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Longleaf pine (*Pinus palustris* Mill.) fire scars reveal new details of a frequent fire regime

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Abstract

Question: How frequent and variable were fire disturbances in longleaf pine ecosystems? Has the frequency and seasonality of fire events changed during the past few centuries?

Location: Kisatchie National Forest, Western Gulf Coastal Plain, longleaf pine–bluestem ecosystem, in relatively rough topography adjacent to the Red River, Louisiana, USA.

Methods: Cross-sections of 19 remnant pines exhibiting 190 fire scars were collected from a 1.2-km^2 area. Tree-rings and fire scars were precisely dated and analysed for the purpose of characterizing past changes in fire and tree growth. Temporal variability in fire occurrence and seasonality was described for the pre- and post-European settlement periods. Seasonality of historic fires was determined by the scar position within the rings. The relationship between fire and drought was investigated using correlation and superposed epoch analysis.

Results: The mean fire return interval for the period 1650-1905 was 2.2 years (range 0.5 to 12 yr). Significant new findings include: evidence for years of biannual burning, temporal variability in fire seasonality, an increase in fire frequency and percentage of trees scarred circa 1790, and synchronous growth suppression and subsequent release of trees coinciding with land-use changes near the turn of the 20th century. Drought conditions appeared unrelated to the occurrence of fire events or fire seasonality.

Conclusions: Multi-century fire history records from longleaf pine ecosystems are difficult to obtain due to historic land-use practices and the species high resistance to scarring; however, our results indicate potential for reconstructing detailed fire histories in this ecosystem. Fire scars quantitatively documented one of the most frequent fire regimes known. Fire regime information, such as the temporal variability in fire intervals, prevalence of late-growing season fire events and biannual burning, provide a new perspective on the dynamics of longleaf pine fire regimes.

Introduction

It is widely accepted that frequent fires were a historically important disturbance in the southeastern USA and especially important for maintaining longleaf pine (*Pinus palustris* Mill.) ecosystems (Wright & Bailey 1982; Bridges & Orzell 1989; Frost 2006). Despite these ideas, little quantitative data exist that document frequent fire events (e.g., ≤ 3 yr) prior to major EuroAmerican settlement influences (e.g. circa 1800) (Henderson 2006; Huffman 2006; Bale 2009). In historically fire-maintained ecosystems long-term fire regime information is valuable for understanding ecosystem processes, designing scientifically-based fire management objectives and explaining the ecology of fire to the public (Swetnam et al. 1999; Bowman 2007). As a perpetual and repeated disturbance, fire historically maintained ecosystems and habitats for numerous fire-dependent birds, plants and animals. Changes in fire regimes (e.g. frequency, severity, seasonality) from historic conditions have the potential to eliminate fire-maintained habitat for hundreds of species that are dependent upon fire disturbance. There are 16 federally threatened or endangered plant species associated with the longleaf pine ecosystem for which fire

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suppression is cited as a contributing factor (Van Lear et al. 2005). There are at least 187 other rare plant species native to the longleaf pine ecosystem (Walker 1993) and, of these, the majority is expected to decline without fire.

Longleaf pine is considered the most fire-adapted tree species of the eastern USA, partly because it has moderately thick bark and is able to survive recurring and frequent fires. Longleaf seedlings undergo a ‘grass stage’, during which the growing meristem is protected by a thick bush of green needles, extending as much as 2 dm beyond the central stem. These may be burned away by a passing fire, leaving the carbohydrate-rich meristem unharmed and capable of sprouting a new mass of needles within the same season. Thus longleaf pine can reproduce even under an annual fire regime. Many seedlings remain in this protected ‘safe’ stage for several years, storing up carbohydrates in a large tap root. When enough reserves have been accumulated, the young stem ‘bolts’, elongating from a few dm up to 1-m tall within a season or two, while simultaneously building a thick layer of loose bark to resist fire. It has been suggested that the long – up to 3 or 4 dm – and highly flammable needles constitute a mechanism that serves to increase fire frequency by providing fuel continuity between clumps of grass, and invasive understorey hardwoods that catch needles on their branches. The sometimes heavy needle drape increases flammability and may ensure that the hardwoods are killed by any passing fire (Johnson & Gjerstad 2006). These specialized adaptations bespeak a long evolutionary history in a landscape with fire.

Longleaf pine forests once constituted a major forest ecosystem covering approximately 37 million hectares of the southeastern USA, extending from southeastern Virginia south to central Florida and west into eastern Texas (Frost 1993). Presently, longleaf pine only occupies approximately 2% to 3% (841 800 ha) of its original upland range (Frost 2006). Major factors responsible for the loss of longleaf pine include heavy logging, land conversion and changes in fire regimes (Frost 2006). As a highly fire-adapted species it is no surprise that prescribed fire is a primary mechanism for maintaining and restoring longleaf pine in the southeastern USA. Prescribed burning currently occurs on approximately 19% (193 000 ha) of the existing longleaf pine lands (Frost 2006). Despite a large body of literature related to fire in longleaf pine ecosystems, only a few quantitative fire history studies have been accomplished (Henderson 2006; Huffman 2006; Bale 2009). More quantitative information is needed to understand longleaf fire regimes, particularly as it relates to past fire characteristics (e.g. seasonality, severity, size), forest stand dynamics, climate variability and restoration. The purpose of this study was to describe the historic fire regime in a longleaf pine–bluestem grass (*Pinus palustris–Andropogon*) ecosystem in central Louisiana, a state in which no fire scar history studies currently exist.

