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 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 a 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**

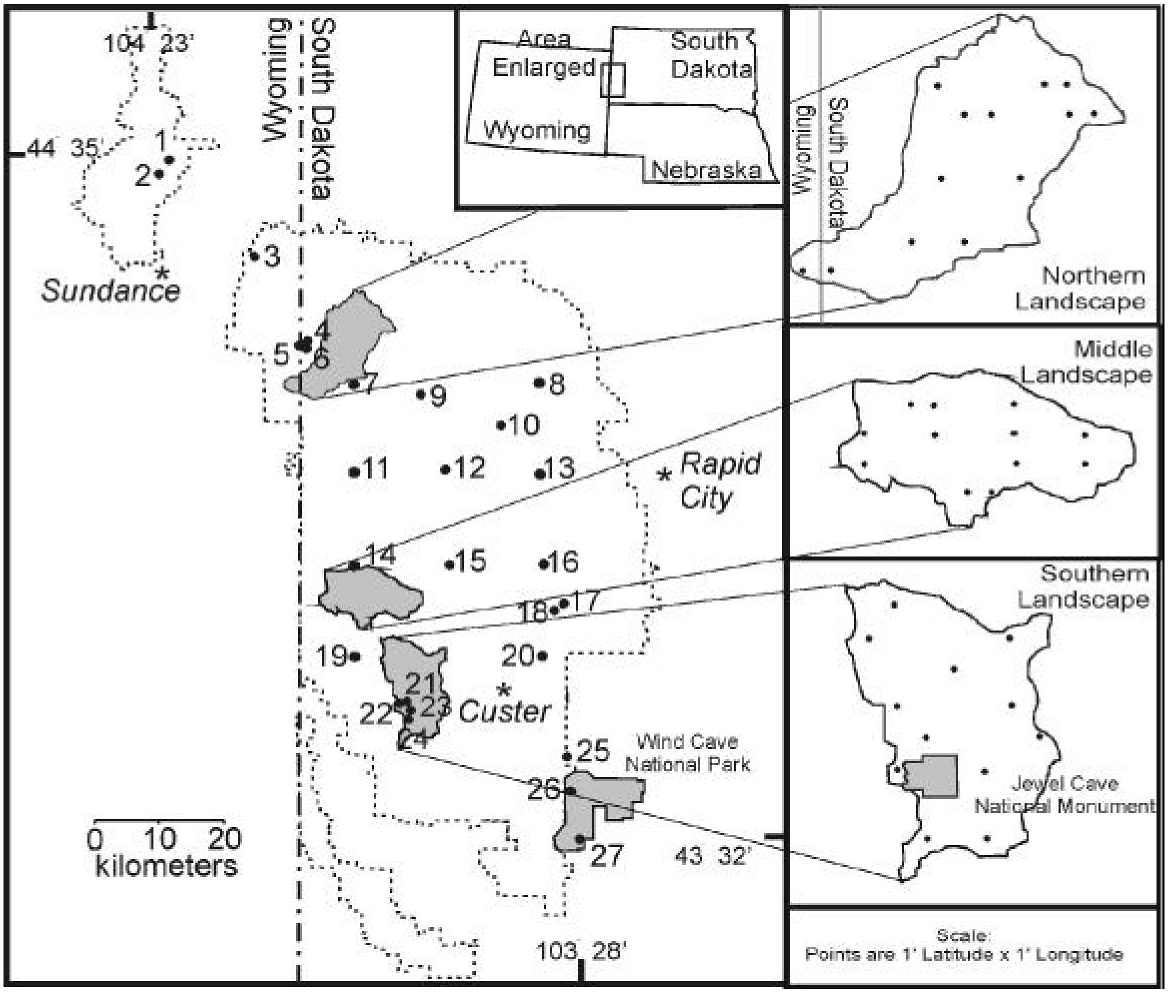


Figure 4.1. Fire history sites collected for this study. Numbers refer to sites in Table 4.1. Boundary of Black Hills National Forest is shown along with boundary of Wind Cave National Park in the southeast.

