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Fire history, related to climate and land use in three southern Appalachian landscapes in the eastern United States

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Abstract. Fire-maintained ecosystems and associated species are becoming increasingly rare in the southern Appalachian Mountains because of fire suppression policies implemented in the early 20th century. Restoration of these communities through prescribed fire has been hindered by a lack of information on historical fire regimes. To characterize past fire regimes, we collected and absolutely dated the tree rings on cross sections from 242 fire-scarred trees at three different sites in the southern Appalachian Mountains of Tennessee and North Carolina. Our objectives were to (1) characterize the historical frequency of fire in southern Appalachian mixed pine–oak forests, (2) assess the impact of interannual climatic variability on the historical occurrence of fire, and (3) determine whether changes in human culture and land use altered the frequency of fire. Results demonstrate that fires burned frequently at all three sites for at least two centuries prior to the implementation of fire suppression and prevention in the early to mid 20th century. Composite mean fire return intervals were 2–4 yr, and point mean fire return intervals were 9–13 yr. Area-wide fires that burned across multiple stands occurred at 6–13-yr intervals. The majority of fires were recorded during the dormant season. Fire occurrence exhibited little relationship with reconstructed annual drought conditions. Also, fire activity did not change markedly during the transition from Native American to Euro-American settlement or during the period of industrial logging at the start of the 20th century. Fire activity declined significantly, however, during the fire suppression period, with a nearly complete absence of fire during recent decades. The characterization of past fire regimes should provide managers with specific targets for restoration of fire-associated communities in the southern Appalachian Mountains. The fire chronologies reported here are among the longest tree-ring reconstructions of fire history compiled for the eastern United States and support the hypothesis that frequent burning has played a long and important role in the development of forests in the southern Appalachian Mountains.

Key words: Cherokees; dendroecology; fire disturbance; fire–oak hypothesis; fire suppression; Great Smoky Mountains National Park; Pinus pungens; *pre-settlement; superposed epoch analysis.*

INTRODUCTION

Fire has influenced vegetation development throughout much of eastern North America's temperate forest region (Abrams 1992, Lorimer 2001). Oak- (*Quercus* L.) and pine- (*Pinus* L.) dominated forests, for example, which cover vast portions of the region, thrive when burned frequently (Brose and Waldrop 2006, Hutchinson et al. 2008). Fires also reduce tree density and maintain an open understory (Harrod et al. 2000, Signell et al. 2005). Forests in this region have remained largely unburned for decades, though, because of fire suppression efforts initiated in the early 20th century. Today, fire-associated species are failing to regenerate and are declining in abundance throughout eastern North America (Lorimer 1984, Nowacki and Abrams 1992, Harrod et al. 2000, McEwan and Muller 2006, Fei et al. 2011) and in other temperate forest regions, including northern and central Europe (Niklasson et al. 2002, 2010). Species composition has shifted toward mesophytic trees such as maple (*Acer* L.) and beech (*Fagus* L.), eroding biodiversity and reducing habitat quality for many wildlife species. Nowacki and Abrams (2008) termed this change "mesophication." They argued that the rather incombustible litter of mesophytic plants will diminish burning further and hasten the loss of pyrogenic vegetation.

Many researchers and resource managers advocate an increase in prescribed burning to restore fire regimes similar to those under which eastern North America's vegetation developed (Brose et al. 2001, Nowacki and Abrams 2008). Once used primarily in the subtropical pinelands of the southeastern U.S. coastal plains, management-controlled burning has emerged as an important tool for many North American ecosystems, including temperate forests, as vegetation shifts have grown more apparent (Pyne 1982).

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Restoring fire implies a need to establish historical reference conditions (Fulé et al. 1997, Swetnam et al. 1999, Taylor 2004). Usually, however, managers do not wish to target the fire regime that prevailed immediately before the fire exclusion era because the late 19th and early 20th centuries witnessed extensive burning that may not have typified earlier fire regimes. From about 1880 until 1930, timber and mining companies built railways deep into the wildlands of the eastern United States (Pyne 1982, Lafon 2010). They cut the forests and left behind logging debris that dried and then burned. The U.S. Forest Service, National Park Service, and state conservation agencies, concerned that the forests would not regenerate, launched fire suppression efforts to promote reforestation. The stands that developed during that period have matured. They cover much of the region today, and still bear imprints of the fires and other disturbances under which they established in their structure and species composition.

Of greater interest is the fire regime that prevailed prior to 1880. Aboriginal peoples cleared forests for settlements and agricultural fields, which likely affected larger areas through fire (Sauer 1950, Rostlund 1957), a topic that has captivated many scholars and engendered considerable debate (e.g., Russell 1983, Denevan 1992, Clark 1997, Vale 1998, Abrams and Nowacki 2008). Frontiersmen and settlers apparently adopted aboriginal burning practices (Prunty 1965, Pyne 1982, Brose et al. 2001), especially in the South, where they burned to maintain an open forest understory conducive to hunting and livestock herding. The frequency and extent of past burning remain uncertain, however. Fire may have been uncommon except near aboriginal, and later, Euro-American settlements, gradually expanding as populations grew, before emerging as a widespread and devastating force during the industrial logging period (Williams 1998, Hessl et al. 2011). Alternatively, widespread burning may have occurred frequently over much of the landscape for a long time, even before Euro-American settlement, promoting extensive oak and pine forests as well as patches of grassland (Pyne 1982, Denevan 1992). The "fire–oak hypothesis" (Lorimer et al. 1984, Abrams 1992, 2001, Brose et al. 2001), for example, proposes that many oak forests developed under centuries of frequent burning that impeded their mesophytic competitors.

Paleoecological data can elucidate past fire regimes. Charcoal fragments recovered from pond and bog sediments and from soils reveal evidence of burning over the last several millennia in several parts of eastern North America (Clark and Royall 1996, Delcourt and Delcourt 1998, Parshall and Foster 2002, Fesenmyer and Christensen 2010), but charcoal does not afford the annual resolution necessary to quantify fire frequency. Dendroecological reconstructions from fire-scarred trees, however, provide such records, albeit shorter than those based on charcoal. Unfortunately, forest clearance and decay have obliterated much of the wood necessary for establishing dendroecological records in eastern U.S. forests. As a result, dendroecological fire history research has been limited primarily to the less disturbed landscapes of the western United States. Some remnants of unlogged or minimally disturbed forests remain in the eastern United States, however, and they preserve important information about disturbance regimes in the region. For the present study we collected cross sections from living and dead fire-scarred trees in the southern Appalachian Mountains to reconstruct the longest possible history of fire at three sites in the region.

One of the earliest dendroecological studies of fire history was conducted in the southern Appalachian Mountains. Harmon (1982) discovered fire-scarred trees in Great Smoky Mountains National Park and documented frequent burning, at approximately a 10-year interval, between 1856 and 1940. No further work or longer chronologies have been published for the southern Appalachian region. However, recent studies conducted in the drier, cooler central Appalachian Mountains of Virginia and Maryland portray a record of frequent fire back to the 1600s and 1700s (Shumway et al. 2001, DeWeese 2007, Aldrich et al. 2010). Researchers have also found old fire-scarred trees in the Ozark-Ouachita Highlands near the western edge of the eastern forest region (Cutter and Guyette 1994, Guyette et al. 2002, 2006, Guyette and Spetich 2003), and in the northern Appalachian Mountains of Vermont (Mann et al. 1994). One important difference between the southern Appalachian region and many other parts of the eastern United States is that substantial Cherokee populations remained through the early 1800s. Therefore, fire history from this region offers a glimpse of anthropogenic influences on fire during the pre-Euro-American settlement period. In the central Appalachian Mountains and elsewhere, native depopulation had occurred up to a century or more ahead of Euro-American settlement, potentially diminishing the incidence of fire for a time (Aldrich et al. 2010, McEwan et al. 2011).

Dendroecological fire history reconstructions can also reveal how fires responded to interannual climatic variations (e.g., Grissino-Mayer and Swetnam 2000, Trouet et al. 2009). The humid environments of the eastern United States permit copious fuel production every year, but the fuel often remains too moist to burn. Drought may have been particularly important under such conditions, but most eastern fire history studies do not include climatic analyses. Schuler and McClain (2003) and McEwan et al. (2007) found little influence of climate on fire occurrence; however, their fire chronologies were limited to the late 1800s and early 1900s, when anthropogenic burning was so widespread that it may have obscured the role of climate.

