Landscape Age Structure of Ponderosa Pine Stands, Limestone Plateau, Black Hills National Forest: Final Report

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Introduction

In ponderosa pine (*Pinus ponderosa* Laws.) forests of the western US, multiple historical, observational, and experimental studies have documented an overall ecological paradigm in which episodic, frequent, low-severity surface fires maintained patchy but generally low tree densities in multisized, multiaged forest stands (e.g., Woolsey 1911, Leopold 1924, Weaver 1943, 1951, Cooper 1960, White 1985, Arno 1988, Savage 1991, Mutch et al. 1993, Covington and Moore 1994, Hardy and Arno 1996, Covington et al. 1997, Fenney et al. 1998, Mast et al. 1999, Kaufmann et al. 2000). Surface fires formed, in essence, a density-independent mechanism for population regulation by killing often abundant tree regeneration before it had a chance to reach canopy status. However, this general pattern has been questioned when applied to the ecology of ponderosa pine forests outside of the Southwest where many, but not all, of these previous studies were conducted. Specifically, Shinneman and Baker (1997) have proposed that possibly extensive (5000+ ha) crown fires established continuous, dense stands in ponderosa pine forests of the Black Hills of southwestern South Dakota and northeastern Wyoming. Shinneman and Baker (1997) use historic photographs and descriptions of forest structure to hypothesize that rare, catastrophic fires constituted a "nonequilibrial" disturbance regime that created different forest structure than a regime of surface fires that also was present in this area (Fisher et al. 1987, Brown and Sieg 1996, 1999, Brown et al. 2000).

In this study, I document pre-settlement tree age structure across two approximately 100 km^2 landscapes on the Limestone Plateau in the western Black Hills in an effort to determine occurrence of crown fires in these areas. Evidence for extensive crown fires in the Black Hills relies on descriptions of even-aged forest structure across large areas including much of the Limestone Plateau (Graves 1899, US Forest Service 1948, Shinneman and Baker 1997). I have two goals with the study: 1) to document forest age structure to assess prevalence and extent of even-aged cohorts in stands; and 2) to provide inferences on the probable long-term role of surface fires, crown fires, and climate variability in structuring Black Hills ponderosa pine

forests. These goals are intended to provide ecologists and land managers in the Black Hills with specific, quantitative information on HRV of fire regimes and forest structure of this area. Historical data on forest processes are crucial for characterization of sustainable ecosystem behavior in areas where recent land use has had often profound impacts on forest conditions (Morgan et al. 1994, Committee of Scientists 1999, Landres et al. 1999, Swetnam et al. 1999).

Methods

To examine landscape patterns of tree age structure that may be the result of stand opening by crown fires, I sampled trees from plots in 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 1). Study landscapes varied from 97 to 121 km^2 in size. The Limestone Plateau has been cited often as an area of extensive even-aged forest structure that presumably resulted from past crown fires (Graves 1899, US Forest Service 1948, Shinneman and Baker 1997). Study landscapes were randomly delineated on a precipitation gradient from wet to dry in the northern, central, and southern portions of the Limestone Plateau. However, I was not able to adequately crossdate enough trees from plots in the northern landscape because of complacent tree-ring series (i.e., not enough variability in ring patterns to cross match between trees), and the northern study area has been excluded from further analysis (see further comments in Discussion).

Within each landscape, plot locations were determined using randomly-chosen latitude-minute by longitude-minute GPS coordinates. Plots were excluded if they fell on private land or in meadows. Twelve plots each were sampled in the middle and southern landscapes and thirteen plots in the northern landscape (Table 1). In each plot, the nearest 30 pre-settlement trees within 50 m radius of plot center were selected for aging. Trees sampled included stumps, logs, snags, and living trees that were not “blackjacks”. Ponderosa pine in the Black Hills have exclusively dark bark until ca. 100 years of age and therefore have established post-Euro-American settlement. Since my interest is in reconstructing pre-settlement patterns of forest age structure, blackjacks were not sampled for this study. For age determination, increment cores were removed from approximately10 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 (if possible; on many eroded logs we were not able to determine location of 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.

