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ABSTRACT—This study documents over six centuries of historic fire events at Devils Tower National Monument in northeast Wyoming, USA. The 691-year tree-ring chronology is based on 37 ponderosa pine (*Pinus ponderosa* C. Lawson) trees collected at the monument. The period of tree-ring record ranged in calendar years from 1312 to 2002 and fire scar dates (n = 129) ranged from 1330 to 1995. The mean fire interval (MFI) for the entire record was 24.6 years, and intervals for individual trees ranged from 4 to 119 years. A period of increased fire frequency (MFI = 5.7 years) occurred from about 1860 to 1880, corresponding to the period of Euro-American exploration and settlement of the region. Comparisons of fire–climate relationships derived from Devils Tower, the Black Hills, and other Great Plains sites suggest that Devils Tower presettlement fire events were more similar to those of grasslands. Despite this, current fire intervals and vegetation assessments suggest that conditions are departed from historical conditions. In the Great Plains, temperature appears to be a strong regional-scale determinant of fire frequency, which may become more evident considering global warming predictions.

Key Words: Devils Tower, drought, fire history, Great Plains, ponderosa pine

INTRODUCTION

Long-term information about fire history is sorely lacking in Great Plains grasslands compared to the western United States. Studies of charcoal and historic documents have provided much of the information to date, while studies based on tree rings have been largely underrepresented. Tree-ring studies are arguably one of the best sources of information about the historic fire environment (Bowman 2007) and likely have much information to bear on the history of Great Plains fire. The lack of information is partly due to the difficulty in procuring evidence of past fire events, limited areas with trees, and a lack of research efforts.

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The Great Plains currently faces some important fire-related issues and questions that are in need of immediate attention. Of particular concern is whether fire severity and frequency will increase in response to climate change (Guyette et al. 2006a; Westerling et al. 2006) and whether or not information about the past fire environment is relevant to the future. Specific issues include deviation from the historic range of variability (e.g., fire frequency, size, seasonality), increased risk to lives and property (e.g., 2006 Texas panhandle fires), woody encroachment (Coppedge et al. 2007), response of ecosystems to climate change, and past importance of grazing on the historic fire environment (Bachelet et al. 2000). In the Great Plains many of these issues have yet to be addressed.

In this paper we use tree-ring-dated fire scars to describe the historic fire frequency at Devils Tower National Monument, Wyoming. Two previous studies have examined the history of fire occurrence at Devils Tower (Thompson 1983; Fisher et al. 1987), but the present study expands the available information with a much longer chronology, is based on more samples, and utilizes new analytical techniques. The extended length of this record is important because it provides more fire event information over a greater range of climate events and length of time prior to Euro-American influences. Finally, during meta-analysis of this and other fire history studies we have found a relationship between fire frequency and temperature that in the future will likely provide additional information about the major forcing factors of fire in the Great Plains.

METHODS

Study Site

The 545-hectare Devils Tower National Monument is located in Crook County, northeastern Wyoming (44°35′N 104°42′W), at the edge of the Great Plains–Palouse Dry Steppe and Black Hills forest provinces (Bailey 1998) (Fig. 1). Average annual precipitation (1970-2001) is 44 cm and the mean maximum temperature is 14.3°C. A monolithic igneous intrusion, Devils Tower rises 386 m above the west side of the Belle Fourche River (National Park Service 2001). Compared to the surrounding region, the landscape of the monument is topographically rough due to the river valley and volcanic intrusions. To the south, west, and north are expansive plains and grasslands (elev. 1200-1300 m) including portions of the Thunder Basin National Grassland at about 1280 m elevation. To the east are the Bear Lodge Mountains and Black Hills, which are densely forested and eventually rise to over 2,200 m.

Currently the vegetation at Devils Tower consists of a mosaic of ponderosa pine woodlands, forests, and mixed-grass prairie. Ponderosa pine woodlands and forests currently cover about 62% of the monument. The current management plan at Devils Tower employs prescribed fire as a means to achieve desired future conditions including reduced fuel loads, open canopy conditions, and increased native grass and forb cover (National Park Service 2004). While prescribed fire, fuels reduction, and fire suppression are the primary forms of fire management at Devils Tower, occasional wildfires do occur at the monument. Records of lightning-caused fires at Devils Tower from 1951 to 1979 show a total of 35 fires, with the highest frequency in June, July, and August; however, more recent records indicate only one lightning fire occurred between 1993 and 2002, burning two acres. Lightning strike frequency and flash density (1 to 3+ flashes km^{-2} yr^{-1}) are highest in northeastern Wyoming and increase from the Palouse Dry Steppe grasslands to the Black Hills (Curtis and Grimes 2004).