Characterizing the fire regime that prevailed during forest development in the southern Appalachian Mountains will inform forest management within this region of extensive public lands. It will also illuminate the

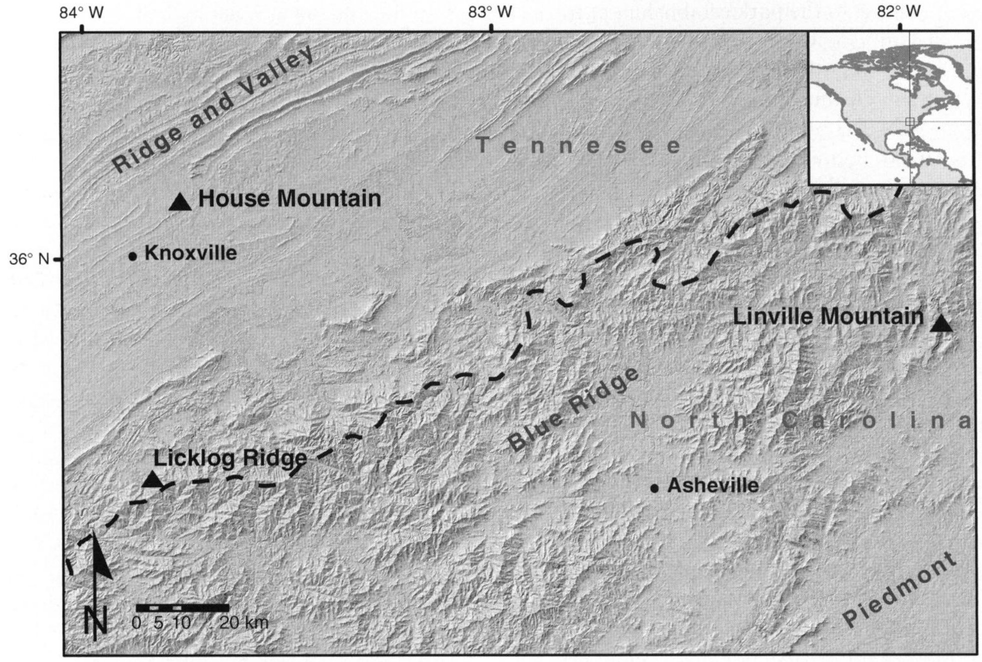

FIG. 1. Location of fire history reconstruction sites in Tennessee and North Carolina, USA.

historic role of fire on temperate forest landscapes more generally, including how land use history and climatic variability affected fire occurrence. Therefore our goal was to answer the following research questions:

1) How frequently did fires occur in the yellow pine stands that occupy ridge tops and dry slopes in the southern Appalachian Mountains during the last three centuries?
2) How did interannual moisture variability influence the occurrence of fire in these stands?
3) Did cultural changes and land use intensification alter fire regimes?

METHODS

Study sites

We reconstructed fire history at three sites in the southern Appalachian Mountains of Tennessee and North Carolina (Fig. 1). The southern Appalachian region has a humid continental climate with cold winters and warm summers (Shanks 1954 and Fig. 2). The vegetation is classified as Appalachian oak, with oak-dominated forests covering the broad submesic to subxeric portions of the landscape (Stephens et al. 1993). Patches of yellow pine (*Pinus*, subgenus *Diploxylon* Koehne) occupy dry ridge tops and south-facing slopes within the oak forest matrix, while mesophytic conifers and hardwoods inhabit the lower slopes, valleys, ravines, and high elevations.

The House Mountain site (36°6′ N, 83°46′ W, elevation 520–610 m) is located within the House Mountain State Recreation Area, Knox County, Tennessee, in the Ridge and Valley Physiographic Province (Fig. 3). Annual precipitation averages 1170 mm at 338 m elevation in Jefferson City, Tennessee, 26 km east of House Mountain, and mean monthly temperatures range between 1.5°C and 24.6°C (NCDC 2002). The Cherokee people inhabited the area before Euro-American settlement (Gragson and Bolstad 2007), which began along the Holston River in 1785 (Rothrock 1946). Today, forests dominated by oaks, hickories (*Carya* Nutt.), and pines cover House Mountain. An agricultural landscape surrounds the mountain. We collected fire-scarred cross sections from three pine stands on the ridge top and upper slopes of the mountain. The pine stands contained Virginia pine (*P. virginiana* Mill.), Table Mountain pine (*Pinus pungens* Lamb.), and shortleaf pine (*P. echinata* Mill.), covering a total of 3 ha within a matrix of oak–hickory forest. Virginia pine was more abundant at House Mountain than at the other sites.

The Licklog Ridge site (35°33′ N, 83°50′ W, elevation 700–900 m) is located in Great Smoky Mountains National Park, Tennessee, on the western side of the Blue Ridge Physiographic Province. Average annual precipitation is 1480 mm at 443 m elevation in Gatlinburg, Tennessee, 29 km northeast of Licklog Ridge (NCDC 2002). Mean monthly temperatures range between 2.4°C and 22.9°C. Cherokees occupied the area during the 18th century (Burns 1957, Shields 1977). They may have farmed Cades Cove, a valley 3 km north of Licklog Ridge, and they likely used fire to maintain open vegetation in the valley. Euro-Americans began to settle Cades Cove in the 1820s (Shields 1977, Dunn 1988). The population of the community had reached about 540 people prior to the park establishment in 1934 (Shields 1977). Many of the forests around the valley were cut, but those on the Licklog Ridge study site suffered little if any cutting (Pyle 1988). The stands we examined are dominated by yellow pines. The three pine stands we sampled contained Table Mountain pine, pitch pine (*P. rigida* Mill.), shortleaf pine, and Virginia pine. They occupy south- and southeast-facing spurs of Licklog Ridge and cover a total of 28 ha. The surrounding forest consists of oak–hickory, white pine, and cove hardwood–hemlock stands.

The Linville Mountain site (35°55′ N, 81°55′ W, elevation 970–1115 m) is located in the Grandfather Ranger District, Pisgah National Forest, Burke County, North Carolina, along the eastern escarpment of the Blue Ridge Physiographic Province. Average annual precipitation totals 1494 mm, and mean monthly temperatures vary between 1.1°C and 21.1°C in Celo, North Carolina, 26 km west of Linville Mountain at an elevation of 817 m (NCDC 2002). The Cherokee and Catawba people hunted in the area during the early 18th century (Phifer 1979), but the study site was remote from their settlements. Euro-American settlement began within Burke County in 1763. Land records housed at the Grandfather Ranger District Office indicate that the initial land grants for the valley below the fire history site were made in the 1770s, while the land grant at the site itself was issued in 1831. The lower and middle slopes of Linville Mountain likely were logged in the early 20th century, indicated by old logging roads and parcel ownership by the Linville Lumber Company. However, the presence of many old pines on the upper slopes of the mountain indicates that the pine stands themselves were not logged. Ownership of the tract was transferred to the Pisgah National Forest in 1939. The sampled forests contained Table Mountain pine, pitch pine, shortleaf pine, and Virginia pine. The surrounding forests are oak–pine–hardwood, white pine, and cove hardwood–hemlock. The two pine stands occupy west-facing spurs of Linville Mountain and cover a total of 6 ha.

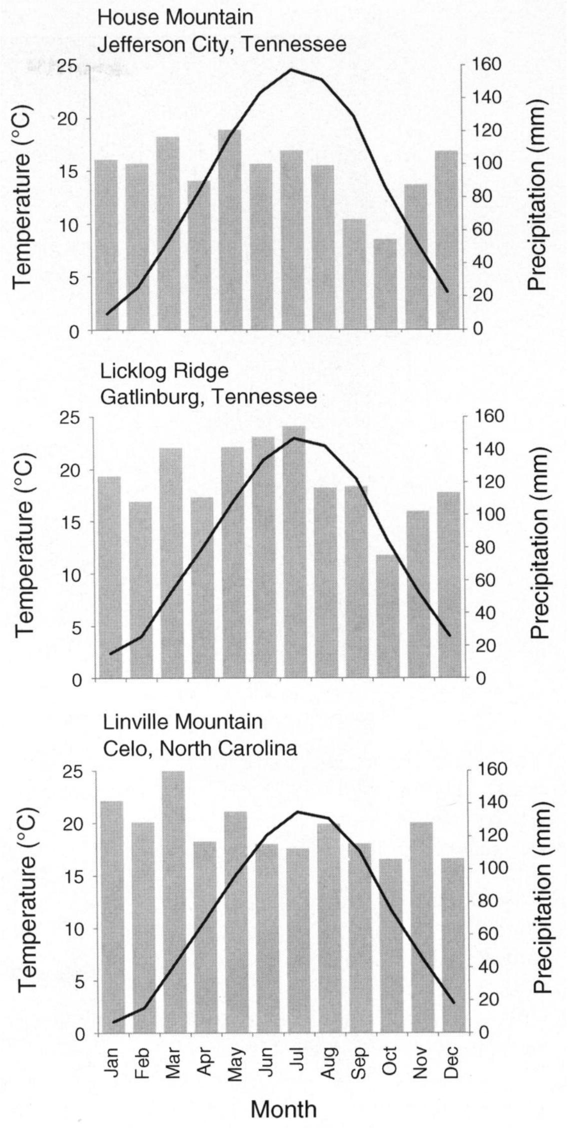

FIG. 2. Mean monthly climate averages for weather stations located near fire-history-reconstruction sites. Bars show precipitation, and lines show temperature.