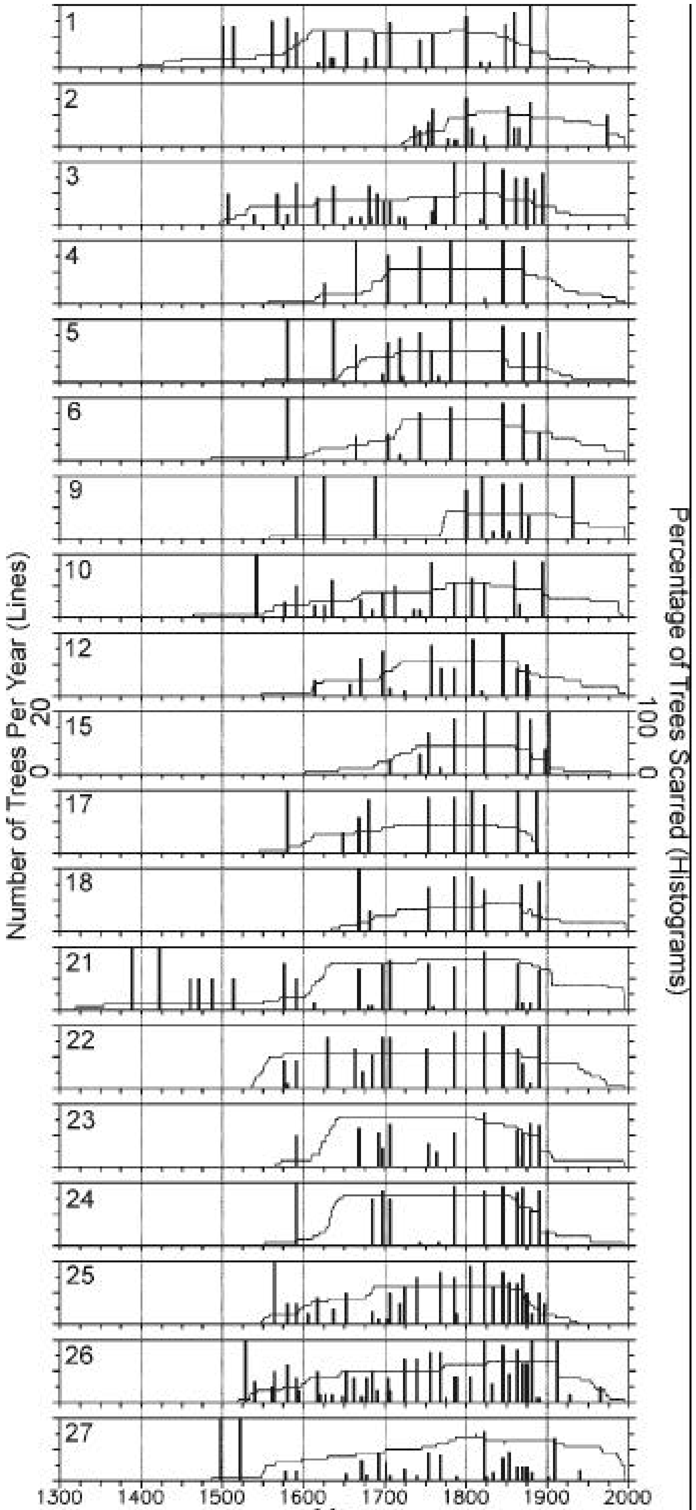


Figure 4.2. Fire chronologies from 19 intensively collected sites. Light line in each plot is the number of trees per year (left axis) and histograms are percentages of trees that recorded a fire scar by year (right axis).

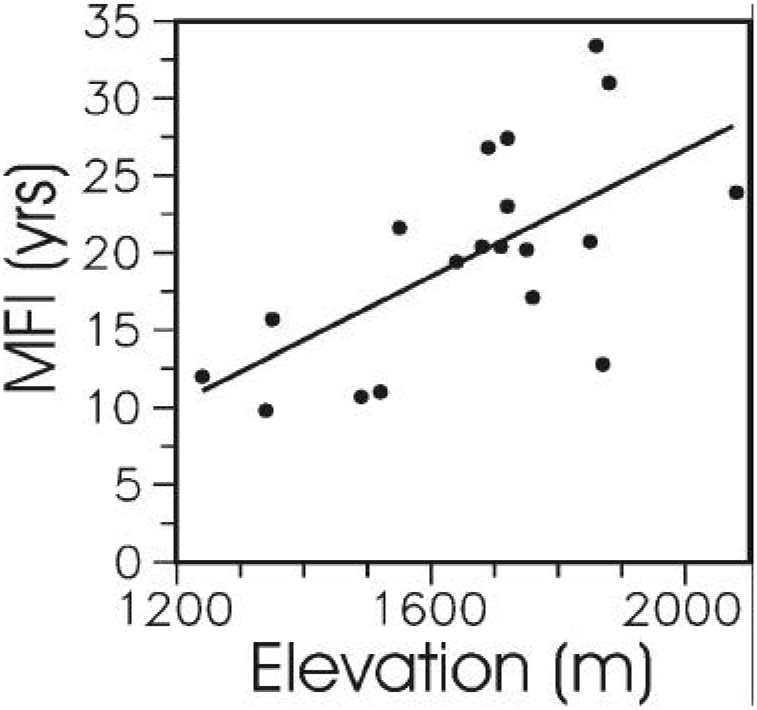


Figure 4.3. Mean fire intervals (MFI) from 1700 to 1900 by elevation for 19 fire chronologies. Regression line is: MFI = 0.0205 m - 14 (R^2 = 0.40).