Site History

Devils Tower represents a historically important landmark in the northern Great Plains. Several Native American tribes are known to have periodically inhabited the vicinity throughout the historic period, including the Eastern Shoshone, Crow, Kiowa, Cheyenne, Arapaho, and Lakota (Hanson and Chirinos 1997). The tower is represented in the legends and cultural narratives of each of these tribes, and is still revered and utilized as a sacred site. The Fort Laramie Treaty of 1868 guaranteed the land would remain free of white settlement, but enforcement of the treaty was short-lived. A period of rapid change in the area began with Euro-American exploration and settlement in the 1870s. A report of an 1874 expedition mentions widespread evidence of extensive fires and lightning-scarred trees in the pine forests of the Black Hills and Devils Tower region (Gartner and Thompson 1972). The Lakota were forced to cede the Black Hills following the Great Sioux War of 1876-77, during which both the Lakota and the U.S. military used fire tactically and defensively (Brauneis 2004). In addition to political changes, the bison population of the Black Hills region had been eliminated by the mid-1870s (Brown and Sieg 1996). By the early 1880s the Belle Fourche Valley was considered safe for settlement by farmers and ranchers (Mattison 1955). Perhaps due to the high visibility of the tower and proximity of railroads, the land around Devils Tower was set aside as a forest reserve as early as 1891, and the area eventually became the nation's first national monument in 1906 (Mattison 1955).

Sample Collection

In September 2006, an exhaustive search was conducted for ponderosa pine remnants (i.e., dead trees) at Devils Tower that exhibited both numerous tree rings and fire scar evidence. Cross-sections were cut at or near ground level using a chainsaw, and the location of each sample was recorded using a GPS unit. Several cross-sections were obtained from stumps left by a recent thinning