Data collection and analysis

During 2008 and 2009, we used chain saws to collect partial cross sections from living and dead pines with basal fire scars (Arno and Sneck 1977). Each of the study sites was searched intensively and all available wood with multiple visible scars was collected. Differences in sample sizes among the sites reflect differences in the size of the pine stands and the density of fire-scarred trees within the stands. In the laboratory, cross sections were sanded with progressively finer sandpaper (Orvis and Grissino-Mayer 2002) to reveal tree rings and fire scars. The following dating procedures were carried out separately for each of the three collection sites. Cross sections collected from living trees were visually cross-dated using skeleton plots (Stokes and Smiley 1996) and measured to the nearest 0.001 mm with a Velmex measuring stage (Velmex, Bloomfield, New York, USA). Statistical cross-dating was accomplished using COFECHA to confirm that all tree rings had been assigned their correct calendar year (Holmes 1983, Grissino-Mayer 2001*a*). A master chronology was then constructed from the successfully dated live cross sections. Remnant wood was statistically cross-dated against the master chronology using 40-year segments (with 20 years overlapping [Aldrich et al. 2010]). Segments that could not be successfully cross-dated were removed from analysis. We used the dated tree rings to assign a precise calendar year to all fire scars, and we designated seasonality according to scar position within the annual ring: earlywood, latewood, or

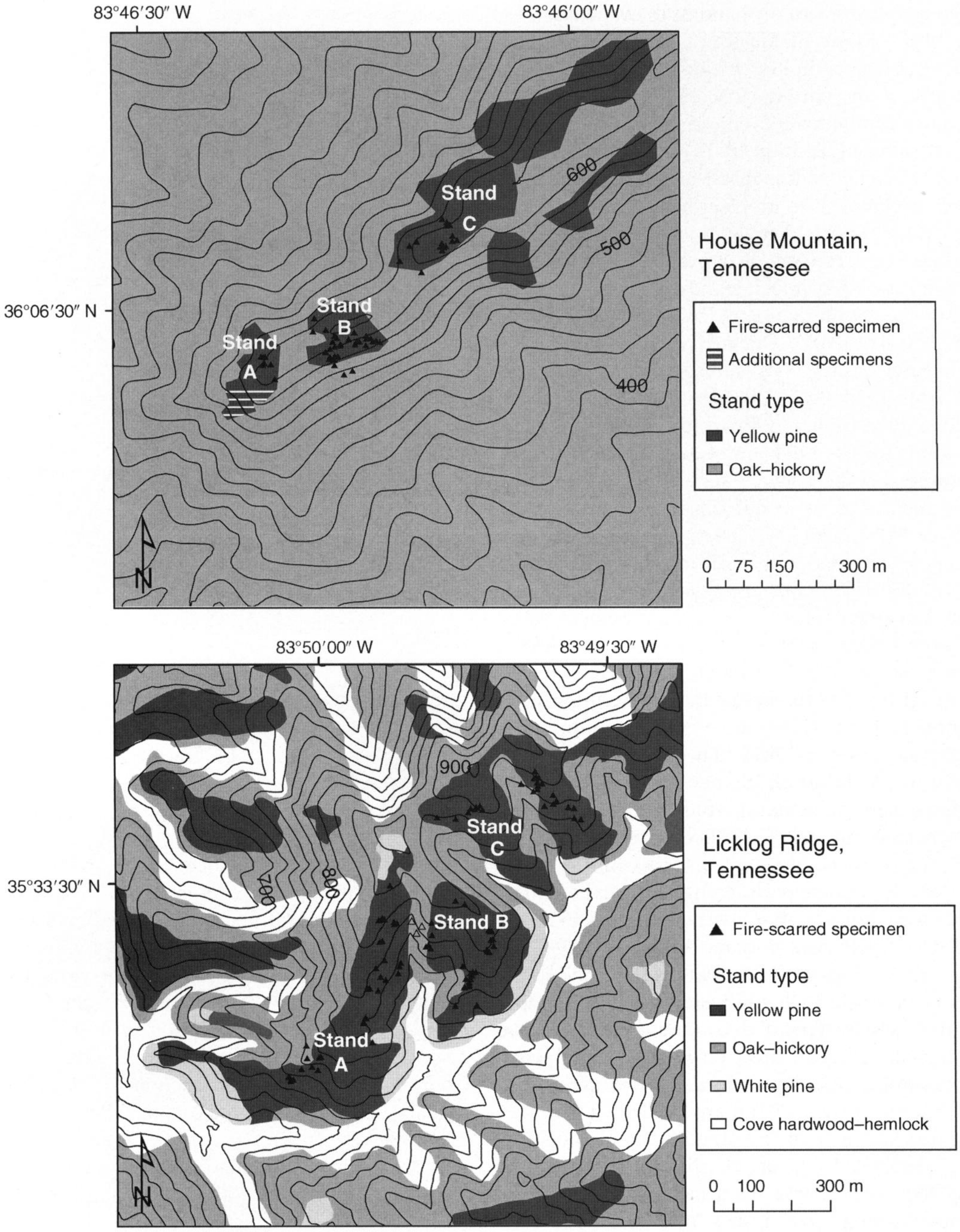

FIG. 3. Study area maps for fire-history reconstruction sites illustrating fire-scarred specimen locations and stand types: House Mountain, Tennessee; Licklog Ridge, Tennessee; and Linville Mountain, North Carolina (on following page). The hatching pattern at House Mountain represents the area where fire-scarred specimens were collected but not georeferenced. Open triangles at Licklog Ridge (west of stand B) indicate fire-scarred specimens that were collected in an intervening oak stand.

dormant (Dieterich and Swetnam 1984, Baisan and Swetnam 1990, Aldrich et al. 2010). Dormant-season scars were assigned the date of the ring formed after the scar, reflecting the fact that more burning occurs during the spring portion of the dormant season than the fall portion across the southern Appalachian Mountains (Barden and Woods 1974). We were able to determine the seasonality of 75.7% of the scars.

We used the FHX2 software package to archive, graph, and analyze fire intervals (Grissino-Mayer 2001*b*). We analyzed fire intervals within the period of reliability, defined for this study as the period following the first fire recorded by at least two trees at a site and preceding the start of the fire suppression era in 1920 (Grissino-Mayer et al. 2004). We excluded the fire suppression period from the fire interval calculations

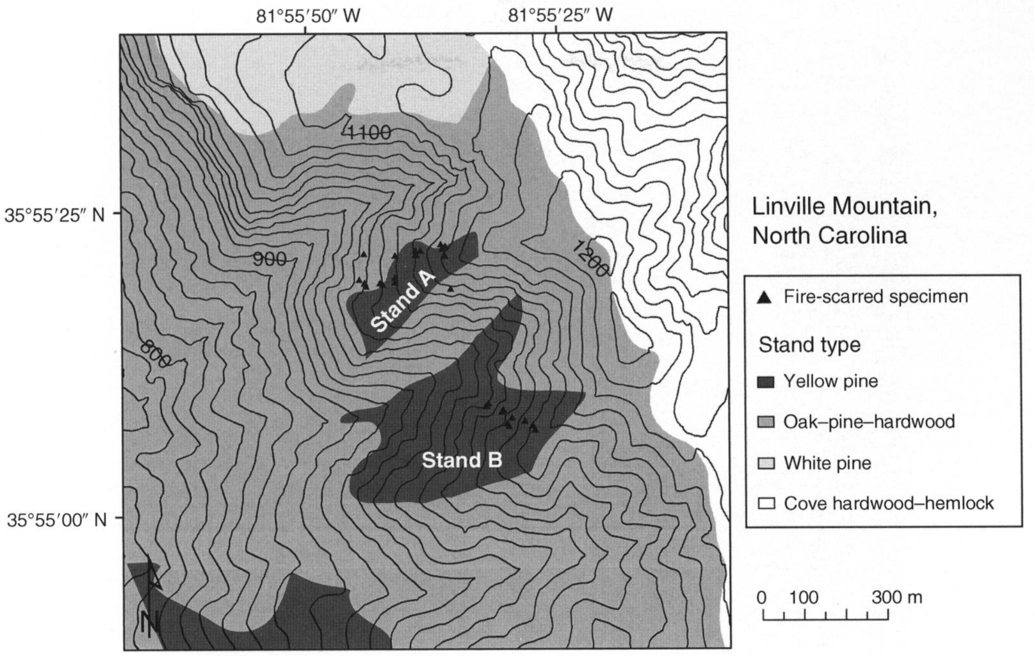

FIG. 3. Continued.

because of our interest in characterizing presuppression fire regimes.