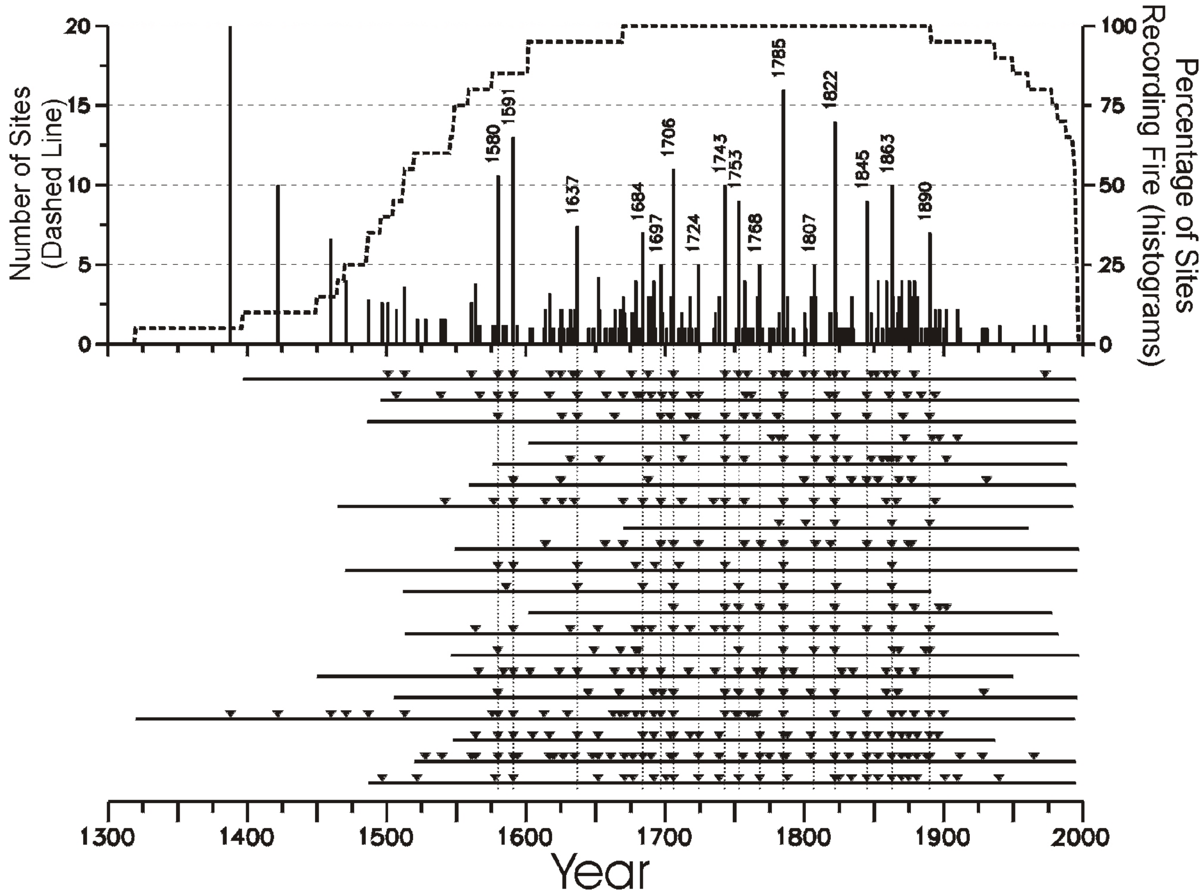


Figure 4.4. Bottom: Composite fire dates from 20 locations across the Black Hills.