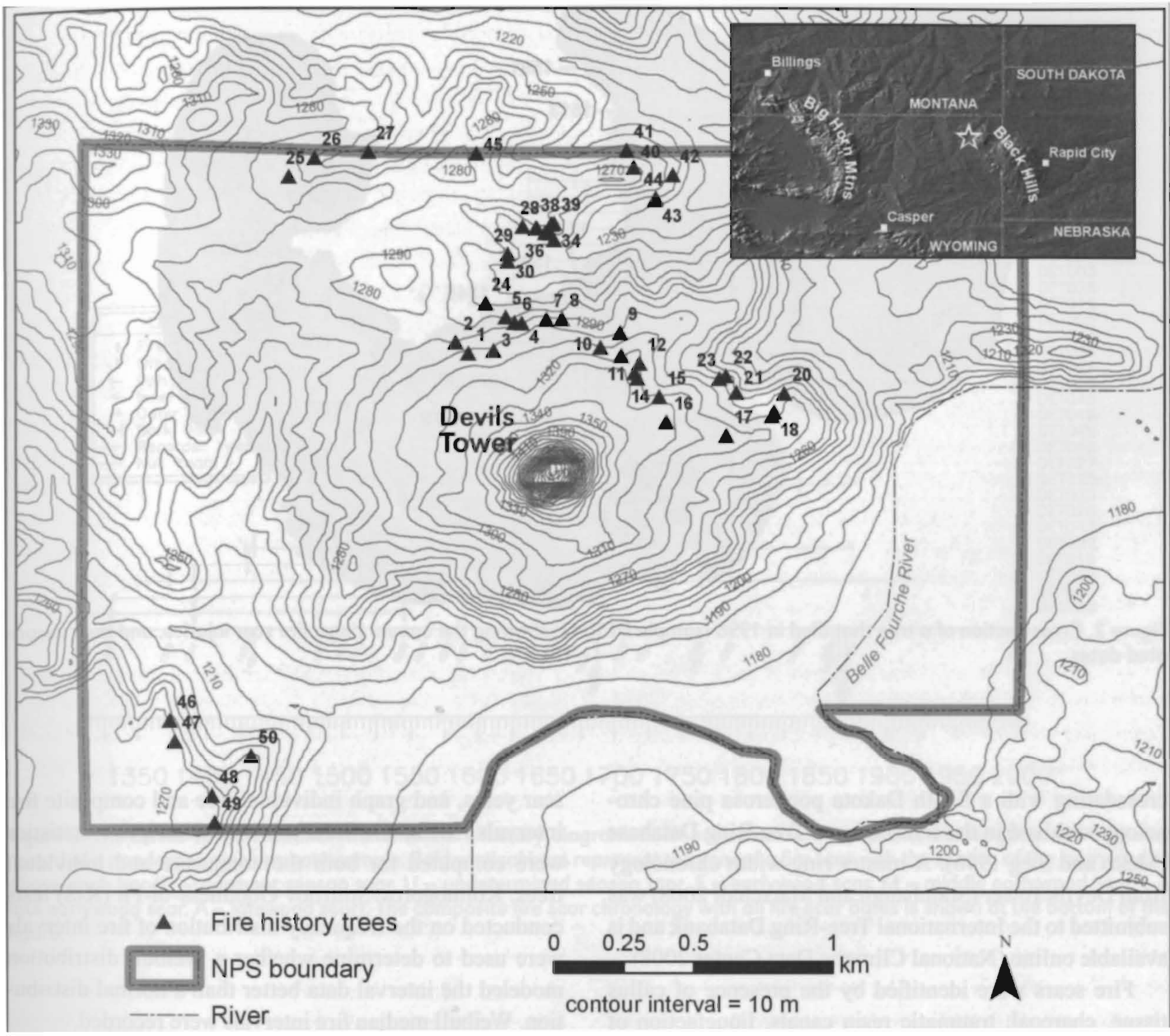

Figure 1. Location and topographic map of Devils Tower National Monument, Wyoming.

operation; however, the majority was from dead trees and fragments standing and lying on the ground. A total of 50 cross-sections were collected from the northern, northeastern, and southwestern portions of Devils Tower at elevations ranging from 1,230 to 1,330 m (Fig. 1).

Dendrochronology

Cross-sections were prepared for tree-ring measurement by planing and sanding (orbital electric sander) with progressively finer sandpaper (80 to 1,200 grit) to reveal the cellular detail of annual rings and fire scar injuries (Fig. 2). A radius (pith-to-bark) of each cross-section with the least amount of ring-width variability due to fire injuries was chosen for tree-ring width measurement. All rings were measured to 0.01 mm precision using a binocular microscope and a moving stage fixed to an electronic transducer. Tree ring-width series from each sample were visually crossdated using ring-width plots (Stokes and Smiley 1968). The computer program COFECHA (Grissino-Mayer 2001a) was used to ensure accurate dating of samples and facilitated identification of false and missing rings, which were identified on multiple samples. Sample ring-width measurements and dates were verified by

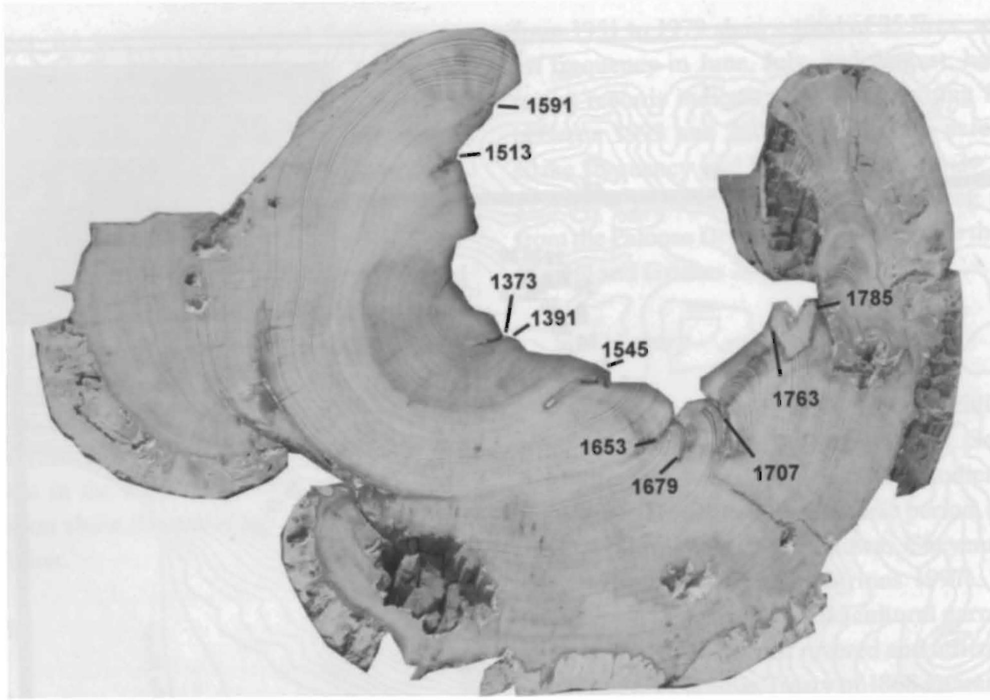

Figure 2. Cross-section of a tree that died in 1998 (sample DET042) showing the annual rings, fire scar injuries, and their associated dates.

crossdating with a South Dakota ponderosa pine chronology archived in the International Tree-Ring Database (Meko and Sieg 1996). A master ring-width chronology from Devils Tower (Stambaugh and Marschall 2008) was submitted to the International Tree-Ring Databank and is available online (National Climatic Data Center 2008).

