch et al. 1993, Covington and Moore 1994, Covington et al. 1997, Fulé et al. 1997, Mast et al. 1999, Moore et al. 1999, Kaufmann et al. 2000, Allen et al. 2002). Fires burned primarily in grasses and herbaceous vegetation and killed a majority of tree seedlings before they had a chance to reach canopy status, but rarely killed mature trees because of their thick bark and high crowns.

Cessation of surface fires occurred as a result of land use change that began with Euro-American settlement beginning in the middle to late 1800s (Covington and Moore 1994, Swetnam and Baisan 1996, Brown and Sieg 1996, 1999, Barrett et al. 1997, Swetnam et al. 1999, Brown et al. 2001b). The lack of surface fires to limit establishment of small trees, coupled with harvest of larger and older trees, has led to contemporary ponderosa pine forests that consist of extensive, dense, closed-canopy stands of young trees. This shift in forest structure has resulted in a feedback to the fire regime, and recent fires have been characterized by large areas of catastrophic fire that killed much of the forest overstory (Allen et al. 2002). These changes have led to widespread efforts to restore historical conditions to ponderosa pine forests throughout its range (Mutch et al. 1993, Covington et al. 1997, Moore et al. 1999, Baker and Ehle 2001, Brown et al. 2001a, Allen et al. 2002).

Although surface fires and open forest structure were a prevalent ecological condition across many ponderosa pine landscapes, substantial areas of tree mortality occurred during some pre-settlement fires in some areas (Shinneman and Baker 1997, Arno et al. 1995, Brown et al. 1999). In ponderosa pine (*P. ponderosa* var. *scopulorum*) forests of the Black Hills of southwestern South Dakota and northeastern Wyoming, early settlement (1870s to 1890s) accounts document large areas (100 to >1000 ha) of almost complete overstory mortality from fire (Graves 1899, Dodge 1965). Large areas (>5000 ha) of even-aged, dense forest structure also were evident at settlement, apparently the result of past stand opening by catastrophic fires or other disturbances (Graves 1899, Shinneman and Baker 1997). Shinneman and Baker (1997) used historic photographs and documents to argue that the prevailing model of a fire regime of low-intensity fires does not hold for many Black Hills ponderosa pine forests, and that stand-replacing fires were a major component of the historical range of variability across large portions of the landscape. This assertion has raised important questions for understanding ecological dynamics and guiding management decisions in these and other ponderosa pine forests, including: how common or extensive were stand-replacing fires in the pre-settlement landscape, and what were the effects of such fires on subsequent forest structure?

Tree-ring evidence has been central to defining fire frequencies and fire effects in ponderosa pine forests (Swetnam and Baisan 1996, Brown and Sieg 1996, 1999, Fulé et al. 1997, Barrett et al. 1997, Mast et al. 1999, Moore et al. 1999, Heyerdahl et al. 2001, Baker and Ehle 2001, Allen et al. 2002). Fire timing and behavior are reconstructed using two general types of tree-ring records: 1) fire scars and other injuries or ring features created during burning; and 2) establishment dates of trees that postdate catastrophic fires (Agee 1993). These are proxy records of fire and fire behavior that record the event in a natural archive. Paleo-fire records are subject to ecological filtering processes that both control the original formation of the record and its preservation through time. Fire scars provide typically unequivocal evidence for annual and, in many cases, seasonal timing of non-lethal fires. Stand-origin data provide indirect evidence of lethal fires that rely on the coincidence of several distinct ecological processes: canopy opening from fire, regeneration of a new cohort of trees, establishment of the cohort into the overstory, and survival of the cohort as a recognizable recruitment event to the present. Stand-origin data approximate fire dates because of lags in establishment of post-fire trees and limitations in methodologies for determining precise dates of tree germination.

In the Black Hills, apparently extensive areas of even-aged forest have been cited as strong evidence that several large stand-replacing fires occurred between 1730 and 1852 (Graves 1899, US Forest Service 1948, Shinneman and Baker 1997). However, reconstruction of past fires from stand-origin data means that alternative explanations for observed even-aged forest structure are ruled out. Stand opening results from many factors other than fire, including other disturbances (e.g., insects or other pathogens, severe windstorm) or climatic events (e.g., extreme drought; Allen and Breshears 1998). The scale of an affected area is often used as a basis for assuming catastrophic fire was the cause of stand opening, as few other disturbances cause synchronous and more-or-less complete canopy opening over landscape scales (10^2 to 10^4 ha). Alternatively, synchronous recruitment of trees may have been the result of optimal climate conditions for seedling recruitment, lack of surface fires, or abundant seedfall years that had little if any relationship to overstory conditions existing at the time of tree germination. This is the case in many open-canopy ponderosa pine forests of the southwestern US, where distinct even-aged cohorts of trees established in response to optimal climate for seedling germination and growth (Pearson 1923, 1933, Peet 1981, White 1985, Swetnam and Brown 1992, Savage et al. 1996, Swetnam and Betancourt 1998) or a lack of surface fires for extended periods of time (Grissino-Mayer and Swetnam 2000, Mast et al. 1999). Climate-driven cohorts tended to occur over much larger regions than most crown fires would be expected to burn - such as across and between mountain ranges - because of large-scale synchrony in climate regimes (Swetnam and Brown 1992, Swetnam and Betancourt 1998).

In this study, I documented fire regimes in ponderosa pine forests of the Black Hills using both fire-scar and tree-age records. I reconstructed fire chronologies for the past four to six centuries from fire scars recorded in tree-ring series at 27 locations. I also reconstructed pre-settlement tree-age structure to assess evidence for past stand-replacing fires across three 100 km^2 landscapes. Three goals of this study were: 1) to describe and compare characteristics of past surface fire regimes across the Black Hills landscape; 2) to explore temporal relationships between climate and changes in land use as possible mechanisms for fire occurrence and forest age structure; and 3) to infer the possible long-term role of stand-replacing fires and climate variability in structuring Black Hills ponderosa pine forests. For the third goal, I use the tree-age data to test two related hypotheses: 1) if stand density controlled tree establishment and past crown fires removed forest overstory, then stand-level tree germination dates will be truncated, even-aged, and asynchronous between landscapes but not necessarily between stands (i.e., crown opening may have been larger than a single stand but not larger than a landscape); and 2) if climate was a major control on tree establishment, then tree germination dates should be generally synchronous between landscapes and correspond to optimal climate conditions at a regional scale.

METHODS

Study area and land use history

The Black Hills are an isolated mountain range that rises over 1000 m above the surrounding relatively flat northern Great Plains. The Black Hills were formed from an intrusive granitic pluton and anticlinal warping of overlying layers of limestones and sandstones forms rough ovals around the central granite core area. The main part of the range is in southwestern South Dakota with a smaller extension, the Bear Lodge Mountains, in northeastern Wyoming (Figure 4.1). Elevations range from 1050 to 1350 m on the margins with the Great Plains to Harney Peak at 2207 m. Precipitation declines from about 740 mm/yr in the north to about 480 mm/yr in the south. Approximately 65% to 75% of the precipitation falls as rain from April to September.

The Black Hills support extensive conifer forests in contrast to adjacent mixed-grass prairies (Shepperd and Battaglia 2002). Ponderosa pine dominates over 95% of the conifer forest. White spruce (*Picea glauca* [Moench] Voss) is a secondary species of higher and wetter forests in the northern Hills. In most areas ponderosa pine is the only tree species present.

Euro-American settlement began with discovery of gold in 1874 (Progulske 1974, Grafe and Horsted 2002). Intensive logging beginning in the late nineteenth and continuing into the twentieth centuries has resulted in large areas of second-growth forest (Graves 1899, Pearson and Marsh 1935). The Black Hills National Forest Reserve (today the Black Hills National Forest) was the first federal forest preserve established in the United States in 1897, partly as a response to intensive and often wasteful timber practices up to that time (Graves 1899, US Forest Service 1948). Severe fires in 1890 and 1893 also were an impetus for the Reserve's establishment. Timber production is still a major use of much of the landscape. Few areas of unharvested forest exist and most are restricted to National Park Service units and a designated wilderness area.

Fire-scar chronologies

I collected fire-scarred ponderosa pine trees from 25 sites in the Black Hills and 2 sites in the Bear Lodge Mountains (Figure 4.1, Table 4.1). Two types of collections were made based on the first two goals of the study. At 19 intensively collected sites, my objective was to reconstruct chronologies of fire dates from proxy fire-scar evidence recorded on 10 to 16 trees in stands from ~10 to 20 ha in size. I use these fire chronologies to describe and contrast stand-level fire frequency across gradients in elevation and landscape position. Stands consisted of relatively uniform slope and aspect to minimize possible fuel and fire breaks within stand boundaries. Locations of two sites, REY and GIL, were selected randomly (see paragraph below). Trees in stands were selected using targeted sampling methods (Baker and Ehle 2001) to maximize temporal length of fire-scar records. Most trees sampled were stumps because of past harvest.

Fire chronologies were compiled using program FHX2, an integrated package for graphing and statistical analyses of fire history data (Grissino-Mayer 2001). I used two measures to describe fire frequency from 1700 to 1900 in the 19 intensively collected sites: mean fire interval (MFI) and Weibull median fire interval (WMFI). WMFI is the fire interval associated with the 50% exceedance probability of a modeled Weibull distribution of fire intervals (Grissino-Mayer 1999). Variance in fire intervals was described by one standard deviation and the range of intervals. I used linear regression to test if fire frequency varied by elevation, a simple variable that integrates weather conditions necessary for burning across spatial scales.