Methods

Study site

The study site straddles the southwestern boundary of the 3520-ha federally designated Kisatchie Hills Wilderness Area located in Natchitoches Parish, Louisiana (31°28′N, 92°59′W) (Fig. 1). The region has a humid, subtropical climate, with a mean annual temperature of 18.8 °C and mean annual precipitation of 136 cm (period 1895-2008; NCDC 1999). The primary lightning season occurs during summer and four to six flashes per square kilometer occur per year (period: 1989-1998; Orville & Huffines 2001)). The terrain of the Kisatchie Hills is underlain by the Catahoula Formation, which forms a prominent topographic ridge paralleling the Gulf Coast shoreline from northeastern Mexico to Alabama (Paine & Meyerhoff 1968). In the Wilderness Area the terrain is particularly rugged, with features such as sandstone cliffs, steep slopes and small mesas. The study site includes this topography

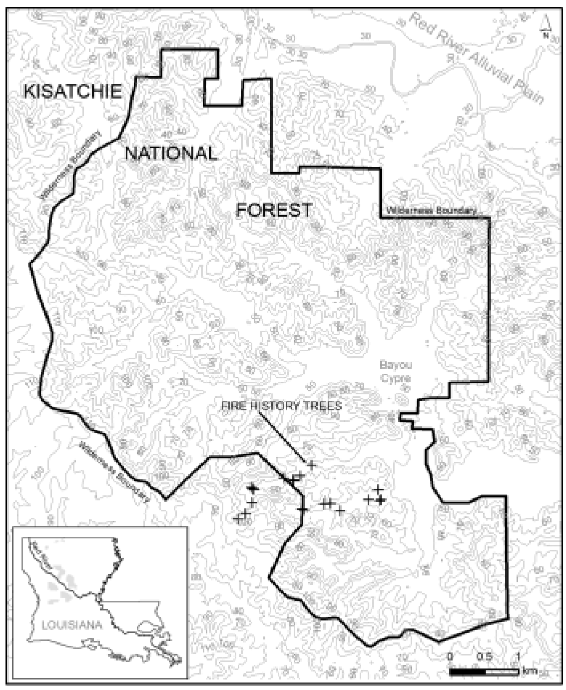

Fig. 1. Map showing fire history sample tree locations within the Kisatchie Hills Wilderness Area (boundary approximate) of the Kisatchie National Forest. Fire scar injuries on trees were dated for the purpose of describing the historic fire regime. The Red River Alluvial Plain, a major historic travel and trade route, is located approximately 10 km to the east of the study area. Lower left: State of Louisiana showing districts of the Kisatchie National Forest (grey) and the area of the enlarged topographic map (black square). Contour interval = 10 m.

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and two upper forks of the Bayou Cypre – a primary drainage leading from the site to the Red River alluvial plain, some 6 km to the east (Fig. 1). Beginning in northern Texas and emptying into the Mississippi River, approximately 2190 km downstream, the Red River basin is the second largest in the southern Great Plains.

Forest composition is dominated by longleaf pine, loblolly pine (*P. taeda* L.) and sweet gum (*Liquidambar styraciflua* L.), with inclusions of oak (e.g. *Quercus falcata* Michx. and *Q. stellata* Wangenh.) (Van Kley 1999). Much of the Wilderness is characterized as having woodland to closed-canopy forest structure (i.e. 50-80% canopy cover), with the exception of riparian bottomlands that are primarily closed-canopy forests. Grass and litter fuels are dominant in upland areas, especially adjacent to the Longleaf Vista overlook. In the absence of fire, invasive shrubs such as Yaupon holly (*Ilex vomitoria* Aiton) have become a major component of the understorey, and development of this shrub layer represents an altered composition and structure from historic fire-maintained communities (Heyward 1939).

Humans occupied portions of the Kisatchie National Forest area throughout the Holocene, as evidenced by remnants of villages and campsites (Burns 1994). During the last millennium until the mid-19th century, Caddo and Natchez tribes occupied portions of northern Louisiana. Although Spanish explorers first traversed northern Louisiana in the 16th century, the first land claim was not made until 1682 by France. In 1699, French explorers reached the vicinity of the study site during expeditions ascending the Red River. Here they established the first French settlement in Louisiana (Natchitoches, est. 1714) approximately 8 km north of the Natchitoches Indian settlement; both located within 30 km of the study site (Burton & Smith 2008). During the period 1743 to 1800, Louisiana changed hands twice, first to Spain and then back to France in 1800 for a brief period before the Louisiana Purchase of 1803 (Fig. 3). Between 1714 and 1800, the population of Natchitoches (not including slaves) increased to about 850 (Burton & Smith 2008) while the total population of Louisiana had increased to approximately 50 000 (Coulson & Joyce 2003). Until about 1790, the population of EuroAmericans did not significantly increase, but by this time native populations had dramatically declined due to an epidemic (Burton & Smith 2008). In the late 17th century, Caddo populations were estimated at 15 000, a reduction from as many as 250 000 originally (Burton & Smith 2008). Their numbers further declined to 13 000 by 1700 and then perhaps as low as 500 by the 1770s (Burns 1994). Major land clearing in the region began during the late 19th century with the arrival of railroads. Lands in the vicinity of the study site were heavily cutover during a lumber boom from approximately 1880 to 1920. Fire was used to maintain newly converted pasture lands. In 1929, cutover lands were purchased to create the Kisatchie National Forest and much of the original longleaf pine lands were replanted with loblolly pine, originally native mostly along wetland margins, and slash pine (*Pinus elliottii* Engelm.), which here was introduced some distance from its natural range along the eastern Gulf Coast. Based on the percentage of Kisatchie National Forest lands burned and work reports of the Civilian Conservation Corps, it appears that fires were not effectively suppressed until the mid-1940s (Burns 1994). The Kisatchie Hills Wilderness Area was established in 1980 and restoration of fire and longleaf pine has become a major goal of the Kisatchie National Forest (Earley 2004; Haywood 2007). No prescribed burning is known to have occurred within the Wilderness Area, however it has been widely conducted outside its boundaries. Wildfires have occurred in the Wilderness Area during the last few decades and evidence of recent fire exists on living trees as scars and charcoal.