Fire scars were identified by the presence of callus tissue, charcoal, traumatic resin canals, liquefaction of resin, and cambial injury. Fire scar dates were assigned to the year and, where possible, season of response to cambial injury (Kaye and Swetnam 1999; Smith and Sutherland 1999). For purposes of analysis, we grouped fire scars in three instances based on the assumption that they likely were formed during one fire event. For example, one latewood scar was dated to 1687 while four dormant scars were dated to 1688. The four dormant scars were moved to 1687 and analysis was performed assuming this was one fire event. This affected fire years at 1687/1688, 1762/1763, and 1859/1860. Between-tree differences in the position of the scar within the ring could be due to several factors such as differences in tree growth periods (e.g., one tree is dormant while another is growing) or a fire event with a long duration (e.g., fires that smolder then flare up). We used FHX2 software (Grissino-Mayer 2001b) to construct the fire chronology, analyze fire scar years, and graph individual tree and composite fire intervals. Mean fire intervals and descriptive statistics were computed for both the composite and individual trees. Kolmogorov-Smirnov Goodness-of-Fit (K-S) tests conducted on the frequency distribution of fire intervals were used to determine whether a Weibull distribution modeled the interval data better than a normal distribution. Weibull median fire intervals were recorded.

Superposed epoch analysis (SEA) was conducted to determine the degree, strength, and influence of regional climate to fire events (Stephens et al. 2003; Fulé et al. 2005). Four climate reconstructions spanning different periods were used in the SEA: (1) reconstructed summer season Palmer Drought Severity Indices [PDSI (average of gridpoints 129, 130), 818-2003 (Cook et al. 2004)] for east-central Wyoming, (2) Southern Oscillation Index [SOI, 1706-1977 (Stahle et al. 1988)], (3) Niño3 SST [1408-1978 (Cook 2000)], and (4) Pacific Decadal Oscillation [PDO, 1661-1991 (Biondi et al. 2001)]. The data were bootstrapped for 1,000 simulated events in order to derive confidence limits. Fire event data were compared to climate parameters to determine if climate was significantly different from average during the six years preceding and four years succeeding fire events. We limited the SEA analysis period to AD 1450 to 1900, a period when