Fire frequency analysis was based on composite fire dates (Dieterich 1980). Fire frequency estimates using composited fire dates from several trees may depend on size of study area and/or number of trees collected (Brown and Swetnam 1994, Baker and Ehle 2001). I also used regression analyses to test for bias in fire frequency estimates based on both numbers of trees sampled and site areas. I did not use fire intervals from single trees to calculate fire frequencies (sensu Baker and Ehle 2001) because of possible bias of fire-scar records found on individual trees. Individual trees may be missing fire dates because of fire scars not being recorded at the time of burning, fire scars lost by burning or decay after formation, or fire scars lost during sampling or sample preparation. Loss of fire scars by decay or during sampling is very likely when having to rely on stumps for reconstruction of fire history.

The objective of sample collection at eight extensively collected sites (Table 4.1) was to document the extent of landscape fires across the Black Hills in relation to both climate variability and changes in land use that began with Euro-American settlement. Fire dates from these sites were combined with those from the 19 intensively collected sites before comparison with climate and land use. I determined locations of ten extensively collected sites from a randomly placed 15-km square grid over the central part of the Black Hills. I then collected cross sections from 6 to 10 fire-scarred trees from areas < 10 ha in size. At two of the sites originally identified as extensively collected sites (sites REY and GIL; Figure 1), I collected more trees from slightly larger areas and these sites were designated as intensively collected sites with composite fire chronologies developed for the stands.

I analyzed relationships between annual variability in precipitation and fire events using superposed epoch analysis (SEA). SEA is based on a null hypothesis that no relationship existed between fire dates and precipitation prior to and during fire years. The precipitation record used is a tree-ring based reconstruction of the percentage of the 1919-1989 August to July annual mean from instrumental stations in the Black Hills and northern Great Plains (Stockton and Meko 1983; data updated by Meko 1992 and Sieg et al. 1996). The reconstruction extends from 1596 to 1990 and is based on ponderosa pine and bur oak (*Quercus macrocarpa* Michx.) ring-width chronologies from the Black Hills and surrounding area. Years during which fire scars were recorded at all of the fire history sites (intensively plus extensively collected sites) and at > 10% of the sites were selected as fire event years. I conducted similar SEA using years when no fires were recorded at any of the sites during the same period. I also used SEA to examine relationships between fire and non-fire years and a tree-ring based reconstruction of winter Southern Oscillation Index (SOI; Stahle et al. 1998).

Stand-origin chronologies

To examine stand to landscape patterns of tree ages that may be the result of stand opening by severe fires, I sampled trees from randomly chosen plots across three landscapes on the Limestone Plateau, a relatively level area of gently rolling hills and canyons on the western margins of the main range (Figure 4.1). The Limestone Plateau is often cited as an area of extensive even-aged forest structure that resulted from past stand-replacing fires (Graves 1899, US Forest Service 1948, Shinneman and Baker 1997). Landscapes were delineated on a precipitation gradient from wet to dry in the northern, middle, and southern portions of the Limestone Plateau, and varied in size from 97 to 121 km^2.

Within each landscape, plot locations were determined using random GPS coordinates. In each plot, the nearest 30 pre-settlement trees to plot center were selected for aging. Trees sampled included stumps, logs, snags, and living trees that were not "blackjacks". Based on extensive observation and sampling of ponderosa pine in the Black Hills, trees tend to have dark bark until ca. 100-120 years of age. Since my interest was in reconstructing pre-settlement age-structures, I assumed all blackjack trees established post-Euro-American settlement. For age determination, increment cores were removed from 10 cm height above ground level on living trees and cross sections were cut from stumps, logs, and snags such that one surface was at an estimated 10 cm height above root crown. Cores sampled had to be no more than a field-estimated 10 years from pith. Tree distance from plot center was measured and tree diameter at 10 cm height was measured on living trees or estimated for remnant trees missing bark, sapwood, and often heartwood. Notes also were recorded for each tree that included presence of fire scars, wood char, and state of decay of remnant trees.

Tree ages were combined to examine landscape and regional patterns of tree recruitment. Ten-cm height pith ages were first corrected to germination dates by subtracting 5 years, the average time estimated for seedlings to grow from germination to 10 cm height. This correction is based on height-growth measurements on open-grown ponderosa pine in the Front Range of central Colorado (Kaufmann et al. 2000; Brown et al., unpublished data) and estimation from nodal growth on seedlings in the Black Hills. Annual sums of estimated germination dates were smoothed using a running 11-year sum. This time series was then compared to the precipitation record for the northern Great Plains (Stockton and Meko 1983), under the assumption that soil moisture availability is a key climatic factor affecting tree establishment. The precipitation index was smoothed with a cubic smoothing spline with a 50% frequency removal at 25 yrs (Cook and Peters 1981) before comparison with the age data. Significant relationships between the smoothed tree-age and precipitation time series were assessed using correlation coefficients. I compared both the full series (1596 to 1900) and 100 year segments overlapped by 50 years to assess changes in strength of the climate/establishment relationship through time.

Crossdating

All cores and cross sections were dendrochronologically crossdated using both locally developed and published chronologies. Crossdating is crucial step to provide the temporal resolution necessary for comparison of fire-scar, stand-origin, and climate datasets across spatial and temporal scales. Visual matching of ring characteristics and correlated measured ring widths were used to assure crossdating. After crossdating of tree rings was completed on fire-scarred cross sections, dates were assigned to fire scars. Intra-annual positions of fire scars also were noted when possible (Brown and Sieg 1996, 1999). On increment cores and cross sections that did not include pith but inside ring curvature was visible, pith dates were estimated using overlaid concentric circles of varying diameters that take into account both average inside ring widths and an estimated distance to pith.

RESULTS

Fire-scar chronologies

Fire chronologies for 19 intensively collected sites are summarized in Figure 4.2. Surface fires were recorded in all sites from the beginnings of the fire chronologies up to the late 1800s or early 1900s. Fire scars were generally absent from all stands after approximately 1890, although numbers of trees sampled declined during the twentieth century because of the reliance on stumps for fire history reconstruction. Fire scars rarely occurred during the early part of the earlywood, and past fires mostly occurred during late summer or early fall (Brown and Sieg 1996, 1999).

High variability in fire frequency is evident in fire chronologies, both within and among sites (Table 4.2). Mean fire intervals (MFIs) from1700 to 1900 ranged from ca. 10 to 15 years in lower elevation savanna forests at the ecotone of the ponderosa pine - northern Great Plains grassland to ca. 30 to 33 years in more mesic interior forests in the northern Hills and central granite core area (Figure 4.3). There were no significant differences in fire frequency based on either number of trees sampled or site area in regression analyses.

Composite fire chronologies from both the intensively and extensively collected sites are summarized in Figure 4.4. Fire dates from proximate clusters of two to four sites (see Figure 4.1 and Table 4.1) were grouped at Jewel Cave National Monument (JC), Riflepit Canyon (RP), Upper Pine Creek (UP), and the Bear Lodge Mountains (BL) for determination of larger-scale fire years. The most extensively recorded fire year was 1785 at 16 of 20 locations. Fewer fire dates were recorded from 1724 to 1753 and from 1785 to 1822. Landscape fire years occurred with little evident spatial patterns (Figure 4.5), although fire in 1753 was isolated to the southern sites and the Bear Lodge Mountains and fire in 1768 was recorded only in the southeast. Superposed-epoch analysis (SEA) documents that fire years between 1596 and 1900 were significantly dry years, and that non-fire years were significantly wet years (Figure 4.6). No lagged relationships were seen between antecedent years and precipitation variability, unlike patterns reported for ponderosa pine forests in the Southwest (Swetnam and Baisan 1996, Brown et al. 2001b). SEA using subsets of fire history sites and fire years based on elevation, landscape positions, or season of fire occurrence did not reveal any further significant relations between fire and annual precipitation variability. I also did not find any significant relationships between fire or non-fire years and SOI.

Stand-origin chronologies

I crossdated 644 trees (from a total of 720 trees sampled) from 24 plots in the middle and southern landscapes (Figure 4.7). An additional 110 mainly living trees were dated from the northern landscape. However, I was not able to adequately crossdate enough of the remnant trees from the northern plots to develop plot-level stand-origin chronologies. This area is more mesic than either of the other landscapes and ring widths were mainly complacent, without enough ring variability to crossdate patterns with confidence against master chronologies. Although I was able to count the number of rings to pith age on living trees from the northern landscape, data from the middle and southern landscapes showed that inclusion of remnant trees are critical for interpretation of pre-settlement patterns of stand origins (Figure 4.8). Because of past harvest of the majority of larger (and, thus, older) trees from all stands sampled, the current forest appears to be even-aged even though it may not have been at the time of settlement. Unfortunately, the northern landscape is the area thought to have been most prone to past stand-replacing fires and I was not able to confirm prevalence or absence of even-aged structure in the tree-ring data.