Trees do not record all fires that occur in their area, because fires do not scar all the trees they burn, nor do all fires burn across the entire study area (Baker and Ehle 2001, Van Horne and Fulé 2006). To capture a full range of fire frequency estimates to account for fire records that differ across different spatial scales, we calculated five different fire intervals (Aldrich et al. 2010): point fire interval, composite fire interval, 25% filter composite fire interval, area-wide fire interval, and regional fire interval. Each study site included multiple distinct pine stands separated by minor drainages or intervening oak forest (three pine stands at House Mountain, three at Licklog Ridge, and two at Linville Mountain). For a given site, an area-wide fire year was one with fires recorded in all stands that contained a recording tree (Aldrich et al. 2010). A tree was considered a recording tree for a particular year if the corresponding ring was intact and the tree had previously been scarred (Grissino-Mayer et al. 2004). If a fire occurred during a year with only one stand recording, the year was not considered an area-wide fire year. At Licklog Ridge, three fire-scarred pine cross sections were collected in the oak stand between pine stands A and B. Since these specimens were roughly equidistant between the two pine stands, we removed them from the area-wide interval calculations but retained them for all other fire interval calculations. Regional fire years were those with a fire recorded at all three study sites. For each type of fire interval, we used FHX2 to calculate mean fire interval, Weibull median fire interval, standard deviation, lower exceedance interval, and upper exceedance interval (Grissino-Mayer 1999, 2001*b*). The exceedance intervals describe the range of variability in the fire intervals, as modeled by the Weibull distribution (i.e., 75% of the fire intervals are expected to fall between the two exceedance levels and demarcate statistically long and short fire intervals).

We performed superposed epoch analysis (SEA) to assess the influence of interannual moisture variability in years that preceded fire occurrence to better understand specific climate drivers of wildfire activity. SEA compared climate conditions during fire years to climate conditions that preceded fire years (Swetnam and Baisan 1996, Hessl et al. 2004, Allen and Palmer 2011). We obtained the estimated moisture conditions from the Cook et al. (1999) reconstruction of Palmer Drought Severity Index (PDSI), gridpoint 238. SEA was conducted separately on the composite fire record, filtered composite fire record, and area-wide fire record from each site. SEA was also conducted for regional fires recorded at all sites.

To assess the influence of changing land use on fire frequency, we divided the fire history record into four land use periods: (1) The Cherokee period included the earliest portion of the record at Licklog Ridge. For both House Mountain and Linville Mountain, data were too sparse for statistical assessment of the Cherokee period. (2) The Euro-American settlement period began in 1790 at House Mountain, 1820 for Licklog Ridge, and 1770 for Linville Mountain, and continued until 1879. (3) The industrial period, characterized by large-scale industrial logging, was from 1880 to 1919 at all sites. (4) The fire suppression period at all sites was 1920–2009. To compare fire activity during the different land use

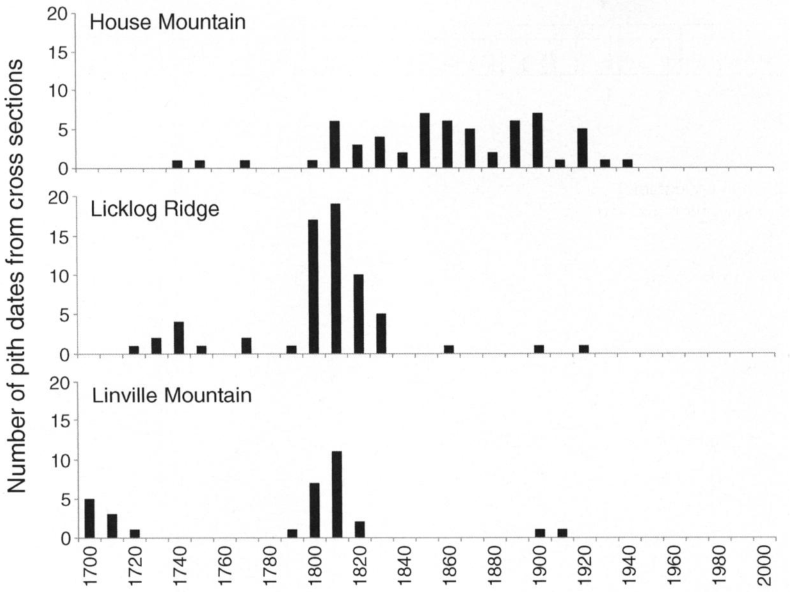

FIG. 4. The number of pith dates by decade for fire-scarred yellow pine cross sections for the years 1700–2000.

periods, we calculated the number of fire scars per recording tree by decade at each of the sites (Hoss et al. 2008). The number of fire scars per recording tree provides a fire activity index that can be used to compare across decades with different sample sizes of recording trees. A nonparametric Kruskal-Wallis *H* test (Sokal and Rohlf 2003) was used to test for differences in the mean of this decadal fire frequency index among the different land use periods at each site, and also to look for differences in the index values among the three sites. We then performed post hoc pairwise comparisons between the land use periods at each site, and between the sites, to identify which periods and sites differed significantly (Dunn 1964, Zar 1999).

RESULTS

Fire history

The pine stands at all three sites contained dead and living fire-scarred pines that established during the 18th, 19th, and 20th centuries (Fig. 4). We successfully cross-dated 82 of 84 cross sections collected at House Mountain, 116 of 138 cross sections from Licklog Ridge, and all 44 cross sections from Linville Mountain. Together, these trees recorded ~300 years of fire history per site. The fire history for House Mountain spans the period 1742 to 2009 (Fig. 5) based on 304 scars that recorded 37 fire dates. The earliest recorded fire occurred in 1763. The Licklog Ridge fire history spans 1723 to 2009 based on 593 scars that recorded 91 fire dates, with the earliest recorded fire in 1729 (Fig. 6). The Linville Mountain fire history spans the 1701 to 2009 period (Fig. 7) based on 181 scars that recorded 30 fire dates, with the earliest fire recorded in 1725. We were able to determine the seasonality of 75.7% of the scars (Table 1). At all three sites, the majority of scars occupied the dormant position. The various fire interval estimates for the presuppression fire regimes range between 2 and 13 years (Table 2).

Temporal change in fire activity

Climatic variability had little influence on fire occurrence. SEA identified no significant relationship between major fire years and moisture conditions during the fire year or preceding years (Fig. 8). Analysis of additional fire types and fire seasonality yielded similar results, except for a single significant relationship between drought and dormant-season fires at House Mountain. Fire occurrence showed little response to changing culture or land use, either, except during the most recent fire suppression period, when burning declined (Fig. 9). Kruskal-Wallis *H* tests indicated that the mean number of fire scars per recording tree per decade differed between land use periods at each of the three sites (House Mountain, $H = 9.11$, $P = 0.03$; Licklog Ridge, $H = 16.90$, $P = 0.001$; Linville Mountain, $H = 8.96$, $P = 0.03$). Post hoc comparisons, however, revealed no significant differences between any of the three early periods (Table 3). The fire suppression period stands out as having low fire activity compared to one or more of the earlier periods at each site.

The mean number of fire scars per recording tree per decade also differed among the three sites (Kruskal-Wallis *H* tests, $H = 6.7$, $P = 0.04$). Post hoc comparisons identified a significant difference between Licklog Ridge and Linville Mountain.