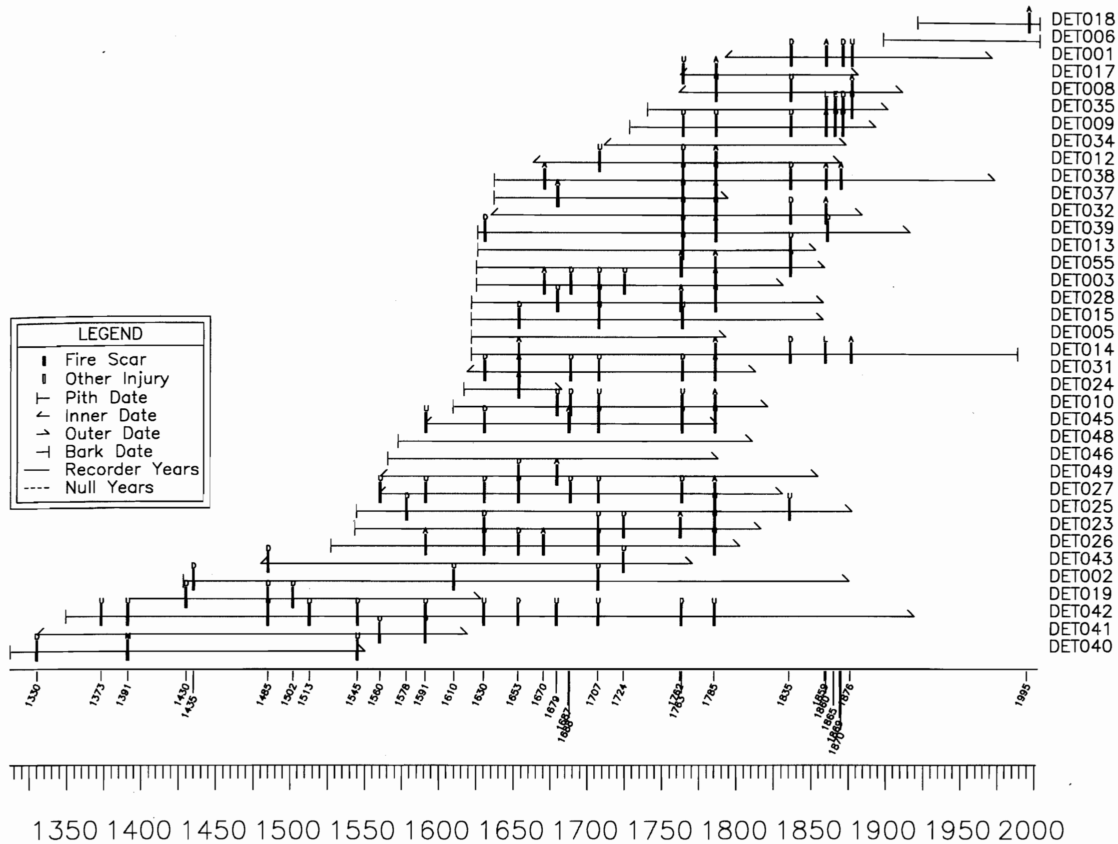

Figure 3. The Devils Tower National Monument fire history diagram. Each horizontal line represents the length of the tree-ring record of a ponderosa pine remnant sample. Bold vertical bars represent the year of a fire scar with the season of the injury coded above each bar (D = dormant season scar, U = undetermined season scar, E = earlywood scar, M = middle earlywood scar, L = late earlywood scar, A = latewood scar). The composite fire scar chronology with all fire scar dates is shown at the bottom of the figure.

at least five trees were represented in the fire history and synchrony and replication of fire events appeared high. We chose climate data and analyses that were similar to those done in the Black Hills (Brown 2006) so that results could be compared.

RESULTS

The tree-ring record spanned the period AD 1312 to 2002. A total of 8,718 years (tree rings) were analyzed on 37 samples. Thirteen samples were excluded due to lack of fire scar injuries, poor sample quality, or difficulty in tree-ring dating. We identified and dated 129 fire scars that occurred from 28 different fire events. Fire scar dates ranged in calendar years from 1330 to 1995 (Fig. 3). Prescribed fires that occurred since 2004 were not captured by our chronology.

For the entire period of record, the mean fire interval (MFI) was 24.6 years (Table 1). The lengths of presettlement (pre-1850) fire intervals were remarkably consistent for the majority of this time span. A brief period of increased fire frequency occurred from about 1850 to 1880. During this period, the MFI decreased dramatically to 5.7 years. Fire intervals for the entire period of record ranged from a minimum of 4 years to a maximum of 119 years, the latter of which occurred from 1876 to 1995.

Fire severity (percentage of trees scarred) was temporally variable at Devils Tower, with severity increasing after about 1700 (Table 1). Analysis of fire severity was conducted only for fire years where sample depth was at least three trees. Prior to 1700, mean percentage of trees scarred in fire events was 25.6%. After 1700, mean percentage of trees scarred increased to 40.4%. The most severe fire years at Devils Tower were 1762 (57% scarred)

TABLE 1
SUMMARY OF FIRE HISTORY ANALYSIS

Number of samples	37
Period of record	1312-2002
Length of record (yrs)	691
Total number of tree rings	8718
Number fire scars	129
Number fire years	28
MFI (yrs) 1312-2002	24.6
MFI (yrs) 1850-1880	5.7
Weibull (yrs) 1312-2002	20.2
Weibull (yrs) 1850-1880	5.8
Percentage of trees scarred 1373-1700	25.6
Percentage of trees scarred 1700-1876	40.4

Notes: MFI = mean fire interval, Weibull = Weibull median fire interval. Percentage of trees scarred is calculated for years where sample depth was at least three trees.

and 1785 (69% scarred). With respect to regional drought these years were moderately wet (PDSI = 1.6) and near normal (PDSI = -0.8), respectively. Percentage of trees scarred was not significantly correlated with PDSI, but more fire events occurred in drier than normal conditions ($n = 16$) than wetter ($n = 11$). Fire scars were nearly exclusively positioned in the latewood or dormant ring position. Latewood fire scar positions likely correspond to mid- to late summer season (July to September) while dormant positions are likely later in the year. Historic dormant season fires are more likely to have occurred in the early portion of the dormant season (e.g., August to October) than the latter (e.g., November to May), considering the timing of (1) lightning ignitions, (2) decreased precipitation in late summer, (3) production and curing of fuels, and (4) snow and persistence of snowpack. Fire scar positions suggest that nearly all historic fires occurred in this period of the year. In addition, fire scar positions suggest that seasonality changed during the mid-19th century from primarily dormant season to growing season (Table 2). Prior to about 1850, 47 of 71 fire scars (66.2%) identifiable to a season occurred during the dormant season. After 1850, 11 of 16 fire scars (68.8%) occurred in the growing season. Superposed epoch analysis showed little evidence for fire being related to climate parameters. Conditions two years prior to fire events were significantly dry (Fig. 4).