All trees sampled were ponderosa pine except for three aspen (*Populus tremuloides*) from a single plot in the middle landscape. Many of the tree-ring samples, especially cross sections removed from remnant trees, recorded fire scars (Figure 4.7). Outside dates (i.e., not death dates) on many of the remnant trees occurred at fire scars. The outside edge of woundwood formation in ponderosa pine trees often forms at fire scars as a result of compartmentalization of the wound area (Smith and Sutherland 2001). Heartwood of remnant ponderosa pine trees may last a very long time in the environment although erosion or burning of heartwood surfaces was evident on older remnants. An additional 5 trees that dated before 1500 from plots 201, 203, and 207 are not shown in

Figure 4.7. Of these trees, three logs had pith dates of 1190, 1192, and 1206 and are the oldest known tree-ring dates from the Black Hills.

Germination dates from the three landscapes document discontinuous tree establishment across all three areas (Figures 4.7, 4.8, and 4.9). Pith dates occurring in the combined 140 years between 1525-1560, 1605-1640, 1770-1805, and 1830-1865 account for over 80% of all pith dates during the 401 year period between 1500 and 1900. In many plots at least two distinct clusters of pith dates were evident (Figure 4.7). However, in plots 103, 104, 105, and 106 in the middle landscape and plot 212 in the southern landscape most trees formed a single cluster of pith dates during 1770-1805 or 1830-1865. In plots 103, 105, and 106, there were one or more trees that established earlier than the clusters of pith dates and dated through the 1770-1805 period. Only in plots 104 and 212 were clusters of pith dates not spanned by earlier trees. In plot 104, chronologies from three logs dated to before the establishment of the cluster in the 1770-1805 period. These logs likely died before the cluster established, but all were heavily eroded and death dates may have occurred after the other trees established at the site. In plot 212, only 18 trees (out of 30 sampled) were able to be crossdated. I was not able to crossdate samples from an additional 12 remnant trees because of complacent ring series and it is likely these trees dated before the cluster that established during the 1830-1865 period.

Clusters of establishment dates that occurred across all three landscapes largely corresponded to wet periods in the northern Great Plains precipitation reconstruction (Figure 4.9d, Table 4.3). The most abundant pulse of establishment between1770-1805 occurred during the wettest 20 year period in the precipitation record, and followed one of the worst droughts in the record from 1756 to 1761. Other regional cohorts during the early 1600s and middle 1800s also strongly corresponded to wet periods in the precipitation record. Two local cohorts (i.e., restricted to only one landscape) in the late 1600s in the middle landscape and early 1700s in the southern landscape did not correspond to wet periods (Figure 4.9d). These cohorts may represent more local disturbances, including more severe fires, in these areas.

DISCUSSION

Fire timing and behavior in the Black Hills

Abundant fire scars indicate that surface fires were common disturbances in Black Hills ponderosa pine forests prior to Euro-American settlement (Figures 4.2, 4.4, and 4.7). The relative area burned in any single year was often very extensive (Figure 4.5), and fires related to dry conditions in a regional rainfall reconstruction (Figure 4.6). Changes in elevation integrate changes in moisture and temperature regimes that also affected fire frequency (Figure 4.3). However, dramatic changes in the fire regime coincident with settlement overrode both annual climate variability and local fuel conditions. The pervasive cessation of fires during the twentieth century corresponds to patterns found in virtually all ponderosa pine forests of the western US (Savage 1991, Swetnam and Baisan 1996, Brown and Sieg 1996, 1999, Barrett et al. 1997, Fulé et al. 1997, Swetnam and Betancourt 1998, Brown et al. 1999, 2001b, Allen et al. 2002).

Tree ages within and among landscapes on the Limestone Plateau document highly synchronous episodes of tree recruitment that largely corresponded temporally to wet periods in the northern Great Plains (Figure 4.9, Table 4.3). This is support for hypothesis 2 stated in the introduction. Extended wet conditions would have promoted abundant tree regeneration and faster seedling growth. These factors in combination would have permitted more seedlings to reach canopy status, therefore becoming more "fireproof" during later surface fires. Further evidence to support climate as a major control on tree demography in the northern Plains is the presence of abundant tree establishment during the early 1600s and latter 1700s in ponderosa pine forests of the southern Bighorn Mountains, located in northern Wyoming approximately 250 km W of the Black Hills (P.M. Brown, 2000, unpublished report to The Nature Conservancy, Tensleep, WY). Timing of cohorts in the Bighorn Mountains corresponds exactly to those in the Black Hills.

If broad-scale tree establishment resulted from wet conditions in the northern Plains, how likely is it that trees established in openings created by stand-replacing fires? The tree-ring data provide only equivocal evidence. In many stands where even-aged cohorts are evident, older trees are also present suggesting that if the cohort established in response to severe fire there was not complete canopy kill within plot boundaries (Figure 4.7). Trees existing at the time of cohort establishment suggest that more patchy disturbances (including patchy mortality during moderately severe fires) caused sufficient stand opening for seedling recruitment during wet periods. Abundant regeneration that occurred during rare episodes of optimal climate may not have been limited by any existing overstory because open stands were maintained for long periods by recurrent surface fires and other disturbances. If this were the case, mortality and regeneration were largely uncoupled processes and even-aged structure may never be definitive evidence of stand-replacing fires in ponderosa pine forests.

An example of the equivocal nature of the tree-ring record is timing of events that surround an extensive crown-replacing fire that has been argued to have occurred sometime around 1790 on the Limestone Plateau (Graves 1899, US Forest Service 1948, Shinneman and Baker 1997). Shinneman and Baker (1997) cite evidence of this fire to argue that the prevailing model of frequent surface fires does not hold for perhaps a majority of the Black Hills landscape. The most widespread fire date recorded in fire chronologies reconstructed by this study was 1785 (Figure 4.4), and undoubtedly this is the correct date for this fire. However, abundant tree establishment occurred before 1785 (Figures 7.7 and 7.9) and, therefore, cannot be the result of crown opening during 1785. Alternatively, regeneration during the 1770s to 1780s followed an extended and severe drought from 1756 to 1761 (Figure 4.9d; Stockton and Meko 1983). Evidence of this drought in the form of pronounced narrow rings is present in trees throughout the Black Hills. Dry conditions may have promoted more severe fire behavior, but tree mortality from drought stress also undoubtedly contributed to canopy opening that provided space for the 1770s cohort to become established. Another factor that may have killed trees during this and other periods was mountain pine beetle (*Dendroctonus ponderosae* Hopk.) or other disturbances such as windthrow. Mountain pine beetle has been a major cause of extensive tree mortality in the Black Hills during the recent century (Shepperd and Battaglia 2002) and a severe outbreak in drought-stressed trees could have contributed to stand opening during and shortly after the 1750s drought.

Increased survivorship of trees from the 1770s cohort is probably also the result of the fire history after 1785. Across the Black Hills, fire in 1785 was followed by a period with few fires until the next widespread fire in 1822 (Figure 4.4). The 37 year-long fire-free period between 1785 and 1822 is the longest in the pre-settlement record in several stands (Figure 4.2). In the absence of surface fires, more trees would have reached canopy status, leaving abundant evidence of this cohort to survive to the present. Abundant tree establishment in many southwestern ponderosa pine forests during the early 1800s also has been related to both wet conditions and a period of reduced fires in this region (Swetnam and Betancourt 1998, Mast et al. 1999, Grissino-Mayer and Swetnam 2000). Long fire-free intervals are evident in many of the Black Hills stands after pulses of seedling establishment (Figure 4.7). Thus, it is likely that the absence of surface fire was more critical to structuring the current forest than any potential variation in fire behavior.

Fire effects on forest structure

In contrast to stand-replacing fires, some ecologists have considered surface fires to be ecologically benign or relatively unimportant disturbances in forests (Johnson and Gutsell 1994, Shinneman and Baker 1997, Minnich et al. 2000). Stand-replacing fires cause extensive tree mortality over large areas that often result in even-aged, often dense, post-fire tree establishment in some forest types. Conversely, during most surface fires mature trees are rarely effected and forest structure and overstory density change only slightly. However, the combination of multiple surface fires over time creates different, but no less ecologically important, structural characteristics than those created by stand-replacing fires (Cooper 1960, Weaver 1985, Savage 1991, Covington and Moore 1994, Kaufmann et al. 2000). The main effect is that surface fires kill a majority of tree regeneration, limiting the number of trees that ultimately reach canopy dominance. Occasional seedlings or patches of regeneration are able to survive to reach maturity and eventually form uneven-aged stands. Tree regeneration and mortality under a surface fire regime occur over longer time spans and across a greater range of spatial scales than that resulting from immediate, extensive stand-replacing fires.

There is increasing agreement among ecologists and managers that historical data are crucial for understanding ecosystem flux and its driving factors (Landres et al. 1999, Swetnam et al. 1999). However, historical information from one region may not adequately represent historical conditions in other regions even when they consist of apparently similar ecosystems or community types (Allen et al. 2002). Surface fire frequency in the Black Hills was less than ponderosa pine sites in the Southwest, and there are large differences in climate regimes that contributed to variation in stand productivity and fuel dynamics between the two regions. Less frequent fire in the Black Hills than in the Southwest was the result of shorter fire seasons, and climate gradients that occur with latitude exhibit strong control on fire frequency, fire seasonality, and synoptic-scale fire/climate relationships (Brown and Shepperd 2001; P.M. Brown and T.W. Swetnam, unpublished manuscript). Longer intervals between fires would have permitted greater fuel buildup, formation of larger patches of denser forest structure, and, as a consequence, more severe fire behavior across larger areas than in ponderosa pine forests that burned more often (Keane et al. 1990). For example, early records from the Black Hills document apparently extensive areas of crown mortality from pre-settlement fires (Graves 1899, Dodge 1965), conditions that were largely absent from any Southwestern ponderosa pine forests (Allen et al. 2002).