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

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

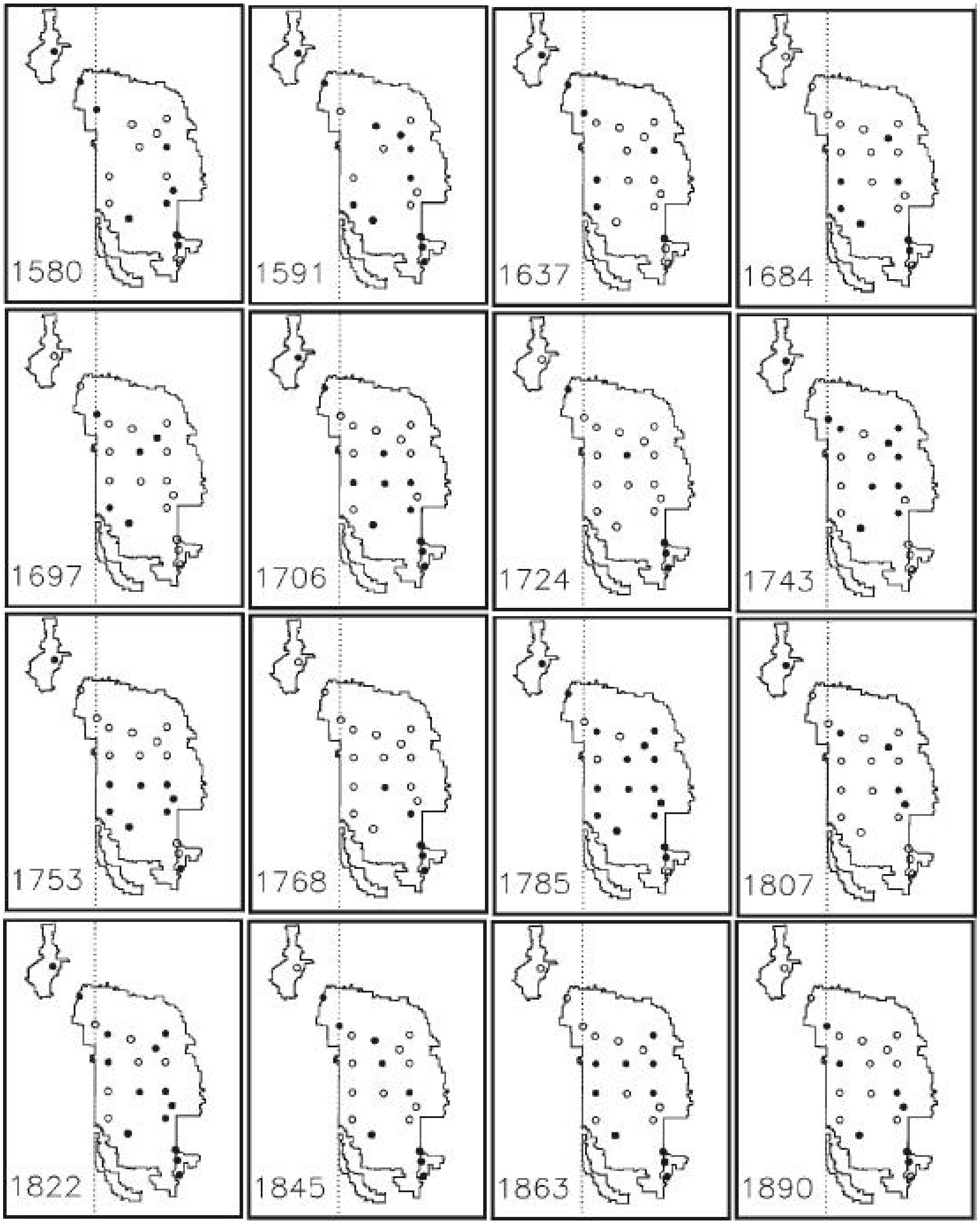


Figure 4.5. Sites that recorded fires (closed circles) or not (open circles) for landscape fire years (years marked in Figure 4.4). See Figure 4.1 for relative scale.

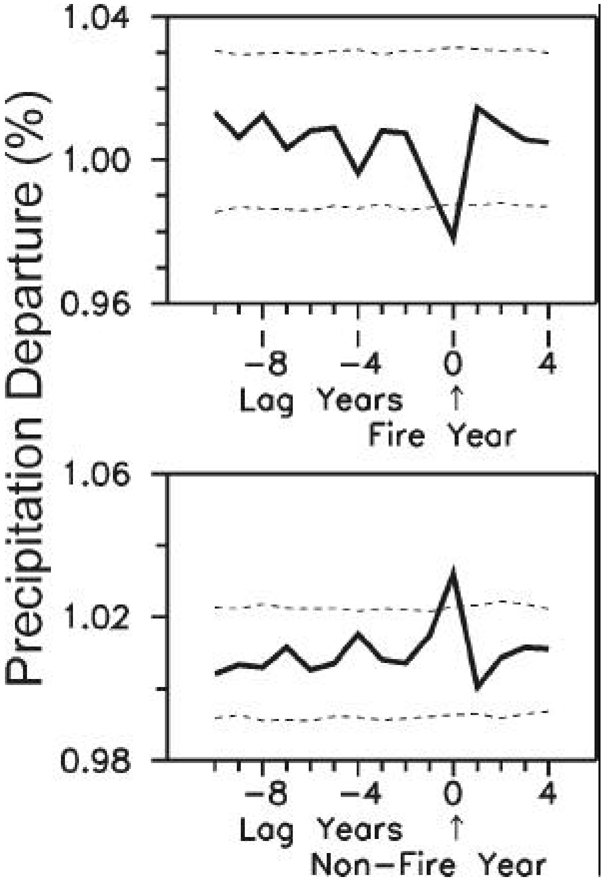


Figure 4.6. Superposed epoch analyses (SEA) for fire years and non-fire years in the Black Hills. Event years (0 lag in graphs) plus antecedent and following years were compared to reconstructed annual precipitation departures from the northern Great Plains (Stockton and Meko 1983). SEA was conducted 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.