DISCUSSION

The general patterns of historic fire (e.g. fire frequency, fire severity, fire seasonality, temporal variability) at Devils Tower are comparable to those found at other fire history study sites both in the Black Hills region (Brown and Sieg 1996, 1999; Brown et al. 2000) and in the northern Great Plains (Umbanhowar 1996). The pattern of longer fire return intervals in the era prior to Euro-American settlement, a period of increased fire frequency in the late 19th century, and subsequently reduced fire frequency following settlement corresponds to patterns found at other sites in the Black Hills (Brown and Sieg 1996, 1999; Wienk et al. 2004). The post-1850 increase in fire frequency followed by dramatically decreased fire in the 20th century also corresponds to records of charcoal in lake sediments across the northern Great Plains (Umbanhowar 1996). The scale of this pattern suggests anthropogenic causes because (1) the timing of changes corresponds with known historical events, and (2) the pattern transcends the important biophysical differences between different locations throughout the region such as elevation, temperature, precipitation, vegetation, and topography.

Similarities in fire regimes existing before Euro-American settlement (pre-1850) typically reflect similarities in topography, climate, human occupation, and weather. The mean fire intervals at Devils Tower prior to 1850 were relatively stable, particularly from the late 15th to early 18th centuries (range of 11-32 yr). We attribute the brief increase in fire frequency in the latter half of the 19th century to a combination of factors, particularly increased ignitions by settlers and explorers and conflicts between the Sioux and Euro-American settlers (Umbanhowar 1996; Brown and Sieg 1999). Following the late 19th-century period of frequent fire an unprecedented 119-year fire-free interval (4× the long-term mean) occurred at Devils Tower. Although fewer trees are represented in the record during the 20th century, previous reports found similar results (Thompson 1983; Fisher et al. 1987). The decrease in fire during the 20th century combined with the elimination of bison grazing led to important biophysical changes in the region such as increased forest density and fuel loading and decreased areas of grassland (Brown and Sieg 1999); however, less is known about changes of the grasslands of the Palouse Dry Steppe. Reasons for the longer fire intervals since the initial period of settlement include the advent of fire suppression policies, reduced fine fuel loads due to livestock grazing, logging, and fragmentation (Brown and Sieg 1996, 1999).

TABLE 2
SUMMARY OF FIRE SCAR POSITIONS FOR TWO PERIODS OF INTEREST AND ALL YEARS

Period	Dormant	Early early-wood	Middle early-wood	Late early-wood	Latewood	Undetermined	Total
1312-1850	47	0	1	0	23	40	111
1850-2002	5	1	0	2	8	2	18
1312-2002 (all years)	52	1	1	2	31	42	129

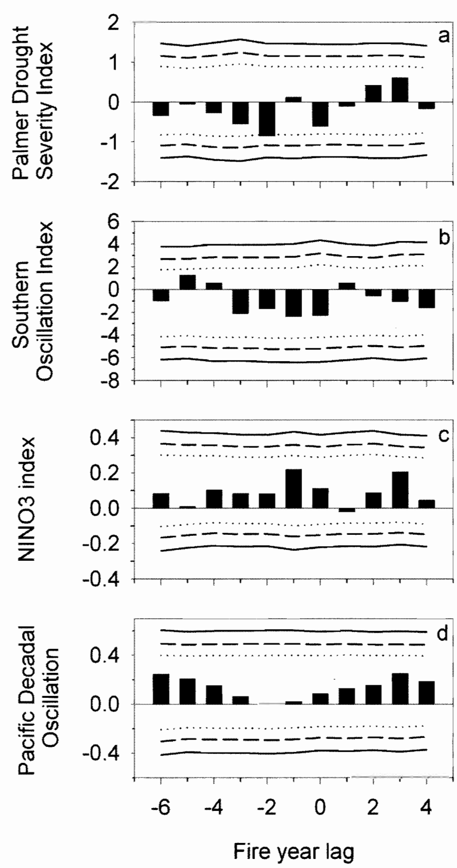

Figure 4. Superposed epoch analysis (SEA) of mean climate parameters and fire events: **(a)** reconstructed summer season Palmer Drought Severity Indices [PDSI (average of gridpoint 129, 130); 818-2003 (Cook et al. 2004)] for east-central Wyoming; **(b)** Southern Oscillation Index [SOI; 1706-1977 (Stahle et al. 1988)]; **(c)** Niño3 SST [1408-1978 (Cook 2000)]; and **(d)** Pacific Decadal Oscillation [PDO; 1661-1991 (Biondi et al. 2001)]. All climate parameters are available from the National Climatic Data Center (http://www.ncdc.noaa.gov/paleo/treering.html). Bars represent deviation from normal conditions based on 1,000 simulations. Confidence limits are 90% (dotted line), 95% (dashed line), and 99% (solid line).