However, despite climatic, environmental, and historical differences between Black Hills and Southwestern landscapes, consistent ecological themes run through all ponderosa pine ecosystems. The ubiquity of fire-scar evidence across the Black Hills documents that relatively frequent surface fires occurred over a majority of the landscape. As in other ponderosa pine forests, surface fires affected forest structure by creating open, low-density forest stands and heterogeneous landscape patterns. Photographs taken in 1874 during the initial Euro-American exploration of the Black Hills record many open stands with fewer and larger trees in areas that are today covered by dense canopies of smaller trees that grew up after fire cessation (Progulske 1974, Grafe and Horsted 2001). Historic photographs also document many more openings, more extensive meadows, and larger areas of forest savanna than are present in the current landscape. Although these photographs are mainly from the southern portion of the Hills where both surface fire frequency was generally higher and stands are less productive than in the more mesic northern areas, they contribute to a conclusion that forest conditions in perhaps a majority of the Black Hills have changed dramatically over the past century. The historical model provided by multiple lines of evidence, although imprecise, provides ecological justification for restoration of open, low-density forest stands and surface fire regimes over large portions of the Black Hills landscape.

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Table 4.1. Sites collected for fire chronologies.

	Site	Code	Aspect	Elevation range (m)	Area (ha)	No. trees crossdated [1]	Site type [2]
1	Bear Lodge N.	BLN	S	1520-1550	17.6	13	I
2	Bear Lodge Central	BLC	N	1520-1560	18.8	11	I
3	Cold Springs Creek	CSC	E	1350-1390	6.5	10	I
4	Riflepit Canyon N.	RPN	S	1830-1860	7.6	11	I
5	Riflepit Canyon W.	RPW	E	1850-1890	20.0	10	I
6	Riflepit Canyon E.	RPE	W	1840-1880	12.9	13	I
7	O'Neill Pass	ONP	NW	1930-1940	7.6	6	E
8	Nemo	NEM	Flat	1580	5.3	6	E
9	Spearfish Canyon N.	SCN	SE	1870-1910	15.6	9	I
10	Black Hills Exp. For.	BEF	E	1730-1760	11.7	11	I
11	Deerfield Reservoir	DER	S	2020-2040	5.3	6	E
12	Reynold's Prairie	REY	SW	1740-1780	16.4	11	I
13	Silver City	SLC	SW	1460-1500	4.1	7	E
14	Moon Campground	MON	Flat	2000	7.0	5	E
15	Gillette Prairie	GIL	S	2070-2090	20.1	9	I
16	Hill City	HIC	Flat	1590	4.7	7	E
17	Upper Pine Creek	UPC	E	1660-1690	12.9	9	I
18	Upper Pine Mid-Basin	UPM	S	1670-1720	16.4	10	I
19	Dead Horse Flats	DHF	W	1720-1740	4.7	3	E
20	Custer	CUS	S	1680-1700	4.1	8	E
21	Jewel Cave Central	JCC	N	1670-1710	18.8	16	I
22	Jewel Cave N.	JCN	Flat	1720	10.0	11	I
23	Jewel Cave E.	JCE	S	1680-1740	14.1	16	I
24	Jewel Cave S.	JCS	SW	1580-1670	10.6	16	I
25	Wind Cave N.	WCN	E	1470-1510	17.0	12	I
26	Pigtail Bridge	PIG	E	1340-1350	10.0	14	I
27	Gobbler Ridge	GOB	N	1220-1260	11.7	16	I

[1] Number of trees crossdated may less than number collected owing to difficulty of crossdating in some areas.

[2] I: intensively-collected site; E: extensively-collected site (see text)

Table 4.2. Fire frequency from 1700 to 1900 for 19 intensively collected sites.

Site	No. of intervals	MFI (± SD)	Range of intervals	WMFI
BLN	8	21.6 ± 11.3	11 to 41	20.8
BLC	13	11.0 ± 7.3	3 to 30	10.1
CSC	12	15.7 ± 10.4	4 to 34	14.1
RPN	5	33.4 ± 8.8	22 to 42	35.0
RPW	9	20.7 ± 17.5	4 to 64	17.7
RPE	6	31.0 ± 18.1	14 to 64	29.4
SCN	6	12.8 ± 4.2	8 to 19	12.9
BEF	9	20.2 ± 10.0	7 to 37	19.5
REY	10	17.1 ± 8.7	2 to 33	16.1
GIL	8	23.9 ± 12.6	10 to 42	23.0
UPC	5	26.8 ± 10.4	15 to 42	26.7
UPM	5	27.4 ± 12.0	15 to 46	27.0
JCC	9	20.4 ± 17.4	1 to 47	15.4
JCN	8	23.0 ± 14.4	6 to 45	21.1
JCE	9	20.4 ± 17.0	1 to 47	15.7
JCS	10	19.4 ± 10.9	7 to 37	18.4
WCN	18	10.7 ± 6.5	3 to 29	9.9
PIG	19	9.8 ± 5.4	2 to 18	9.1
GOB	15	12.0 ± 7.9	3 to 34	10.9

Table 4.3. Correlations between 25 yr smoothed precipitation index (dashed line in Figure 4.9d) and 11 yr running sum of tree ages (solid line in Figure 4.9d) for different periods. Bold correlations are positive and significant (P < 0.001).

Period	Correlation
1600 to 1700	**0.597**
1650 to 1750	-0.408
1700 to 1800	**0.549**
1750 to 1850	**0.653**
1800 to 1900	**0.531**
1596 to 1900	**0.476**

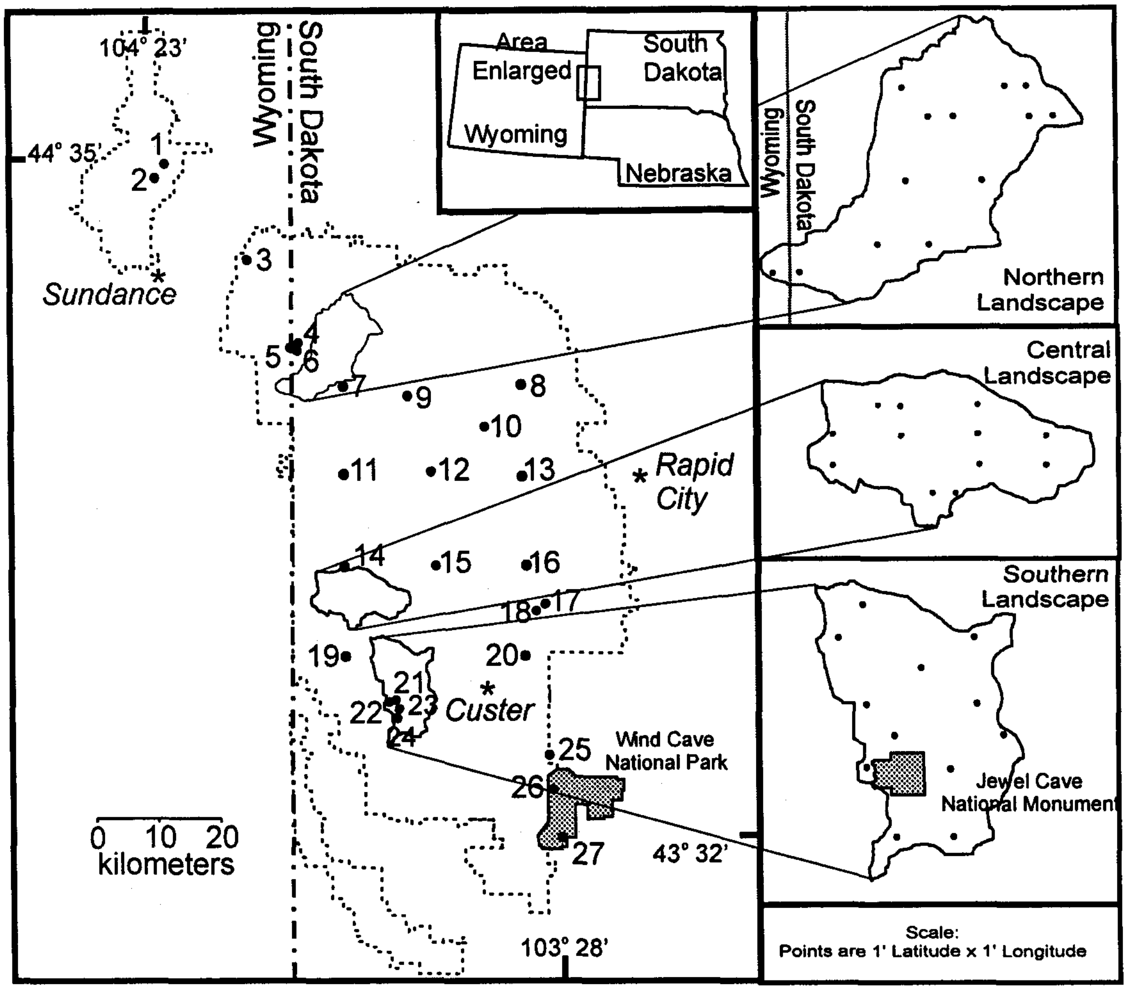


Figure 4.1. Fire history sites collected for this study. Numbers refer to sites in Table 4.1. Boundary of Black Hills National Forest is shown along with boundary of Wind Cave National Park in the southeast.