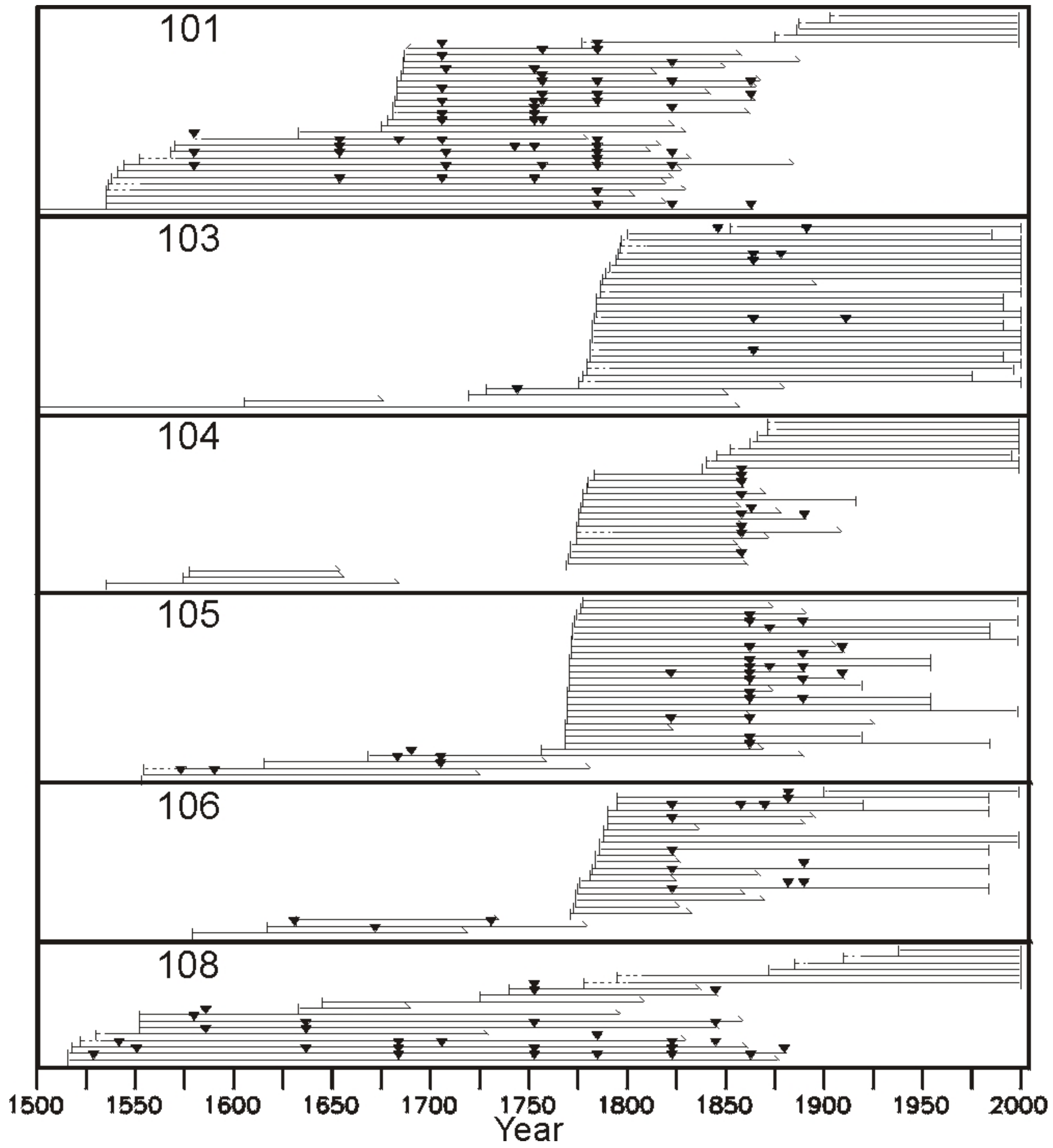


Figure 4.7. Chronologies of individual trees sampled for forest age structure by plot for the middle and southern landscapes. Time spans of trees are represented by horizontal lines with dates of fire scars marked by inverted triangles. Dashed lines are estimated number of years to pith. Vertical lines 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.