All cores and cross sections were prepared and crossdated using standard dendrochronological procedures (Brown et al. in press). Sample preparation involved sample stabilization and surfacing with hand planers, belt sanders, and hand sanding until cell structure was visible in tree-ring series. Crossdating involved cross matching of climatically controlled ring characteristics between trees and sites (Stokes and Smiley 1968). Both visual matching of ring characteristics and correlated 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 (Dieterich and Swetnam.

1984). On increment cores or 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. Once crossdating was verified on trees at each site, composite age and fire chronologies were compiled (Dieterich 1980, Brown et al. in press). Composite chronologies also were compared to 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.

Results

In the middle and southern landscapes, I was able to crossdate increment cores and cross sections from 644 trees (from a total of 720 trees sampled) from 24 plots. Of these trees, 611 (309 from the middle and 302 from the southern landscape) had pith or I was able to estimate a pith date for them. Plot chronologies for landscapes are shown in Figures 2 and 3. Details of plot chronologies discussed more fully in Appendix A. Many of the tree-ring samples, especially cross sections removed from stumps, logs, and snags, recorded fire scars, and fire dates in plots are discussed in Appendix A. Outside dates (i.e., not death dates; see caption for Figure 2) on many of the remnant trees occurred at fire scars. The outside edge of heartwood in ponderosa pine trees often forms at fire scars as a result of compartmentilization of the wound area (*sensu* Shigo 1984; Brown et al. in press). 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 3. 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.

Temporal clustering of pith dates is evident both within and between plots (Figure 2 and 3). Pith dates occurring between 1525-1560, 1605-1640, 1770-1805, and 1830-1865 account for over 75% of all pith dates between 1500 and 1900 (see also Figure 4). These four periods comprise 140 years of the total 501 year period (28%). In almost all plots, at least two distinct clusters of pith dates are evident. However, in plots 103, 104, 105, and 106 in the middle landscape (Figure 2) and plot 212 in the southern landscape (Figure 3) most trees form a single cluster of pith dates during 1770-1805 or 1830-1865. In plots 103, 105, and 106, there are one or more trees that established earlier than the clusters of pith dates and date through the 1770-1805 period. Only in plots 104 and 212 are clusters of pith dates not spanned by earlier trees. In plot 104, chronologies from three logs date 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 date before the cluster in the 1830-1865 period.

Clusters of pith dates in plots can be related to wet periods in northern Great Plains precipitation records (Figure 4). Abundant establishment between1770-1805 occurred during the wettest 20 year period in the precipitation record, and followed the worst drought in the record

from 1756 to 1761. The approximately 10- year lag in start of establishment at 1770 and the beginning of the wet period in the early 1760s is the result of the time between tree germination and 10 cm height pith dates in data reported here. Wet periods during the early 1600s, early 1700s, and middle 1800s also correspond with slight lags to clusters of pith dates from plots. Clusters of pith dates also tend to correspond with periods of reduced fire frequency across the middle and southern landscapes (Figure 5 and 6). Many of the fires recorded in plots were also recorded in fire chronologies over the rest of the Black Hills, and periods of reduced fire occurrence in the early 1600s and latter 1700s to early 1800s correspond to similar periods in the regional data (Brown in review).

Finally, tree sizes and pith ages document impacts of past harvest across the two study landscapes (Figure 7). Pre-settlement landscapes were dominated by older and larger trees than those extant on the landscape today. Few living trees older than the 1770–1805 cohort were found on any of the plots sampled. Structural characteristics in the data collected for this study (e.g., density, stocking levels through time and between plots) have not been fully explored as of this time, but will be in a future manuscript.