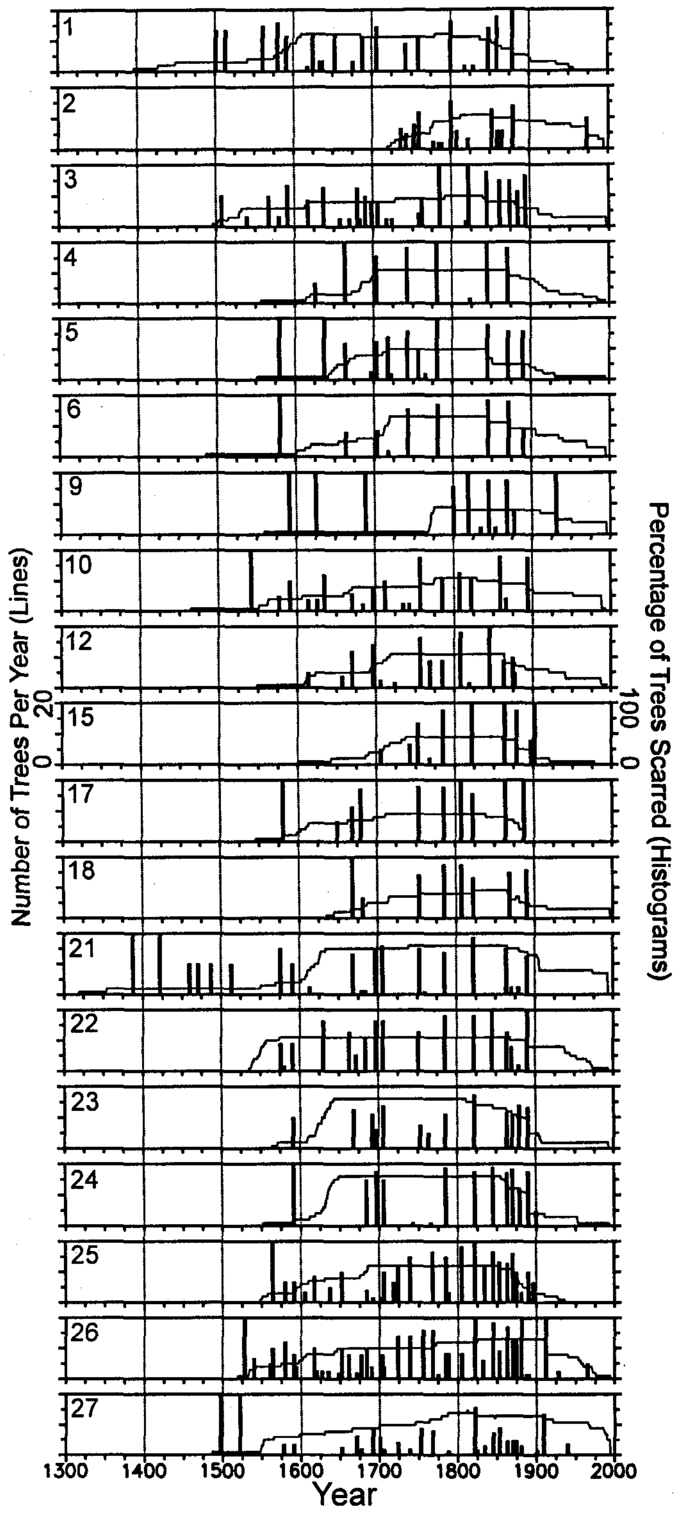


Figure 4.2. Fire chronologies from 19 intensively collected sites. Light line in each plot is the number of trees per year (left axis) and histograms are percentages of trees that recorded a fire scar by year (right axis).

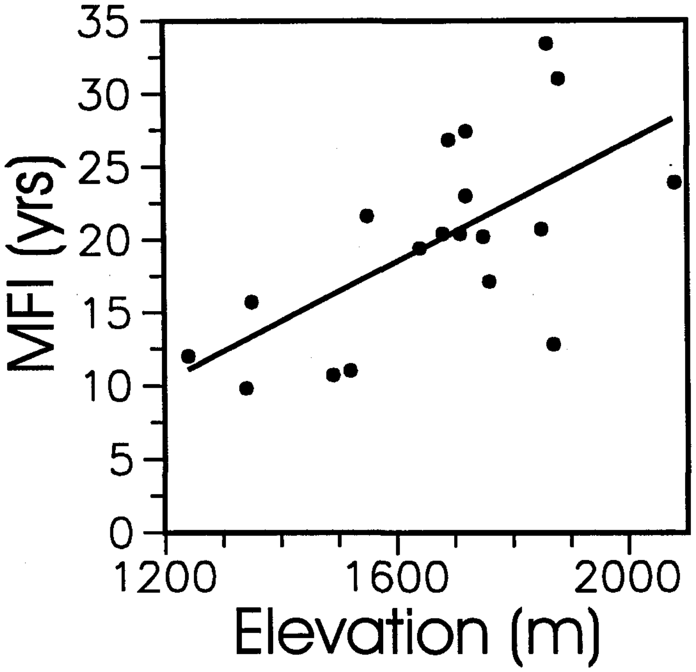


Figure 4.3. Mean fire intervals (MFI) from 1700 to 1900 by elevation for 19 fire chronologies. Regression line is: MFI = 0.0205 m - 14 ($R^2 = 0.40$).

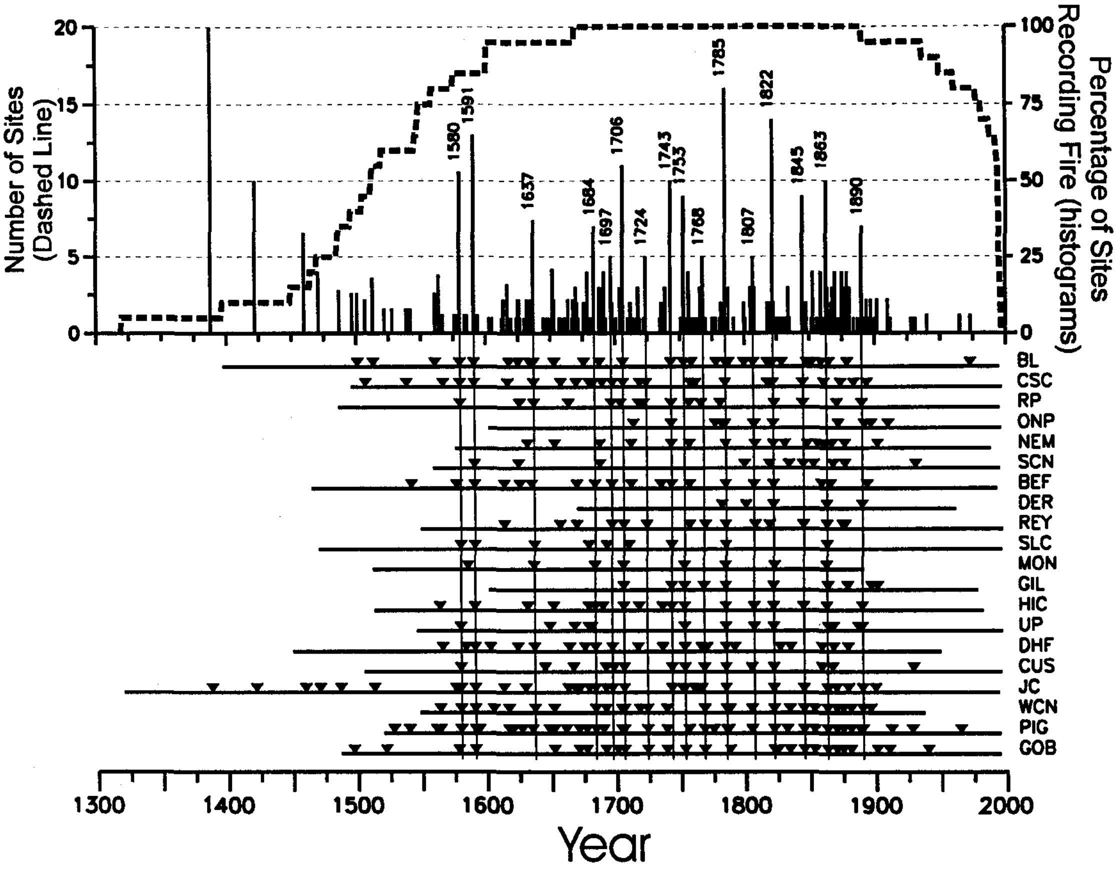


Figure 4.4. Bottom: Composite fire dates from 20 locations across the Black Hills. Horizontal lines are time spans of chronologies with inverted triangles at dates of fire events. Two letter codes designate composite data from proximate clusters of sites at Bear Lodge Mountains (BL), Riflepit Canyon (RP), Upper Pine Creek (UP), and Jewel Cave National Monument (JC) (Figure 4.1). Top: Summary fire chronology for the Black Hills. Dashed line is the number of sites per year (left axis) and histograms are percentages of sites that recorded fire by year (right axis). Years marked are those when fires were recorded at 25% or more of the sites.