Fire severity is an important descriptor of fire regimes because of the effects on vegetation, tree mortality, seed sources, and vegetation structure. The most severe fire year (measured as the highest percentage of trees scarred) at Devils Tower (1785) was also a major fire year at several locations throughout the Black Hills (Brown and Sieg 1996, 1999; Brown et al. 2000; Wienk et al. 2004), but not at a location about 150 km to the southwest in the Rochelle Hills (Perryman and Laycock 2000). Interestingly, none of the samples collected in the southwestern portion of the monument were scarred during 1785. Only two fires years (1591 and 1785) at Devils Tower corresponded to the 18 regional presettlement (pre-1850) fires reported in the Black Hills by Brown (2006). (Five of 16 pre-1850 fire events at Jewell Cave National Monument [Brown and Sieg 1996], located approximately 160 km to southwest, were shared with Devils Tower.) Contrary to the Black Hills (Brown 2006), we found little evidence for a significant relationship between climate parameters and fire events at Devils Tower prior to Euro-American settlement. This was surprising considering (1) the length of the fire chronology allowed for multiple climate-fire comparisons, and (2) the multiple climate parameters (i.e., drought, atmospheric circulation patterns) related to fire years in the Black Hills (Brown 2006). These differences suggest an important control on the fire environment is dissimilar between the Black Hills and Devils Tower so that fire frequencies may be similarly recorded, but fire events occur in different years. Further analysis shows that mean climate conditions during fire years at Devils Tower were near normal for all climate parameters (Fig. 5). Similar results were also obtained in the eastern Great Plains on loess hills (Stambaugh et al. 2006), in the southwestern Great Plains on the Palouse Dry Steppe (Guyette et al. 2006b), and from a preliminary analysis of presettlement fire years listed in Perryman and Laycock (2000) for the Rochelle Hills (Thunder Basin National

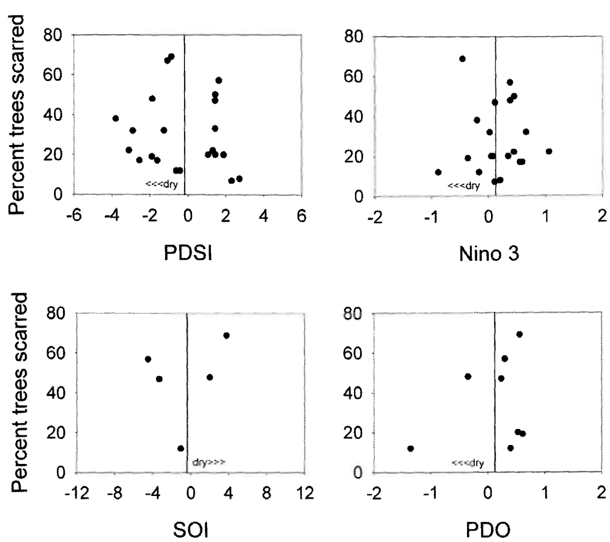

Figure 5. Scatterplots of the percentage of trees during presettlement (pre-1850) fire events by climate parameters. Vertical lines signify the mean climate condition for all fire events. See Figure 4 caption for climate parameter descriptions.

Grasslands, WY). From this comparison it appears that the Devils Tower historic fire regime has characteristics more common to grassland than forest ecosystems (i.e., Black Hills). Grasslands fire events can occur during wetter years because the fine fuels dry quickly compared to forests with typically heavier fuels and longer fuel moisture time lags. Optimum conditions for grassland fires may correspond to normal climate conditions because drier than normal conditions limit fuel production and continuity, while wetter than normal conditions limit ignition potential and fire spread. Within this relationship landscape topographic roughness (Stambaugh and Guyette 2008) likely accentuates the differences between grasslands and forests with respect to drought and fuels. Grasslands are commonly on topographically smooth landscapes with minimal differences in aspect, which facilitates increased homogeneity in fuel moisture. In comparison, forests on topographically rough landscapes may have fuel moisture contents that are more heterogeneous (due to fetch, slope, and aspect) and require drier conditions to facilitate burning (i.e., ignition, fire spread).

An apparent tree establishment event (clustering of pith dates) in the early 1600s, possibly precipitated by a 1591 fire, was also observed at Jewel Cave National Monument in the interior Black Hills (Brown and Sieg 1996). Studies of ponderosa pine establishment patterns in the Black Hills show abundant recruitment occurred in the late 1700s during a prolonged wet period (Stockton and Meko 1983; Brown and Cook 2006); they also note that their cohorts match those in the Bighorns and Little Belt Mountains to the west. It is unclear whether the lengthened fire intervals at Devils Tower during the 18th century led to increases in ponderosa pine establishment at the monument. It is plausible that the lengthened fire intervals during this century resulted in the concomitant increase in percentage of trees scarred during fire events due to increased fuel accumulation. Considering the effects of decreased fire events in the last century (e.g., increased tree density, fuel accumulation), it is also plausible that a future wildfire event could be severe and have historically unprecedented fire effects. Seemingly uncharacteristic fire effects have recently been observed in the northern Great Plains (e.g., 2006 fire at Charles M. Russell National Wildlife Refuge).