Dendrochronology and fire scar analysis

Longleaf pine is ideal for use in fire history research based on its longevity and resistance to decay following injury and death; however, its resistance to fire scarring is a major limiting factor in locating and constructing fire scar history chronologies. Initially we searched an approximately 15-km^2 area in the southwestern portion of the Wilderness for remnant pine woods (i.e. stumps and dead standing trees) exhibiting both numerous tree rings and external evidence of fire scarring. After suitable samples were found in a somewhat clustered location, we then identified an approximately 1-km^2 study area within which we exhaustively searched and sampled. A study area of 1 km^2 was desired because it is comparable in area to many other fire scar studies and therefore facilitates between-site (i.e. ecosystem) comparisons. Cross-sections were cut from the base of 19 remnant trees in two adjacent drainages near the southwestern Wilderness boundary. Additional sections were cut higher up the bole if more suitable callus tissue or additional fire scars were present. Based on the history of the site, the ecology of pines on frequently burned wet sites (Haywood & Grelen 2000), high sample wood density (specific gravity > 0.95) (Forest Service 1965), anatomical and ring characteristics, and tree abundance and proximity to other longleaf pines, we concluded that these remnant trees were also longleaf pines. Locations of samples were recorded using a GPS unit, and photographs and measurements were taken of each sample's physical orientation with respect to aspect, slope and height above ground level. The final area encompassing the sample trees was

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approximately 1.2 km^2. In addition to remnant wood, 17 increment cores were collected from living longleaf pines in the vicinity of the study area for the purpose of developing an absolutely dated master ring-width chronology that could be used to precisely date remnant wood.

In the laboratory, cross-sections were surfaced with an electric hand-planer and the cellular detail of annual rings and fire scar injuries was revealed by sanding with progressively finer abrasive paper, from ANSI 80 to 1200 grit (180 to 4.5 μm). Radii (pith-to-outer tree ring) of cross-sections with the least amount of ring-width variability due to injury were chosen for measurement. Widths of the latewood and earlywood portions of tree rings were measured separately (0.01-mm precision) and summed into a total annual ring width. Cross-dating potential of longleaf pine appears to be enhanced by considering only latewood ring-width portions (Meldahl et al. 1999; Henderson & Grissino-Mayer 2009); therefore we used only the latewood ring-width series of cores and dead wood samples in cross-dating (Stokes & Smiley 1968). Cross-dating of samples utilized visual pattern matching of ring-width plots and anatomical wood features. COFECHA software (Holmes 1983; Grissino-Mayer 2001a, b) was used for cross-dating quality control and to assess inter-tree cross-dating. Ring-width plots of individual trees were used to examine temporal changes in growth and to relate changes in growth to the timing of other events. Master ring-width chronologies were developed separately for live tree cores and dead remnant wood. Once the two master chronologies were constructed, we cross-dated them to form a single chronology spanning 1587 to 2007 (series intercorrelation = 0.56, average mean sensitivity = 0.45). ARSTAN software (Cook & Kairiukstis 1990) was used to develop master chronologies.

Once all tree-ring series were absolutely dated, then calendar years were assigned to fire scars. Fire scars were identified by the presence of callus tissue and were commonly associated with charcoal, liquefaction of resin and cell injury. Fire scar dates were assigned to the year of cambial response to the injury. If possible, the season of fire occurrence was determined based on the position of the scar within the ring. Fire scar positions were classified as being in the earlywood (early, middle or late portions), latewood or between rings (dormant season) (Kaye & Swetnam 1999). Scar dates and scar positions were analysed using FHX2 (fire history) software (Grissino-Mayer 2001a, b), which facilitated the construction of the fire scar chronology chart and calculation of summary statistics by selected time periods. Analysis of fire events began with the first fire scar year (1650). Kolmogorov-Smirnov (K-S) goodness-of-fit tests were used to determine whether a Weibull distribution described the fire interval data better than a normal distribution. In cases of biannual burning (i.e. evidence of two fire scars in one calendar year), we used a fire interval length of 0.5 in our analysis of fire intervals. Because of the unfamiliarity with biannual burning in ecosystems (possibly never before documented by fire scars), we chose to take a conservative approach and only consider biannual burning event years if indicated on a single tree. It is possible that biannual burning could be also represented by fire scars on separate trees (e.g. one tree showing earlywood fire scar in 1700 while another tree shows latewood fire scar in 1700), however between-tree differences in the timing of tree growth could also be due to phenological differences associated with sites, genetics or tree ages.

Mean fire return intervals and Weibull median fire return intervals were derived from the composite fire scar chronology and represented the occurrence of fire somewhere in the study area (i.e. because not all fires may have burned the entire study area). Percentages of trees scarred were described for years when at least five trees were represented (1628-1884). Superposed epoch analysis (SEA) was conducted to determine the association of regional wetness/dryness to fire events (Fulé et al. 2005). Annual drought data consisted of reconstructed Palmer Drought Severity Indices (PDSI) (Cook et al. 2004) for north-central Louisiana. Data were bootstrapped for 1000 simulated events to derive confidence limits. Fire event years were compared to climate parameters to determine if drought was significantly different from average during the 6 years preceding and 4 years succeeding fire events. These tests were conducted for the full period (1650-1904) and 50-year sub-periods using a 25-year step. In addition to SEA, we used Pearson correlations to determine whether percentage trees scarred and drought were related.

Results

Although longleaf pine currently occupies uplands in the study area, we found the majority of remnant trees (i.e. stumps and snags) in sandy, alluvial bottomlands. Most of these trees exhibited external fire scars and charcoal on scar faces that ranged from 0.3- to 3.0-m tall (Fig. 2). A few stumps exhibited no external evidence of scarring, but when cut were found to have internal fire scars. Two scarred stumps with external charcoal were found submerged in small pools of water within drainages (Fig. 2). Nearer to Bayou Cypre one large remnant was located a few meters from more recently formed bald cypress (*Taxodium distichum* L.) knees. Remnant wood found outside of drainages was located on steeper slopes and in fire-protected microsites. Tree-rings of dead wood samples spanned the years 1587 to 1905 (319 yr). A total of 3392 years (tree rings) were represented by all samples and the

Fig. 2. (Top left) Example of an open-structured, upland longleaf pine forest adjacent to the Kisatchie Hills Wilderness Area. (Top right) Workers cross-cutting a 5-m tall remnant pine tree (sample KIS014) that exhibits a large scarface with charcoal. A band of tape is wrapped around the tree just below the cutting kerf so that wound wood is held in place. (Bottom left) A remnant stump with a charred scarface located in the riparian zone and partially submerged in a pool of water. (Bottom right) Microscopic view of fire scars (white arrows). The bottom three scars occurred during a span of ca. 12-15 months and suggest biannual burning (i.e. two fires in 1 year).

mean and maximum number of rings on samples was 162 and 244, respectively. Cross-dating of samples indicated that no rings were missing from any of the sample ring-width series.

