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# Fire History in Interior Ponderosa Pine Communities of the Black Hills, South Dakota, USA

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**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 tires 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.

**Keywords:** *Pinus ponderosa;* Dendrochronology; Crossdating; Fire scars; Fire chronology; Mean fire interval

## 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 l-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 tires 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 fiie 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* ([Tort-.] 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 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

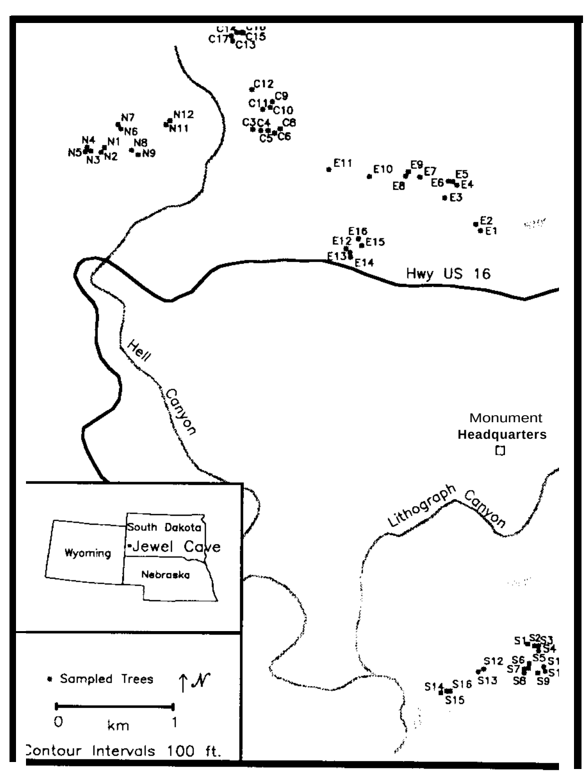


Figure 1. Locations of fire-scarred trees collected at Jewel Cave National Monument. Site designations are: Jewel Cave East (E numbers), Jewel Cave South (S), Jewel Cave Central (C), and Jewel Cave North (N). All sites are within the current or original boundaries of Jewel Cave National Monument.

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 I). 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 Dam 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 fiie 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 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 57 trees collected at the four sites (Figure 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 la). 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). 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 lb).

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) in the early 1700s (Table 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 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 two times (Table 2). At the fourth site (JCS), the

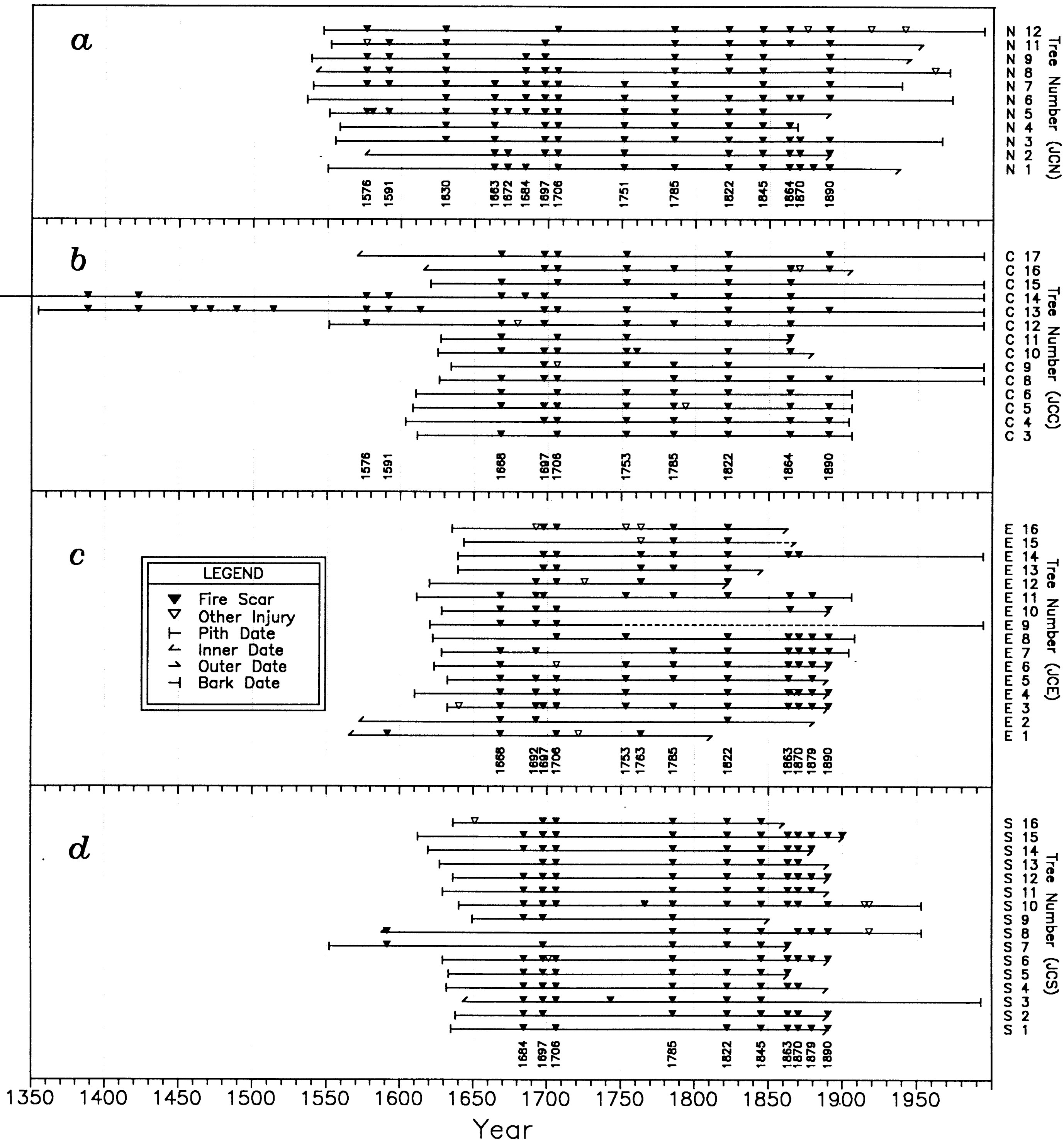


**Figure 2.** Fire chronologies for Jewel Cave National Monument sites. Time spans of individual trees are represented by horizontal lines, with fire scars noted by triangles at the dates they were recorded. Open triangles are other injuries or questionable fire scars recorded within the ring series. (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).