Future Fire and Climate Change

Today, as lightning fires are commonly extinguished and prescribed fires become the norm, the role and values of humans and policies are becoming increasingly important in influencing fire regimes. Fire surrogates such as fuel treatments are used to maintain historic fire-mediated communities and mimic fire effects (severity, intensity) within the historic range of variability (Dillon et al. 2005). Based on the recent lengthening of fire intervals and the LANDFIRE Fire Regime Condition Class departure index (Hann et al. 2004), the conditions at the study area have departed from historic range of variability. Recently, prescribed burning and fuels reduction have been undertaken at Devils Tower in order to mitigate the severity of effects and risks of the next wildfire event.

Currently, and in the future, influences such as climate change, invasive species, and land use changes will significantly impact ecosystems and possibly determine a future range of variability. Of these factors, climate changes are likely to be most widespread and influential on U.S. fire regimes. Despite the differences between Devils Tower and fire history sites in the Black Hills (e.g., geographic, topographic, elevational), the overall fire frequency at Devils Tower was similar and fits into a larger-scale temperature-fire trend (Fig. 6). Recent analyses using multiple (>100) fire history sources have illuminated a continental-scale trend of increasing fire frequency with temperature (Guyette et al. 2006a). The temperature-fire frequency relationship in the Great Plains shows historic mean fire intervals decrease in length by approximately two years with each 1°C increase in annual mean

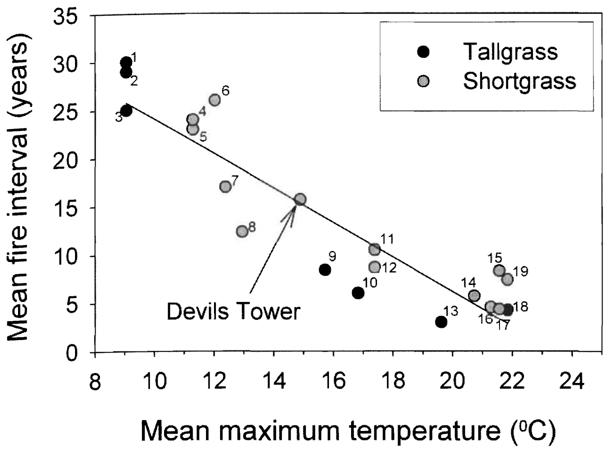

Figure 6. Scatterplot of mean fire intervals, prior to Euro-American settlement, by annual mean maximum temperature (Daly et al. 2002, available online at http://www.prism.oregonstate.edu/). Mean fire intervals were previously developed by multiple investigators using tree-ring based fire history methods in shortgrass and tallgrass ecosystems primarily in the Great Plains region (1 = Frissell 1973; 2 = Clark 1990; 3 = Spurr 1954; 4 = Brown 2003; 5 = Brown and Sieg 1996; 6 = Stambaugh and Frost (in prep.); 7 = Brown 2003; 8 = Brown 1996; 9 = Perryman and Laycock 2000; 10 = Bragg 1985; Guyette et al. (in prep.); 11 = Stambaugh et al. 2006; 12, 13 = Guyette et al. 2006b; 14 = Guyette and McGinnes 1982; 15, 17, 20 = Sakulich 2004; 16, 18 = Camp et al. 2006, 19 = Clark 2003).

maximum temperature (Fig. 6). These analyses utilize only fire frequency information prior to Euro-American settlement in order to reduce the influences of known anthropogenic factors (e.g., warfare, domestic grazing, population density, agriculture). Temperature is likely related to fire frequency because increased temperatures can (1) cause a lengthening of the fire season, (2) shorten drying times of fuels, (3) decrease snowpack and duration, and (4) directly influence the rate of combustion (via the Arrhenius equation). The frequency of fire at Devils Tower is well predicted based on the relationship developed using multiple fire history sites in the Great Plains (Fig. 6). Based on this temperature-fire frequency relationship it is reasonable to expect increased fire frequency with global temperature increases, all else being equal. Presently, warmer and earlier springs are attributed to increased wildfire activity and areas such as the Black Hills region may be particularly vulnerable (Westerling et al. 2006). Further information about changes in fuel characteristics, vegetation communities, and moisture regimes in response to global warming would further the utilization of the temperature-fire relationship.

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