A total of 190 fire scars were dated and compiled into a composite (site) fire event chronology (Fig. 4). Scars represented 120 different fire events between the calendar years 1650 and 1902. Fire intervals on individual trees ranged in length from 0.5 to 12.0 years. The composite (i.e. based on all trees) mean fire return interval (MFI) for the pre-European settlement period (1650-1713) was 3.2 year (Table 1). A slight decrease in fire frequency occurred beginning with settlement of Natchitoches (1714). Overall, the MFI was unchanged during the period 1714-1790 (MFI = 3.3 yr), however, beginning circa 1790, the fire frequency dramatically increased and near-annual burning persisted for almost a century (MFI = 1.3 yr, period: 1791-1880) (Fig. 3).

We detected physical evidence of two fires occurring in a single calendar year on two different samples (Fig. 2). This biannual burning was represented on individual samples by the progression of a fire scar during the dormant season, followed by a fire scar within the ring of the next year, followed by a fire scar during the next dormant season (i.e, three fires within a period of ca. 1.5 yr) (Fig. 2). These events were replicated in six different calendar years (1700, 1826, 1852, 1853, 1867, 1872). Each of these years of biannual burning occurred within sub-periods when annual burning was occurring at the site.

Table 1. Fire scar history statistics for sub-periods and the full period of the fire scar record (1650–1905). MFI = Mean fire interval, FIRE SCARS = total number of fire scars on all trees, FIRE EVENTS = number of different fire event years. Seasonality of fire scars was determined by the location of the scar tissue within or between rings. Seasonality codes: Undet. = Undetermined scar seasonality, Dormant = scar position in dormant season, EarlyEW = scar positioned within the early portion (first 1/3) of earlywood, MiddleEW = scar positioned within middle portion (middle 1/3) of earlywood, LateEW = scar positioned within late portion (last 1/3) of earlywood, Latewood = scar positioned within the latewood.

Period	1650–1713	1714–1790	1791–1880	1881–1905	1650–1905
MFI	3.2	3.3	1.3	5.8	2.1
FIRE SCARS	22	33	130	5	190
FIRE EVENTS	21	23	72	4	120
	Fire scar seasonality				
Undet.	3	3	22	3	31
Dormant	7	5	37	0	49
EarlyEW	1	0	1	0	2
MiddleEW	2	1	4	0	7
Late EW	0	2	4	0	6
Latewood	9	22	62	2	95

The percentage of trees scarred during fire years ranged from 6% to 46% (Fig. 5). Percentages of trees scarred

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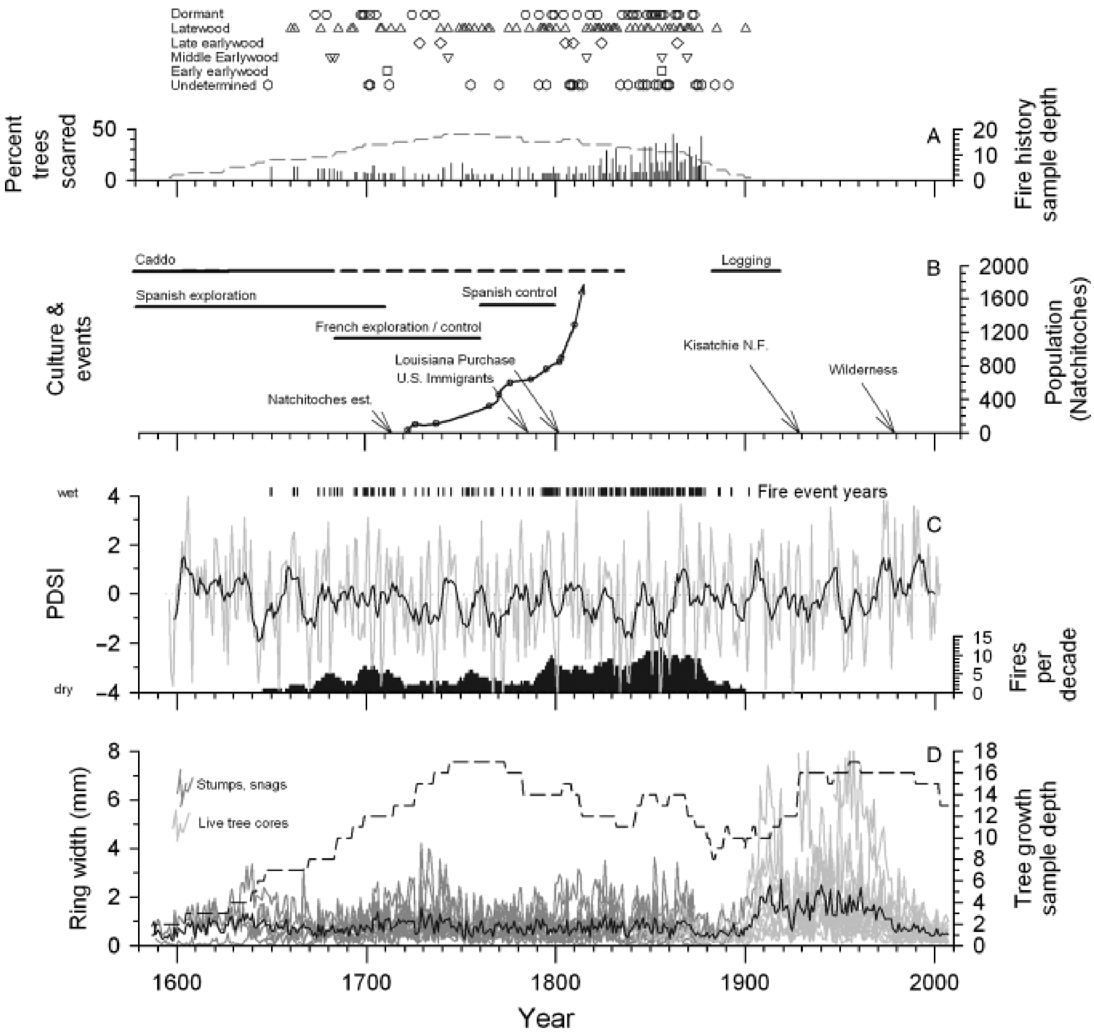