DISCUSSION

Fire frequency

Our reconstructions of fire history extend the annually resolved fire record beyond the period of logging and

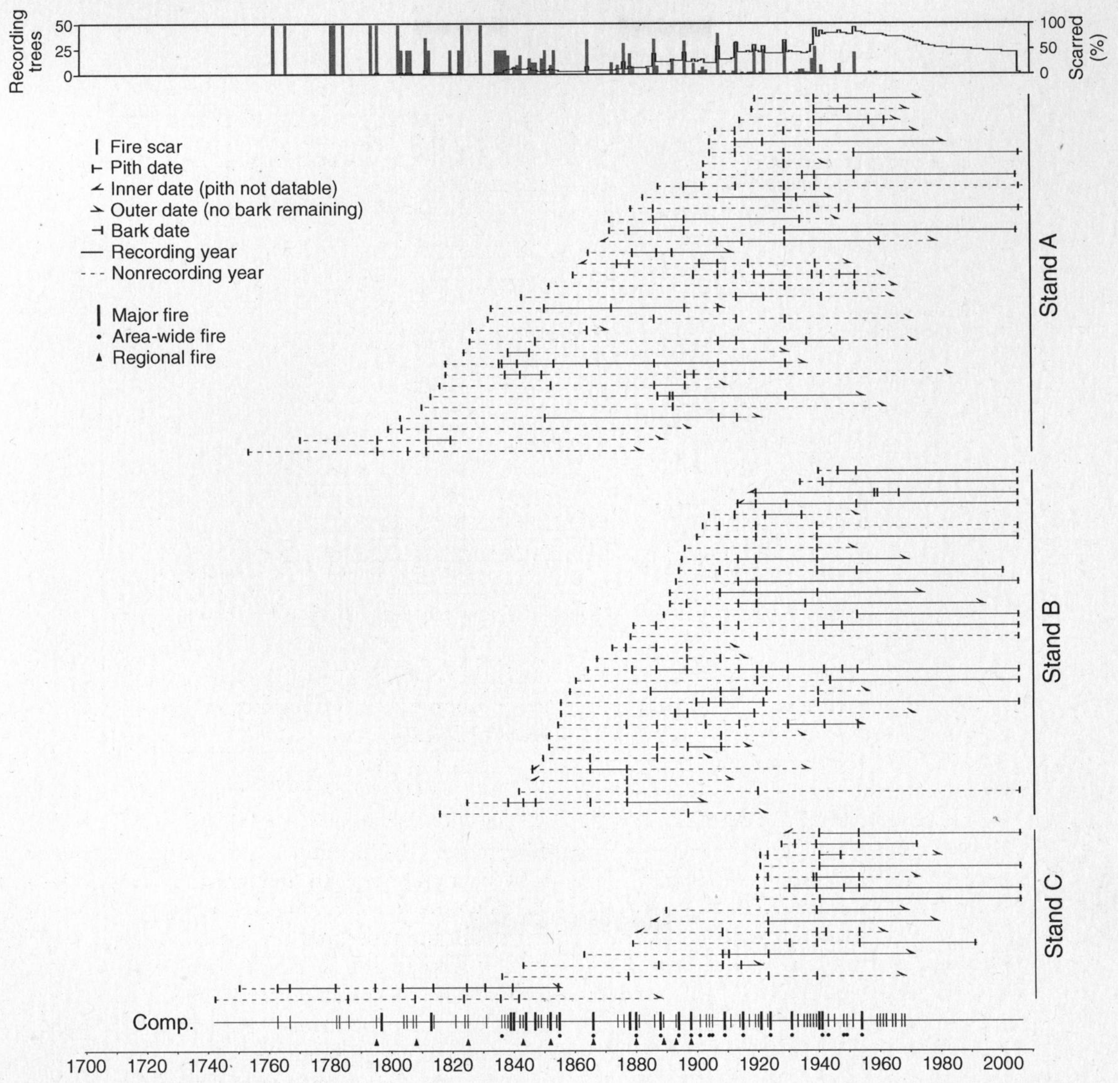

FIG. 5. Fire chronology for House Mountain, Tennessee, showing the dated fire scars for each tree cross section, from 1742 to 2007. In the upper panel, the line shows the number of recording trees, and the histogram bars show the percentage of recording trees scarred. Horizontal lines in the lower panel indicate the time spanned by each tree, with dashed lines indicating nonrecording years and solid lines indicating recording years. Short vertical bars represent dated fire scars. The horizontal line at the bottom represents the composite (Comp.) fire record, combining all fires that occurred at the site. On the Comp. line, thin vertical bars indicate less extensive fire years, and thick vertical bars indicate major fire years. Below the Comp. line, solid circles indicate area-wide fire years, and triangles indicate regional fire years.

industrial disturbance to include early Euro-American settlement and a period of Native American land use. Fires burned at all three study sites frequently. The lower fire frequency at Linville Mountain may reflect slightly wetter and cooler conditions at higher elevations, or its more isolated location. Fires of low to moderate severity must have dominated the fire regime at all three sites, as individual trees in our study were scarred by as many as 13 fires without being killed. Frequent burning would have limited fuel accumulation and diminished the likelihood of severe fire (Wimberly and Reilly 2007, Jenkins et al. 2011).

Yet our results provide some evidence that more severe fires burned on occasion. Frost (1998) hypothesized that the Table Mountain pine–pitch pine stands of the southern Appalachian Mountains developed under a "polycyclic" fire regime that consisted of relatively mild surface fires at roughly 7-year intervals and more severe burns at approximately 75-year intervals. Relatively severe fires may have killed enough overstory pines to initiate new pine cohorts, a pattern suggested by the clustered establishment dates of the fire-scarred trees we sampled at Licklog Ridge and Linville Mountain. The establishment histograms presented here require cau-

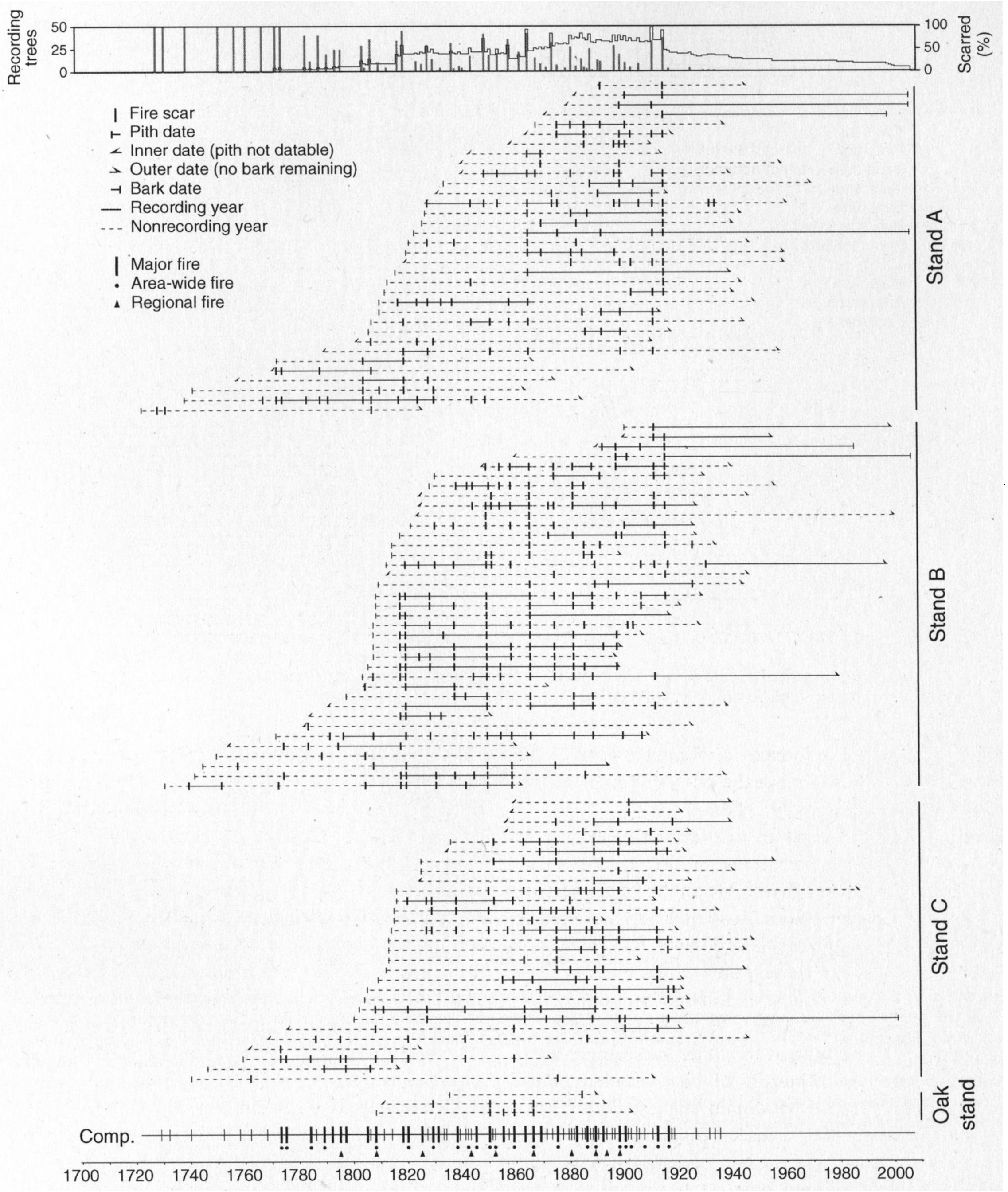

FIG. 6. Fire chronology for Licklog Ridge, Tennessee, showing the dated fire scars for each tree cross section, 1723–2008. See Fig. 5 for an explanation of the symbols used.

tious interpretation, of course, because the cross sections were targeted for collection due to visible fire scars rather than according to a systematic sampling design. Nonetheless, these establishment-date distributions align with plot-based histograms of age structure from other Table Mountain pine–pitch pine stands (Williams and Johnson 1990, Brose and Waldrop 2006, Aldrich et al. 2010).