Discussion

The presence of even-aged cohorts of trees has often been used as evidence of past stand-opening fires (e.g., Henry and Swan 1974, Heinselman 1981, Lorimer 1985, Johnson and Gutsell 1994). This evidence depends on the coincidence of two distinct ecological processes: canopy opening as a result of trees killed during burning and subsequent even-aged establishment of a new generation of trees into those openings (Brown et al. in press). However, in ponderosa pine forests canopy opening may be caused by many environmental factors and even-aged cohorts are often the result of optimal climatic or other environmental conditions for tree establishment that may exhibit little if any dependence on existing overstory conditions (Pearson 1923, 1933, Peet 1981, White 1985, Swetnam and Brown 1992, Savage et al. 1996, Swetnam and Betancourt 1998, Kaufmann et al. 1999, Grissino-Mayer and Swetnam 2000). In this study, age structure documents very pulsed recruitment (Figures 2 and 3) that corresponds temporally to both wet periods in the northern Great Plains (Figure 4) and reduced surface fire frequency across study landscapes (Figures 5 and 6). Extended wet conditions likely promoted abundant tree regeneration and fast growth and longer periods between surface fires would have permitted more trees to reach canopy status, therefore becoming more “fireproof” during later surface fires. Abundant tree establishment in many southwestern ponderosa pine forests during the early 1800s also is related to both wet conditions and a period of reduced fires in this region (Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000).

The first crown fire cited is thought to have occurred around 1730 to 1740. This date is based on ring counts to fire scars on stumps and ages of trees assumed to have established after the fire (Graves 1899). Pith ages from plots in the southern landscape show a distinct pulse of establishment between 1730 and 1745 (Figure 4) that occurred in several plots (205, 206, 207, 209, and 213; Figure 3). This cohort likely matches that cited as evidence of crown fire at about this time by Graves and others. However, other environmental factors may account for the presence of this cohort across the Black Hills landscape. Establishment of trees during the early 1700s corresponded to a period of high precipitation in the Northern Great Plains and followed a period of low precipitation from 1712 to 1720 (Figure 4a). Surface fire history of the entire

Black Hills generally shows an absence of fires from ca. 1725 to 1750, with only one landscape fire (recorded at 50% of 20 locations) in 1743 (Brown in review). Several individual stands also recorded the longest intervals between fires in the early 1700s (Brown and Sieg 1996, 1999, Brown in review), and a prominent gap in fires is evident in fire-scar data from plots in the southern landscape (Figure 6). In plots 205, 207, 208, and 213, trees predate the 1730-1745 cohort and suggest that if crown fire occurred, there was not complete crown mortality within the bounds of individual plots (i.e., within >50 m radius of plot centers). In plots 206 and 209, no trees predate this cohort (Figure 3a), which may indicate canopy opening by crown fire, although other factors also may have resulted in a previously unforested stand into which these trees established. For example, drought stress during the 1712 to 1720 period of low precipitation may have led to tree mortality in the stand. Also, mountain pine beetle (*Dendroctonus ponderosae* Hopk.) has been a major cause of extensive tree mortality in the Black Hills during the twentieth century (e.g., Thilenius 1971, Hoffman and Alexander 1987) and there is no reason to suspect such was not the case in the past. While I have no evidence these other factors led to stand opening in this plot prior to early 1700s cohort, neither is there definitive evidence that crown fire was the cause.

The next extensive fire referenced in historic records presumably occurred sometime around 1790 to 1800, again based on evidence from fire scars and large numbers of trees that established at that time (Graves 1899, US Forest Service 1948, Shinneman and Baker 1997). Age data from this study confirm that large numbers of trees established during the latter 1700s (Figures 4b and 4c). However, this cohort also corresponded to the wettest 20-year period in the northern Great Plains since the late fourteenth century (Figure 4a), and it is probable that persistent high annual precipitation led to widespread tree establishment. Regional impacts of the 1770-1805 wet period on tree demography in the northern Great Plains is supported by the presence of abundant establishment during this same period in ponderosa pine forests of the southern Bighorn Mountains, located in northern Wyoming approximately 240 km W of the Black Hills (unpublished data). Abundant tree establishment during the latter 1700s also followed a major drought in the Black Hills region from 1756 to 1761 (Figure 4a). Tree establishment in plots may have been enhanced as a result of stand opening from mortality of trees caused by moisture stress during the drought.