Fig. 3. Timelines depicting changes in the fire environment at the Kisatchie Hills Wilderness fire history site. (**a**) Fire scar seasonality (symbols), percentage of trees scarred during fire events (bars), and fire history sample depth (dashed line); (**b**) timeline of changing cultures and events during the period of fire history. Colonial period Natchitoches population estimates (dotted line) spanning 1722-1810 (source: Burton & Smith 2008); (**c**) (top) vertical ticks indicate fire event years, (middle) annual reconstructed Palmer Drought Severity Indices (PDSI) (Cook *et al*. 2004) for north-central Louisiana (grey line) and a seven-point moving average (black line) emphasizing the lower frequency variability in drought, (bottom, black bars) fires per decade, (**d**) Raw ring-widths from dead (dark grey lines) and living (light grey lines) trees, with annual mean (black line). Dashed line represents the annual sample depth of the growth chronology.

during dormant season fires showed near equal percentages compared to scarring from growing season fires. The 10 years with the highest percentage of trees scarred were all late-growing season events and occurred between 1827 and 1886. The highest percentage of trees scarred during a fire event was 46% (1862), followed by 43% (1877) – again, both late-growing season fires. Reconstructed drought conditions for both of these years showed normal conditions. Percentage of trees scarred was not correlated with drought conditions and generally decreased as conditions departed (in either direction) from normal (PDSI = 0) (Fig. 5). Beginning in approximately 1800, the percentage of trees scarred generally trended upward (Fig. 4). Prior to this date, the mean percentage of trees scarred during fire events was 8.9% while afterwards it was 16.3%.

Fire scars of all seasons were represented in the fire scar record (Table 1, Fig. 5). For all scars, approximately two-thirds occurred during the growing season. Of the growing season fires, most (approximately 88%) were late-growing season events represented by fire scars in the latewood ring position. Early-growing season scars were least represented in the record ($n = 2$), followed equally by mid-growing season scars (middle earlywood, $n = 6$; late earlywood, $n = 6$). All fire seasonality types were most frequent during normal climate conditions (Fig. 5). Only late-growing season fires ($n = 10$) occurred between 1745 and 1786 (two undetermined seasonality scars occurred in this period). For any individual fire event year, the seasonality indicated by different trees was mostly in agreement, however, for 10 years fire seasonality differed between trees. Seasonality disagreements between trees were most commonly represented as latewood and dormant season fire scar positions.

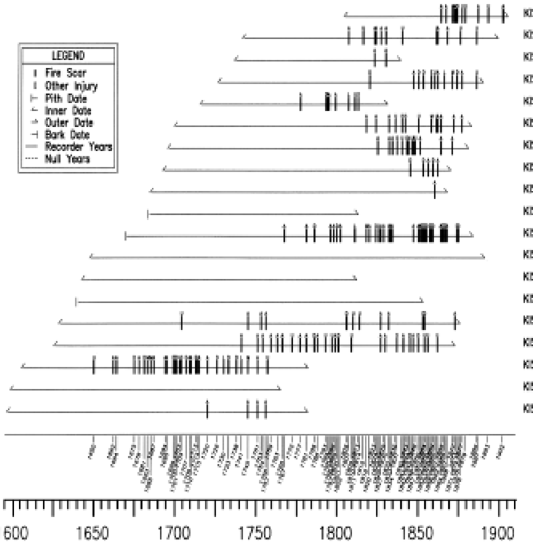

Fig. 4. Fire scar history chart from the Kisatchie Hills Wilderness Area, Kisatchie National Forest, Louisiana. Each horizontal line represents the length of the tree-ring record of a remnant longleaf pine sample tree. Bold vertical bars represent the year of a fire scar, with the season of the injury coded above each bar (D = dormant season scar, U = undetermined season scar, E = early earlywood scar, M = middle earlywood scar, L = late earlywood scar, A = latewood scar). The composite fire scar chronology with all fire scar dates is shown at the bottom of the figure. Years of biannual burning (i.e. two fire scars in 1 year) occurred in 1700, 1826, 1852, 1853, 1867, 1872. Bold vertical bars for these events are not shown.

No significant relationships were found between the year of fire events and drought conditions. SEA suggested that fire event years were not significantly drier or wetter than normal, including tests of lagged effects (i.e. climate conditions prior to and following the fire year). Of the extreme drought years (i.e. PDSI < 3.0), 48% had fires. A frequency distribution of the percentage of trees scarred by PDSI resembled a normal distribution (Fig. 5). Similarly, the frequency of fire events by PDSI class and seasonality appeared normally distributed.

Discussion

Over the last 30 years, fire scar history data have become increasingly available and utilized by end-users, many of whom are unfamiliar with the intricacies of fire scar history methods and data. For these reasons, we have included as much information as possible that portrays the data or interpretation presented (e.g. investigator expertise, field notes, sample conditions). One concern with these data is likely the low overall sample size, particularly in the early portion of the fire record. Sample size (and other factors; size of area sampled) can potentially influence rates of fires documented (Van Horne & Fulé 2006). This may be particularly important to fire histories, such as longleaf pine where highly asynchronous scarring exists between trees and perhaps more