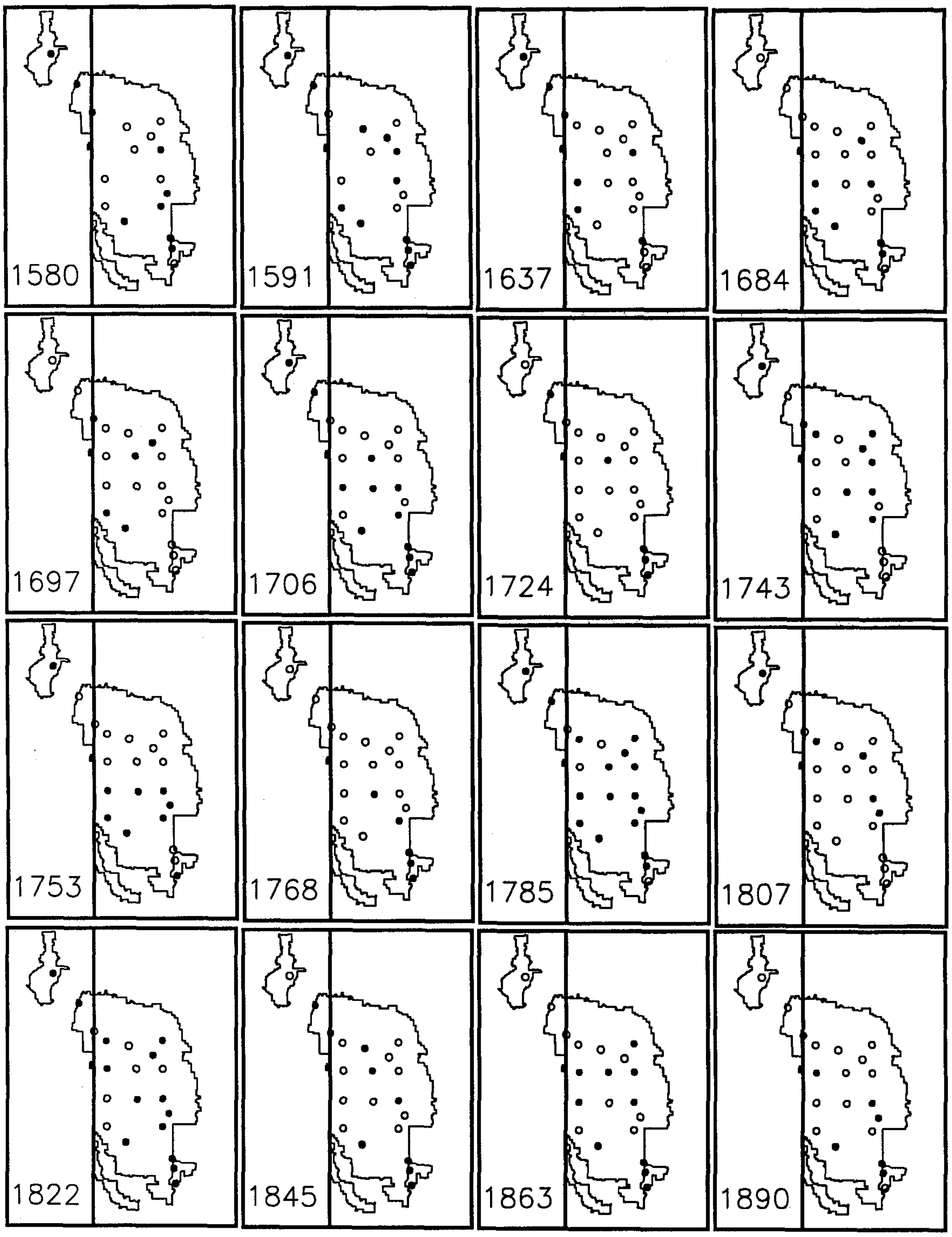


Figure 4.5. Sites that recorded fires (closed circles) or not (open circles) for landscape fire years (years marked in Figure 4.4). See Figure 4.1 for relative scale.

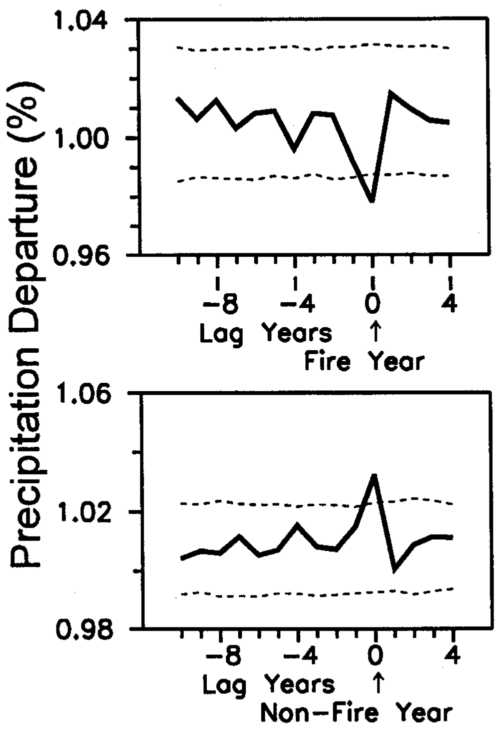


Figure 4.6. Superposed epoch analyses (SEA) for fire years and non-fire years in the Black Hills. Event years (0 lag in graphs) plus antecedent and following years were compared to reconstructed annual precipitation departures from the northern Great Plains (Stockton and Meko 1983). SEA was conducted for: top; all fire years recorded at any site for the period 1596 to 1900 (n = 136 years); and bottom; years when no fires were recorded at any site from 1596 to 1900 (n = 169 years). Dashed lines in each graph are 99.9% confidence intervals calculated from Monte Carlo simulations of precipitation departure values.

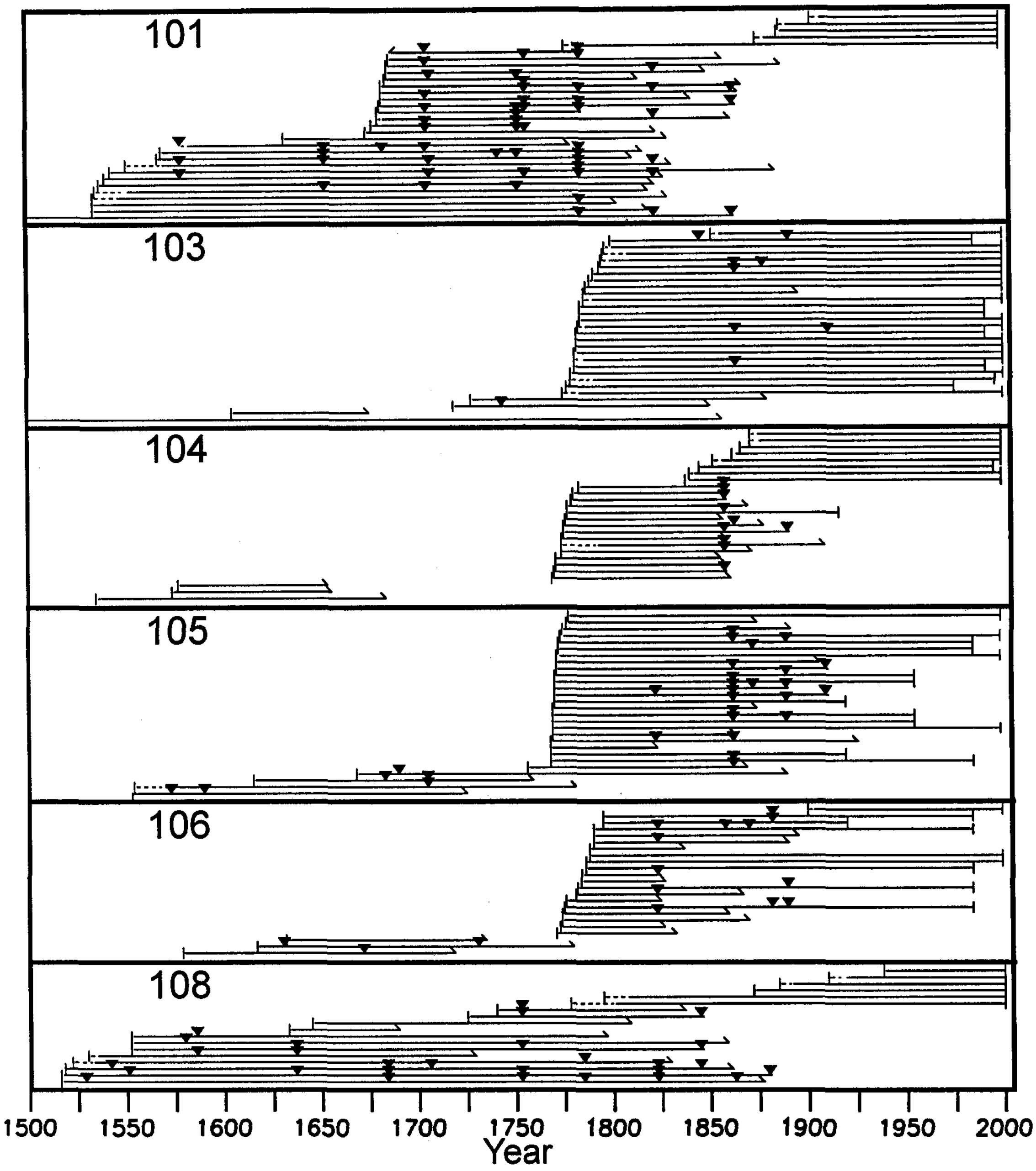


Figure 4.7. Chronologies of individual trees sampled for forest age structure by plot for the middle and southern landscapes. Time spans of trees are represented by horizontal lines with dates of fire scars marked by inverted triangles. Dashed lines are estimated number of years to pith. Vertical lines to left on tree chronologies are pith dates with inside dates (i.e., unknown number of years to pith) marked by slanted lines. Vertical lines to right on tree chronologies are bark dates (= death dates) with outside dates (i.e., unknown number of years to death date) marked by slanted lines.