The most widespread fire date recorded in fire chronologies across the Black Hills was 1785 (Brown in review; see also data presented in Appendix A), and undoubtedly this is the correct date for the historically referenced event around 1790 (Graves 1899). Trees in almost all plots established before 1785 and, therefore, cannot be the result of stand opening caused by crown fire during 1785 (Figures 2 and 3). Spatial extent of fire during 1785 likely was promoted by increased seedling density across the Black Hills landscape, especially when coupled with increased fine fuels that probably resulted from wet conditions and a lack of surface fires in most sites after the 1756-61 drought (Figures 5 and 6). In many sites, fire in 1785 was followed by a period without any fire until the next widespread fire in 1822 (Brown in review; Appendix A). In several sites, the 37 year-long fire-free period after 1785 is the longest in the pre-settlement record (Brown in review). The period from 1785 to 1822 was also a period of few fires across the entire Black Hills (Brown in review). Again, lack of surface fires would have allowed more trees in plots to reach canopy status.

It is possible that very dry conditions during the 1756-61 drought resulted in more intense

fire behavior, including crown fires, in some plots. In plots 103, 104, 105, 106, 109, and 111 from the middle landscape (Figure 2) and plots 208 and 210 in the southern landscape (Figure 3b), the 1770-1805 cohort forms the bulk of tree age structure in each plot. However, in all but plot 104 trees date through the 1770-1805 cohort, again suggesting that if crown fire occurred during the drought it did not cause complete overstory mortality within plot boundaries. No unusual growth responses were noted on any trees dating through the middle 1700s period that might suggest either severe crown scorch or an abrupt release from competition if neighboring trees were killed (*sensu* Lorimer 1985). Only plot 104 contained remnant trees that do not overlap in time with the cohort. Death dates of trees killed by burning is one means to confirm crown fire behavior in forests (Brown et al. 1999, Brown et al. in press). However, the three remnant trees from plot 104 exhibited heavy erosion and burning on outer surfaces, and it is possible these trees did not die before cohort establishment in the late 1700s. I cannot confirm that crown fire occurred in this plot using available tree-ring data.

The last extensive crown fire cited for the Black Hills is thought to have occurred in the early 1800s, possibly around 1842 (Graves 1899, US Forest Service 1948, Shinneman and Baker 1997). Fire scars were recorded in many sites in 1845 (Brown in review; Appendix A). Age structure in several plots (104, 204, 206, 207, 209, 212, and 213; Figures 2 and 3) shows a cohort at this date. This cohort corresponds, again, to an extended wet period in the northern Plains precipitation reconstruction (Figure 4). In only one plot, 212, is this cohort not preceded by other trees in the stand. However, I was not able to crossdate 12 remnant trees from plot 212, and it is likely that many if not all of these trees would have predated the middle 1800s cohort, suggesting, once again, that if crown fire occurred it was not complete canopy kill within the plot boundaries.

A similar inability to crossdate most trees from most plots in the northern landscape (Table 1) also led me to exclude these plots from analysis of forest age structure. Most living trees that I was able to crossdate from this landscape dated to the latter 1700s cohort. However, I was not able to crossdate most remnant trees and these likely would have predated the cohort, suggesting again that canopy mortality was not complete within plot boundaries. If one were to use only living trees for determination of pre-settlement age structure in most areas, one would find even-aged structure that is the result of past harvest, not crown fire removing all older trees from the stand (Figure 7).