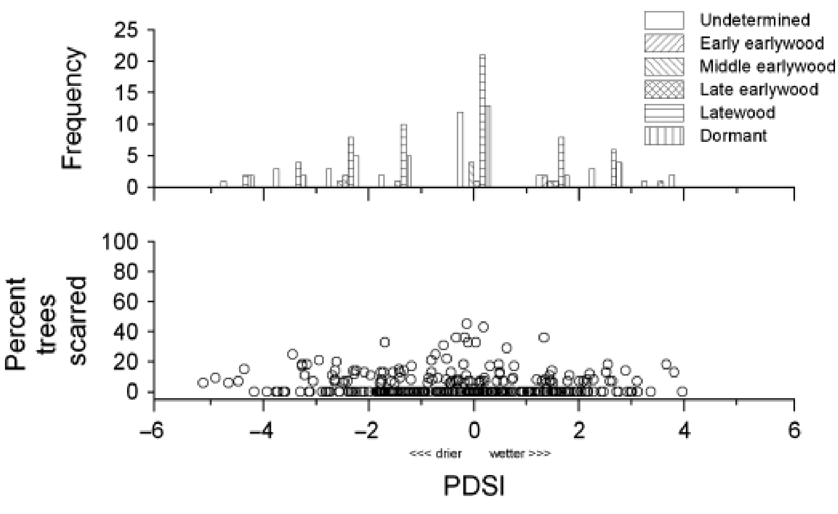

Fig. 5. (Top) Frequency distributions of scar seasonality by Palmer Drought Severity Index (PDSI) class. Groups of seasonality (coded bars) shown as midpoints of eight PDSI classes: $x \leq -4$, $-3.9 \leq x \leq -3.0$, $-2.9 \leq x \leq -2.0$, $-1.9 \leq x \leq -1.0$, $-0.9 \leq x \leq 0.9$, $1.0 \leq x \leq 1.9$, $2.0 \leq x \leq 2.9$, $3.0 \leq x \leq 3.9$, $x \geq 4.0$. (Bottom) Scatter plot of percentage of trees scarred during fire events by PDSI. Percentages were calculated for fire event years with more than five trees in the record.

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samples could contribute new fire dates. From our experience, longleaf pines have potential to be very good recorders of historic fire conditions under certain conditions (topographic, stem size, existing open wound) and likely other contributing factors exist (species associations, time periods). In contrast, it has been documented that frequently burned stands of longleaf pine show little to no scarring. For these reasons, this record (and others) should be interpreted with caution, and fire intervals (frequencies) considered as potentially maximum intervals, since some fire events may not have been captured.

Confirmation of long-term frequent fire in Gulf Coast longleaf pine

Regardless of the potential for fires to be missing from our record, the fire scar chronology for the Kisatchie Hills represents the most frequent long-term fire regime yet documented for longleaf pine or the southeastern USA. Within the spatial extent of our samples ($\sim$1.2 km^2), the mean fire interval was 2.2 years for a 254-year period (1650 to 1905) – a fire frequency in agreement with or slightly shorter than coarse-scale mapped estimates for the region (e.g. Frost 1998; Guyette et al. 2006).

Only four fire history studies are known in the range of longleaf pine. Bale (2009) reported similar pre- and post-EuroAmerican fire frequencies to this study for longleaf pine forests located in the mountains of northern Alabama (ca. 650 km east of the study site). Huffman (2006) found a mean fire interval of 3.2 years (1678-1868) in a Florida coastal savanna (ca. 750 km southeast of the study site). Other studies in the coastal plain [e.g. Huffman et al. (2004) (ca. 750 km southeast of the study site), Henderson (2006) (sites primarily to the east in the Coastal Plain)] reported slightly longer fire intervals than these studies. Outside of the longleaf pine ecosystem, only a few locations in the USA have documented a sustained high fire frequency (i.e. $\leq$ 3 yr) spanning two centuries or more within a comparable study area [e.g. Mogollon Rim, Arizona (Van Horne & Fulé 2006), southern Illinois (McClain et al. 2010)].

We hypothesize that in certain locations, longleaf pine may have excellent potential for documenting multi-century fire history, despite the species' high resistance to scarring. Marginal longleaf pine lands, such as the rugged Kisatchie Hills, the southern Appalachians or perhaps riparian areas, may hold important fire regime information (temporal variability in intervals, severity, frequency, fire–climate interactions, longleaf growth response and survival) not otherwise attainable from the lower Coastal Plain region. It is generally believed that the lower Coastal Plain, particularly longleaf pine–wiregrass systems, burned as or more frequently than upland and montane longleaf pine (Frost 1998). In light of the high fire frequency found in this study, new questions arise concerning plausible fire regime characteristics for other portions of the longleaf pine ecosystem, particularly those areas with gentler topography and larger fire compartments, or that were in closer proximity to major Native American population centres. Following Frost (2006), smaller fire compartments likely burned less frequently than larger ones because the ignition frequency increases with compartment size. Based on this suggestion, we hypothesize that Coastal Plain regions could have historically burned more frequently than found in the Kisatchie Hills or found by Bale (2009) in the southern Appalachians.

New findings

One value of studies documenting long-term changes in fire is the illumination of temporal variability. Arguably as important as average burning frequency is the long-term variability in fire intervals. Fire intervals ranged from 0.5 to 12 years during the full period examined. To our knowledge, biannual burning has not been previously documented through fire scars, although it was observed long ago along the Gulf Coast (Ilkin 1841). Biannual burning may be limited to regions where: (1) fuels can be replenished twice per year, (2) climate conditions are suitable for two fire seasons or a continuous fire season, and (3) ignitions (natural or anthropogenic) are not limited during different seasons. All but 1 year of biannual burning occurred in the 19th century, implicating humans, specifically EuroAmericans, in both frequent burning and biannual burning. This supports Heyward's (1939) speculation that settlers burned longleaf pine areas more frequently than Native Americans.

Despite having a relatively small sample size, several interesting patterns are suggested by the temporal variability in the fire regime. Generally, the frequency of fires increased from 1650 to 1880; however, a step-up increase in fire frequency occurred beginning about 1790. This transition was likely due to increased anthropogenic burning due to its coincidence with rapid increases in population. A rapid influx of settlers occurred during this period due to the Spanish governor's opening of the Natchitoches colony to US immigration prior to the Louisiana Purchase (Burton & Smith 2008). The Natchitoches population tripled during the Spanish rule, reaching 900 residents by 1803, while the state population nearly doubled during the same period (Coulson & Joyce 2003). Despite fires burning every 2 to 5 years in the decades prior to 1790, for fire frequency to increase abruptly circa 1790 and burn every 1 to 2 years suggests that the fire regime was in an ignition-limited stage,

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whereby more ignitions result in more fires. Stages of anthropogenic fire regimes were proposed by Guyette et al. (2002) and have since been considered in other locales (McEwan et al. 2007; Pausas & Keeley 2009; Aldrich et al. 2010). Interestingly, our results suggest that despite very frequent burning, there is no evidence that the fire regime reached a fuel-limited stage (i.e. more ignitions does not result in more fires because lack of fuel limits fire occurrence). Our results suggest that in very productive environments, such as within the range of longleaf pine, a fuel-limited stage of fire regimes may not occur without being burned very frequently (e.g. annually or more frequently).