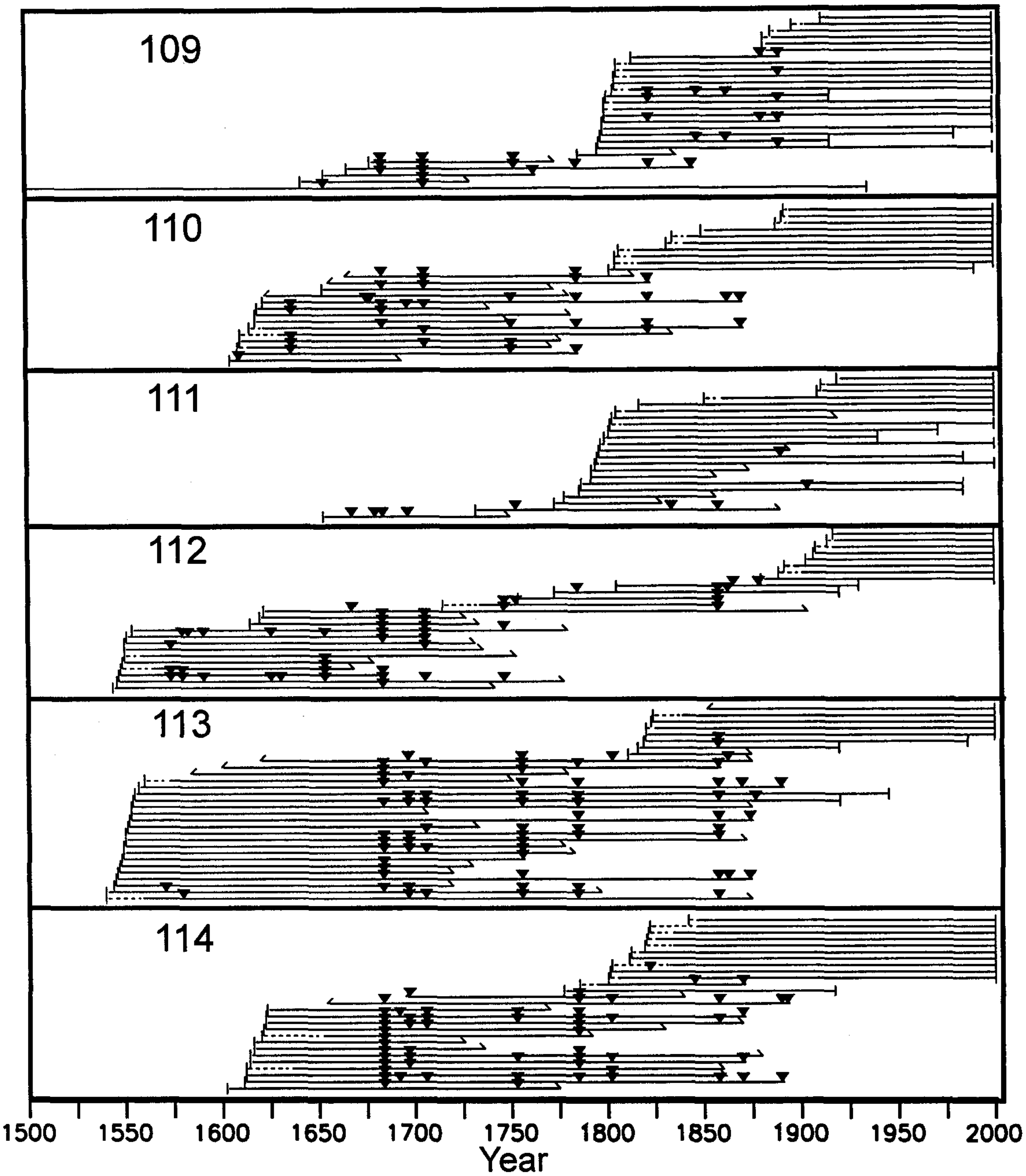
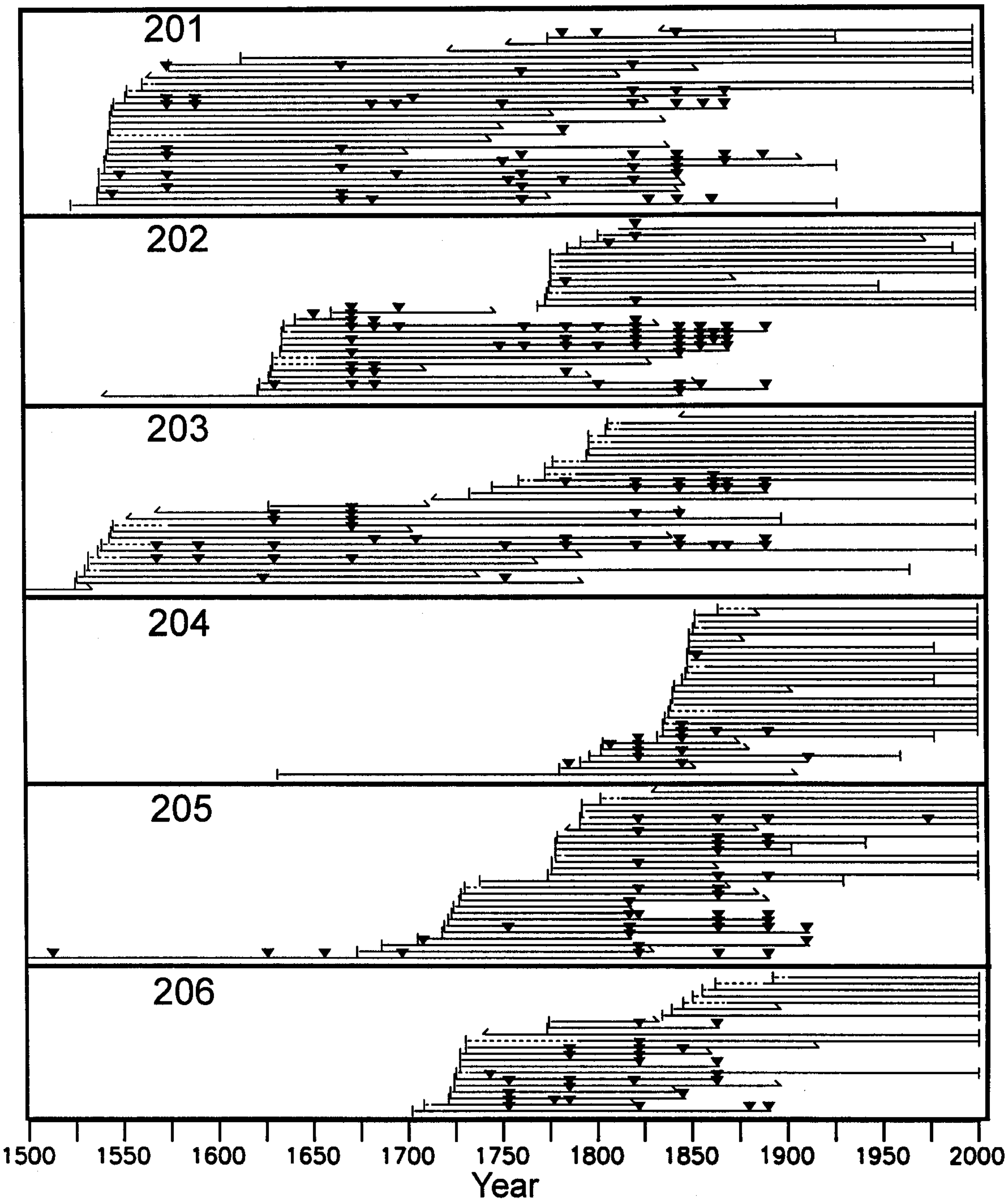


Figure 4.7 continued.