Summary and Management Implications

Episodic surface fires as reconstructed from fire scars occurred at all sites and plots sampled in the Black Hills (Figures 5 and 6; Brown and Sieg 1996, 1999, Brown et al. 2000, Brown in review). Sites and plots were collected using both directed and random methods and they occur over a large portion of the Black Hills ponderosa pine forest (Figure 1). The ubiquity of fire-scar records documents that surface fire was a major form of disturbance for the past several centuries before Euro-American settlement in the late nineteenth century.

Surface fires in Black Hills forests established similar stand and forest structural characteristics as those documented in ponderosa pine forests of the Southwest (e.g., White 1985, Savage, 1991, Covington and Moore 1994, Fulé et al. 1997), Sierra Nevada, (e.g., Weaver 1943), and northern Rocky Mountains (e.g., Arno 1988, Kaufmann et al. 2000; Figures 2 and 3). In contrast to crown fires, some ecologists have considered surface fires to be ecologically “benign”

disturbances in forests (Johnson and Gutsell 1994, Shinneman and Baker 1997). Crown fires cause extensive tree mortality over large areas that, in some forest types, result in even-aged, often dense, post-fire tree establishment (e.g., Heinselman 1981, Johnson and Gutsell 1994). In contrast, during most surface fires, overstory trees are rarely effected and forest age structure and density change little. However, it is the combination of multiple surface fires over time that creates dissimilar, but no less ecologically important (Cooper 1960, Weaver 1985, Savage 1991, Covington and Moore 1994, Kaufmann et al. 2000), structural characteristics than those created by crown fires (*sensu* Holling 1992). Surface fires kill a majority of understory tree regeneration before it has a chance to reach canopy status. Surface fires also cause episodic mortality of patches of overstory trees in locations where more intense burning occurs. Other disturbances (e.g., insects and other pathogens, windthrow) and climate variability (e.g., drought) contribute to heterogeneity in forest structure by also killing trees at other spatial and temporal scales. Thus, overstory tree establishment and mortality occur over longer time spans and across a greater range of spatial scales than that resulting from most crown fires (Kaufmann et al. 2000; Figures 2 and 3).

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, Committee of Scientists 1999). As in any ecological inquiry, spatial and temporal scales of applicability of data must be established before their use in management decisions. 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. In the Black Hills, surface fire frequency was less than ponderosa pine sites in the Southwest (unpublished manuscript). Less frequent fire than in the Southwest likely was the result of shorter growing seasons in these more northern stands, and climate gradients that occur with latitude exhibit strong control on fire frequency, fire seasonality, and synoptic-scale fire/climate relationships (unpublished manuscript). Longer intervals between fires in the Black Hills likely permitted greater fuel buildup and possibly more severe fire behavior than in ponderosa pine forests of the Southwest. The only well-documented historically extensive crown fire in a ponderosa pine forest has been found in central Colorado (Brown et al. 1999). This fire occurred in 1851 and followed a 128-year long period during which few other fires were recorded across the landscape (Brown et al. 1999). In Black Hills forests, it is possible that canopy mortality during surface fires occurred more frequently and over larger areas than in the Southwest. However, this study found no evidence to document that crown fires effected forest structure over large areas, and even-aged forest structure that has been cited as evidence of crown fires can be related to other historical processes. Hypothetical occurrences of crown fires, therefore, should not be considered as part of the historical range of variability in fire regimes in Black Hills ponderosa pine forest until other quantitative data exist to prove otherwise.