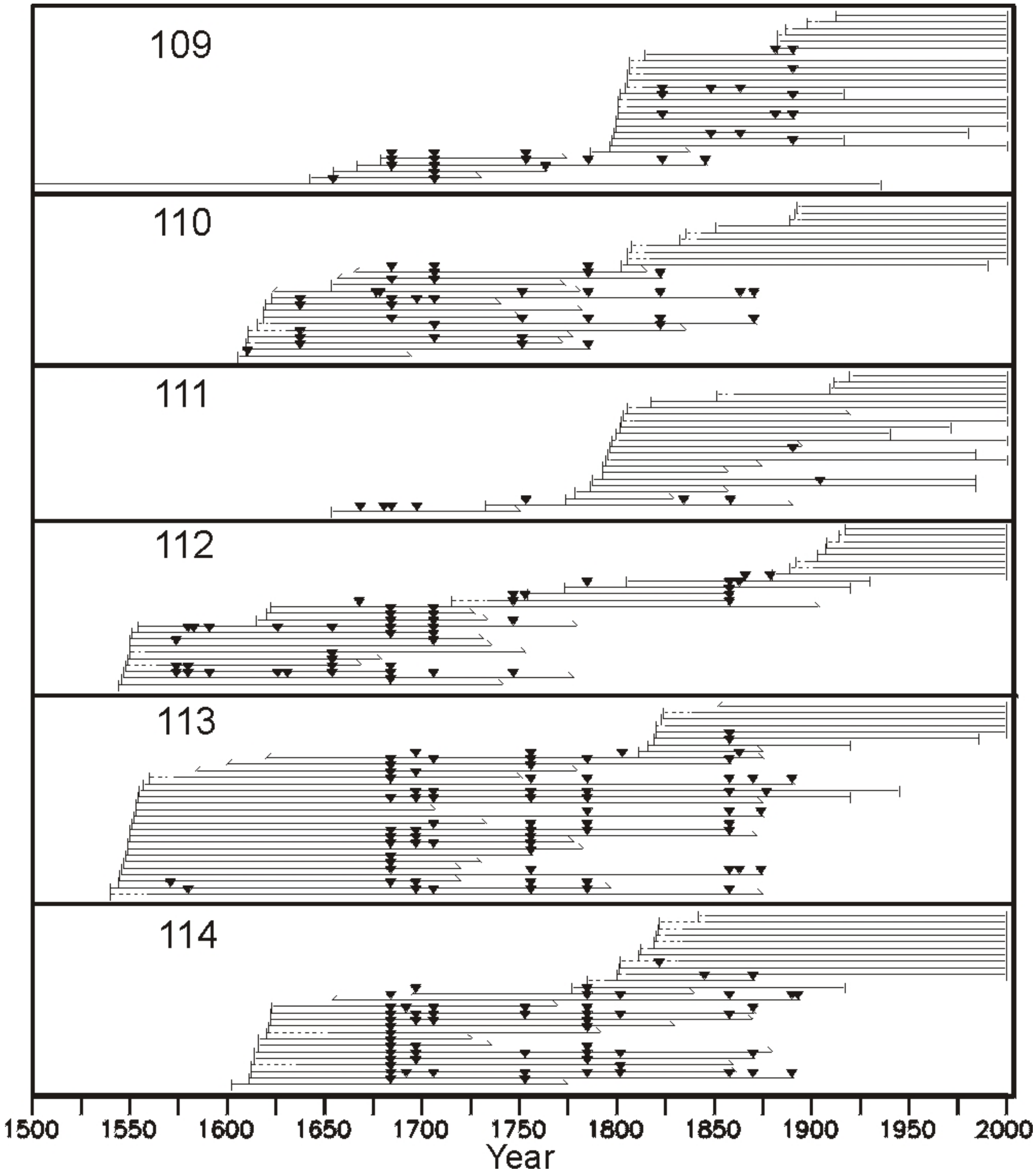
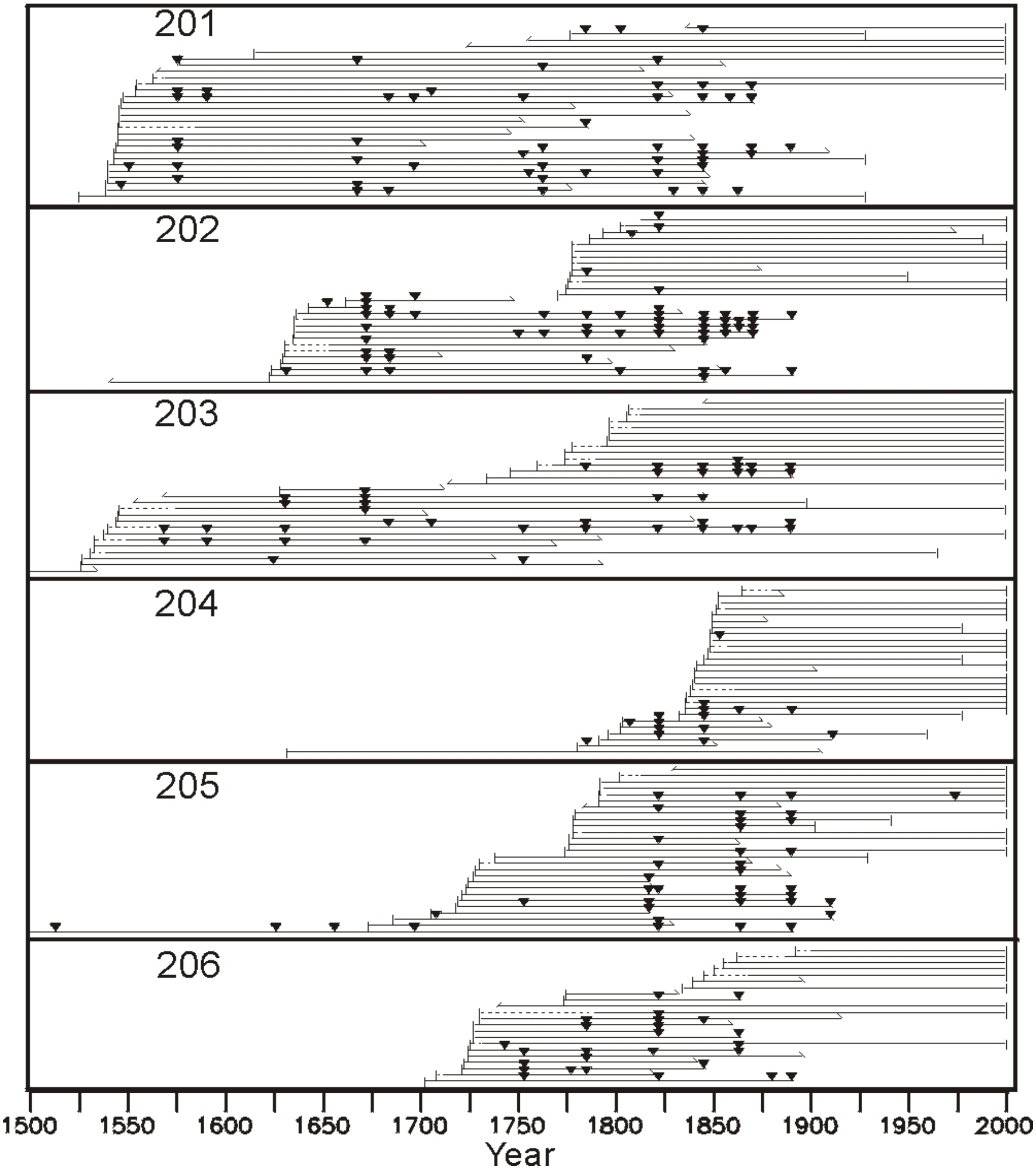


Figure 4.7, continued.