In addition to temporal changes in fire frequency, the fire scar record demonstrates that fire seasonality was not static through time, but was variable and represented by all seasons with fires, albeit dominated by late-growing season fires. Particularly interesting is the late-18th century, when fires appeared to be nearly exclusively late-growing season events. Henderson (2006) reported primarily ($>$ 70%) dormant season fires occurring at Big Thicket (Texas); however, about two-thirds of these fires occurred during the 20th century. In the same study, fire events documented from Eglin Air Force Base (Florida) showed a mixture of early-growing season, late-growing season and dormant fire seasonality. Nearby, primarily mid-growing season fires occurred on the Florida Gulf coast and at a site on a barrier island (Huffman et al. 2004; Huffman 2006). Bale (2009) found a dominance of dormant season fires at montane longleaf pine sites in Alabama. A local pinning or micro-coring experiment is needed to precisely determine seasonal wood formation alignment with calendar months (Mäkinen et al. 2008), and therefore the seasonal timing of fire scars. However, even with this information, potential exists for year-to-year variability due to climate conditions and phenology. Generally, earlywood formation initiates in late February to March and latewood formation is completed by November or December. Huffman (2006) found similar monthly correspondence with growth ring zones observed in longleaf and slash pines growing on the Florida panhandle coast.

Locations of our remnant samples and an absence of living longleaf pine trees suggests that the species has declined in riparian locations within the study area. We found many samples (in situ) with fire scars located in sandy riparian areas, and remnant dead standing fire-scarred pines that germinated in the 17th century located within 5 m from live and apparently recent bald cypress trees and knees (Fig. 2). This is not unusual since in the Southeast, mesic and wet longleaf pine savannas constitute the communities most sensitive to fire suppression. With reduction in fire frequency, they are rapidly invaded by loblolly pine and hardwoods. Logging of the original longleaf pine, in combination with fire exclusion, often resulted in rapid and complete replacement by loblolly pine and dense, multistoried hardwoods. The resulting dense shade can lead to complete exclusion of the original fire-dependent savanna herb layer, and this has been the fate of the some 97% of the southeastern landscape from which longleaf pine has been eliminated (Frost 2006). This may explain the presence of old, longleaf pine stumps in bottomlands at our study site, now transformed to loblolly pine and hardwoods.

Based on this study, there likely still remains a detailed and ecologically significant body of fire history information preserved in fire-scarred remnant trees of longleaf pine. Long-term dynamics and characteristics of very frequent fire regimes (i.e. $\leq$ 3 yr) are largely unknown, but could broaden perspectives on factors influencing the fire environment when there are short time intervals between events and fast rates of fuel production. This information likely has much bearing on current fire science concepts, such as the importance of fuel type and production rate in controlling fire frequency, or the relevant temporal scale for investigating fire–climate interactions.

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References

Aldrich, S.R., Lafon, C.W., Grissino-Mayer, H.D., DeWeese, G.G. & Hoss, J.A. 2010. Three centuries of fire in montane pine–oak stands on a temperate forest landscape. *Applied Vegetation Science* 13: 36–46.

Bale, A.M. 2009. *Fire effects and litter accumulation dynamics in a montane longleaf pine ecosystem*. M.S. Thesis, University of Missouri-Columbia.

Bowman, D.M.J.S. 2007. Fire ecology. *Progress in Physical Geography* 31: 523–532.

Bridges, E.L. & Orzell, S.L. 1989. Longleaf pine communities of the West Gulf Coastal Plain. *Natural Areas Journal* 9: 247–263.

Burns, A.C. 1994. *A history of the Kisatchie National Forest*. USDA Forest Service, Pineville, LA, US.

Burton, H.S. & Smith, F.T. 2008. *Colonial Natchitoches: a creole community on the Louisiana–Texas frontier*. Texas A & M University Press, College Station, TX, US.

Cook, E.R. & Kairiukstis, L.A. 1990. *Methods of dendrochronology: applications in environmental science*. Kluwer Academic, Dordrecht, NL.

Cook, E.R., Meko, D.M., Stahle, D.W. & Cleaveland, M.K. 2004. *North American summer PDSI reconstructions*. World Data Center for Paleoclimatology Data Contribution Series #2004-045. Available at: http://www.ncdc.noaa.gov/paleo/newpdsi.html. Accessed 28 May 2009.

Coulson, D.P. & Joyce, L. 2003. *United States state level population estimates: colonization to 1999*. USDA For. Serv. Gen. Tech. Rep. RMRS-111, 55pp.

Earley, L.S. 2004. *Looking for longleaf: the fall and rise of an American forest*. University of North Carolina Press, Chapel Hill, NC, US.

Frost, C.C. 1993. Four centuries of changing landscape patterns in the longleaf pine ecosystem. In: *The longleaf pine ecosystem: ecology, restoration and management*. (ed.) Hermann, S.M. pp. 17–43. Proceedings Tall Timbers Fire Ecology Conference No. 18 Tall Timbers Research Station, Tallahassee, FL, US.

Frost, C.C. 1998. Presettlement fire frequency regimes of the United States: a first approximation. In: Pruden, T.L. & Brennan, L.A. (eds.) *Fire in ecosystem management: shifting the paradigm from suppression to prescription*. pp. 70–81 Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tall Timbers Research Station, Tallahassee, FL, US.

Frost, C.C. 2006. History and future of the longleaf pine ecosystem. In: Jose, S., Jokela, E.J. & Miller, D.L. (eds.) *The longleaf pine ecosystem – ecology, silviculture, and restoration*. pp. 9–48. Springer, New York, NY, US.

Fulé, P.Z., Villanueva-Diaz, J. & Ramos-Gomez, M. 2005. Fire regime in a conservation reserve in Chihuahua, Mexico. *Canadian Journal of Forest Research* 35: 320–330.