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Table 1. Plots collected for forest age structure, Limestone Plateau, Black Hills.

plot no.	latitude (deg. N)	longitude (deg. E)	elevation (m)	aspect	slope (%)
Northern Landscape					
1	44° 13'	104° 04'	1925-28	SW	5-12
2	44° 13'	104° 03'	1965	NW	8
12	44° 14'	104° 00'	2048	ENE	11
14	44° 14'	103° 58'	1972	E	5
33	44° 16'	103° 59'	2000	SE/S	3
36	44° 16'	103° 56'	1920-26	S/SW	20
59	44° 18'	103° 58'	1875-1878	NW	7
60	44° 18'	103° 57'	1892	S	2
63	44° 18'	103° 54'	1815	SW	9
64	44° 18'	103° 53'	1845-48	NNW	15
68	44° 19'	103° 59'	1878-82	NNW	16
72	44° 19'	103° 55'	1829-40	E	22
73	44° 19'	103° 54'	1798-1810	ENE	23
Middle Landscape					
101	43° 56'	103° 54'	1999-2005	SW	9
103	43° 54'	103° 54'	1923-1930	W	20
104	43° 54'	103° 51'	2011-2014	E	15
105	43° 55'	103° 54'	1951-1957	SW	8
106	43° 53'	103° 55'	1871-1880	W	6
108	43° 56'	103° 58'	1926	S	2
109	43° 56'	103° 57'	1978	SE	4
110	43° 55'	103° 57'	1899-1914	SW	23
111	43° 53'	103° 56'	1911-1914	SW	5
112	43° 55'	103° 51'	2048	NE	4
113	43° 54'	102° 57'	1850-1858	W	25
114	43° 53'	103° 52'	1959-1966	N	15
Southern Landscape:					
201	43° 42'	103° 50'	1548-1567	NW	29
202	43° 42'	103° 48'	1668-1676	NE	15
203	43° 44'	103° 51'	1679-1698	SSW	25
204	43° 44'	103° 48'	1736-1737	S	3
205	43° 45'	103° 50'	1761-1766	SE	8
206	43° 45'	103° 46'	1762-1780	NE	50
207	43° 46'	103° 51'	1780-1788	NE	15
208	43° 46'	103° 47'	1900	SSW	2
209	43° 47'	103° 49'	1884	E	2
210	43° 48'	103° 52'	1830-1834	E	5
212	43° 49'	103° 51'	1914-1917	NE	5
213	43° 45'	103° 48'	1856-1862	S	12

Figure 1. Locations of sites collected for development of fire chronologies and age structure in the Black Hills. Numbers refer to sites collected for fire history only. Landscapes are areas sampled for forest age structure.

Figure 2. Chronologies of individual trees in plots sampled for forest age structure in the middle landscape (Figure 1). 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. Shaded areas mark clusters of pith dates between 1525-1560, 1605-1640, 1770-1805, and 1830-1865.

Figure 3. Chronologies of individual trees in plots sampled for forest age structure in the southern landscape (Figure 1). See caption for Figure 2 for explanation.

Figure 4. a. Tree-ring based reconstruction of 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). Heavy line is 10-yr smoothed series to emphasize low-frequency patterns in the reconstruction. **b.** Annual sums of pith dates on trees in the middle landscape. **c.** Annual sums of pith dates on trees in the southern landscape. Shaded areas mark wet periods in the precipitation reconstruction.

Figure 5. a. Annual sums of pith dates on trees in the middle landscape. **b.** Summary fire chronology for the middle landscape. Dashed line is the number of sites per year in the chronology (left axis), and histograms are percentages of trees that recorded a fire scar for individual years (right axis). **c.** Composite fire chronologies for 12 plots from the middle landscape. Horizontal lines are time spans of chronologies with inverted triangles at dates of fire events. Shaded areas mark groups of pith dates.

Figure 6. a. Annual sums of pith dates on trees in the southern landscape. **b.** Summary fire chronology for the southern landscape. Dashed line is the number of sites per year in the chronology (left axis), and histograms are percentages of trees that recorded a fire scar for individual years (right axis). **c.** Composite fire chronologies for 12 plots from the southern landscape. Horizontal lines are time spans of chronologies with inverted triangles at dates of fire events. Shaded areas mark groups of pith dates.

Figure 7. Diameters at sample height (10 cm) of stumps and living trees according to pith dates. Diameters measured on living trees and estimated on stumps missing bark, sapwood, or heartwood.