Outbreaks of southern pine beetle (*Dendroctonus frontalis* Zimmermann) may also have influenced establishment patterns by opening the canopy and enabling the emergence of pine cohorts (Lafon and Kutac 2003, Brose and Waldrop 2006). Major drought occurred in 1799 and 1801, followed by a less severe but extended period of drought from 1810 to 1820. It is possible that these droughts precipitated severe fires,

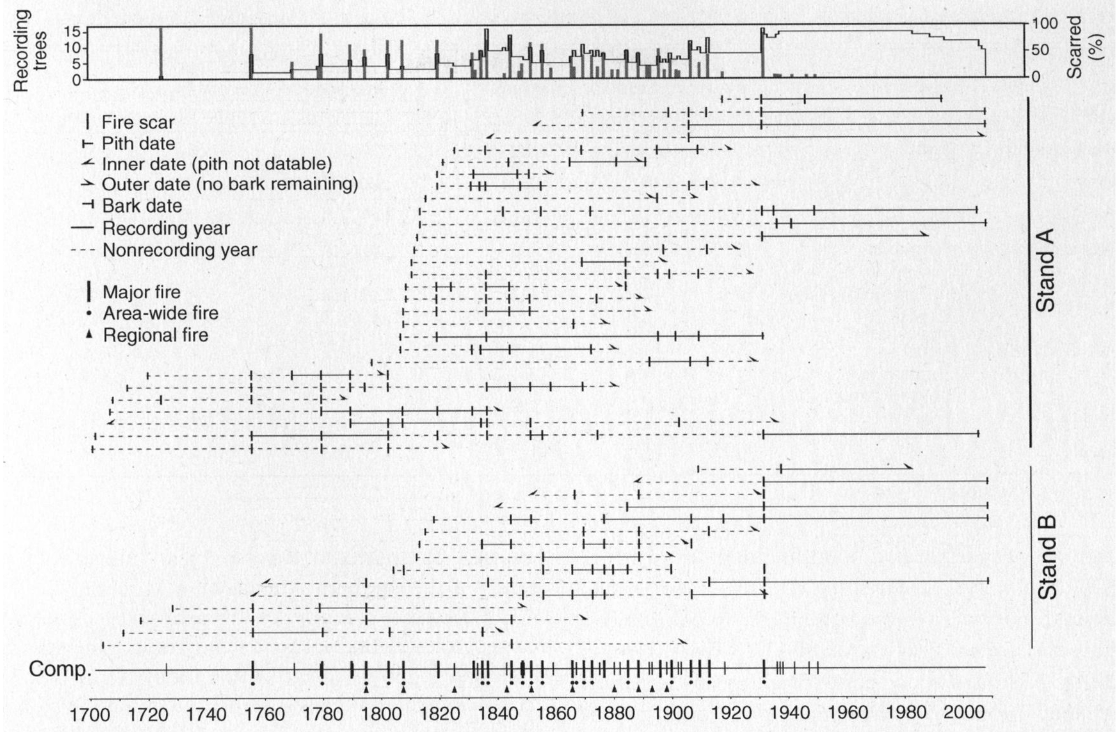

FIG. 7. Fire chronology for Linville Mountain, North Carolina, showing the dated fire scars for each tree cross section, 1701–2009. See Fig. 5 for an explanation of the symbols used.

southern pine beetle outbreaks, or a combination of the two disturbances, resulting in the observed pine cohorts that established in the early 1800s.

Between-site differences in fire frequency may have been associated with variations in fire severity. The lower fire frequency at Linville Mountain likely permitted heavier fuel accumulation, fostering burns of greater severity and resulting in the most distinct pine cohorts of the three sites. The relatively low abundance of fire-scarred trees that we found at Linville Mountain may indicate that patchy severe fires had destroyed more of the fire-scarred pines than at the other sites. In contrast, the uneven-aged distribution of the abundant fire-scarred pines at House Mountain suggests a different fire regime in which fires or insects regularly killed a few trees, creating a shifting mosaic of canopy gaps that almost constantly favored pine establishment in some part of the stands. Frequent burning probably rendered individual trees susceptible to beetle attack, while also maintaining a low stand density that would discourage large outbreaks (Schowalter et al. 1981). These frequent, mild disturbances would favor an uneven-aged structure. A similar distribution of establishment dates emerged among fire-scarred trees dominated by Virginia pine in western Virginia (Hoss et al. 2008) and three Table Mountain pine stands in northern Georgia (Brose and Waldrop 2006), suggesting, perhaps, that differences in fire severity among sites resulted in both even-aged and uneven-aged stands across the region. The Licklog Ridge site appears intermediate between House Mountain and Linville Mountain in terms of cohort establishment. Its intermediate nature may reflect its high fire frequency, which would favor stand dynamics similar to House Mountain, combined with moister conditions and/or differences in human activity that favored heavier fuel accumulation and occasional severe fires resembling those at Linville Mountain.

Regardless of the specific patterns of fire severity in the stands we sampled, our results agree with the general view that fires occurred regularly in the forests of eastern North America. The findings resemble other fire-scar records from the Appalachian Mountains. Pine stands in

TABLE 1. Seasonality of fire scars.

Site	Dormant season (%)	Early season (%)	Late season (%)	Undetermined (%)
House Mountain	59.1	18.6	0.7	21.5
Licklog Ridge	67.6	6.7	0.3	25.3
Linville Mountain	56.1	18.5	0	25.4

TABLE 2. Mean fire return intervals from the beginning of the period of reliability until the period of fire suppression.

Location	Fire interval type	Initial fire year	Mean fire interval	Weibull median fire interval	SD	Lower exceedance interval	Upper exceedance interval	Range	No. intervals
House Mountain	Point	1797	9.8	8.1	8.9	2.3	18.6	1–57	51
	Composite	1797	2.6	2.1	2.2	0.6	4.9	1–11	48
	Filtered composite	1797	7.9	6.5	6.6	1.9	14.9	1–26	15
	Area-wide	1836	7.2	6.2	5.5	2.0	13.2	1–19	11
Licklog Ridge	Point	1773	9.1	8.0	6.3	2.8	16.2	2–50	274
	Composite	1773	2.2	2.0	1.5	0.7	3.9	1–9	66
	Filtered composite	1773	4.6	4.4	2.6	1.9	7.6	2–12	31
	Area-wide	1773	6.5	5.9	4.2	2.3	11.3	2–19	22
Linville Mountain	Point	1756	13.1	11.1	11.1	3.3	24.7	2–59	53
	Composite	1756	4.0	3.4	3.0	1.1	7.3	1–14	41
	Filtered composite	1756	6.5	5.8	4.8	2.1	11.7	2–24	24
	Area-wide	1756	9.2	7.7	7.4	2.3	17.4	1–27	17
Regional		1795	11.4	11.3	5.0	6.2	16.9	4–18	9

Note: SD is standard deviation.

Virginia and Tennessee had point fire intervals of 10–13 years (Harmon 1982, Aldrich et al. 2010) compared to the estimates of 8–13 years we obtained. An oak stand in Virginia had a point fire interval of 17–18 years (Hoss et al. 2008). Although these point fire intervals are quite short, they probably overestimate the length of the actual fire interval because every surface fire probably did not scar every tree (Dieterich and Swetnam 1984, Van Horne and Fulé 2006). According to the filtered composite fire interval, considered a reliable estimate of fire frequency (Van Horne and Fulé 2006), fires typically burned at intervals of about 7–9 years in pine stands in Virginia and West Virginia (Aldrich et al. 2010, Hessl et al. 2011), and about 12 years in an oak forest in Virginia (Hoss et al. 2008). The equivalent estimates that we obtained here are even shorter, and indicate that fires occurred at approximately 4–8 year intervals in pine stands of the southern Appalachian Mountains.