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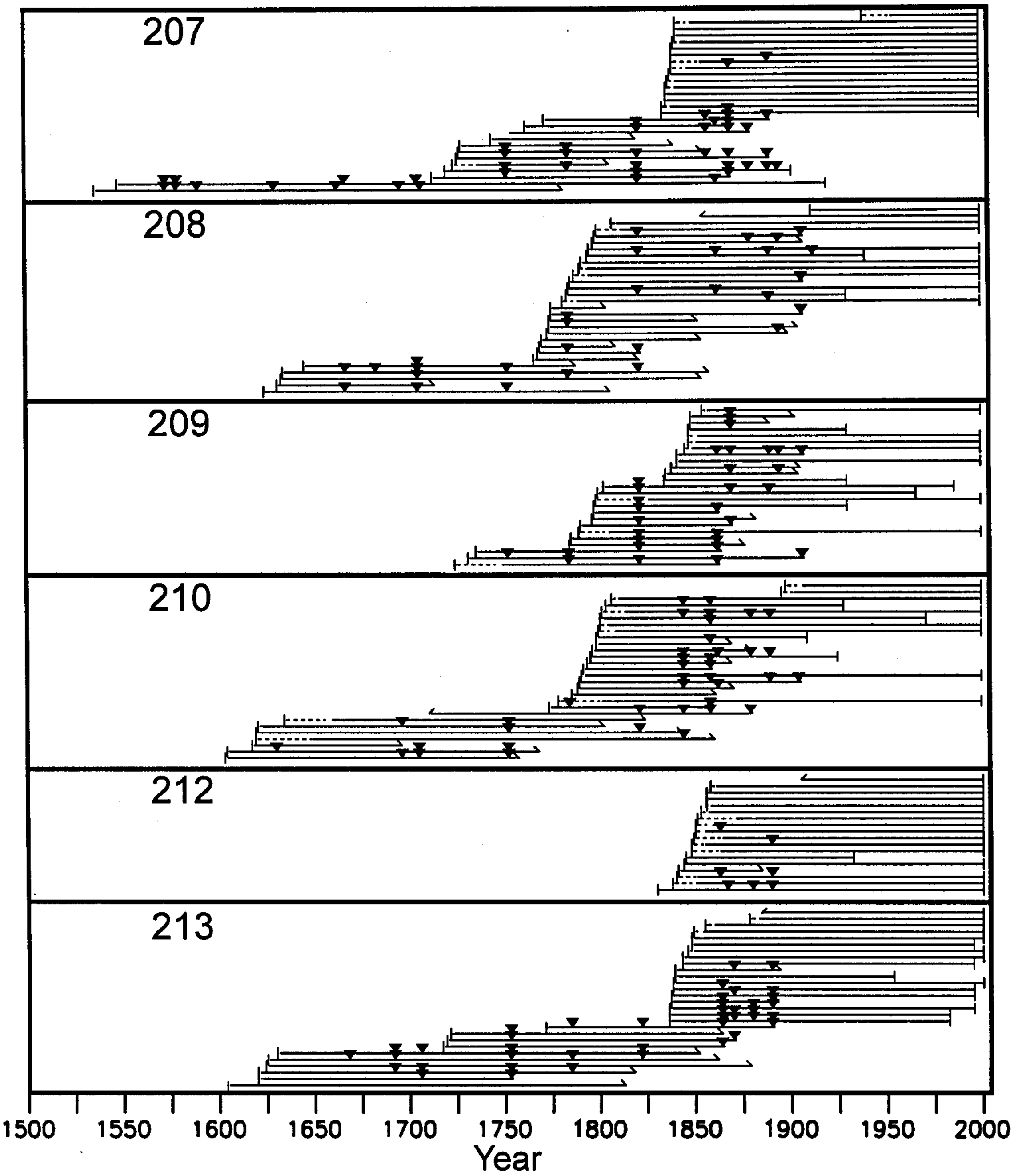

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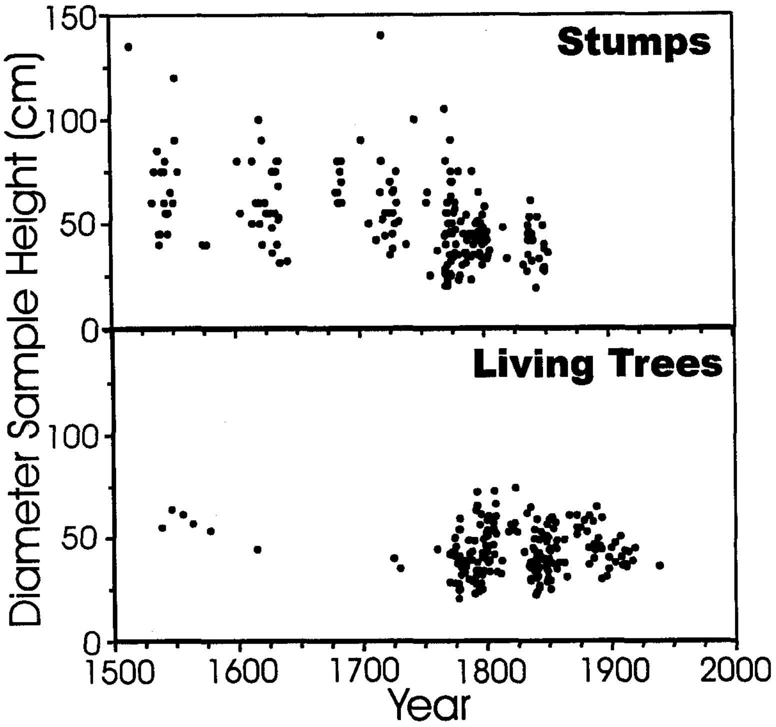

Figure 4.8. Diameters at sample height (10 cm) of stumps and living trees by pith dates. Diameters measured on living trees and estimated on stumps missing bark, sapwood, or heartwood.

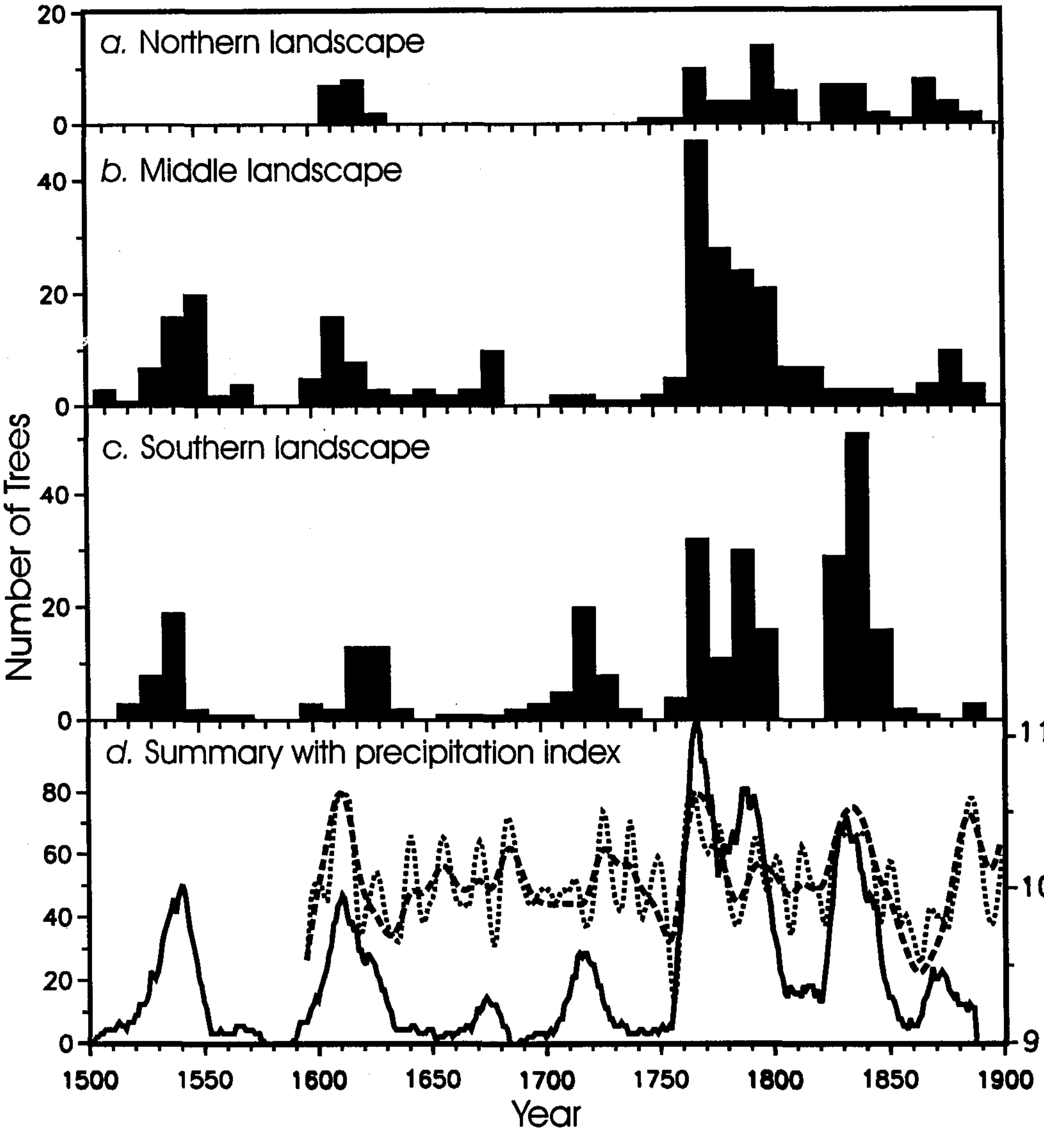

Figure 4.9. Ten-year sums of germination dates (pith dates - 5 years) for all dated trees from: a. northern landscape; b. middle landscape; c. southern landscape. 4.9d. Solid line: 11-yr running sum of annual germination dates from all trees. Dashed line: reconstruction of the 1919-1989 August to July precipitation annual mean from climate stations in the Black Hills and northern Great Plains (Stockton and Meko 1983) smoothed with a 25 yr cubic smoothing spline. Dotted line: precipitation index smoothed with a 11 yr spline to emphasize decadal patterns.