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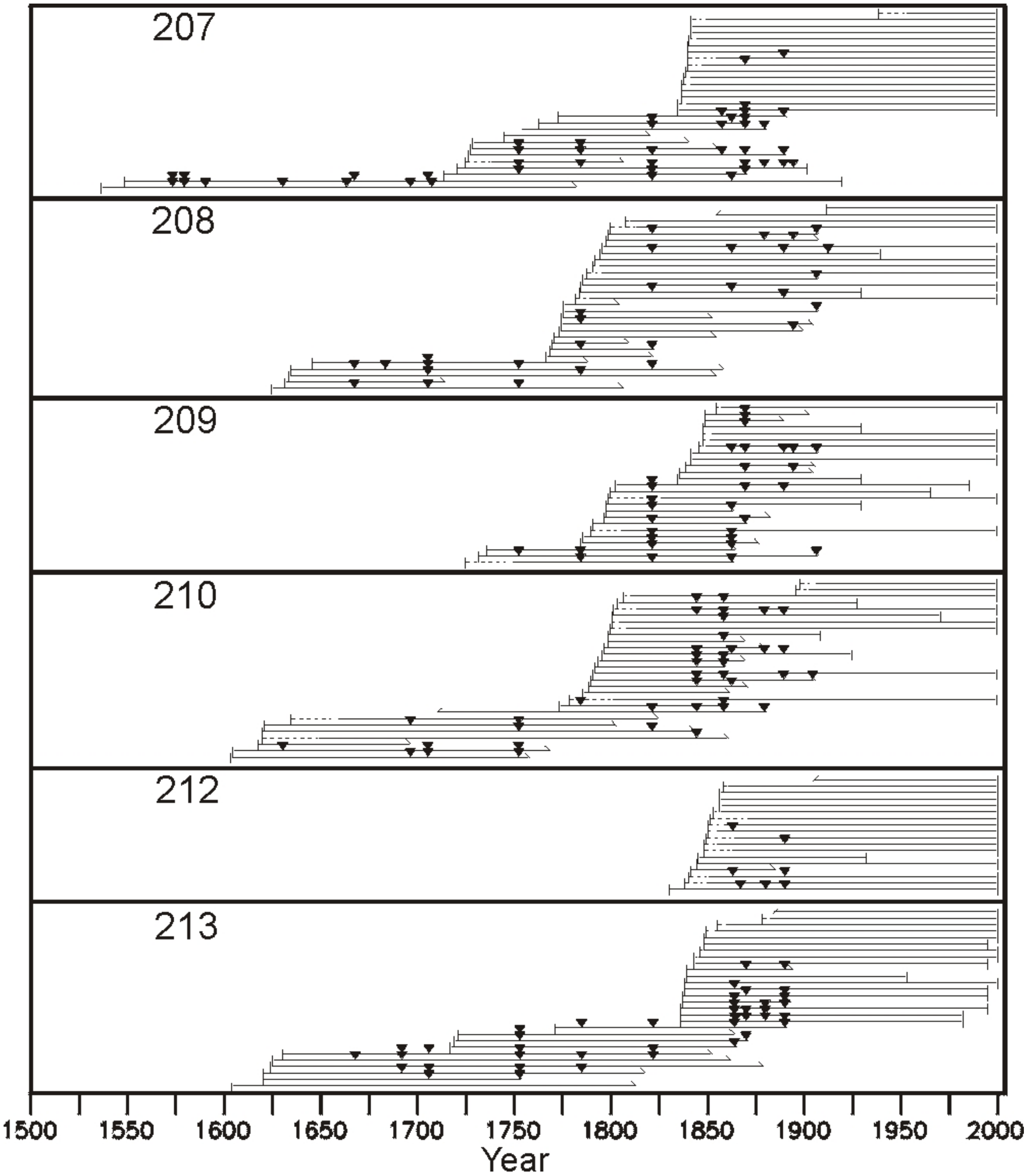

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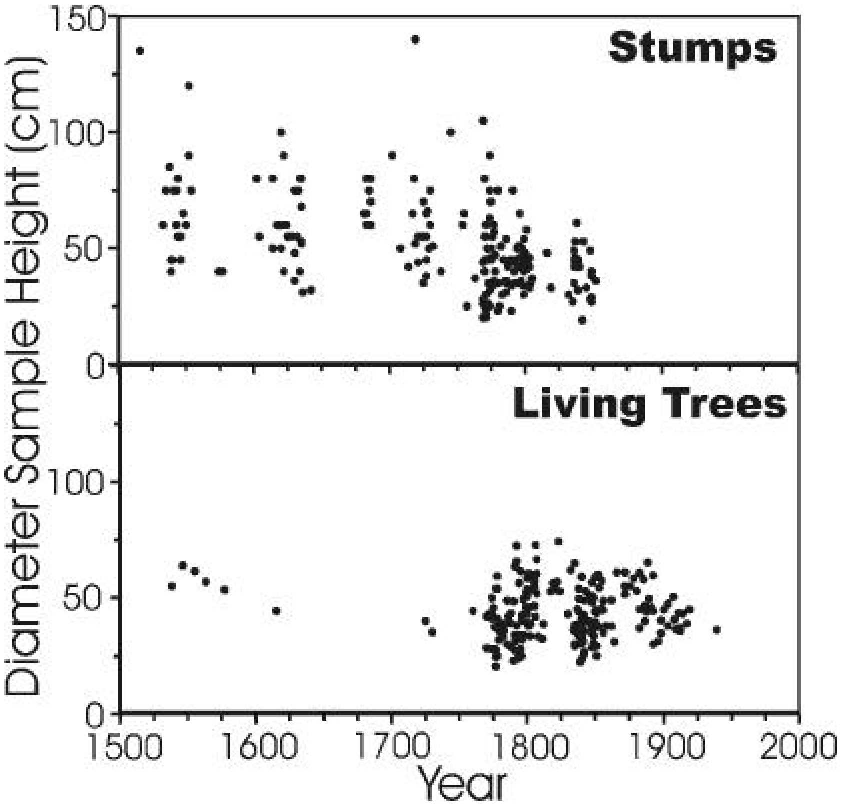