The frequent occurrence of area-wide fires, which scarred trees in multiple, noncontiguous pine stands at 6–13 year intervals, suggests that many of the fires were large in extent and burned across the mountain slopes to encompass the pine stands as well as the oak–chestnut forests inhabiting the slope facets between the pine stands. Aldrich et al. (2010) found that area-wide fires were also common on a central Appalachian landscape in western Virginia. These area-wide fires may indicate that the hardwood forests burned frequently in the past, consistent with the fire–oak hypothesis. The three scarred pines we collected in the intervening oak stand at Licklog Ridge provide further evidence of burning in the oak-covered portions of the landscape. Indeed, at each of the three study sites, we found individual fire-

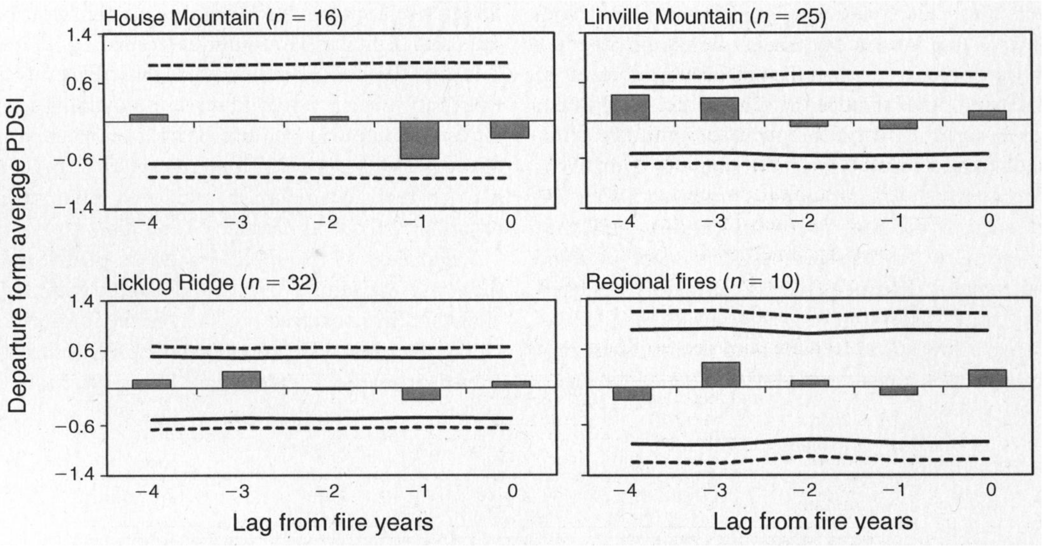

FIG. 8. Superposed epoch analysis for major fires, comparing Palmer Drought Severity Index (PDSI) during fire years to average PDSI conditions throughout the record. Solid and dashed lines represent confidence intervals at the 0.05 and 0.01 level, respectively. Sample sizes are the number of fire years examined.

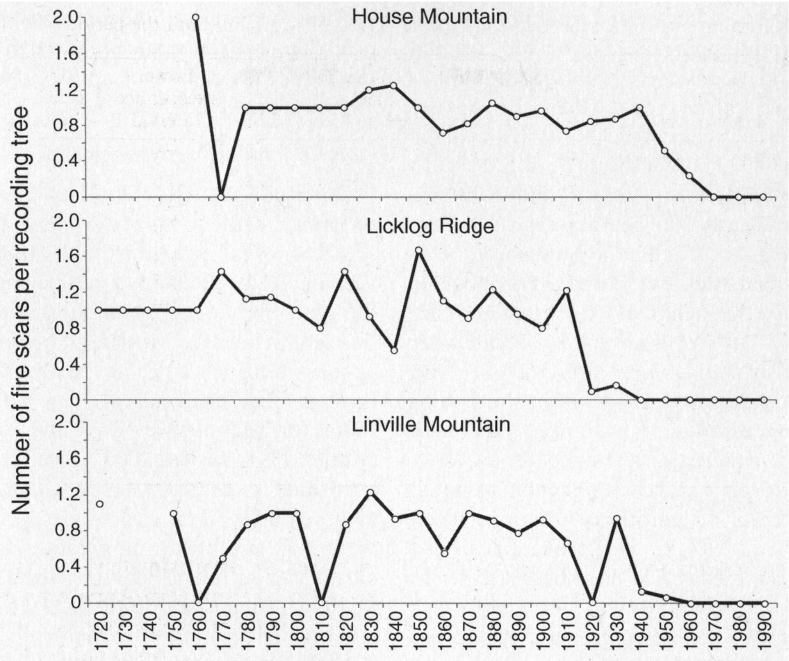

FIG. 9. The temporal trend in fire activity, as indicated by the number of scars per recording tree by decade. Missing values indicate an absence of recording trees during corresponding decades.

scarred pines within the broader hardwood forest matrix, outside of the pine stands. We also noted wounds on the uphill base of hardwood trees, typical of fire-scarring, throughout the hardwood stands at each of the three sites. At Licklog Ridge, fire-scarred hardwoods and hemlocks extended downslope to the stream edge. Even on the modern landscape, wildfires often spread across multiple slope facets and through different forest types, as revealed by digital maps of fire perimeters (Flatley et al. 2011).

Frequent burning likely maintained an open, flammable understory across pine and hardwood stands alike, where continuous fine fuels, including pine and oak litter as well as grasses and small shrubs, abetted the spread of fire (cf. Harrod et al. 2000). Relatively open forests would have admitted much sunlight and wind, enabling fuels to dry rapidly. When not suppressed, fires can smolder through precipitation events and then resume their spread once the fuels have dried again, as Cohen et al. (2007) have documented for unsuppressed lightning-ignited wildfires in the Great Smoky Mountains. Such intermittent fire spread is rare today because of suppression, but likely was common in the past. Precipitation patterns in southern Appalachia often feature one or more wet days followed by runs of several consecutive rain-free days (NCDC 2012). These weather patterns encourage intermittent fire spread, which ultimately can yield large burns (Cohen et al. 2007).

The occurrence of large burns in the past could help account for the high fire frequency we have documented, especially on sparsely populated landscapes such as Linville Mountain. Relatively few ignitions would have been needed to maintain frequent burning, even in forest stands isolated from human settlements and other ignition sources, if the fires commonly expanded far beyond their ignition point (Guyette et al. 2006, Aldrich et al. 2010).

Fire–climate relationships

The periodic bouts of dry weather that typify the southern Appalachian climate apparently enabled un-

TABLE 3. Mean fire scars per recording tree per decade for each of the land use periods.

Site	Cherokee period	Euro-American settlement period	Industrial period	Fire suppression period
House Mountain	–	1.00^{a}	0.91^{ab}	0.42^{b}
Licklog Ridge	1.10^{a}	1.10^{a}	1.05^{a}	0.03^{b}
Linville Mountain	–	0.82^{a}	0.82^{ab}	0.14^{b}

Notes: For each site, means followed by the same letter were not significantly different from each other according to post hoc comparisons ($\alpha < 0.05$). The dashes for the Cherokee period indicate that, although fires were recorded at both sites, the reconstructions did not include enough recording trees for statistical assessment.

suppressed fires to burn widely even during nondrought years, as no statistically significant relationship emerged between fire years and reconstructed PDSI. Our findings correspond with two other Appalachian fire history studies that discovered weak fire–climate associations (Schuler and McClain 2003, McEwan et al. 2007). In those cases, widespread anthropogenic ignitions during the late nineteenth and early 20th century appear to have overwhelmed the signal of climatic influences. Our results could imply that such overriding anthropogenic influences were typical throughout a longer period of fire history. People may have chosen not to burn under drought conditions to avoid severe fires (Schuler and McClain 2003), but, instead, to burn within short rain-free intervals during normal or even wet years. On modern landscapes of the eastern United States, only one or two rainless days are sufficient to enable burning, although the probability of ignition is low under such conditions (Haines et al. 1983; C. W. Lafon, *unpublished data*). Ignition probabilities would have been greater in the past because of intentional and accidental fires associated with hunting, livestock grazing, and other rural activities (Whitney 1994), resulting in a substantial level of burning even during nondrought years. Today, in contrast, a high ignition probability exists only after many consecutive rainless days have desiccated the fuels (Haines et al. 1983; C. W. Lafon, *unpublished data*), and widespread burning is restricted largely to drought years (Baker 2009, Flatley et al. 2011).