**Table 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).

| 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 | 16 | 20 ± 14 | 4 - 45 |
| JCC | 1388 to 1890 | 22 | 23 ± 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 |

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 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 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 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

**Table 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).

| 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 |

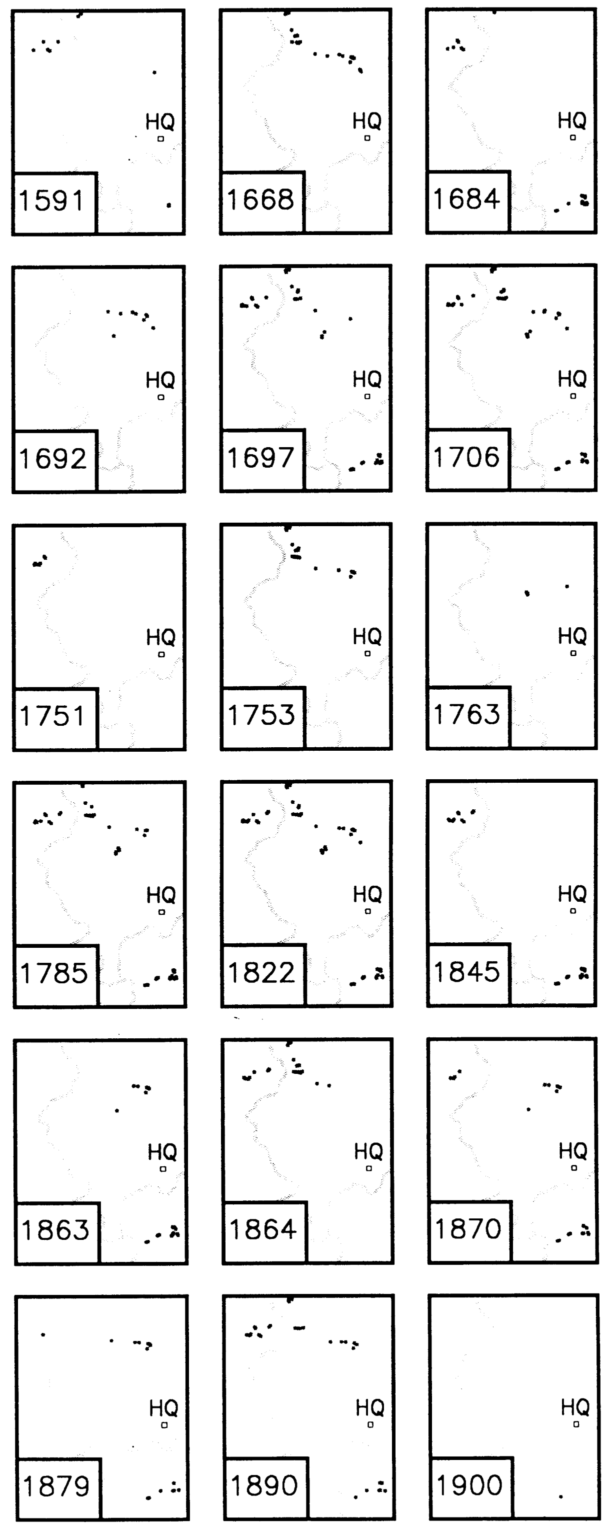


**Figure 3.** Maps of fire occurrence for selected fire years at Jewel Cave National Monument sites. Black stars represent trees recording a fire scar for each fire year. HQ in each map is location of Monument headquarters and light lines are locations of Hell and Lithograph Canyons. See Figure 1 for more detailed map for reference of locations of collected trees.

**Table 3. Number of fire scars by position within annual rings. Scar positions are: Unknown earlywood: position within the earlywood cannot be defined more precisely; Earlysarlywood: 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 | | 12 | 22 | 29 | |
| JCC | 6 | 5 | 3 | 10 | 27 | 28 | 37 |
| | | | 6 | | | | 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%) |

establishment in the Jewel Cave area. There was a clustering of pith dates in the 1540s to 1560s at site JCN (Figure 2a) while the remaining sites had a majority of pith dates from 1610 to 1650 (Figure 2b, c, and d). Two trees at JCC recorded their earliest dates in the early 1300s (Figure 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 1 and 2). Furthermore, all sites recorded similar fire scar seasonal positions during individual fire years (Table 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 fiie 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. Amo 1976, Barrett and Amo 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 Amo 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). 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 (Figure 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 3). Hell Canyon, especially north of the highway crossing in the Monument (Figure 1), is a very steep walled canyon with rocky slopes. Lithograph Canyon south of the Monument headquarters (Figure 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 3). Another example was in 1845 when fire burned on only the west and south sides at sites JCS and JCN (Figure 3) 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 (Figure 3). 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 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 bum programs at both Jewel Cave National Monument and nearby Wind Cave National Park in the south central Black Hills.

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