Grissino-Mayer, H.D. 2001a. FHX2-Software for analyzing temporal and spatial patterns in fire regimes from tree rings. *Tree-Ring Research* 57: 115–124.

Grissino-Mayer, H.D. 2001b. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-Ring Research* 57: 205–221.

Guyette, R.P., Muzika, R. & Dey, D.C. 2002. Dynamics of an anthropogenic fire regime. *Ecosystems* 5: 472–486.

Guyette, R.P., Dey, D.C., Stambaugh, M.C. & Muzika, R. 2006. Fire scars reveal variability and dynamics of eastern fire regimes. In: Dickinson, M.B. (ed.) *Fire in eastern oak forests: delivering science to land managers*. pp. 20–39. USDA Forest Service General Technical Report NRS-P-1, USDA Forest Service, Newtown Square, PA, US.

Haywood, J.D. 2007. Restoring fire-adapted forested ecosystems – research in longleaf pine on the Kisatchie National Forest. In: Powers, R.F. (ed.) *Proceedings of the 2005 National Silviculture Workshop*. pp. 87–105. USDA Forest Service General Technical Report PSW-GTR-203, US Forest Service, Albany, CA, US.

Haywood, J.D. & Grelen, H.E. 2000. Twenty years of prescribed burning influence the development of direct-seeded longleaf pine on a wet pine site in Louisiana. *Southern Journal of Applied Forestry* 24: 86–92.

Henderson, J.P. 2006. *Dendroclimatological analysis and fire history of longleaf pine (Pinus palustris Mill.)in the Atlantic and Gulf coastal plain*. PhD Dissertation, University of Tennessee-Knoxville.

Henderson, J.P. & Grissino-Mayer, H.D. 2009. Climate–tree growth relationships of longleaf pine (*Pinus palustris* Mill.) in the southeastern Coastal Plain, USA. *Dendrochronologia* 27: 31–43.

Heyward, F. 1939. The relation of fire to stand composition of longleaf pine forests. *Ecology* 20: 287–304.

Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurements. *Tree-Ring Bulletin* 43: 69–78.

Huffman, J.M. 2006. *Historical fire regimes in southeastern pine savannas*. Ph.D. Dissertation, Louisiana State University and Agricultural and Mechanical College, Baton Rouge, LA, US.

Huffman, J.M., Platt, W.J., Grissino-Mayer, H.D. & Boyce, C.J. 2004. Fire history of a barrier island slash pine (*Pinus elliottii*) savanna. *Natural Areas Journal* 24: 258–268.

Ilkin, A. 1841. *Texas: its history, topography, agriculture, commerce, and general statistics*. Reprint (1964) Texas Press, Austin, TX, US.

Johnson, R. & Gjerstad, D. 2006. Restoring the overstory of longleaf pine ecosystems. In: Jose, S., Jokela, E.J. & Miller, D.L. (eds.) *The longleaf pine ecosystem: ecology, silviculture, and restoration*. pp. 271–295. Springer, US.

Kaye, M.W. & Swetnam, T.W. 1999. An assessment of fire, climate, and Apache history in the Sacramento Mountains, New Mexico. *Physical Geography* 20: 305–330.

Mäkinen, H., Seo, J.-W., Nöjd, P., Schmitt, U. & Jalkanen, R. 2008. Seasonal dynamics of wood formation: a comparison between pinning, microcoring, and dendrometer measurements. *European Journal of Forest Research* 127: 235–245.

McClain, W.E., Esker, T.L., Edgin, B.R., Spyreas, G. & Ebinger, J.E. 2010. Fire history of a post oak (*Quercus stellata* Wang.) woodland in Hamilton County, Illinois. *Castanea* 75: 461–474.

McEwan, R.W., Hutchinson, T.F., Long, R.P., Ford, D.R. & McCarthy, B.C. 2007. Temporal and spatial patterns in fire occurrence during the establishment of mixed-oak forests in eastern North America. *Journal of Vegetation Science* 18: 655–664.

Meldahl, R.S., Pederson, N., Kush, J.S. & Varner, J.M. 1999. Dendrochronological investigations of climate and competitive effects on longleaf pine growth. In: Wimmer, R. & Vetter, R.E. (eds.) *Tree ring analysis: biological, methodological and environmental aspects*. pp. 265–285. CABI, Wallingford, UK.

National Climate Data Center (NCDC). 1999. Monthly surface data. National Climate Data Center, Asheville, North Carolina, USA. Available at: http://www.ncdc/noaa.gov/. Accessed January 2010.

Orville, R.E. & Huffines, G.R. 2001. Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–1998. *Monthly Weather Review* 29: 1179–1193.

Paine, W.R. & Meyerhoff, A.A. 1968. Catahoula formation of western Louisiana and thin-section criteria for fluviatile depositional environment. *Journal of Sedimentary Petrology* 38: 92–113.

Pausas, J.G. & Keeley, J.E. 2009. A burning history: the role of fire in the history of life. *Bioscience* 59: 593–601.

Stokes, M.A. & Smiley, T.L. 1968. *Introduction to tree-ring dating*. University of Chicago Press, Chicago, IL, US.

Swetnam, T.W., Allen, C.D. & Betancourt, J.L. 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications* 9: 1189–1206.

USDA Forest Service. 1965. *Southern wood density survey: 1965 status report*. USDA Forest Service Research Paper FPL-26 USDA Forest Service, Madison, WI, US.

Van Kley, J.E. 1999. The vegetation of the Kisatchie sandstone hills, Louisiana. *Castanea* 64: 64–80.

Van Horne, M.L. & Fulé, P.Z. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern USA ponderosa pine forest. *Canadian Journal of Forest Research* 36: 855–867.

Van Lear, D.H., Carroll, W.D., Kapeluck, P.R. & Johnson, R. 2005. History and restoration of the longleaf pine–grassland ecosystem: implications for species at risk. *Forest Ecology and Management* 211: 150–165.

Walker, J. 1993. Rare vascular plant taxa associated with the longleaf pine ecosystems: patterns in taxonomy and ecology. In: Hermann, S.M. (ed.) *Proceedings of the Tall Timbers Fire Ecology Conference, No. 18*. pp. 105–125. Tall Timbers Research Station, Tallahassee, FL, US.

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