Fire seasonality is another factor that may have contributed to the weak fire–drought relationships we observed. At present, fire activity in the southern Appalachian Mountains shows a bimodal distribution with peaks in spring and fall (Barden and Woods 1974, Baker 2009). Therefore, the dormant-season scars that dominated our historical fire record likely formed in the spring or fall. This pattern of fire seasonality reflects the weather conditions common in spring and fall, when the wind is relatively strong, humidity is low, and the forest floor is exposed to the drying effects of wind and sun in the absence of the deciduous canopy (Lafon et al. 2005). Because we assigned all dormant-season fires to the year following the scar, fall-season fires do not match the proper year of climate; the inability to separate spring and fall fire activity likely weakens our ability to discern fire–drought relationships. Additionally, growing-season rainfall reconstructions may not adequately represent drought conditions during the fall and spring fire season. Such a limitation would affect fire–climate analyses in other parts of eastern North America, and also in parts of western North America where dormant-season scars are common but drought reconstructions pertain to the growing season (e.g., Grissino-Mayer et al. 2004). Nonetheless, drought typically persists for several months, at least, and therefore if climatic variability exerted a strong control on fire occurrence at our study sites, we would expect a more pronounced negative relationship with growing-season PDSI during the fire year and/or the previous year. It seems most probable that the weak fire–drought association in our record is the product of anthropogenic burning within myriad climatic contexts.

Fire and changes in human culture and land use

Our study suggests that Native Americans and Euro-American settlers burned widely, either by intent or accident. The proximity of House Mountain and Licklog Ridge to human settlements may account for the high fire frequency at those sites. Fires were also frequent at Linville Mountain, however, suggesting that people influenced broad portions of the landscape through fire, for example, by burning along travel routes or to improve rangeland and wildlife habitat (Hatley 1995, Brown 2000). Fire frequency varied little over time. It was high even during the late 18th and early 19th centuries when Euro-Americans were first settling the region and human population was likely the lowest during our record. In contrast to fire history records in Missouri, Illinois, and Indiana, we found no evidence of a hiatus in fire during or following the transition from Native American to Euro-American settlement (Cutter and Guyette 1994, Guyette et al. 2003, McClain et al. 2010). As suggested previously, if large fires were common, they could have maintained frequent fire under relatively low ignition density, thereby diminishing the sensitivity of the fire regime to changes in human activities.

Licklog Ridge provided the most substantial record of fire during the Cherokee period, due to the length of the record and the later settlement of the site. For House Mountain and Linville Mountain, only a few fire-scarred trees predated Euro-American settlement. Nonetheless, the record of burning extends back to the Cherokee period at all three study sites and demonstrates the occurrence of fire during that time. It should be noted that Cherokee land use practices, including the use of fire, may have been in flux during the 18th century, due to the impacts of disease, war, trade, and the adoption of some European crops and agricultural practices (Hatley 1995, 2006). In particular, the harvesting of deer skins for European markets may have intensified the use of fire for hunting (Foster and Cohen 2007, Bolstad and Gragson 2008). Cherokee fire use during the 18th century, therefore, was not necessarily typical of earlier periods of Native American burning.

Lightning ignitions probably help account for the steady rate of burning as well. Lightning ignitions, by themselves, probably did not occur with sufficient density to maintain the high frequency of burning we have documented (cf. Flatley et al. 2011). They contribute substantially to the present fire regime, however (Cohen et al. 2007, Lafon and Grissino-Mayer 2007), and undoubtedly played an important role in the past when they could spread across the landscape, unfettered by fire suppression or by landscape fragmentation (Lafon 2010). Lightning probably had a more important role at Linville Mountain than at the other sites because climatic conditions along the eastern escarpment of the Blue Ridge promote a high incidence of lightning ignitions compared to other parts of Appalachia (Lafon and Grissino-Mayer 2007, Baker 2009).

We expected to observe an increase in fire frequency during the industrial period. Fire frequency remained stable, however, in contrast with the view that logging and mining combined with a growing agricultural population to unleash a devastating new fire regime during the late 19th and early 20th centuries (Williams 1998, Brose et al. 2001, McEwan et al. 2011). Large, severe fires clearly did occur in logging slash during this period (Lambert 1961, Pyle 1988), and undoubtedly they spread into the stands that we sampled. Because many trees survived and continued to form fire scars, however, we can conclude that the fires did not disturb these unlogged stands in a catastrophic manner. The unlogged stands probably resisted catastrophic fire because they lacked heavy loads of dead fuel. Severity aside, the important point that emerges about fire history during the industrial period is that it did not see an unusual frequency of burning compared to previous land use phases. Frequent fire had a long history across southern Appalachia before the industrial period, and that finding agrees with evidence that has accumulated from other parts of the Appalachian Mountains. Fire-scar records from Virginia (Hoss et al. 2008, Aldrich et al. 2010), Maryland (Shumway et al. 2001), and Vermont (Mann et al. 1994) also reveal long histories of frequent burning.

It is the recent period, the era of fire suppression, that stands in contrast to the previous land use episodes. The drastic reduction in fire frequency underscores the effectiveness of state and federal fire suppression efforts in the temperate forests of the eastern United States. Other reconstructions of fire history match the pattern of complete fire cessation (Harmon 1982, Schuler and McClain 2003, McEwan et al. 2007, Hoss et al. 2008, Aldrich et al. 2010, Hessl et al. 2011). If, as we suggest above, large-extent fires were common, much of the 20th century decline in fire frequency can be explained by the aggressive suppression of small fires before they enlarged (cf. Pyne 1982, Ward et al. 2001). Suppression would be most effective on a sparsely populated landscape with low ignition density. A more heavily populated landscape, such as House Mountain, may have promoted numerous fires of relatively small extent (Syphard et al. 2008, Yang et al. 2008). Subduing frequent fire under such conditions would have been more difficult than on a landscape with a lower ignition density, possibly explaining why burning persisted through the mid 20th century at House Mountain.

Fire has grown increasingly rare during recent decades, suggesting that fire suppression has become more effective. The continuing absence of fire may also reflect an ongoing transition toward mesophytic conditions (Nowacki and Abrams 2008), wherein forest canopies gradually close, mesophytic species invade, and leaf litter declines in flammability as time passes without fire. Outbreaks of southern pine beetle may accelerate this process of mesophication by removing mature pines from the canopy and promoting hardwood trees and shrubs.

CONCLUSION

The three study sites identified here provided large numbers of fire-scarred trees, permitting thorough reconstructions of fire history that yielded some of the longest dendroecological fire chronologies assembled for the eastern United States. These chronologies reveal that fires occurred frequently for at least two centuries before the fire suppression efforts of the 20th century. Our study adds to the accumulating evidence suggesting that temperate forest vegetation of eastern North American developed under a history of frequent fire that predates the industrial logging/mining period of the late 19th and early 20th centuries. The fire chronologies developed here could represent the history of fire in upland pine and oak forests over the broader southern Appalachian region. Our study sites encompass much of the regional heterogeneity in terms of climate, terrain, and surrounding human land uses. The House Mountain site, for example, occupies a solitary ridge surrounded by farmland, while Linville Mountain is situated in an extensively forested, mountainous landscape that has been more isolated from human activities. Regardless of the environmental differences among the study sites, fire occurred at all three landscapes frequently, until the advent of effective fire suppression.

The change in fire regime during the fire suppression era appears to have contributed to fundamental changes in species composition and structure in the Appalachian Mountains and throughout the oak and pine forests of eastern North America (e.g., Harrod et al. 2000, Nowacki and Abrams 2008). Many plant and animal species associated with fire-disturbed ecosystems are currently threatened or declining in the Appalachian Mountains, e.g., Peters Mountain mallow (*Iliamna corei* Sherff), mountain goldenheather (*Hudsonia montana* Nutt.), eastern turkeybeard (*Xerophyllum asphodeloides* (L.) Nutt), and red-cockaded woodpeckers (*Picoides borealis*) (Gross et al. 1998, Bourg et al. 2005). Resource managers have been using fire to attempt to restore fire-associated vegetation and wildlife habitats of the federal, state, and privately owned wildlands of the Appalachian Mountains (Elliott and Vose 2010, Jenkins et al. 2011). Our study supports such efforts by underscoring the historic role of fire in the region and by providing fire frequency estimates that could be targeted in such restoration efforts. The low-severity, low-risk prescribed burns preferred by managers may be sufficient to maintain pine and oak dominance if conducted on the 4–8 year cycles that typified fires in the past, and if combined with periodic fires or other disturbances of greater severity to open the stands and facilitate pine regeneration. Low-severity fires alone are inadequate for pine establishment (Welch and Waldrop 2001, Brose and Waldrop 2006). Fire-associated vegetation in the southern Appalachian Mountains has been altered by mesophytic encroachment and increased stand density (e.g., Harrod et al. 2000), and likely would require initial disturbances of moderate to high severity before frequent surface fires could be applied effectively. Some urgency exists in the need for restoration, as the abundance of yellow pine seed sources is declining through periodic insect outbreaks and other disturbances (Lafon and Kutac 2003, Elliott et al. 2012).

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