Figure 4.8. Diameters at sample height (10 cm) of stumps and living trees by pith dates. Diameters measured on living trees and estimated on stumps missing bark, sapwood, or heartwood.

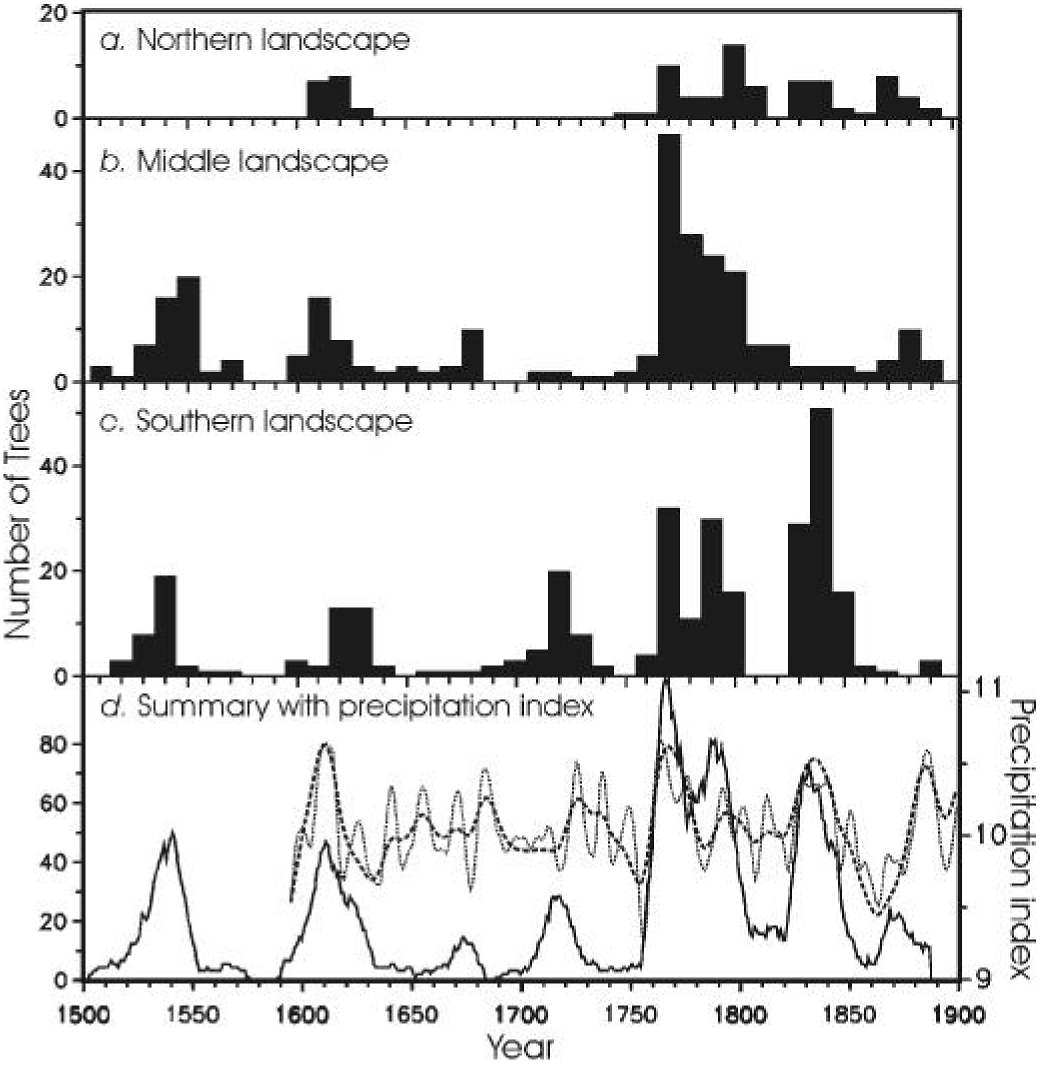

Figure 4.9. Ten-year sums of germination dates (pith dates - 5 years) for all dated trees from: a. northern landscape; b. middle landscape; c. southern landscape. 4.9d. Solid line: 11-yr running sum of annual germination dates from all trees. Dashed line: reconstruction of the 1919-1989 August to July 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.